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NASA SP-5038

TECHNOLOGY SURVEY

Technology Utilization Division

MAGNETIC TAPE RECORDING

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By Skipwith W. Athey, Ph. D.

(Prepared Under Contract NASw-945)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

The Administrator of the National Aeronautics and Space Administration has established a technology utilization program for "the rapid dissemination of information . . . on technological developments . . . which appear to be useful for general industrial application." From a variety of sources, including NASA Research Centers and NASA contractors, space-related technology is collected and screened; and that which has potential industrial use is made generally available. Information from the nation's space program is thus made available to American industry, including the latest developments in materials, processes, products, techniques, management systems, and analytical and design procedures.

Magnetic tape recorder technology differs somewhat from the technology of some of the other fields that are being covered. The magnetic tape recorder is a highly developed device and its detailed technology is hidden below a thick layer of practical engineering design. It is therefore difficult to extract technology per se from the tape recorder field, nor would this be very useful under the objectives of the survey program. Hence, this particular survey does not deal to as great extent as some others with specific details of technology but broadly covers two aspects of the applied technology in the development of which NASA has participated.

One area of technology which is specifically NASA sponsored is that which has led to the development of miniature severe-environment tape recorders for satellite and space probe use. In this area NASA has directly sponsored innovation, emphasizing reliability if not new concepts. The biggest dollar impact of NASA work on tape recorder technology has been as a major customer for commercial ground-based tape recorders for telemetry data acquisition and related purposes. It would be impossible to extract NASA's specific contributions to data acquisition and data reduction technology from the mass of application lore and knowhow which has been built up in this area. As a major customer, however, NASA has had a strong indirect influence on the recorder development that has taken place through purely commercial channels. This survey, therefore, discusses the entire range of recorder technology with emphasis on the miniature high environment recorder and work in which NASA may be seen to have had a major influence.

THE DIRECTOR, *Technology Utilization Division*
National Aeronautics and Space Administration

Acknowledgments

Ideally, a survey is complete and precise; this one is neither as complete nor as precise as I would have liked to make it. Some of its shortcomings can be charged to the difficulty of obtaining information in time to include it. The "cut-off date" of the information is uneven; the average cut-off date was toward the end of 1964 although some 1965 information is included. Other faults, however, involving sins both of commission and omission, are chargeable only to the particular approach I have taken and for which I must accept full responsibility.

Thanks are naturally due to the NASA contractors and subcontractors who have cheerfully supplied information. Equal thanks are due to those recorder manufacturers who, although not specifically suppliers of new recorder technology under contract to NASA, have given the writer much information about their techniques.

The following organizations have been of considerable help in supplying information in general terms: Ampex Corporation, Mincom Division of the Minnesota Mining and Manufacturing Company, Consolidated Electrodynamics Corporation, Sangamo Electric Company, Genisco Data, Borg-Warner Controls, Tech-Center Division of Cook Electric Company, College Hill Industries, Leach Corporation, Precision Instrument Company, Radio Corporation of America, Astro-science Corporation, Lockheed Electronics Company, Ralph M. Parsons Company, Raymond Engineering Laboratory, Inc., and of course, the Jet Propulsion Laboratory of the California Institute of Technology.

In the course of performing this Survey, I visited Goddard Space Flight Center, Lewis Research Center, the George C. Marshall Space Flight Center, the Manned Spacecraft Center, Langley Research Center, Wallops Station, and the Flight Research Center. The cooperation and assistance, particularly of the Technology Utilization Offices of these Centers was es-

sential to the accomplishment of this task. It is perhaps appropriate to single out Mr. Pleasant T. Cole, manager of the Recording Techniques Group at Goddard Space Flight Center, whose original persistence led to the preparation of this Survey; Mr. John Warden of the Patent Office at Jet Propulsion Laboratory, who somehow managed to obtain contractor data in quantities well beyond my expectations from the Jet Propulsion Laboratory files, and Mr. Leonard Ault of the Congressional Relations Office of Goddard Space Flight Center for his tireless efforts in digging out other information from NASA files.

SKIPWITH W. ATHEY

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CHAPTER 1

Introduction

NASA's contribution to tape recorder technology may appear to lie in such glamorous devices as the tape recorders of the Tiros and Nimbus satellites which receive signals carrying weather information during an orbit around the earth and then transmit those signals back to the ground when the satellite is in view of ground stations. These quite important recording devices are, however, only useful as members of a complex hierarchy of devices all of which participate in the ultimate process of obtaining information from NASA's efforts. Their existence and utility is based on the existence of many more prosaic recording devices which have been involved in the development of such spectacular units.

Satellite recorders must operate without maintenance, must show great reliability, and must consistently deliver performance closely related to the needs of the program in which they are used. Such recorders must be conservatively designed and exhaustively tested. They invariably sacrifice peak of state-of-the-art performance for reliability and the ability to exist in unfriendly environments. The development of such recorders represents the combination of considerable effort by many manufacturers and government laboratories, but the average home hi-fidelity fan can purchase for $150.00 in a local furniture store a recorder which appears to have considerably higher performance specifications. The differences in environment and reliability are responsible, of course, for this peculiar situation.

The output of one of the specialized satellite or space probe recorders will invariably be recorded on the ground by a commercial instrumentation recorder of conservative design but of considerably higher performance than the device in the satellite. The output of this ground recorder will be reproduced and analyzed again and again through the use of further conventional commercial recorders.

In the development of almost every single piece of NASA hardware of any degree of complexity beyond a single bolt and nut, conventional or commercial magnetic recorders have been involved. Quantities of data have been collected from tests in the laboratory, at ground test sites, in static firing tests, in ballistic vehicle firings, and in preliminary orbital shots leading to the development of the complete booster/satellite combinations now in use. The use of magnetic recording in the development process far outweighs the amount of recording done either on the ground or in flight in satellite or space probe programs.

It is as a major user, directly and indirectly, of such test recording procedures, that NASA has made its real contribution to tape recorder technology. As a most demanding customer with almost unlimited requirements in magnetic recording, NASA, its contractors, its subcontractors, and its sub-sub-contractors have represented a great part of the market influence which has encouraged the development of recorders of improved performance by commercial manufacturers. In this role lies NASA's greatest importance as a supporter of tape recorder technology.

It would be impossible to extract and present in an organized manner the mass of knowhow that NASA and its contractors have obtained about the use of magnetic recording. Occasionally a specific development can be traced to the needs of a particular NASA program but, as often as not, other government programs, directly or indirectly, have had sufficiently similar requirements that it is difficult to separate the NASA influence from that of other organizations. It was to deal somehow with this massive NASA influence that the format of the present Technology Survey was evolved.

The entire range of current tape recorder technology is presented here in survey and outline form. Except in isolated cases, no attempt is made to say that NASA has been responsible for this or that aspect of the commercial recorders currently available. It is believed that the technology for the acquisition of which NASA is at least in part responsible can best be made available to industry by presenting a broad view of the current state of the art. Both to the user and to the potential designer of sophisticated magnetic recording equipment such a survey should provide some assistance. It is hoped that the user will be made sufficiently aware of the capabilities and limitations of magnetic recording that he can make proper system decisions in his utilization of magnetic recording. To the designer this report may not seem as sophisticated a document as it will to the user, but it may, by emphasizing the user's problems and interest, guide in some small measure the development of new recording instruments. In specific instances, the breadth of the survey will make it possible to present material not adequately presented previously in either periodical or textbook literature. Although not exhaustive, the coverage has been designed to be complete enough to give warning where problems of development or extension of recording capabilities may exist.

The purpose of magnetic recording is to receive electrical signals of a wide variety and to record and store those signals in a form which allows their accurate reproduction at a later time. The ideal recorder is one for which the only difference between the electrical signal received by the recorder and that reproduced by the reproducer is the gross time delay between recording and reproduction. All the characteristics of the electrical signal should be preserved perfectly.

To describe the accuracy of reproduction, the same terms may be used that are used to describe the accuracy of transmission of an electrical signal through some transmission means. Typically, such transmission is described in terms of signal-to-noise ratio, bandwidth, and distortion of various types, including both phase and amplitude. Of relatively small importance in most transmission systems is any disturbance of the time scale of the signal, although such disturbances are encountered in sky wave radio transmission and VHF transmission subject to variable diffraction. Time scale disturbances are, however, inherent in any recording process.

The state of the recording art can thus be described in terms of the standard electrical characteristics of the transmission system, to which must be added specification of disturbances of the time scale of the input signal. As in most complex systems, the various electrical performance characteristics as well as the time scale disturbance are interrelated in the typical recording system. Likewise, almost every element involved in the recording part of the process and the mechanism transporting the recording medium has some effect on all the characteristics by which the performance of the overall system is described.

In addition to the effect of the recording and reproducing process on the signals handled as in a transmission system, the storage process has another dimension. This dimension is the volume of storage medium required to preserve a signal or signals of particular performance characteristics and lasting for a given length of time. This storage volume parameter is supplementary to the "nonsignal" parameters which recording shares with other transmission systems. Such nonsignal parameters include volume, power consumption, and physical dimensions as well as weight.

The presentation of the recording art is made for several purposes, including advising the reader what he may find available in the way of capabilities of solving his recording problems as well as the tutorial purpose of establishing the design principles which have led to this current state of the art. To accomplish both these purposes, the survey presentation is organized at several levels. Initially the interrelationship between the elements of the process and the effects on recording performance will be described in general terms. The several elements of the recording process will be separated and characterized in general terms. Under each of these elements the basic design principles will be presented, and in this process, the effect of the elements on performance will be analyzed. Where necessary, separate analyses will be presented of the relationship between process elements which cannot actually be separated in such a straightforward manner. At the conclusion of this synthetic process a final presentation of complex complete recording systems will be made, and these complex systems will be analyzed to show design philosophy, information flow, and the complex tradeoffs necessary between the various elements of a complete recording system.

CHAPTER 2

The Field of Magnetic Recording

It would be neither practical nor appropriate to include in this survey, in detail, every current application of magnetic recorders—impractical because the field is too wide, inappropriate because this NASA-supported study should not range too far from NASA's specific interests in recorders. To place NASA's areas of greatest concern in perspective, this initial section will, however, contain a brief description of the entire broad field of recording applications. In light of the background so presented the selection of the parts to be covered in detail on the basis of NASA's interests and uses will then be discussed.

Covering in detail only selected types of recorders and recorder applications will fortunately not result in the omission of any important technology. The field of magnetic recording contains such internal relationships that all important aspects of recorder technology will necessarily be covered in describing the relatively limited area in which NASA is interested. There will be, however, one deliberate omission—rapid start/stop mechanisms for tape transports to be used as memories for digital computers will not be covered, on the basis that their technology is in no way NASA-inspired.

ENTERTAINMENT RECORDING

Magnetic recording first made a name for itself in the field of sound entertainment (broadcasting and disk recording). Wire recorders had extensive use as "electronic notebooks" in World War II, and crude metal-tape recorders were used for such special applications as 1-minute voice recorders for speech training in the 40's. Not until modern tape made of plastic and oxide became available and ac bias made improved signal-to-noise ratio and fidelity possible did magnetic recording have any impact on broadcasting and professional sound recording. The reusability of magnetic tape, the high signal-to-noise ratio it provided (originally seeming almost limitless), and the opportunity it gave for simple editing made tape appear to be the answer to nearly every sound recording problem. Although disillusion set in after the initial enthusiasm and few of the potentials of tape proved to be as great as originally predicted, the net utility and performance level of the magnetic recorder has continued to increase over the years. It has not displaced the disk record and may very well never do so, but it is now essential to the modern field of high-fidelity disk recording. Although the tape signal-to-noise ratio has proved not to be limitless and, about 3 or 4 years ago, appeared to be the factor setting an absolute upper limit to the utility of magnetic tape for sound, recent developments have lowered the noise barriers once more and even greater signal-to-noise ratio is now available.

The development of the use of magnetic recording for sound naturally branched into two paths. One path led to the home recorder used by the enthusiast to record sounds generated by him or his musical (or other) friends or to record sound radio broadcasts. With the increased availability of such recorder/reproducers in the home, the market for commercially prerecorded tape has developed until it is now a major factor in the United States entertainment market. A wide range of recorders for such application is available, from extremely crude battery-operated units costing a few dollars to equipment which, at least in its nominal specifications, has performance equivalent to that of professional recorders. Except for the crudest of such recorders, they all follow the same mechanical scheme. They differ in such sometimes controversial refinements as the use of torque motors for supply and takeup reeling rather than less expensive clutches or brakes of nominally poorer performance. The current amateur recorder is, on casual examination, clearly related in mechanical scheme to the first post-World-War-II professional audio recorders; it may not, however, approach even the earliest models in refinement and performance.

The other main path of development of the entertainment sound recorder was directed to professional use. Except for minor variations, this development has consisted of refinement of basically the same recorder that was introduced immediately following World War II. Those early recorders were used for recording radio broadcasts for later scheduling, and for recording the master tapes from which disk records would later be made. Such recorders could be used for editing their own tapes and the science and art of editing tape by physically cutting and splicing it reached a high degree of refinement. Within this general field, specialization has naturally taken place; semiportable equipment is available for broadcast recording in the field and bulky equipment of extremely high performance has been developed for production of master tapes in the studio.

The first magnetic sound recorders of 1946–47 were close copies of the German broadcast equipment developed during World War II (Hansell [1945]) (Ranger [1947]) (Lindsay and Stolaroff [1948]). They delivered quite satisfactory tape moving performance for applications where the human ear was the judge of the smoothness of tape motion and there has therefore been little encouragement for improvement in sound recorder mechanical design. The parallel development of magnetic recording for sound in motion pictures used the same mechanisms as were already in use for motion picture optical sound tracks, and such mechanisms are in use to this day. The relatively stiff sprocketed film is simply coated with magnetic material and placed in basically the same mechanisms that were developed for optical recording (Miller [1947]). Attempts have been made to apply this motion-picture based technique of sprocketed tape handling to instrumentation recording without much success. Interestingly enough, a part of the motion picture recording technique was carried over later to instrumentation recorders but in such a form that, although the parent equipment and its descendants resemble each other physically, they do not really operate on the same principles.

INSTRUMENTATION RECORDINGS

It was soon obvious that, by simply running the tape faster, sound recorders could be adapted for the recording of scientific information in analog form. For scientific use one does not usually know what the spectrum of the signal to be recorded will be, so it is necessary to expect any signal amplitude at any frequency. The high-frequency preemphasis which contributed heavily to the signal-to-noise ratio of sound recording was therefore not usable for scientific applications. The signal-to-noise ratio achieved by early instrumentation recorders was naturally much worse than would have been expected by scaling up from the sound recorders which preceded them.

By modern standards, the first instrumentation recorders were rather crude. The signal-to-noise ratios were marginal for many applications and they had a lot of flutter. This flutter included some at relatively low frequencies which might have bothered the audio user and, with higher bandwidths, the high-frequency flutter originating in tape scrape and in the vibration from unsupported tape also became important. These early recorders, nevertheless, made possible the acquisition of data which previously had been inaccessible and they were hailed with enthusiasm. Certain of their shortcomings were, perhaps, inadequately evaluated. The broadening of the spectrum of a desired signal by the broadband flutter that was invariably present somehow did not seem important to many early users, and many early recordings may reproduce data signals which resemble the flutter characteristics of the recorder more closely than they do the characteristics of the instrument from which the data was acquired. Only recently has the subtle damage which this broadening of spectrum can do been fully understood and an intensive effort made to eliminate it (Ratner [1965]).

It was not long before the instrumentation user demanded recording equipment with better signal-to-noise ratio and with dc response. FM recording on the tape was then introduced to supplement direct or analog recording. Even with the relatively high flutter of early instrumentation recorders, FM recording offered advantages in signal-to-noise ratio and permitted obtaining dc response. Broadband flutter was, of course, the major limitation on the utility of FM recording, and flutter compensation techniques were soon devised (Peshel [1957]). These techniques removed a good deal of the noise produced by the flutter but left the initial flutter in the recovered data. It is only quite recently that this data flutter has received major attention. Flutter reduction has been the main mechanical design goal of instrumentation recorder designers. The original open-loop tape handling system borrowed from audio recording soon began to give place to so-called "tight-loop" tape drives which minimized the amount of unsupported tape and the consequent high-frequency flutter problems and provided improved isolation of the uniform tape motion from external disturbances (Schoebel [1957]).

As the use of instrumentation recording broadened, instrumentation engineers adapted new kinds of modulation to their systems for telemetering data. They became interested therefore in recording these new kinds of modulation. The tape recorder had to be able to deal with pulse amplitude modulation, pulse width modulation, and pulse position modulation as well as frequency modulation. More recently, pulse code modulation has acquired great importance for telemetering precise data, and more sophisticated pulse schemes such as pulse frequency modulation and single-sideband frequency modulation have come into use. The characteristics of instrumentation recorders had to be modified to deal adequately with such modulation schemes, and the instrumentation recorder has gradually become a complex modular assembly made up of a basic tape moving mechanism plus an almost limitless number of plug-in units to adapt the recorder to the many types of signals it must handle.

TRANSVERSE RECORDING

While in the middle 1950's sound recording for entertainment was developing in a straightforward nonspectacular way and the performance of instrumentation recorders was likewise slowly improving, the rotary-head recorder, developed to record entertainment television signals, suddenly appeared on the scene and made available greatly increased recording capability (Ginsburg [1957]). This recorder used transverse recording paths across a wide tape in order to obtain high head/tape speed without correspondingly high longitudinal tape speed. Because the signal recovered from the relatively narrow track used in this recorder was nonuniform in amplitude, a frequency modulation scheme was used. This modulation system violated all the normal rules of FM and could almost be proved by engineering calculations to be impossible (Anderson [1957]). However, the particular form of signal distortion which it produced did little damage to the visual effect of a television picture reproduced from such a modulation scheme. Since this visual effect was the ultimate criterion for evaluating this recording technique in its initial application, this "impossible" recording mode was quite successful. It made possible recordings with a bandwidth of greater than four megacycles and the instrumentation engineer soon attempted to apply this recorder to his requirements. In these more severe applications, the peculiar transfer characteristic of the "video recorder," quite satisfactory for television use, made it a relatively poor analog recorder but quite a good pulse recorder.

About the time that the video recorder became available for instrumentation use, interest developed in so-called predetection recording (Klokow and Kortman [1960]). In predetection recording a data signal is intercepted in the telemetry receiver IF before it has been passed through the final demodulator and is heterodyned down into a band which can be recorded directly on an instrumentation recorder. In simplest terms this scheme has the advantage that the instrumentation engineer gets a "second chance" in his choice of the demodulation mode with which he will recover his final data signal. When the received signal is marginal in quality it gives him an opportunity to derive the optimum amount of information by optimizing his second detector. Since frequency modulation is almost universally employed for the RF transmission link of telemetered data, the predetection recording is made from an FM carrier. The signal-to-noise ratio improvement of FM over AM then takes place after playback and the requirements on signal-to-noise ratio in the recorder are therefore not severe. Relatively low signal-to-noise ratios in predetection recorders are quite useful. More recently, the predetection technique has been applied where no existing recorder has the necessary characteristics to record the post-detection signal, i.e., in the case of single sideband frequency modulation of data onto the multiplex input to the telemetering transmitter.

Longitudinal tape speeds have been pushed up to 120 inches per second and the number of cycles recordable per inch has been greatly increased, and predetection recording is now done with both the rotary head and longitudinal recorder (Riley [1962]). The difficulty of eliminating the time base instability in the rotary-head recorder, resulting from switching its rotating heads four times per head drum turn, has somewhat delayed its acceptance for predetection recording. The linear recorder, now able at 120 inches per second to record a 1½ megacycle bandwidth, has almost monopolized the predetection field. The wider bandwidth of the rotary-head recorder is essential, however, for some predetection applications, and with newly developed time-stabilization and slow-switching techniques it now provides the best overall time stability of any recorder (±25 nsec) (Ampex [1964]).

DIGITAL RECORDING

The term "digital recording" is used here, in a somewhat inaccurate sense which it has acquired through extensive use, to cover magnetic recording in equipment peripheral to digital computers. "Digital recording" in the more general sense, i.e., the recording and reproduction of pulses which represent numbers in the typical digital computer format, is widely used in instrumentation recording. However, the digital recorder, in the sense of this particular subtopic, provides mass memory for a digital computer.

Since the digital computer operates on the principle that all the data with which it deals is in the form of binary numbers, every binary digit of each number has almost equal importance for the accuracy of the overall results of the computation. Although error-checking and error-correcting techniques are available, the data stored in the memories of a computer must be essentially perfectly accurate if the computer is to be successful. When magnetic tape recording is used for the mass memory function, it is required to conform to this rigid standard of accuracy. The design of a tape recorder for association with a computer must obviously be extremely conservative; the density with which digital computer data is recorded has lagged by 5 or 10 to 1 below the density used for other recording applications.

When the need for extensive mass memory for computers first became apparent, magnetic recording on drums and disks soon was applied to this service, and continues to be so applied to this day. The drum or disk produces a continuous flow of data, but any particular piece of data is not accessible at any particular instant; it becomes accessible when the drum or disk has turned. Computer systems and static electronic submemories were designed to complement drum and disk memories and deal with this inherent accessibility delay. Part of the requirements of such rotary memories were carried over to initial applications of tape memories. The tape memory of the recorder of a modern digital computer is typically used to "dump" relatively large masses of data either into a static electronic memory or into a subsidiary drum or disk memory, and, similarly, to accept a batch of data from one of the submemories in a relatively sporadic operation. An essential requirement of a computer tape transport is therefore the ability to start and stop very rapidly on command. A modern computer may operate at a bit rate from about 100 kilobits per second up to a megabit per second or higher. A delay in starting of a millisecond or two on the part of a tape transport represents the passage of a long time in computer operation. Digital tape recorders for computer use therefore typically start in between ½ and 10 milliseconds and stop in about the same length of time. The rapid stop is essential to efficient utilization of the tape area, since a longer stop period means that a larger area of the tape is not available for recording data.

Fast start/stop transport mechanisms for digital computers usually use storage columns in which the tape is retained by vacuum or, in some transports, by an array of rollers mounted on light movable spring-loaded arms which store a few feet of tape. These storage mechanisms provide a supply of tape to the heads and capstans while the relatively massive reels are being accelerated or take up the tape while they are being decelerated.

Several tracks (usually 7 to 16) are recorded across the width of digital computer tapes and, as the density of the recording on the tape goes higher, it becomes more difficult to maintain the proper time relationship between data spread across the various tracks. Fixed misalignment between head and tape produces "static skew," and other than perfect guiding of the tape as it passes the head results in "dynamic skew." Both effects damage the time relationships between the data on the several tracks. The reduction of dynamic skew remains a major problem in computer tape transports. The problem is so severe that formats are often designed to avoid insofar as possible requiring association of data distributed across the tape, and to favor distributing the data in a given "word" serially along an individual track. Complex local storage buffers have been designed to permit the data from various tracks to be stored locally at the relatively irregular rate at which it may arrive from the far-from-flutter-free tape transport so that, at the other end of the buffer, the local computer clock can move the data out at the precise rate the computer requires (Gabor [1960]).

AIRBORNE RECORDING

The term "airborne recording" is used here to cover the application of all those recorders, usually rather small and light, which must perform on aircraft, missiles, or satellites. Such recorders must operate unattended with great reliability and survive rather unfriendly environment. They generally have a balance between design factors quite different from those of equipment used in friendly environments on the ground. The term "airborne" is often not quite accurate because in quite a few applications recorders of this class do not fly in a vehicle of some sort but must meet all of the other requirements typical of "flying" conditions. The term is chosen for convenience rather than accuracy.

It was initially extremely difficult to provide any kind of reliable performance in unfriendly environments and early airborne recorders were extremely crude. But recorders for such programs now as Nimbus, OGO and OSO are quite impressive performers even by ground-based standards. Such superior performance is, however, the exception, and a deliberate choice is often made to minimize the performance requirements placed on the airborne recorder at the cost of placing more severe requirements on the ground recorder which will receive the playback from the airborne unit. Compensating means sometimes are also provided for correcting errors produced in the airborne unit to produce an overall data transmission link of a quality impossible to achieve otherwise.

THE SCOPE OF THIS SURVEY

The primary development of tape recorder technology for NASA use has been in the area of the small airborne high-reliability recorder. At the same time, NASA has been a major customer of ground-based equipment and NASA engineers and contractors have devised elaborate systems for sophisticated application of such ground-based equipment. In a deliberate and arbitrary way the scope of this survey is limited to these two fields.

By definition, therefore, the "high-fidelity" audio recorder is eliminated, but where audio recording is associated with instrumentation recording in the form of a voice monitor or a cue track it is included, at least by reference. That a bio-medical recorder for use in the Gemini program happens also to carry a voice track does not eliminate it from the survey. Nor are certain instrumentation recorders which can also be used for audio service eliminated on this arbitrary basis.

The digital recorder, in the sense of the fast-start/stop recorder for computer peripheral use, is specifically eliminated as being beyond the scope of the survey. Most of the technology of such recorders, except for the fast-start/stop mechanism itself is, however, covered.

The magnetic recorders covered in this survey include, naturally, not only the recorders developed specifically for NASA's uses but also commercially available units which NASA has purchased. These commercially available units include "off the shelf" items in the case of large ground-based recorders as well as airborne recorders developed for other services which have been purchased and used by NASA. In this discussion of recorder types no distinction will be made between those developed for and those simply purchased by NASA. The classification of recorders will be based on technical characteristics rather than sponsorship.

Recorders employed by NASA can be divided into two groups roughly on the basis of size and weight. One group of recorders is intended to be installed in a more or less fixed position on the ground. Such recorders can be large and heavy and are usually provided with fairly friendly environments during operation. The other large group of recorders for NASA's applications is made up of those which are air or space-borne. Such recorders are subjected to unfriendly environments in both operation and nonoperating modes, must be small and light, and must use very little power. Recorders of this second class are not accessible for maintenance or for changing the recording medium. They therefore must be extremely reliable and must provide operating modes which use and reuse the recording medium very effectively.

GROUND-BASED RECORDERS

The products of six manufacturers dominate the field of ground-based recorders currently purchased and installed. These recorders have basic similarities and differ only in certain performance figures and in the flexibility with which they may be applied to different tasks.

Mechanically, such recorders are typically reel-to-reel devices, usually taking a full 14-inch diameter reel, and employ a closed-loop tape metering system (chapter 6). They all employ some form of tension servo designed to regulate the tension at the entrance (and sometimes the exit) of the closed loop. These tension servos may themselves be of the (electrical) open- or closed-loop type and range from those which determine tension by measuring differential supply pressure in an air-lubricated turn around post to those which shine a light past the tape reel onto a photocell to determine how much tape remains on the reel.

Typically these machines use torque motors for takeup and for supply reel holdback. Some use mechanical brakes for starting and stopping but others use dynamic braking of the torque motors themselves for dealing with transient conditions. These latter usually employ some sort of solenoid-operated "brute force" dog brake to lock the reels when the recorder power is shut off.

These machines may also be divided into those which do and do not use differential capstans. Those not using differential capstans use a single capstan for defining both the exit and the entrance of the closed metering loop. These machines depend on the maintenance of entrance and exit tensions to assure tension within the closed loop but, as discussed in chapter 6, they are not alone in requiring this condition. The differential-capstan machines are further divided into two groups. One type employs a "two-diameter" capstan (described later), with separate pinch rollers causing the tape to touch the larger or the smaller diameter of the capstan in order effectively to meter more tape out of the closed loop than is metered in. The other type of differential-capstan machine employs either two capstans of different diameter driven at the same speed or capstans of the same diameter driven at slightly different speeds to accomplish the same end.

Most of these machines provide tape lifting facilities of one kind or another so that the tape does not run across the heads when it is being moved rapidly forward or rewound. These may either be literal tape lifters which operate to move the tape away from the heads or may accomplish the same result by moving the heads away from the tape. The implication of the provision of this feature is that much shuttling back and forth of the tape is often involved, as it is indeed for certain applications of such recorders. In a tracking station a recorder may simply be used to record an original tape which is then taken off the machine without rewinding since the station procedures are usually based on minimum local tape handling and minimum use of the machines which do the essential initial recording. Auxiliary to the work of such recorders, sometimes in the station, and more often in data reduction centers, much shuttling back and forth, rewinding and dubbing of tapes takes place and the tape lifters are useful in these applications.

Currently available ground machines provide wide variation in their flutter and time displacement error performance. The (absolute) time displacement error varies at present with commercial machines from plus or minus a quarter millisecond to plus or minus half a microsecond at a tape speed of 120 inches per second. Two machines may have similar flutter performance although they differ to this degree in time displacement error performance. The low-time-displacement-error machines have improved low-frequency flutter but the high-frequency flutter follows about the same pattern as in other recorders. The combined flutter of the low-time-error machines therefore is similar to that of more conventional machines. The goal in all recorders tends to be limitation of the amount of unsupported tape in the vicinity of the heads, since this unsupported tape is generally believed to be the source of the high-frequency flutter which for many wideband applications is the significant flutter.

Such machines invariably are fitted with speed-control servos. This control mechanism can be a rather straightforward device which makes a record of the precise frequency of the local power at the time that the recording is made so that the machine can be locked to the local power on playback. It may also permit locking a recorder reference tone to a local crystal oscillator at the reproduce point within a half-microsecond on playback. In accomplishing this wide range of speed control, the machines use both direct and alternating current motors; at one time one manufacturer used a number of very small dc motors to minimize the rotating mass, and in another case, a printed circuit motor is used for the same reason. In general, dc motors seem to be preferred for tighter speed control.

Starting and stopping such recorders is an important problem and significant differences exist between the various models in the way in which they treat the tape during such transient conditions. The modern recorder usually starts in a rather complex way, often bringing the supply and takeup reels up to speed before the pressure roller clamps the tape against the capstan in order to minimize starting transients. (Some manufacturers emphasize that they do *not* do this.) When the start-stop controlling mechanism fails or is misadjusted, errors may be produced in the recordings and the tape damaged may be beyond repair. The user's choice between recorders often is made on the basis of how well the individual unit deals with the start-stop condition rather than on some of the numbers in the overall specification.

Although many tape recorders still in use on the ground have vacuum-tube electronics, all those currently supplied for the more sophisticated services are entirely solid state. Occasionally tubes may be found in the servo motor-drive amplifiers of a machine which is otherwise solid state.

As described later (chapter 4), there are many different record and playback "modes," almost every one of which requires its individual electronics assembly. Broadband FM, direct record, PAM, PDM, PCM, and predetection recording modes are all encountered in modern installations. In tracking stations it is common for each of these modes to be provided for almost every track of multitrack recorders since such tracking stations have to deal with the output of a wide range of satellites with a correspondingly wide range of recording requirements. In data reduction stations, more limited flexibility may be provided, although in some central data handling installations the full range of normal modes is required and is extended by special playback modes required by peculiar recording conditions. This latter condition is particularly true where data is recovered by playback from an airborne unit and is to be reduced on the ground. It is a major feature in such recorders for most of their applications that they be easily and logically converted from one mode of operation to another and that several tracks on the same tape can successfully be used simultaneously in different modes.

Ground-based recorders are subjected to routine preventive maintenance and to continuous calibration and checkout procedures. Important features of such recorders are long head wear and uniformity and stability of calibration. Difficulty in providing these features may not be crippling, however, since in a particular situation an expensive and elaborate maintenance procedure may be worth while if it makes available an otherwise unavailable special recording mode. Typically such machines operate in rooms in which human beings are reasonably comfortable and, although they may be subjected to dampness or dust, the environment is usually similar to that of the laboratory in which the equipment was developed.

FLIGHT RECORDERS

Typically the flight recorder is small, light, and uses very little power. These characteristics outweigh the importance of most of the electrical performance features which are significant in ground-based equipment. The exact specifications of a spaceborne recorder usually are determined by deciding how much the miniature unit can be simplified at the price of elaborate methods of processing its output on the ground. Flutter, for example, may be accepted in a flight recorder with the specific intent of using elaborate flutter compensation at some later process in the reduction of the data from the recorder.

The tape in a flight recorder may be transported from reel-to-reel or supplied from and taken up into an endless loop. Although the reel-to-reel configuration has fewer uncertain mechanical problems, it usually limits the playback modes available and requires relatively complex control techniques. Most endless-loop recorders are so constructed that continuous slippage takes place between many layers of tape in the tape pack. Reel-to-reel recorders often have been used where an endless-loop machine was more logical because of the potential unreliability of the loop device.

Flutter in flight recorders may be acceptable when it is up to 10 or 20 times as severe as in ground-based equipment. Either providing enough mass for straightforward flutter reduction techniques or a refined enough mechanical filter or servo control mechanism usually adds too much undesirable weight or complexity for adequate reliability in unmaintained equipment. One percent peak-to-peak flutter is perfectly acceptable for a flight recorder. The usually severe environment of the flight recorder also requires that such items as pressure rollers or resilient elements be used with care because of problems of failure of the specialized materials involved. Many flight recorders even eliminate the capstan pressure roller entirely by providing a large wrap around the capstan.

There are two major classes of spaceborne recorders. One class is used in satellites where the typical application is to obtain data during an entire earth orbit and to return it to a receiving ground station during the relatively short time when the satellite is in radio view of the ground station. These recorders therefore have relatively slow record and fast playback characteristics. The other class of recorder, used mainly for deep space probes, operates in exactly the opposite way. Data is recorded in real time at a fairly conventional rate but is played back at an extremely slow rate because of the bandwidth limitations of transmission over interplanetary distances. The high ratio of record to playback speeds raises both electronic and mechanical problems in this application. For some space applications, where the playback speed may be one one-thousandth of the record speed, the problem is particularly severe.

The most important single characteristic that distinguishes the flight recorder from one based on the ground, in the current period of relatively large boosters and somewhat relaxed weight and power requirements for such machines, is the extreme reliability required. A recorder that is to be used for space or satellite probe application must usually have an unattended failure-free life of at least 1 year. The problems of mechanical reliability under these conditions have proven to be the most severe to overcome.

A secondary class of flight recorders includes those which do not play back on command to produce signals to be telemetered to a ground station but in which the tape itself, along with the recorder, is recovered. These fall roughly into two groups. In studying reentry conditions the recorder travels with a reentry test object and records what happens during the severe accelerations and decelerations of reentry. Such a recorder must be able to withstand a severe mechanical environment and survive so that the tape may be recovered. A related application is one in which transmission is blacked out by flame attenuation of boosters or separating rockets during part of a research investigation. To obtain the data that normally would be transmitted via radio waves to the ground during this blackout condition, a recorder records continuously and reproduces continuously, the reproduced signal having a fixed delay relative to the recorded signal. By recording both the original and delayed signals on the ground, a flame-attenuation blackout of 10 to 50 seconds would not cause any data to be lost. The recorder and tape do not, of course, have to be recovered, but the construction must be as rugged as that of a recoverable unit.

Another group of recorders producing recoverable tape is associated with manned space flights. These recorders have to survive a somewhat rugged environment but, since they travel with a man, they are usually treated little worse than the man. They must be reliable and have long playing times to produce archival records over an extended mission of information otherwise transmitted directly. Beyond this, the requirements on these units are not too severe.

CHAPTER 3

The Elements of the Tape Recorder

Certain common elements are basic to the operation of every magnetic tape recorder. These are a recording medium, recording and reproducing transducers, a mechanism for moving the medium past the transducers, and electronic devices which process the input and output signals (and sometimes control the tape-moving mechanism). Each element affects the performance characteristics of the complete recorder, and the influence of each element interacts with that of the others.

THE RECORDING MEDIUM

Although several forms of magnetic recording media are currently in use, one form monopolizes most applications. This medium consists of a thin plastic backing or base on which is coated microscopic magnetic oxide particles dispersed in and bound to the base by a thermoplastic or partially thermosetting binder. The action of this form of medium will be discussed in detail (chapter 9); that of the less common forms will be reviewed briefly in relationship to the rather specialized applications to which these forms have been applied. Other media of some importance include metallic nickel-cobalt layers electroplated or electroless-deposited on a "base metal" carrier, usually of phosphor bronze or similar material, and metallic coatings of the same general type placed on a plastic base.

When the oxide-particle recording medium moves past the magnetic field of the recording head, each of the very large number of particles in the magnetic coating is somewhat differently affected by the recording field. When a particular section of the medium has moved away from the record field, remanent magnetization is left in the medium. Just as the magnetic material is made up of many different particles, the remanent magnetization is made up of the magnetic effect of a large number of individually magnetized particles. When this composite remanent field is passed over the intercepting gap of the reproducing head, each magnetized particle has its individual effect in inducing flux into the reproduce head and, hence, signals into the recorder output. The net process is thus one of transmitting the signal from the input of the recorder to the output of the reproducer in the form of the integrated influences of a very large number of individual particles. That the coating is particulate rather than continuous is thus important to the recording process and the total number of particles is a significant operating parameter. Interaction between the large number of individual particles also makes the operation of the medium complex.

In most information transmission systems a certain number of samples (electrons, film grains, magnetic particles) proportional to the average instantaneous value of a signal is transmitted. The number of such samples received is subject to a statistical random variation around the average to an extent dependent on the number of samples involved. This is an elaborate way of saying that in the magnetic recording system, as in any other discrete-sample (electron, grain, particle) system, the fundamental signal-to-noise ratio of the received signal depends on the number of samples transmitted, or in this case, on the number of magnetic particles involved (Schade [1948]). This signal-to-noise ratio is roughly proportional to the square root of the number of particles. There are, of course, other sources of noise beside this basic one (Mee [1964]), but in general, the more particles in the magnetic medium, the better the signal-to-noise ratio.

An important qualification to that last statement is: "all other things being equal." When particle size changes, almost all the other magnetic properties of the particle change. The total remanent flux and the magnetic stability of the medium decrease if one simply changes particle size without changing anything else (same total volume of magnetic material). The art of making the modern magnetic particle dispersion includes, among other things: (1) obtaining enough total remanent magnetism; (2) having as large a number of particles as possible; (3) holding the particles mechanically firmly on the base; (4) retaining other important magnetic characteristics such as "squareness ratio" and high saturation magnetization; and (5) making the particle dispersion perfectly uniform (see chapter 9).

The tools available to the magnetic medium (tape) designer include making minor changes in the chemical (and hence magnetic) properties of the particles as well as changing their size. The exact nature of the oxides used by the various tape manufacturers is probably guarded by them more carefully than any other trade secret. It will not be possible to discuss other than the crudest outlines of the influences at work in this field because most knowledge is maintained on a completely proprietary basis.

In any group of very fine particles the same agitating influences which lead to the familiar Brownian Movement are at work. There is thus a certain thermal energy contained in the fine magnetic particles of a tape. If the particles become smaller, the amount of thermal energy of each particle eventually becomes greater than its magnetic energy. Under these circumstances although a particle can be magnetized and aligned in a magnetic field, it immediately reverts to random alignment when the field is removed (superparamagnetism) (Mee [1964]). With particles this fine, the tape would not be able to retain any remanent magnetism even at room temperature. Before reaching this extreme state of instability, there are intermediate states for intermediate particle sizes where only a slight increase in temperature or a slight amount of mechanical work (bending around a mechanical guide) will affect the remanent magnetism of a recorded tape, a situation which is not tolerable for precision recording and reproducing.

For proper recording and reproduction to take place, the magnetic medium must come into close contact with the record and reproduce transducers. This means that the surface of the tape must be extremely smooth and the actual magnetic material must not be shielded from the transducers by a perceptible layer of binder. At the same time, the tape must be mechanically strong enough to retain the magnetic material in position when subject to frictional movement across the head. The smoothness of the tape and head surfaces also controls the uniformity of speed with which the mass of magnetic particles is moved past the transducer. If either surface is rough, the medium will fail to contact the head and the relative movement of the medium past the head will tend to be irregular. Therefore surface properties are also significant in determining the signal-to-noise ratio.

Action affecting the signal-to-noise ratio thus occurs at the surface of the tape, or more exactly, the surface at which the tape and the transducers interact. Within the tape an analog to surface smoothness, that is, the uniformity of dispersion of the magnetic particles, similarly affects signal-to-noise ratio. The gaps of the recording and reproducing transducers deliberately introduce sharp discontinuities in the external effects of the magnetic properties of these transducers. At these points of sharp discontinuity the detailed structure of the medium interacts with the transducers. Nonuniformity in the detailed structure of the tape, that is, of the uniformity of dispersion and, hence, microscopic uniformity of magnetic properties, is examined in the recording and reproducing process. Hence, although made of particles the tape must, in a sense, act as if it were perfectly uniform for additional noise not to be created in the record and reproduce process.

The factors discussed so far seem concentrated on the signal-to-noise ratio. Suppose, now, that the thickness of the medium were increased. Assuming their size is maintained the same, the number of particles involved in recording would also be increased. From what was said above this would appear to increase the signal-to-noise ratio. It would do so, but only for long wavelengths, that is, for signals requiring low recording resolution. To record with high resolution, that is, with good mechanical definition on the tape, the influences of the recording and reproducing transducers must be limited to short distances along the direction of tape motion. As we will see elsewhere, increasing the distance of portions of the medium from the transducer decreases the definition with which the transducer is able to specify the record and reproduce points for those portions of the medium (Eldridge [1960]). This happens in the parts of the thick coating far from the transducer. Therefore, for good performance at both short and long wavelengths, the tape coating must be as thin as possible and still produce a large enough reproduce signal.

Desirable characteristics of the medium are, then, that it have as large a number of particles per unit volume in the coating as possible, that the coating be physically as smooth as possible, that the dispersion of particles within the coating be very uniform, and that the magnetic properties of the material be such that as thin a coating as possible can be used for a given signal. The importance of these properties of the medium is only slightly influenced by the properties of other parts of the record system.

RECORDING AND REPRODUCING TRANSDUCERS

Except for very special applications, most magnetic tape recording and reproducing transducers in use today are of one single design. The recording transducer or head consists of a closed magnetic circuit, usually made of laminated high-permeability metal, in which a gap of controlled dimensions is provided. On this magnetic circuit are wound coils for inducing a magnetomotive force in the circuit. A typical recording head is made of laminations roughly of the shape of the letter "C," placed together tip to tip to produce a structure which usually looks like an O with flattened sides and a rounded top and bottom. One of the two gaps in the structure is made as small as possible and the other is made of controlled dimensions. This assembly produces a fringing flux at the controlled gap which has elements along the direction of tape movement past the gap and hence is able to produce a longitudinal remanent magnetization in the tape. The physical forms of such record heads may vary widely but the essential elements will be the same (chapter 8).

The typical reproduce head of the modern tape recorder is sensitive to rate of change of flux or dϕ/dt. The magnetic and electrical structure of such a head is esssentially identical to that of the record head. The operating gap in the reproduce head, however, is usually considerably smaller than that in the record head, and the windings of the coil are designed to match the input impedance of reproducing amplifiers rather than the output impedance of the recording drivers. When the gap of such a head encounters the flux pattern recorded on the tape, flux passes into the magnetic circuit and change in that flux induces voltage in windings, hence dϕ/dt.

Special reproduce heads are sometimes used. They may, for example, be sensitive to the value of the flux rather than to its rate of change. These are particularly useful where the tape moves so slowly on reproduction that very little voltage is induced by a change in flux. Such flux-sensitive heads include those in which the presence of the flux from the tape in the front gap modulates the reluctance of a partially-saturated magnetic circuit supplied with an external flux source so as to change the total amount of flux in the circuit. The external flux applied is usually alternating and the output signal is thus a carrier modulated by the tape flux. Many variations of this scheme have been used. Another common flux-sensitive head is made by introducing a piece of semiconductor material particularly sensitive to the Hall effect into either the front or the back gap of the head. These specialized forms of heads will be considered later.

An important characteristic of the common heads just described is that they define sharply the fringing flux field at the point where they contact the tape. This requires extreme precision and accuracy of mechanical construction. Typically, the mating faces of head gaps are lapped to optical finishes as are the rounded surfaces of the front of the head which contacts the tape. The head structure is usually made of a ferrite or of metal laminations from 2 to 6 mils in thickness. Ferrites are particularly hard and, if they are properly constructed of proper materials, have a very long wear life. Ferrites also become particularly useful at relatively high frequencies where losses in most magnetic metals increase (above 2 megacycles per second).

The lines defining the sides of the gap of a precision head must be perfectly parallel and perfectly straight to produce good resolution and maximum utilization of the recording medium. This accuracy must be accomplished with magnetic metals which tend to be rather soft and to gall. Techniques of construction of such precision heads have been greatly refined in the last few years; heads of almost any desired mechanical characteristics can now be made, although this was not true 10 years ago.

The accuracy with which a head interacts with the tape is determined largely by the accuracy of construction and the finish of the front of the magnetic head. The head also must not vibrate and must be stiff enough so that it does not, by moving, become a part of the problems of maintaining uniform relative head-tape motion.

THE TAPE MOVING MECHANISM

The function of the tape moving mechanism is to move the magnetic medium in a smooth and uniform manner past the recording and reproducing transducers. The designer's problems include both preventing irregularities of motion originating within the mechanism itself and protecting the tape motion from external influences which may tend to force the mechanism to move in an irregular manner. To perform these functions properly the tape moving process is usually separated into two steps. One step is that of supplying the tape from a supply reel and winding it up on a takeup reel, referred to here as "Tape Reeling." The second step is that of metering the movement of the tape past the transducers with uniformity, referred to as "Tape Metering." The design of the complete mechanism involves designing as smooth a metering mechanism as possible and providing a reeling mechanism which protects the movement within the metering mechanism from disturbing influences originating in the supply and takeup process or outside the recorder proper.

All parts of the tape moving mechanism, with emphasis on those charged with metering the tape, must be designed to minimize the typical irregularities of mechanical devices. Such irregularities are nonuniformity of rotation from tooth effects in gears, motion jerks from splices in drive belts, nonuniformity of torque with rotation in bearings, out-of-roundness or runout in rotating members, and chatter or stick-slip problems everywhere in the mechanism. In addition, nonuniformity in drive from the prime mover, originating in cogging in alternating current motors and commutator effects in direct current motors, must be minimized.

In the takeup and supply mechanism, lumped together in the "reeling" function, other sources of irregularity of motion are encountered. Typically, elements of the reeling mechanism move more slowly and have lower rotational rates than those within the metering mechanism, and they often include frictional devices such as clutches or brakes. The supply and takeup reels are often not part of the recorder but are brought to the recorder after a history of handling which is not under the recorder designer's control. Reels which have become warped or bent can seriously influence the operation of the recorder.

In many flight recorders, an endless loop replaces the supply and takeup reel. Such devices have entirely different motion irregularity problems, resulting primarily from the requirement that the layers of tape slide continuously past each other without chatter or hang-up.

Errors in any of the elements of the tape moving mechanism will, of course, produce irregularities in the time scale of the reproduced signal. In effect, such irregularities add a peculiar kind of noise to the overall transmission. The significance of this noise will be discussed in detail later. In addition to the obvious first order effect of the signal not coming out at the expected time, there are second order effects of modulation of the time scale which produce spurious signals particularly difficult to separate from the desired signals.

A particular point of interaction between the medium and the moving mechanism is the generation of high-frequency random speed variation at the point of friction between the medium and the transducer. Wherever the tape is not continuously supported and, at one end or the other of its unsupported section, passes with friction over some portion of the mechanism, any lack of smoothness of the tape or of the device over which it passes will tend to shock-excite the unsupported tape into both lateral and longitudinal vibration. The effect of this vibration is to produce a type of random speed variation with a broad irregular spectrum which creates a kind of noise particularly difficult to deal with. It is thus essential that the mechanism designer make all parts which contact the tape as smooth as possible and minimize the amount of unsupported tape in the tape path he chooses. Air lubrication to support the tape completely free of frictional movement is a powerful technique for dealing with this frictional excitation problem.

In the simplest tape recorder mechanisms the metering mechanism may be driven by a governor-controlled or synchronous motor and straightforward techniques may be used to provide the varying speed-torque characteristics necessary for the supply and takeup reels. In high performance recorders, however, some sort of servo control of the tape speed is almost universal. At this point there is interaction between the electronic elements of the recorder and the mechanical elements. For the most sophisticated servo speed controls, interaction takes place between the medium and the electronic and mechanical elements of the recorder. (This speed-control interaction is supplementary to the fundamental mechanism/medium/electronic interaction taking place at the transducer.)

Speed control servos range from simple to complex. The simplest servo control is used in connection with the synchronous motor drive of the recorder and involves the recording of the frequency of the supply mains power by modulating it onto a carrier of the tape. This carrier is played back while reproducing and the power frequency derived therefrom is compared with the frequency of the reproducing power source. Compensation is then provided to lock the two power systems together. This type of servo guarantees that the average speed of the recorder and reproducer are identical and therefore that there will be no gross time error (Davies [1954]). It makes no compensation, however, for instantaneous speed variations. More sophisticated servos have recently come into use in which an approximately 100 kilocycle signal is recorded at the same time as the desired information signal. This 100 kc signal is played back in reproduction and is compared with a local crystal oscillator-generated signal. The instantaneous error between the timing of these two signals operates in a very fast-acting servo loop so as to minimize the time displacement between the recorded 100 kc signal and the locally generated signal (Schulze [1962]). Within the last 5 years, the capabilities of such precision servos have progressed from providing a gross time displacement of plus or minus 5 microseconds at the normal maximum tape speed to current time displacement accuracy of a half-microsecond.

The discussion so far has been limited to the characteristics and performance effects of the tape moving mechanisms of essentially isolated recorders. Only indirect reference has been made to such external disturbing influences as variation in the supply power, voltage or frequency, mechanical shock and vibration. Large ground-based recorders do in practice operate in an environment which is essentially isolated. However, in many important applications, recorders are subject to extremely hostile environments. The tape moving mechanism then must be able to perform its basic function without being seriously affected by such an environment.

Such a tape moving mechanism must not be seriously affected by wide temperature variation or thermal shock and also must continue to move the tape smoothly under severe mechanical shock and vibration. The design of such mechanisms often involves avoiding design solutions which would be satisfactory if the environment were not severe but which may magnify vibration effects or react catastrophically to shock. Specific design factors will be discussed in greater detail later (chapter 11). The severe environment mechanical design decisions may, however, be characterized by citing a few specifics.

A formal decision is often necessary between shock mounting and hard mounting the entire recorder, depending on the nature of the vibration environment and the structure of the device in which the recorder is mounted. The design of a capstan bearing assembly, a relatively straightforward process for a ground-based recorder, involves for a shock-environment recorder discarding many potentially useful ball bearings because they cannot survive shock; reevaluating bearing loads and load life, and perhaps discarding whole system designs because the recorder must also operate in a vacuum with its lubrication limitations.

Although vibration and temperature problems may cause difficulties with electronics it is in the mechanical elements of the recorder that the severe environment raises the most difficult design problems.

ELECTRONICS

The electronics of a magnetic tape recorder must conform generally only to the electronic requirements of other typical electronic equipment for similar environments. In only a few specific areas is specialized electronic performance required for the recorder. These include equalization and input amplifier signal-to-noise ratio.

The recording and reproducing process usually involves laying down a magnetic pattern on the tape, the intensity of which is roughly proportional to the intensity of the current passing through the recording head. A reproducing device sensitive to the flux in the tape would then approximately reproduce, except for secondary effects, an output signal identical to that applied to the recording head. The most commonly used reproduce transducer is, however, a device sensitive not to flux but to rate of change of flux. The output signal therefore tends to be the time derivative of the record signal. The signal emerging from the reproduce transducer must thus be integrated in order to reconstruct the recorded signal in the output. In the linear (analog) recording mode, and in many nonlinear recording modes, this integration of the signal takes place in the electronics. It is often accompanied by the post-emphasis or equalization needed to compensate for wavelength (and hence frequency) signal intensity losses occurring in recording and reproduction as well as to remove the effect of pre-emphasis applied to improve signal-to-noise ratio.

Both recording and reproduction are scanning processes in which the mechanical characteristics of the transducers interact with those of the medium to produce typical wavelength-sensitive responses. As in all scanning processes, both recorded and reproduced signals tend to decrease in amplitude with decreasing wavelength on the tape. Again, as in all scanning processes, there are actual nulls in the system response where the effective gap dimensions of transducers bear certain relationships to the wavelengths of signals recorded on the tape (Westmijze [1953]). Equalization to compensate for these mechanical effects must accompany the integrating process if the signal is to be restored to its original form.

Any equalization process equalizes the noise generated both in the tape and in the early stages of the electronic equipment along with the desired signal. Magnetic recorders therefore have rather complex and nonuniform output noise spectra. Combined with the degradation of signal-to-noise ratio produced by the nonuniform spectra is the normal tendency, as the storage capacity of the medium is pushed farther and farther, for the signals reproduced to become smaller and smaller. The net result is that the input amplifier which handles the signal from a reproducing transducer in a magnetic recorder must deal with a very severe signal-to-noise problem. In recorders operating at the limits of the state of the art, the noise capability of the input amplifier rather than the noise of the recording medium may determine the system noise performance. Many a recorder manufacturer has been embarrassed when he found he could not take advantage of an improvement in the recording medium because the noise in the input circuits of his reproducing equipment masked the improvement in the characteristics of the medium.

The interrelationship between the medium noise and system noise is quite complex and will be discussed later (chapters 5, 9, 10). Where precise control of the movement of the tape is obtained with a servomechanism this relationship is further complicated. Relatively fast-acting servos have recently been introduced to magnetic recorders to control the motion of the tape, particularly on reproduction, by attempting to minimize electrically the time error in a reference signal recorded on the tape. The degree to which this time error can be reduced is a measure of how much the overall performance of a recording system which depends not only on amplitude but also on time accuracy can be improved. Studies have recently shown that there is a practical and theoretical maximum to the degree to which this improvement can be accomplished (Develet [1964]). This limit on improvement is typical of many such situations in which error compensating schemes, for which the improvement available has no theoretical limit, reach a practical limit when noise generated either in the original system or in the correcting system succeeds in confusing the compensation process.

Although electronic elements are essential to the transducing of signals relative to magnetic tape, the magnetic recording process is basically a mechanical one. The complete process generates an electrical signal which depends on the combined effects of mechanically dispersed separate particles which contribute, depending upon their mechanical position and the smoothness of their mechanical movement, to the magnetic flux intercepted by a mechanical gap in a reproducing transducer. Therefore, except for improvement in input amplifiers, to which improvement there is a theoretical upper limit, progress in magnetic recorders is made primarily through improvement in mechanical elements.

SUMMARY

This brief discussion attempts to relate the various elements of the recording system to show the way in which their qualities interact with each other. The organization of the analytic portion of this Technology Survey is based on treating each of the individual elements and their interactions more deeply. For this reason several chapters are labeled with the detailed elements which make up the recorder and reproducer. To these element chapters are added certain chapters on interaction. Specifically, the head/tape interaction process cannot be discussed adequately by considering the head and the tape alone and therefore the two are discussed in a combined section. Irregular tape motion in the form of flutter and time displacement error is related to both the tape reeling and the tape metering mechanism as well as in part to head/tape interaction. Therefore a separate section analyzes tape motion irregularity. The section immediately following this one is entitled "Recording Methods" and deals with the various ways in which the basic magnetic recording process can be used to produce overall system-transmission to optimize certain qualities. This section clearly partakes of elements of all the other sections. There is also a brief analysis of the storage capability of magnetic recorders and a discussion of the degree to which the theoretical storage capability is currently realized in practical recorders. Beside the analysis of recorder elements and how they effect recorder performance, several sections have been added to make the Survey complete. One of these is on "Methods of Testing and Evaluating Recorders" and one is on "Complete Recording Systems." This last section deals with the methods which are used by systems engineers to recognize the limitations of each portion of the system and to design the system so as to minimize the effect of these limitations. A third section partakes of both analysis and system specification in describing the problems and current solutions peculiar to the airborne miniature tape recorder in which NASA's specific development efforts have been concentrated.

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CHAPTER 4

Recording Methods

Modern magnetic tape—a dispersion of magnetic oxide particles carried on a plastic backing—was first put into widespread use at the end of World War II. Some tape recorders used methods of recording with this new type of tape which had been devised when the available magnetic recording media were quite different. Recording methods better adapted for wire or for tape rolled from magnetic metals were thus used in some early tape recorders (Begun [1937]). The recorded magnetic field was often perpendicular to the surface of the tape, or was induced to lie in the plane of the tape by placing recording head pole pieces on opposite sides of the tape. Such older recording techniques have essentially disappeared from practical use. "Longitudinal recording," that is, with the remanent flux directed along the direction of tape motion, induced by fringing flux surrounding a gap in a closed magnetic structure in contact with one side of the medium, is almost universally used. Some research and advanced development work is now being done in other than longitudinal recording and in ways of achieving longitudinal recording by other than the currently used means (Mee [1964]).

What is now substituted for the original variety of methods of impressing the magnetic impulses on the tape is a variety of ways in which the information to be recorded is processed before it is placed on the tape and is reprocessed after reproduction. This processing involves either recording the input signal directly or converting it to pulse, FM or other form in a "coding scheme."

The almost universally employed fringing recording field is produced by a precisely controlled gap placed in a magnetically soft structure. By some means, the information to be recorded is caused to vary the magnetomotive force applied to the magnetic structure and the fringing field surrounding the gap in the structure correspondingly varies the magnetic intensity operating on the magnetic material of the tape. As longitudinal recording densities have increased and methods like those of magnetic tape recording have been applied to drum and disc computer files, methods of recording other than by the use of a fringing field have been investigated. No great strides have been made in this area but some current work in the use of so-called "horseshoe heads," as yet unpublished, shows promise.

The various recording methods (coding schemes) used with magnetic tape fall broadly into two categories. One method, which might be referred to as the "linear" method, operates on the basis that the transfer characteristic of magnetic tape can be made to be approximately linear. By transfer characteristic is meant the relationship between the instantaneously applied signal magnetomotive force and the remanent magnetism in the tape. This is the basic mechanism used for audio recording which gave tape recording its practical start during World War II. Linear recording is achieved by mixing the recorded signal with a high frequency bias. In the absence of the bias the transfer characteristic of magnetic tape is far from linear. By a somewhat related mechanism called the use of "dc bias," a similar linear effect can be produced. There is, however, a vast philosophical difference between the ways in which dc bias linearization and ac bias linearization take place.

Much of the fundamental or semifundamental research and advanced development work applied to the magnetic recording process has been concerned with explaining and thereby, hopefully, mastering the ac bias process of linearization (Spratt [1964]). Many incomplete and even erroneous explanations of this process have been widely accepted and publicized primarily because relatively few people have gone into the subject in any depth. It is now correct to say, however, that the linearization process is fairly well understood, although the precise mechanism cannot be pinpointed in detail. The process is well enough understood to use a current statement of its mechanism as a tool for evaluating development of heads, tapes, and head-tape interaction devices.

The linear recording process was referred to above as being "approximately linear." Of the entire scope of variation of linearized remanent magnetism from maximum positive to maximum negative, only the center one-third in amplitude is linear enough to be considered essentially free of distortion. The center linear portion is bounded by two non-linear portions of a shape which is apparently inherent in the ac biased tape recording process. The distortion introduced in audio recording by the shape of these curved end portions of the transfer characteristic is relatively acceptable to the human ear. Tape recording, therefore, acquired an initial reputation of being a "linear process which overloads gracefully." In a way, this is unfortunate because the graceful overload is a term properly descriptive only of audio recording. In technical recording the intermodulation distortion caused by the overload can be disastrous.

Any method of using magnetic tape which depends on the linearity of the so-called linear portion, and also on limiting the signal excursions to the linear portion, necessarily limits the degree of utilization of the tape. For many applications, not very much of the linear portion is adequately linear enough, and other recording modes have had to be devised. These recording modes do not in general depend on linear properties of the tape but solely on its ability to indicate that it is magnetized in one direction or another or not magnetized at all.

Such recording modes, to which the term "pulse recording" can conveniently be applied, depend only to a secondary degree on linearity of transfer characteristic of the tape. Some current sophisticated uses of pulse recording do require that the tape transfer characteristic be under control, but for the purpose of a general review of recording modes, pulse recording can be considered to depend only on a "plus, minus, or zero" signal from the tape.

Pulse recording on tape can be divided into two main mechanisms. One of these carries information in the variation in pulse start and stop times. The other depends only on the presence, absence or polarity of the pulse within a more or less fixed time pattern. In the first group of time dependent pulse recording methods are pulse duration modulation (PDM), pulse position modulation (PPM), and pulse frequency modulation (PFM); both of the latter are variants of PDM. The non-time-dependent pulse recording methods are based on digital pulse modulation such as is employed in memory devices for computers. With this type of modulation, the recorder is asked only to deal with pulses, the number, position and polarity of which carry the total signal. The relationship of the recorder to a signal already in digital form is in this case clearcut. Where the signal is in analog form, it must be encoded by a relatively complex scheme before it can be recorded in pulse form.

LINEAR OR ANALOG RECORDING

The essence of the analog recording process is that it can be considered to be essentially linear. The action of the high-frequency bias which makes this linear operation possible is treated in detail under "Head-tape Interaction." One application note is, however, appropriate to discuss here since it deals with the actual degree of linearity achieved.

The audio recordist and many instrumentation recording engineers will usually quote a fairly definite figure for the difference in the output between a signal which causes one percent third harmonic distortion in an analog recording system and a signal which produces three percent third harmonic distortion. The signal which represents full saturation of the tape is also usually quoted as having a fixed relationship to the one percent signal. There are differences between tapes, although they are surprisingly small, in the values quoted for these numbers. It is safe to say that the shape of the semilinear transfer characteristic is roughly the same for all tapes. The way of arriving at the signal levels representing various amounts of distortion bears comment here, however.

If one operates an analog recorder by adjusting level and bias so as to produce normal operation with an output signal containing one percent third harmonic distortion, this signal output level can be called "zero level." If the input signal level is then increased until the output signal distortion reaches three percent third harmonic, the level change is almost invariably 6 db, or 2 to 1 in voltage. When the input level is increased until the output level essentially stops increasing, saturation is considered to be reached (the output level sometimes decreases with increased level where the higher level may produce tape erasure). This output level is often quoted to be 13½ or 14½ db above the one percent third harmonic output level. This figure must, however, be used with considerable care, since it depends on a peculiarity of the instrumentation typically used to measure the phenomenon. If one operates a tape recorder so as to get an actual instantaneous input/output plot of the transfer characteristic, one finds, as stated above, that the linear part of the characteristic extends only over one-third of the total positive-to-negative saturation characteristic. Measurements show that if the one percent distortion point is considered to be reached with a signal swing from plus unity to minus unity in output voltage, the saturation point will represent a swing from plus three to minus three units approximately. This represents, on an absolute basis, about 9 or 9½ db as measured in the laboratory. The difference between the 9½ db and the 13½ or 14½ db figure results from the use of the typical linear full wave rectifier meter in measuring the higher figure. The meter is not "concerned" by the fact that the output wave has changed from the sine wave for which it is normally calibrated to read into a square wave. As saturation increases and the corners of the sine wave are filled out to become a square wave, the meter simply interprets this filling out as increased output. With the typical non-sinusoidal signal with which the instrumentation recorder deals, this misinterpretation by the meter can be quite serious.

Further consideration of the linear recording process is postponed for discussion under "Head-tape Interaction." The nonlinear recording modes will be discussed in approximately historical order, starting with the FM mode and proceeding through such older pulse modes as the PDM and PWM to PCM variations thereon. PAM (pulse amplitude modulation) will be discussed in this section but its requirement of recording linearity will be referred to the appropriate later section of the Survey.

FM RECORDING

Shortly after the introduction of magnetic recording for scientific recording of analog signals it became apparent that there were many analog recording applications for which a simple extension of audio recording techniques was not adequate. This was particularly true for signals containing dc components and for signals for which the signal-to-noise ratio of existing analog recorders was inadequate. To deal with these two recording problems FM recording was the first new recording mode to be introduced.

In the current form of FM recording the input signal frequency modulates an oscillator, the output of which is recorded on the tape. Typically, saturation recording is used on the tape, that is, the FM carrier is applied either as a rectangular or sine wave signal directly to the recording head at such an amplitude as to saturate the tape either in one direction or another. The function of the tape is thus limited to storing the times of the axis crossings of the FM signal. A standardized set of FM values and relationships has been in use for many years. The center carrier frequently is usually 9/10 the number of inches per second at which the transport is operating in kc, i.e., 13.5 kc for 15 inches per second. Recently these carrier frequencies have been doubled with consequent improvement in system bandwidth. Typically the FM carrier is modulated 40 percent and, up until recently, the bandwidth in kc has always been 1/6 the tape speed in inches per second; for example, 2.5 kc for 15 inches per second. Systems with twice and even four times these bandwidths have been introduced within the last few years. More recently, FM systems with bandwidths up to 400 kc for recorders operating at 120 inches per second have appeared to complement the 1½ megacycle bandwidth analog recording capability (table 4–1).

TABLE 4–1.—*FM Recording Bandwidths*

Standard Response

Tape speed ips	Bandwidth	Carrier
120	0–20, 000 cps	108 Kc
60	0–10, 000 cps	54 Kc
30	0– 5, 000 cps	27 Kc
15	0– 2, 500 cps	13. 5 Kc
7½	0– 1, 250 cps	6 75 Kc
3¾	0– 625 cps	3 38 Kc
1⅞	0– 312 cps	1. 68 Kc

Extended Response

Tape speed ips	Bandwidth	Carrier
120	0–40, 000 cps	216 Kc
60	0–20, 000 cps	108 Kc
30	0–10, 000 cps	54 Kc
15	0– 5, 000 cps	27 Kc
7½	0– 2, 500 cps	13 5 Kc
3¾	0– 1, 250 cps	6 75 Kc
1⅞	0– 625 cps	3 38 Kc

Double Extended Response

Tape speed ips	Bandwidth	Carrier
120	0–80, 000 cps	432 Kc
60	0–40, 000 cps	216 Kc
30	0–20, 000 cps	108 Kc
15	0–10, 000 cps	54 Kc
7½	0– 5, 000 cps	27 Kc
3¾	0– 2, 500 cps	13 5 Kc
1⅞	0– 1, 250 cps	6 75 Kc

Wideband

Tape speed ips	Bandwidth	Carrier
120	400 Kc	900 Kc

The FM recording system currently used usually offers 10 to 15 db better signal-to-noise ratio than the corresponding analog signal-to-noise ratio obtained at a given transport speed. These increased signal-to-noise ratios are purchased directly at a loss in recorded bandwidth, of course. The noise in the FM record system is limited almost entirely to the FM noise produced by flutter in the recorder. When an FM record system is operated with proper limiting, the output is insensitive to the amplitude modulation produced by the recorder noise and instantaneous speed variation or flutter produces the only important noise. For many FM recording applications a steady carrier of 100 kc is recorded at the same time as the signal on the same or an adjacent track. By playing back this carrier through a separate discriminator, a signal representing the flutter noise is obtained. This flutter signal can be applied to the data signal discriminator in such a way as to compensate for much of the flutter noise. Improvements in signal-to-noise ratio of 6 to 12 db are achieved by this compensation technique. Although this compensation reduces the noise from flutter, it does not remove the flutter from the recorded data signal (chapter 7).

There is some confusion in the present usage of the terms "narrow band FM" and "wide band FM" depending on the application for which such recording is applied. For the purposes of this discussion, the terms shown in the table will be used to refer to "narrow bandwidth FM," "extended bandwidth FM," and "double extended bandwidth FM." "Wide band FM" will be used to refer to the 200 and 400 kc systems used with the 1½ megacycle analog recorder. The term "narrow band FM" has occasionally been applied to the analog recording of FM/FM telemetered signals such as those following the standard IRIG FM/FM channel scheme. Reference to such recording will be made here only as a special case of analog recording. The frequency multiplexing of the IRIG multichannel scheme would not operate were the rest of the system nonlinear. Unless the recording is in the linear analog mode, interchannel modulation would destroy the utility of the telemetering system (IRIG [1960]).

A typical FM-mode electronic assembly provided as an accessory to a ground-based instrumentation recorder uses a voltage controlled multivibrator oscillator to generate the FM signal. Much proprietary sophistication goes into these VCO's and there are dozens of different models on the market. Multiloop positive and negative feedback is used to stabilize these VCO's. Since the FM recording mode system is expected to carry dc, the VCO's and their associated amplifiers are usually chopper-stabilized. The output of an FM record electronic unit is a rectangular wave usually designed to have such current and voltage levels as to be applicable directly to a record head. Some manufacturers, however, provide a head driver which is basically a relatively high powered linear amplifier matched precisely to the head which can accept a variety of input signals which are not in proper form for direct application to the head.

The FM recording mode may be used in a satellite, space probe, or high environment recorder because it optimizes some recorder transfer characteristics that are not necessarily those for which the ground-based recorder user purchases an FM system. Such flight recorder electronics are therefore optimized for lightness, low power, and high reliability in severe environments, usually at the cost of the typical stability refinement just mentioned.

The FM playback electronics unit accepts a signal either directly from the head or from a head preamplifier which is used for all recording modes. There is still some variety in the types of discriminator used in FM playback units commercially supplied but the majority are of the pulse-counter type or the more elaborate phase-locked-loop type.

A typical FM playback unit would receive input signals which are successively negative and positive spikes representing the axis crossings of the recording rectangular wave. After amplification these spikes are often converted to unidirectional form and applied to a one-shot multivibrator or delay line device which produces from each spike a pulse of standard length. When this pulse is severely clipped, it becomes a constant-energy or constant-charge pulse. In the simplest discriminator, this train of constant energy pulses is applied to an averaging circuit which may not be more complicated than a resistor/condenser combination, but usually is that combination followed by a filter of fairly complex design. The filter is low pass, designed to cut off just above the useful data bandwidth, to maintain uniform phase and amplitude characteristics up to the cutoff and to attenuate as rapidly as possible beyond cutoff so as to eliminate the carrier represented by the pulse train from the output. Typically a maximally-flat amplitude response or maximally-flat time delay response (optimum phase equalization) option is provided in the filter, often with a switch.

The performance of such a very simple system depends on heavy limiting in the record unit to assure that the axis crossings which are applied to the tape are defined as sharply as possible. This must be followed after reproduction from the tape by equally severe limiting to eliminate the effects of signal amplitude variation inherent in the tape recording process. The degree to which the "constant energy" pulses are in fact constant energy is also dependent on stabilized time determining elements in the multivibrator and heavy and accurate limiting of the pulse amplitude. For a flight recorder much of the refinement may be eliminated in the interest of low power and low weight with the result that the system may be slightly tape amplitude variation sensitive but, of course, much less so than an analog system.

The phase-locked-loop discriminator has been extensively discussed in the literature (as has, of course, the simple discriminator just described) and no elaborate description of it will be undertaken here (Gilchriest [1957]). It will be enough to describe the general principles on which it operates. In the phase-locked-loop discriminator, the shaped and limited input signal is compared in a phase detector with the signal from a local voltage-controlled oscillator. The output of the phase detector is used to vary the frequency of the local oscillator so as to keep it locked in phase with the incoming signal. The control voltage from the phase detector to the voltage controlled oscillator is the output signal. This is clearly a more complex device than the simple averaging detector described before and its use has therefore been limited to sophisticated FM recording requirements. Its great advantage is that it may be made extremely stable and may be made to give a useful output signal over a wider range of signal-to-noise ratios than the simple pulse counter discriminator. To a certain extent it also is easier to add a flutter compensation signal to such a discriminator.

The phase-locked-loop discriminator is used almost universally in ground station telemetry equipment to interpret the output of FM/FM telemetry systems (McRae and Sharla-Nielsen [1958]). Such a telemetry discriminator invariably has an input for a flutter compensation signal. This flutter compensation technique is currently more widely applied to the telemetry discriminator than it is to the FM record system itself. In other words, an FM/FM telemetry signal which has been analog-recorded will usually have a 100 kc reference signal recorded along with it and this reference signal will be used to eliminate flutter noise from the output of the individual telemetry discriminator.

Flutter compensation is considered in more detail in chapter 7; certain aspects of this compensation are mentioned here because they relate to the performance of FM recording as a coding scheme.

The FM flutter compensation technique is very useful but it is sharply limited in the improvement that it can provide, in much the same way that the desirable features of FM recording are limited as a higher level of performance is sought. For example, the typical flutter compensation scheme operates by deriving in a reference discriminator, as explained above, a signal proportional to the flutter noise generated in the recorder. The flutter noise signal is delayed, as it passes through the reference discriminator, relative to the data signal; the data signal must be correspondingly delayed if accurate compensation is to be achieved. For a wide band system, achieving this delay without distorting the prime data can be very difficult (Ott [1962]). It is also appropriate to anticipate chapter 7 by noting that straightforward FM flutter compensation removes only flutter noise and does not remove flutter from the data. Only very elaborate correction schemes can make this next step of improvement beyond the simple compensation.

The video recorder, primarily designed for broadcast use, introduced a new series of FM recording techniques to the magnetic recording field (Ginsburg [1957]). The video recorder appears at first examination to operate in an FM mode which violates every rule of FM transmission. The carrier frequency is usually about 4 megacycles, the modulating signal has a bandwidth of 4½ or 5 megacycles, and the maximum FM deviation is considerably less than this bandwidth. Part of the FM spectrum so generated is cut off or "folded over" at zero frequency and another part of it is suppressed by the limited bandwidth of the recorder. This peculiar modulation scheme might never have been tried were the particular application for which it was first attempted not itself peculiar in that the overall result was to be judged as a TV picture by the human eye. Obviously, this recording scheme inherently produces high distortion, but the particular kind of distortion involved appears to be such as to be easily tolerated by the eye viewing a television signal so treated. More recently, sophisticated versions of this modulation scheme have been developed in which the violations of normal FM recording relationships are largely compensated for. Such video-type recording systems are now able to produce relatively low distortion and quite impressive bandwidths.

A rotary-head recorder can also be used for predetection recording, that is, for recording a signal directly from a receiver IF before it has entered the second detector. The received signal in this case is always frequency modulated, and is heterodyned down from the IF frequency to one which fits the recorder bandwidth. It is not passed through the FM modulator and demodulators used when putting an analog signal through the recorder, but is recorded direct. The video recorder, because it uses a rotary head rather than the fixed head of other instrumentation recorders, has flutter and time displacement error characteristics quite different from those of the longitudinal recorder. The FM noise characteristics likewise differ. The process of developing adequately stable rotary-head recorders for sophisticated broadcast use including color television has reached the point where it is now possible by the use of variable electrical delay lines to reduce the total time instability to ±25 nanoseconds. These techniques are now available for making extremely stable predetection recordings (Klokow and Kortman [1960]) (Ampex [1964]).

SPECIAL FM RECORDING SYSTEMS

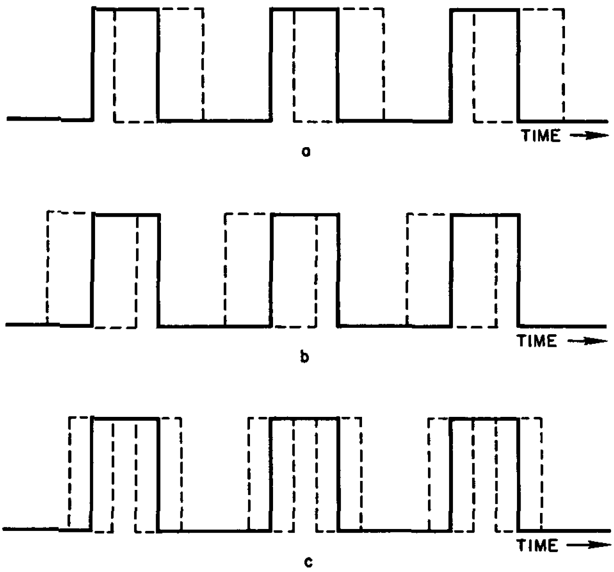
Analog recording of telemetered data on ground recorders for the space effort has been concentrated on FM/FM telemetry. Because of the standardization offered by the IRIG telemetry agreement, there has been a tendency to limit data transmission to the characteristics and bandwidths of the IRIG standard bands. Recently, however, many users have found the rigid limits of these bands, with their constant percentage deviation and hence their carefully ordered increase in bandwidth from one end of the standard band to the other, unnecessarily confining. New FM/FM standards have therefore arbitrarily been used by some organizations and an alternate constant-bandwidth system is being considered by IRIG to supplement the previous constant-percentage-bandwidth system.

Many of the telemetry ground equipment manufacturers also offer nonstandard constant-bandwidth systems despite the pressure to use the IRIG standards. A further development of the full utilization of FM/FM, not for long-distance telemetry but simply for convenient test-data handling, is the introduction by some manufacturers of complex multiplexing systems to provide many more channels than either the present or the proposed IRIG standards do. Such equipments consist basically of modular units that permit putting 75 or more uniform FM data channels of 1 to 2 kcps bandwidth on the direct record tracks of an instrumentation recorder operating at a moderate speed (Martin [1963]).

There is a continual ebb and flow of interest in the telemetering community in the various methods of telemetry and, correspondingly, interest in the recording problems these forms raise. FM/FM telemetry is still considered perfectly satisfactory by some groups doing quite complex work. Other groups have abandoned it almost completely for PCM, and still others use mixed systems. Each group maintains a position that is largely based on the way in which its particular field has developed. The recorders and auxiliary equipment available in the commercial market have characteristics that have been arrived at by the interaction of the characteristics of previously available equipment and the changing needs of users. It is therefore quite impossible to predict the future direction of development of telemetry recording equipment. Analog recording can probably be expected to decline in importance with a corresponding increase in importance of PCM and wideband FM, recorded either directly or in a predetection mode.

PULSE DURATION MODULATION

Pulse duration modulation (PDM) was introduced to the magnetic tape recording field about the same time as was FM modulation. In pulse duration modulation, the modulating signal is caused to vary the time of occurrence of the leading edge, the trailing or both edges of a train of equal-amplitude pulses forming a pulse carrier (fig. 4–1).



(*after Black "Modulation Theory"*)

FIGURE 4–1—Pulse-duration-modulation (PDM) wave forms

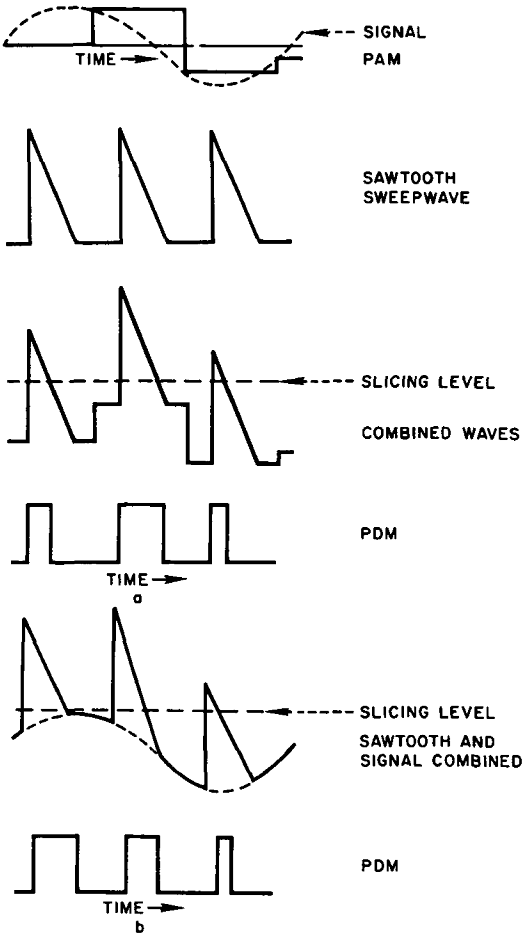
(a) Leading edge of pulse fixed, trailing edge modulated, (b) trailing edge of pulse fixed, leading edge modulated, (c) both edges of pulse modulated symmetrically around center

This modulation system does not require a linear amplitude characteristic in the recording process, which is concerned only with establishing with accuracy the start and stop times of the pulses.

With PDM, during modulation the short-term area average changes and hence the ac axis moves. In fact, one method of extracting the information from PDM pulses is simply to determine the average value of the signal by a filtering process. Because the axis moves, the transmission system must handle the movement with fidelity. This means that the auxiliary equipment, including all the signal circuits within the recorder proper, must be linear if the system is to be linear overall. The tape itself, because it is concerned only with pulse times, is relieved of amplitude linearity. Particularly in early use of magnetic recording for scientific data collection, the price of auxiliary circuit linearity was gladly paid for the advantage of eliminating the need for tape linearity.

There are many ways in which duration modulated pulses may be produced. Figure 4–2 shows two ways of accomplishing this for pulses in which the trailing edge alone is modulated. The conversion technique shown at a is known as uniform sampling because the successive pulse durations are proportional to values of the signal at uniformly-spaced signal sampling times. The procedure here is to sample the signal at uniform intervals and convert each sample to a steady value which remains until the time of the next sample, at which time the steady value changes to that associated with the new sample. This gives a peculiar kind of PAM (pulse-amplitude-modulated) wave as shown. This PAM wave is then added to a sawtooth generated by the same synchronizer as drives the original signal sampling process. The combined signals are then passed through a slicer which is a device with the property that its output is zero when its input is below a certain value and is a maximum when its input is above that value. In effect, it takes a slice of the wave at the point marked "slicer level" and converts it into pulses which are positive when the input signal is above that value and zero when it is below. The result is a pulse-duration-modulated wave. The production of such a uniform sampling wave is somewhat complex. A somewhat simpler technique for deriving the PDM wave is shown in b of figure 4–2 and is known as natural sampling. The sawtooth is simply added to the signal wave and passed through a slicer as before. The output is PDM, but differs in form from the PDM derived by the first method because the lengths of the sampling intervals are dependent upon the values of the signal. This is a much simpler signal to generate but it is much more complex to regenerate at the end of the transmission system. The usual practice is to regenerate it as if it were a uniform-sampling signal and to accept the distortion produced by the nonuniform sampling times.

The purpose in describing in such detail the mechanics of PDM signal generation is to emphasize one of the significant characteristics of pulse transmission systems. This characteristic is that one almost invariably knows some specific thing about the pulse arrival time which often makes it possible to improve the overall time stability of the transmission system. This knowledge, for example, may be that the starting times of the pulses are exactly evenly spaced. With this knowledge a system can be devised for recreating at the far end of the system pulses with exactly the same starting times and lengths



(*after Black "Modulation Theory"*)

FIGURE 4–2.—Methods of generating PDM.

(a) Uniform sampling, (b) natural sampling

as those that were fed into the system. Thus the time instability of the recorder may be removed. The same function can be performed for pulse amplitude modulation and for pulse code modulation. In the latter case, not only are the times of the pulses known but also the amplitudes in that the information is contained only in whether the pulse is present or not or, for some more elaborate coding schemes, whether the pulse has the value "one" or "zero."

The usual PDM recording practice is to convert the rise at the beginning of a PDM pulse and the fall at its conclusion to either bidirectional or unidirectional spike signals for recording on the tape. The circuits immediately associated with the tape recording process itself need deal only with these spikes and therefore need not have dc response. A "boxcar" circuit or bistable multivibrator or, for the most modern equipment, one of the more sophisticated modern alternates to these circuits, is used to convert the spikes back into a train of duration-modulated pulses (fig. 4–3). Only those parts of the entire system preceding the conversion to spikes and following the reconversion to pulse form need carry the low-frequency components of the PDM signal. Typically a manufacturer's specification for a ground-based instrumentation recorder will note that there is a certain maximum length of PDM pulse which the recorder can accept. This specification usually means that the manufacturer has placed this limit on pulse length so that the low frequency response of the "prespike" and "postspike" circuits will not be exceeded.

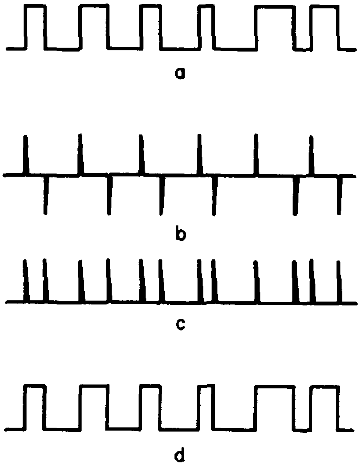


FIGURE 4–3.—PDM recording wave forms

(a) PDM input wave form to recorder, (b) bidirectional spikes derived from (a), (c) unidirectional spikes derived from (a) or (b), (d) output PDM wave form reconstructed from (b) or (c)

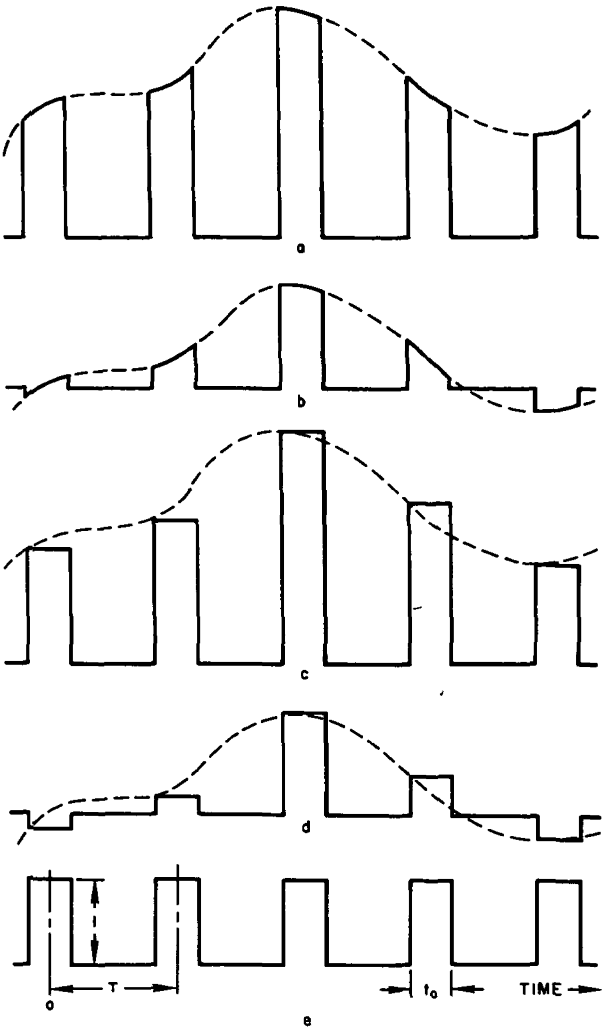
PDM is limited in use primarily to relatively low-frequency signals, often where many signals are multiplexed together by time division. A typical PDM system may have a 900 pps repetition rate, with pulse lengths from 60 to 900 microseconds. In the limit, it approaches FM in the efficiency of its trade of bandwidth for signal-to-noise ratio, but would never be chosen for that factor alone. Its primary appeal lies in the simplicity of magnetic recording circuits needed with it and the corresponding simplicity of circuits used in converting the raw data to this form.

PULSE AMPLITUDE MODULATION

Pulse amplitude modulation or PAM has also been used for data collection, particularly where data is multiplexed, and tape recorders have therefore been required to store this form of modulation with accuracy. The use of PAM differs from that of PDM and FM in that the choice to use PAM is almost always made entirely by the system engineer for reasons unrelated to magnetic recording problems. The choice of FM modulation in the recording is a recording engineer's solution to the problem of providing a high signal-to-noise ratio and dc response. PDM was initially also used by recorder engineers for this purpose, but at present, this modulation scheme is normally chosen by the system engineer acting in full cognizance of magnetic recorder problems. PAM would seldom be chosen either by a recorder engineer or a system engineer to simplify recorder problems since it requires that the recorder be operated in the analog or linear mode. The one desirable feature which PAM offers for recording is that it can be made not to depend on accuracy of maintenance of the time scale by the recorder, but it does not naturally operate this way.

Pulse amplitude modulation takes many forms, some of which are shown in figure 4–4. The choice of the form used may be based either on simplifying the encoding and/or decoding process or improving the effective performance of the transmission system. In the magnetic recorder the double-polarity flat-top pulse version of PAM is probably the easiest to deal with but, as must be emphasized, the recorder engineer seldom makes the choice of this particular coding scheme.

Several combinations of sampling techniques and pulse transmission means have been used to produce other pulse modulating schemes related to the two just discussed. Few of these have seen extensive use in systems involving data handling through magnetic recording. There is, however, one relatively new and popular scheme known as "*pulse frequency modulation*" which the recorder is often called on to handle. Pulse frequency modulation or PFM has great advantages for certain classes of telemetered transmission but is not particularly easy for a tape recorder to deal with. Basically it partakes of the problems inherent in both FM and PDM recording. The PFM signal is a series of periodic bursts of pulses, the repetition rate within the individual bursts being controlled by the data so that, in effect, it is a discontinuous FM transmission scheme. Its great advantages are an impressive FM-like noise immunity and very simple techniques of generation and detection (Rochelle [1963]).



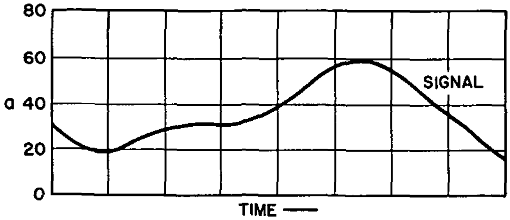
(*after Black "Modulation Theory"*)

FIGURE 4-4.—Pulse-amplitude-modulation (PAM) wave forms

(a) Single-polarity pulses, (b) double-polarity pulses, (c) single-polarity flat-topped pulses, (d) double-polarity flat-topped pulses, (e) unit sampling wave form, I is pulse amplitude, T is pulse period, t_0 is pulse length

PULSE CODE MODULATION (PCM)

In pulse code modulation an analog signal is converted to digital form and transmitted, recorded, reproduced and otherwise handled entirely as a digital quantity. The instantaneous value of the analog signal is sampled at specified intervals and the sample is quantized and converted into a digital number (fig. 4–5). When such a signal is recorded and reproduced by a magnetic tape recorder, the recorder is charged only with guaranteeing that the same digital number received at the input is delivered to the reproducer output. The system engineer employing PCM must also deal with the problem of assuring that the sampling and quantizing processes are optimized.



b	31.88	18.32	23.77	31.60	37.77	57.10	55.06	36.61	15.98	EXACT VALUE
c	32	18	24	32	38	57	55	37	16	NEAREST WHOLE NUMBER
d	100001	010011	011001	100001	100111	111010	111000	100110	010001	BINARY VALUE

FIGURE 4–5—Pulse code modulation (PCM) processes

(a) Signal wave form (made unidirectional), (b) exact value, to 4 significant figures, of signal wave form at equally spaced sampling instants of vertical lines, (c) quantized signal values, that is, for this example, changed to nearest whole number (actual range of signal allowed is 0 to 63), (d) quantized value (nearest whole number) converted to binary form, these numbers transmitted in sequence will form the PCM signal.

The concept of PCM as a means of transmission of a signal predates the existence of the digital computer as we know it today (Reeves [1942]).

PCM and the computer are now, however, intimately tied together. In order for a digital computer, which can deal only with numbers and not with continuous signals, to analyze data presented in the form of continuous signals, the signals must be sampled and quantized. Thus the processes of PCM are essential to the use of computers in data reduction. The magnetic drum or disc or tape memory of the computer therefore deals with the computer's input data signals in digital PCM form as well as handling instructions and addresses in strictly machine-language digital form.

Entirely aside from the relationship of PCM to the computer certain advantages of transmitting, recording and reproducing important data in digital form have encouraged the use of PCM purely as a transmission means (Oliver et al. [1948]). There are, therefore, PCM transmission systems and recording and reproducing modes which produce PCM formats not directly usable by any computer simply because it is a good data handling scheme. There is, admittedly, a tendency to shift the format of PCM as a pure transmission means toward one compatible with its use by a computer, since the data almost invariably is eventually used by a computer.

A detailed discussion of the problems of the conversion of analog signals to PCM form is beyond the scope of this survey. Those parts of the problem germane to an analysis of the utilization of magnetic recording are discussed in chapter 15. It will suffice here to state the general dimensions of the problem.

The magnetic recorder may be required to deal with a PCM signal at any point in its progress from initial sensor to final data reduction. This means that the PCM signal may be a frequency-modulated carrier which is to be predetection recorded, or it may be an amplitude modulated carrier transmitting a PCM signal, or it may be the raw PCM data itself, either "bit-serial" or "bit-parallel" form. The present analysis deals solely with the actual PCM data as it encounters the recorder and not in the other forms it may take during other portions of system transmission.

The PCM data will be in the form of pulses, each of which is normally expected to occur during a specific assigned time interval. Identification of the pulse with its time interval may occur in two forms.

In bit-serial recording a train of pulses representing the digits of the binary number corresponding to one single sample is transmitted along a single pair of wires. Such a pulse train is usually accompanied by additional pulses which perform such functions as identifying the start of the number, adding redundancy to reduce the number of certain kinds of errors, and providing synchronization. The actual signal sample number with these additional pulses is usually called a "data word." A data word always has the same length and occupies the same time period. If the number to be transmitted were to lie, say, between 1 and 64 (digital engineers would say between 0 and 63) a series of 6 binary bits or digits would have to be transmitted to identify the number. These 6 digits would almost invariably be accompanied by one other digit designed for "parity checking." Another redundant digit might be added to provide what is known as single error correction and perhaps one or more to assist in maintaining the transmission system in synchronism. This particular data word might then contain 9 bits.

In bit-parallel recording essentially the same pattern would be used with the assignment of a series of binary digits to describe the data number and with additional bits for error checking, synchronism and the like. The system would differ from bit-serial, however, in that these pulses would not appear on a single pair of wires but instead each pulse would appear on its own individual pair of wires. This means that for the example given above 9 pairs of wires would be required. All of the bits would in theory appear simultaneously on their particular sets of wires so that the data number or word would be indicated by 9 different parallel bits of information appearing simultaneously.

Conversion between bit-serial and bit-parallel is often performed in computing or data reduction as well as in preparation for data transmission. There are obvious tradeoffs between the requirements of the systems for transmitting PCM data in these two forms. If a single pair of wires is used, for example, the transmission rate must be n times as high as when n pairs of wires are used in parallel. These tradeoffs change sharply, however, when bit-serial and bit-parallel data is fed to a tape recorder. There are very definite reasons why one system should be preferred over the other for a particular application, most of these reasons being entirely mechanical in origin.

If bit-parallel recording is used in the simplest way, all the pulses representing zeros or ones appear simultaneously at a series of recording heads placed across the tape. If the recording and reproducing system is perfect, the corresponding data bits appear simultaneously at the terminals of the reproduce heads when played back. A storage buffer in a data translator can then, for example, extract all the n bits in the data word at once and from these n simultaneously extracted bits draw the conclusion that the number transmitted at that particular moment has a particular value. In a simple low-speed transmission system where the spacing of the individual bits along the tape as it passes the head is relatively large, there should be no difficulty in performing the operation just described. However, if the bit spacing becomes close along the length of the track and many bits, up to 16 or even 32 are spaced across the width of the tape, it becomes quite difficult to assure that the group of bits appearing simultaneously at the terminals of the reproduce head all belong, in fact, to the same data word. Either static or dynamic skew or difference in relative longitudinal position of individual record or reproduce heads can destroy this proper relationship. In practice the mechanical limitations mentioned set a sharp upper limit on how tightly bit-parallel PCM can be recorded.

An illustration in schematic form of the appearance on the tape of a 7 digit bit-serial recording is shown in figure 4–6. The same data is shown as it would appear in bit-parallel form in figure 4–7. These illustrations show the mechanical precision and timing problems involved in the use of each type of recording.

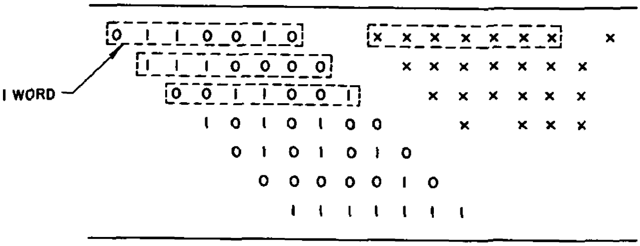


FIGURE 4–6.—Bit-serial PCM on tape.

The word at the left is the first transmitted and is followed, after a space, by that indicated in the line with it at the right as made up of 7 X's representing arbitrary digits. To conserve tape, adjacent tracks spread across the tape are used for successive words transmitted, the array being arranged so that there is an essentially steady flow of words onto the tape In this example the space between the last word entered on the 7th track and the second word entered on the 1st track is such as to give the same word-start spacing as the inter-word spacing Since the words on each track are considered individually, only track to track timing errors greater than a full word length could confuse such a recording system.

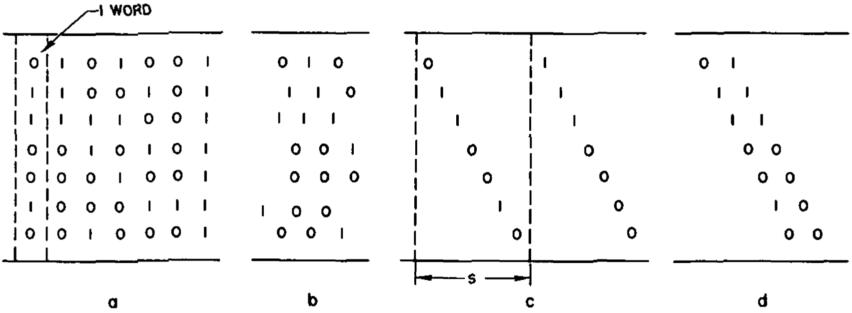


FIGURE 4–7.—Bit-parallel PCM recording.

(a) Successive words are recorded in strips across the tape width for, this case, perfect time alignment between tracks (the words for this figure are the same as for figure 4–6), (b) in this case there is severe inter-track jitter which makes it difficult to see even visually which bits belong to which words, (c) in this case the bits are spread out farther along the tape and the displacement is systematic such as would be caused by skew, S represents the word to word spacing needed with this much skew if no confusion is to exist between individual bits of successive words, (d) the situation of (c) but with close word spacing where interference occurs between the words and no simple technique will untangle the words in the presence of this much skew.

An IRIG standard now exists for recorders designed to receive parallel PCM recording (IRIG [1960]). It is a relatively conservative standard because of the difficulties of achieving close packing density. Many tape recorders are currently available which meet this standard and which operate satisfactorily at longitudinal pulse packing densities of 1,000 bits per inch. These recorders operate in this way without any compensating schemes and without correcting possible errors in bit arrival times; they achieve correct operation simply through maintenance of close mechanical tolerances and uniform tape motion. There are, however, methods available for packing bit parallel PCM much more densely than even with current techniques and also for achieving equivalent high density through the use of bit serial PCM.

PULSE RECORDING WAVEFORMS

The simplest pulse waveform conceptually is the return-to-zero or RZ pulse. This might consist of a recording current (and hence recorded flux) waveform such as shown in figure 4–8a. A "one" is represented by a positive going pulse and a "zero" by a negative going pulse.

This particular waveform is used in elementary equipment but its inefficient use of bandwidth has restricted its use. It is a redundant coding system since there are two flux transitions per bit of information required.

A slightly more efficient waveform is one which remains at either the positive or the negative maximum excursion possible in the absence of a signal. A "one" in this system is represented by an isolated pulse from one extreme of signal to the other or, in the case of tape, from saturation in one direction to saturation in the other direction. At the end of the pulse the original value is resumed and two flux transitions are required for each "one." A "zero" is represented by the absence of a pulse. This is called "return-to-bias" or "RB" recording (fig. 4–8b).

In NRZ coding, redundancy is sharply reduced by assigning, at the most, a single transition to each separate bit. The information derived from this coding scheme in a recorder is whether the flux changed or not. There are several ways in which these two basic pieces of information can be used to give a binary coding scheme. In "straight" NRZ, shown in figure 4–8c, a flux change indicates that the symbol following a given symbol is different from the first symbol. Thus the change from zero to one is indicated by a flux change. When a series of ones follow each other, no flux change is indicated, but when the last one is followed by a zero, there is another flux change. The so-called NRZI coding, which is shown in figure 4–8d, indicates a one by

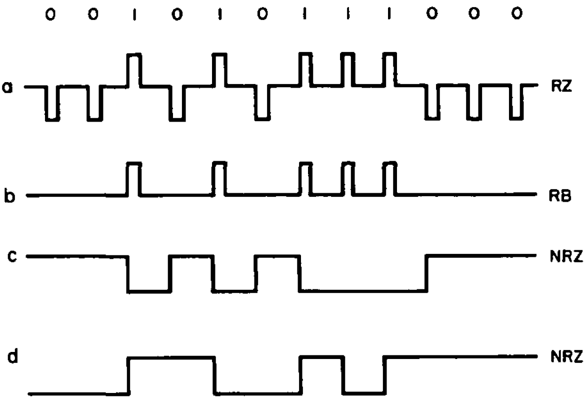


FIGURE 4-8.—Digital recording waveforms.

(a) In RZ recording of the form shown here, the binary bits of the word given above the waveform are indicated by downward pulses for 0's and upward pulses for 1's, (b) for "return-to-bias" or RB recording in the form shown here, a pulse is transmitted for a one and no pulse for a zero, (c) for "non-return-to-zero" or NRZ recording the signal value does not change unless there is a change in the value of the digit, that is, the horizontal line at the left indicates that the first 2 digits are the same as each other, the next downward flux change indicates that the succeeding digit differs from the preceding one, as with the next 4 flux changes since there is a steady alternation of 1's and 0's (sometimes called NRZ (change), (d) in NRZI recording a flux change represents a 1 and no flux change a 0 (sometimes called NRZ (mark)).

a flux change and a zero by no flux change. The primary advantage of NRZI over NRZ is that there is a one-to-one relationship between the signal and the symbol. If there is an error, only the symbol for which the error is made is lost. In straight NRZ, if a flux transition were missed, all successive symbols would be exactly opposite to what they should be until synchronism was somehow regained. These straightforward coding processes have the difficulty that there may be long "floats" in which a particular data combination produces extremely long signal pulses. Low-frequency phenomena in the recorder may therefore affect the accuracy of data containing such long floats.

The NRZ process uses at a maximum one flux reversal per bit of information and on the average uses less than this number. Where there are, for NRZ, long periods of identical symbols, or, for NRZI, long strings of zeros, the coding is very efficient in that fewer flux transitions are used. It is essential for this efficient coding to work that the timing of the flux transitions or their absence be accurately known.

So called "phase modulation" or "Manchester" coding techniques have been introduced to eliminate some of the problems of providing accurate time information in interpreting binary symbols (Hoagland [1963]). Phase shift or phase modulation coding is also called self-clocking. It is so called because there is an identifiable pulse signal in each "cell" in which a binary bit may be found. A signal may therefore be derived from each cell to keep the system in synchronism or to provide a clock. Figure 4–9a shows such a coding scheme. In this particular version of phase shift coding, the zero is represented by a downward flux transition in the middle of the bit cell and a one by an upward transition in the cell. In order to maintain this relationship it is necessary for additional flux transitions to be introduced from time to time when two identical transitions must follow each other. In other words, an extra downward transition must be provided between successive ones and an extra upward transition between successive zeros. There is, however, a derivable output spike, either positive or negative, in the center of each bit cell and this output spike can be used to synchronize a local clocking scheme. In this system it is possible, with proper design, for the rate of data flow (recorder tape speed) to be quite irregular and still to detect properly the piece of in-

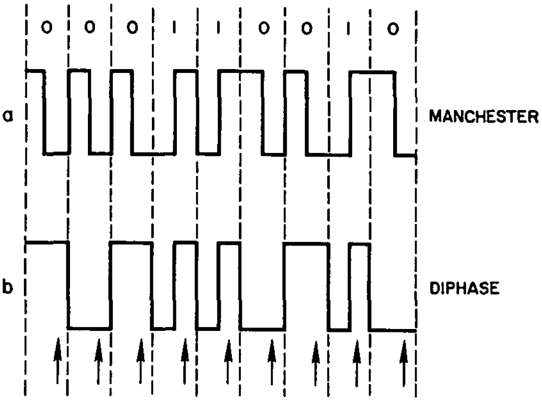


FIGURE 4–9.—Phase-shift or phase-modulation digital recording wave forms.

(a) The "Manchester" form of phase-shift coding designates a zero with a downward flux change in the middle of the "bit cell" and a one with a corresponding upward flux change, (b) this phase-shift coding, known as "modified diphase," indicates a zero by having no flux change during the "bit cell" and a one by having such a flux change, decoding being accomplished by examining the successive values of the wave form at the arrows, which are ¾ of the way through the "bit cell," in determining whether the values are the same for successive examinations (a one) or different (a zero), a flux change always being provided between successive "bit cells" for timing.

formation contained in each binary cell. Many versions of this coding have been devised with various advantages for particular applications. Some of these schemes optimize the simplicity of creating the code and others optimize the accuracy of detecting the output (Gabor [1960]).

A specific version of phase shift coding described as "modified diphase" has been specifically applied to the Gemini onboard PCM recorder. This coding scheme carries the information in whether there is a phase transition within the "bit cell" or not. As illustrated in figure 4–9b, this particular code gives a phase transition within the bit cell for a one and no such transition for a zero. There is always a flux transition at the start of each bit cell from which the clocking scheme can be operated. Detection of the data in this code can be performed by examining the instantaneous signal value three-quarters of the way through the bit cell, as shown by the arrows in the figure. If the signal value changes between any successive pair of examinations, the digit in the bit cell observed is a zero; if the value remains the same, the digit is a one.

Basically the phase shift modulation coding scheme can be seen to have two fundamental frequencies. One of these has the length of two bit cells for a full cycle and the other has the length of a single bit cell. In a simplified way, one might say that the system runs either at one or the other of these two frequencies. In practice, of course, the shift between the two waveforms is irregular and unpredictable, and the result is that a broad spectrum is generated. Basically, however, the highest frequency present in a phase shift modulation coding process is twice that in NRZ. The price of the extra bandwidth is gladly paid in many applications for the improved accuracy with which the data is derived.

OTHER RECORDING METHODS

The several recording modes described in this section do not by any means exhaust the possibilities that have been employed. Only a few other modes have, however, had any extensive use. Perhaps the most important of these is what is called "Carrier Erase."

In carrier erase, the tape is prerecorded with a continuous tone signal of high amplitude and of frequency well above the intelligence to be recorded. The recorder simply dc-erases the carrier in proportion to the intensity of the information signal, which is applied directly to the record head. This technique has the advantage of extreme simplicity in the recorder and not much complexity in the reproducer, since the signal is obtained in the form of a modulated carrier which is relatively easy to demodulate. Although of low recording density, the simplicity and fair linearity of the process have led to its extensive use in very small, severe-service recorders.

CHAPTER 5

Head-Tape Interaction

A convenient way to analyze the difficult subject of interaction between head and tape is to postulate an elementary idealized tape recording process and then to examine in some detail the performance of this process and the factors influencing that performance. As the examination proceeds, it will become apparent what practical changes are advisable in making and reproducing the recording, first, to produce useful results, and then to refine those results. By this procedure, the complex interaction between the elements involved can be developed with a minimum of repetitive analysis.

For the first test recording, let the recorder consist of a tape moving mechanism and a recording head of the type commonly used in modern recorders, i.e., one which produces the recording flux as a fringing field surrounding the recording gap. This recording head is driven from an appropriate linear amplifier which applies test signals directly to the recording head. The tape is smoothly driven at one of the currently standard speeds. After making a test recording and rewinding the tape, it should be possible to reproduce the recorded signals. The recording head could be used for reproduction, but it is more instructive to use a modern reproduce head with slightly different characteristics from those of the record head. The output of this head is connected to another linear amplifier uniform in frequency response.

Two things would be obvious on examining the reproduced output: First, the output would be badly distorted, mostly with odd harmonics, to a degree almost independent of the input signal level. Second, the frequency response of the system would be nonuniform, being roughly "humped," peaking somewhere at the geometric average of the lowest frequency and the highest frequency that the recorder could reproduce. The signal-to-noise ratio would not appear to be too bad, but, since no signal could be reproduced without distortion, there would be no reference signal level for which the signal-to-noise ratio measurement could be specified. Consider now why the hypothetical recorder would operate in the manner just described.

In the first place, the transfer characteristic of the head-tape combination, i.e., a plot of instantaneous input voltage versus instantaneous output voltage, is a severely curved line when an alternating current signal is applied directly to the recording head. The curvature is symmetrical around zero voltage and the distortion produced by the curvature therefore consists entirely of odd harmonics. (See fig. 5–1.)

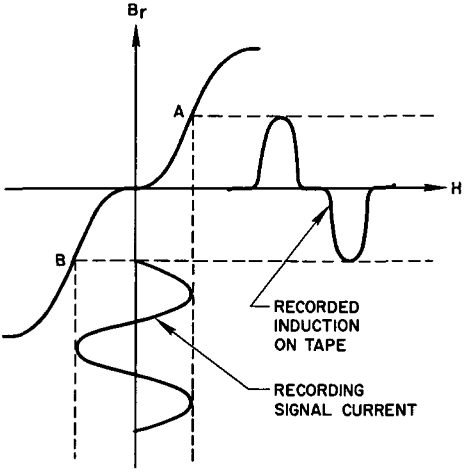


FIGURE 5–1.—Unbiased magnetic recording.

With the distorted portion of the normal tape transfer characteristic between A and B being used the recorded waveform and resulting output are sharply distorted.

This transfer characteristic is often likened to two initial magnetization curves of the magnetic recording medium placed back to back. Although it resembles these curves, the mechanism involved is quite different from that involved in forming the initial magnetization curves.

Having chosen a particular tape speed, the relationship of applied frequency and recorded wavelength is now determined. If there were a means for determining the strength of the flux recorded in the tape, an examination would show that placing a current in the recording head constant at all test frequencies would produce flux in the tape approximately constant at all wavelengths. When this constant-flux recording was reproduced we would find, at least at low frequencies, that the output from the reproducing amplifier was proportional to frequency. This would result from the dependence of the reproducing head output, not on the amplitude of the flux, but on the rate of change of flux. The classic 6 db per octave rise of a differentiated signal thus occurs since, in effect, the input signal has been differentiated in the reproducing process.

In a real recorder/reproducer, however, this 6 db per octave rise would not be maintained as higher frequencies (shorter wavelengths) were approached and the response would eventually flatten out and turn down very sharply. The response would eventually go to zero at a frequency which could be calculated to be that at which the reproducing head gap was effectively one wavelength long (fig. 5–2).

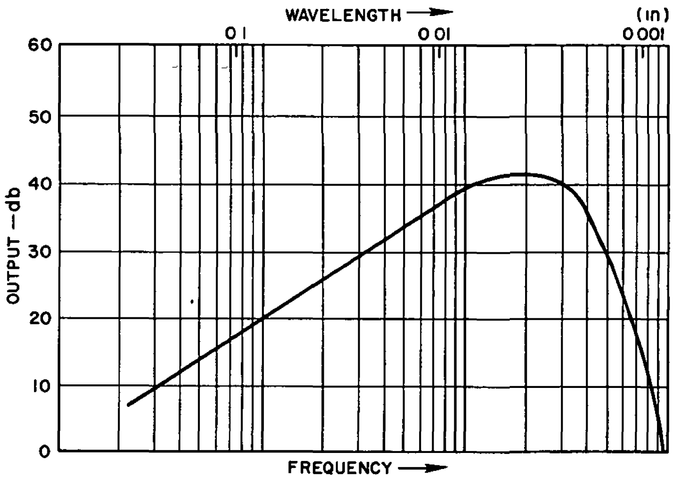


FIGURE 5–2.—Elementary recorder frequency response.

To improve the rather discouraging performance of this tape recorder, which perhaps was the situation that Valdemar Poulsen faced when he invented the first tape recorder at the turn of the century, distortion might be attacked first. The rather unpleasant transfer characteristic of the figure suggests that adding a fixed magnetization to that of the signal so as to shift the operating point of the recorder up from zero to a fairly straight part of the transfer characteristic might help. This would reduce the size of the reproduced signal since less of the total "flux swing" would be used and the noise output of the recorder would increase but the transfer characteristic would straighten out quite well (fig. 5–3). Many modern dictation recorders and even some semiprofessional audio ones use this so called "dc bias" mode of operation. Assuming for the moment that the better linearity of the dc-biased signal is satisfactory, the next concern might be with the very poor frequency response.

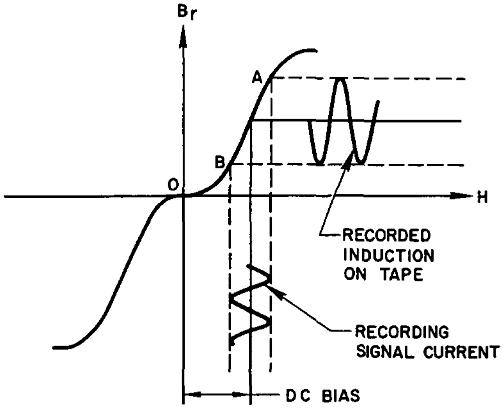


FIGURE 5–3 —Recording with dc bias.

The useful part of the characteristic from A to B is shorter than for the unbiased condition of figure 5–1, but the output is undistorted.

Since the signal is differentiated in reproduction, an integrating equalizer, that is, one with a 6 db per octave downward slope with frequency, could be inserted in the reproducing channel. This would straighten out quite successfully the low frequency portion of the frequency response curve, but the flattening out and droop at high frequencies would be intensified. Some kind of high frequency boost would now be needed; a resonant or feedback RC equalizer could supply enough high frequency gain in the reproducer output to flatten out the response of the complete recording system over a reasonable frequency range (fig. 5–4). The equalization would increase the high frequency noise in the output just as it increased the high frequency signal. The overall signal-to-noise ratio would thus be degraded by the equalization. The final signal-to-noise ratio achieved thus depends on the frequency range the recorder attempts to cover.

The test device would then be a usable magnetic recorder; it is probable that half a million recorders using the same design principles have been commercially sold for amateur and office dictation use within the last 10 years. Such a device is still rather crude and many techniques are now available to improve the performance by several orders of magnitude. First, the dc bias could be removed and ac bias could be added. That is, a steady ac signal of about ten times the maximum signal amplitude could be added to the signal in the recording head.

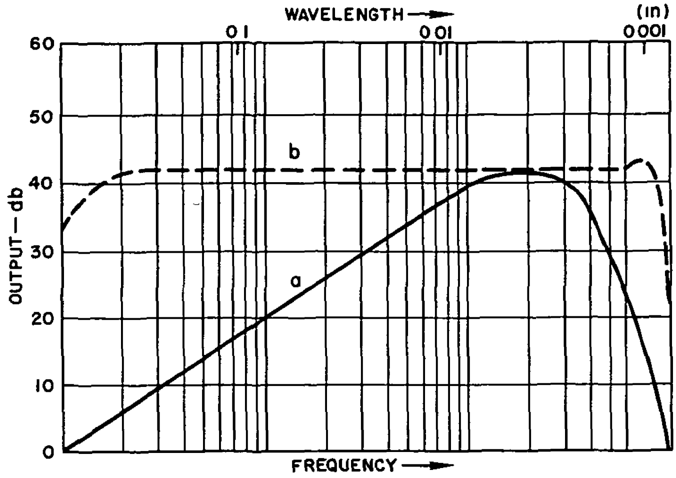


FIGURE 5-4.—Equalization of elementary recorder.

(a) Basic unequalized frequency response, (b) simplified results of, on the left, integration and equalization to remove normal differentiation of dϕ/dt playback head, and on the right, of a peaked equalizer to remove the effects of scanning losses.

It would be found that this would improve the signal and reduce the noise of the reproduced recording. (This biasing technique was the development step that made modern recording possible.) Second, the reproducing head gap could be made as narrow as possible so as to reduce the wavelength and hence raise the frequency at which the output response goes to zero. The recorder would then require less high frequency reproduce equalization and would handle an increased bandwidth.

The record current would still be constant with frequency. If nothing were known about the energy spectrum of the input signal (the usual situation with scientific recording), this record current relationship could not be changed. If, however, something were known about the spectrum of the input signal, as is, for instance, the case in audio recording for entertainment purposes, certain frequencies could safely be preemphasized on the basis that the input signal would not contain significant high-intensity components at these frequencies and there would be little possibility of overloading the tape. A decision was made, early in the development of audio recording, based on the assumption that there was little high-frequency energy in a typical audio signal, to preemphasize high frequencies. Having preemphasized these frequencies, they can be deemphasized in reproducing. That is, less high-frequency reproduce equalization would be used, less high-frequency noise would appear in the output, and the signal-to-noise ratio would be improved. A little low frequency preemphasis could also be used, but high-frequency preemphasis would have the maximum effect. The recorder as now described is essentially that used for both professional and nonprofessional audio recording.

The technique of deciding the amount of preemphasis from the knowledge of the spectral characteristics of the input signal has been described in glowing terms here. In theory this is what is done with an audio recorder; in practice, a study of the actual spectral distribution almost proves that it cannot successfully be done. In other words, a scientific investigation of the spectrum is unable to account for the amount of preemphasis that can be used without harm. The most recent change in audio preemphasis/deemphasis, introduced with a view to improving signal-to-noise ratio, came about as the consequence of some work which showed that the spectrum distribution of music would not permit such preemphasis! (McKnight [1959]) Nevertheless, the new equalization is quite successful and is now almost universally employed for "master" recording (original recording as the basis for mass reproduction of disc or tape copies for home use).

To record a very wide band of frequencies, say twice that of the initial recorder, tape can be run twice as fast and all equalizers and similar devices correspondingly scaled up in frequency. This process can be continued, scaling up many times in bandwidth from the initial audio range. By increasing tape speed, higher-frequency recording can take place at the same wavelength. There is a point at which, however, frequency, *per se*, becomes a limiting factor in certain of the recorder elements. Eddy current and hysteresis losses begin to limit the usefulness of record and reproduce heads and the heads must be made of materials designed for use at these higher frequencies.

As the abilities of the basic tape recorder are pushed higher and higher, second order effects begin to be important and the action of the recorder must be analyzed in greater and greater detail. For example, further investigation would show that there are several complex frequency-sensitive losses which add to the basic reproducing wavelength losses (McKnight [1960]). These losses produce perceptible effects even for the elementary recorder, but become more important for more sophisticated recorders. There is a loss of signal as the portion of tape involved is placed farther and farther away from both the record and reproduce head. This "spacing loss," as it is called, is a function of recorded wavelength. Scanning loss, discussed above, comes mainly from the finite size of the reproduce heads although some characteristics of the record head gaps also affect wavelength response. A widely misunderstood phenomenon called demagnetization loss is also found. It results from a tendency of the tiny permanent magnets placed in the tape on recording to demagnetize themselves, this effect being greater as the magnets get shorter and the wavelength correspondingly shorter. There is another loss which is a function of the thickness of the magnetic material on the tape. This is a form of spacing loss, that is, of loss dependent on spacing of the material away from the head; this spacing differs for different depths in the tape, so that only part of the tape is effectively in contact with the head. The phenomenon has been studied recently in great detail, particularly for digital recording (Eldridge [1960]). The analytic process of separating the effects of all these losses has been discussed extensively in the literature (McKnight [1960]) (Wallace [1951]).

The basic process by which ac bias causes the record characteristic to become linear is often described as being quite mysterious. The current understanding of this phenomenon is not, however, quite so uncertain as this typical reaction implies. A more accurate description is:

1. The process of anhysteretic magnetization is generally considered to be an adequate description of the gross effects of ac bias as the magnetic tape passes through the biased recording fields. An essentially anhysteretic magnetization process takes place when a section of tape is brought up to the record head and passes beyond it. As it approaches the head the bias and signal field get progressively stronger to a peak level and then, as the tape section leaves the head, they gradually fall off. This is precisely the process involved in anhysteretic magnetization where a sample of magnetic material is placed in a field varying just as described.
2. The process by which anhysteretic magnetization takes place is not fully understood at present, although the characteristics produced are fairly well understood to be dependent on the interaction between the magnetic fields of the particles rather than on properties of the magnetic particles themselves. (Schwantke [1958]) (Daniel and Wohlfarth [1962]) (Eldridge [1961]).
3. The detailed process which goes on as the tape approaches the head, passes it, and passes on is not fully understood because the actual magnetic fields present have not been adequately explored. For example, the magnetic field to which the tape is subjected is directed along the surface of the tape in one direction as the tape approaches the head and is along the surface of the tape in the other direction as the tape leaves the head. At some point in the process the field direction must rotate; just

how this takes place and how it affects a set of dispersed magnetic particles is not clearly worked out as yet (Mee [1964]).

If the emphasis is placed on recordings where the time of the starting and stopping of pulses contains the significant information, such characteristics as linearity and frequency response are not of primary importance. The same tape moving mechanism can be used but the current applied to the record head can be chosen to give as much magnetization in the tape as is possible to produce tape saturation. To indicate the start of a pulse this saturating current can be turned on or the current direction can be instantaneously reversed. Alternately, a positive pulse can be recorded by turning on a positive saturating current and turning it off at the end of the pulse, allowing the current to fall then to zero. A negative pulse can be recorded by turning on a saturating current in the opposite direction and the end of the pulse indicated by turning this pulse off. This is called "RZ" or "return-to-zero" recording. Alternately, the current can be turned on in one direction or another to indicate the start or stop of a pulse. This is called "NRZ" or "non-return-to-zero" recording. NRZ recording, because it is more important, will be analyzed in further detail.

If this recording is reproduced with a flat linear amplifier and a conventional reproduce head, a positive output pulse will appear for each positive going recording current transition and corresponding record flux transition; a negative pulse will appear for each negative current transition and flux transition. A satisfactory pulse recorder seems thus to have been provided without very much effort. The elements described are actually the only essential ones in a modern pulse recorder, but for efficient pulse recording, refinement is required. High pulse recording density and sharply defined reproduced pulses are needed, and the mechanism involved in achieving the proper density and signal level in such recording must be analyzed.

When the pulse current through the recording head is turned on or turned off instantaneously, it effectively maps the external flux field of the recording head onto the tape (Eldridge [1960]). (This is the subject of a later analysis.) When this mapped field passes the reproduce head, it produces an output signal essentially proportional to the instantaneous rate of change of difference in the amount of flux passing into the two halves of the reproduce head, one on each side of the reproduce gap. Operating on this difference, it is found that the ability of the reproduce head to define the position of the pulse on the tape is three to six times as poor as that of the record head in placing it there. This is a fundamental relationship, independent of detailed head design. To improve the pulse packing density, attention, therefore, should be directed primarily to the reproduce head.

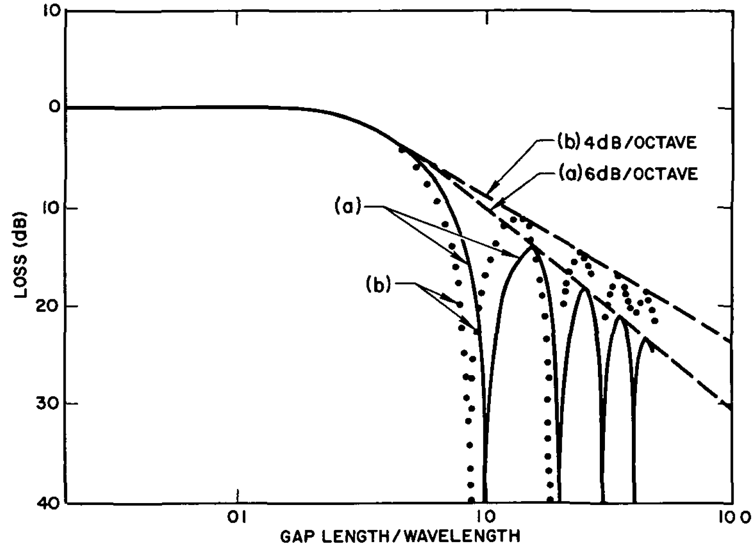
The technique of employing the recorder simply to carry information on pulse starting and stopping times opens up its use for many recording modes quite different from the linear analog mode first discussed for the basic test recorder and first used in audio recording. These different modes, such as PDM, PCM, FM and other modulations, permit optimizing various performance parameters of the complete recording process and providing best fits between a recorder and the rest of a system in which it is used. This subject is discussed in detail under "Recording Methods."

By introducing the initial crude tape recorder and gradually refining it for various applications the basic processes of interaction between tape and head have been discussed in a systematic way. For a general review, this outline treats the subject in adequate depth. Certain parts of the head-tape interaction process which have detailed importance will now be discussed more fully.

HEAD-TAPE GEOMETRY—BIASED RECORDING

The geometrical elements of the head and tape which enter significantly into the record/reproduce process are the shape of the head pole pieces, the dimensions of the head gap, the spacing between the head and the recording medium, and the depth of the recording medium. Each of these geometrical factors has some effect on the response at short and long wavelengths. These wavelength effects are some of the tape recording factors about which our current understanding is most complete.

The most critical dimension of the record and reproduce gap is its length; the depth of the gap and size of the corresponding rear gap in the head structure are also important in determining head performance. The ultimate high-frequency (short-wavelength) limitation to recorder response is the length of the reproduce gap. In an indirect way, the length of the record gap may also influence this limit but the primary effect lies in the reproduce gap. There is always one critical tape wavelength at which the total amount of flux in one direction and the other included within the gap, and therefore affecting the head, is independent of the position of the gap along the tape. At this particular wavelength no output signal is produced. This is an example of a scanning process which typically has a null at one particular wavelength. As with other scanning processes, at wavelengths shorter than the wavelength of the first null there is still some response from the head, and at even shorter wavelengths, a succession of additional nulls. The characteristic shape of response from such a scanning structure is a sin x/x function and is encountered in any process in which waveforms are scanned by a structure which integrates all portions of the wave included within the structure length. Daniel and Axon (Daniel and Axon [1953]) have analyzed the experimental fact that a measurement of the so-called gap nulls and the shape of the scanning effect for magnetic recording does not precisely follow the sin x/x formula. They postulate certain other interrelated phenomenon, giving a more exact function for the response. They include possible mechanisms for the observed fact that the effective length of the gap, judged from the position of the response nulls, is longer than the physical gap (fig. 5–5).



(*after Mee*)

Figure 5–5—Reproducing gap-loss functions

(a) Simple sin x/x formula, (b) more complete formula (see text).

A longer gap includes more flux within the gap pole pieces and therefore produces a greater long-wavelength output. However, the response of such a long gap will fall off faster with decreased wavelengths and at any particular wavelength it is impossible to say without calculation whether widening the gap will increase or decrease the response. The choice of the reproduce gap length is therefore an important one related to the total bandwidth which the recorder is designed to cover. The discussion so far has referred to wavelengths in purely sinusoidal terms. The Daniel and Axon analysis and the sin x/x function do refer to sinusoidal functions; the same sort of gap effect, however, occurs in pulse recording and determines the digital packing density achievable (Eldridge [1960]).

The surface of the typical recording and reproducing head facing the tape forms a gradual smooth curve. The tape is stretched over this curve so as to contact the head over a specific length of tape. The radius of the curve and its relationship to the rest of the geometry of tape movement in the recorder determines the manner in which the tape approaches and leaves the head pole pieces. This rate of approach and the length of head-tape contact affects the response of the recorder at wavelengths of the order of the length of this contact.

When the frequency of the signal recorded on the tape is low enough so that the recorded wavelength exceeds the total length of head-tape contact, the amount of flux which succeeds in entering the pole structure depends on the relationship between the contact length and the wavelength. The result of this dependence is that there is a scanning effect producing variations in response at these extremely long wavelengths quite analogous to the gap-length phenomenon occurring at much shorter wavelengths. The low-frequency scanning effect does not produce nulls in response as sharp as those of the high-frequency gap scanning phenomenon but produces response variations of a few db. These variations in response are sometimes called "head bumps." The shape of the pole pieces and hence the rate at which the tape approaches and leaves the head affects the amplitude of the head bumps. At extremely long wavelengths the head-bump phenomenon may in some cases, by setting the lower frequency limit, determine the number of octaves that can be covered at a given speed by a particular recorder in the direct recording mode.

The depth of the gap, although not as fundamental as its length, is an important parameter of reproduce head design. Gap depth is naturally related to the useful life of the head, in that any head wear resulting from abrasion from continued passage of tape reduces the gap depth. The fraction of the fringing flux from the tape which is "collected" by the pole pieces and induced to cross the gap in the process of being introduced into the magnetic circuit of the head depends on the reluctance of the gap compared to the reluctance of the rest of the head magnetic circuit. As the gap becomes extremely short, even though the reluctance of the rest of the magnetic circuit, constructed of soft magnetic material, is very low, the reluctance of the gap may be small enough to approach that reluctance if the gap is also deep.

The magnetics of the process that goes on in the reproduction of magnetic tape recording is easiest to analyze by analogy to the corresponding recording action. Calculation of the amount of flux which crosses the gap on record, and hence the amount of flux involved in the fringing field, involves the magnetomotive forces induced in the magnetic circuit. The source of magnetomotive force is, of course, the current in the record coil and the total magnetomotive force rise is usually considered to be developed between the two ends of the coil. The magnetomotive force drop in the magnetic circuit with a relatively long gap almost always appears across the gap itself. This magnetomotive force across the gap is the driving force for the fringing flux which actually links the tape and does the recording.

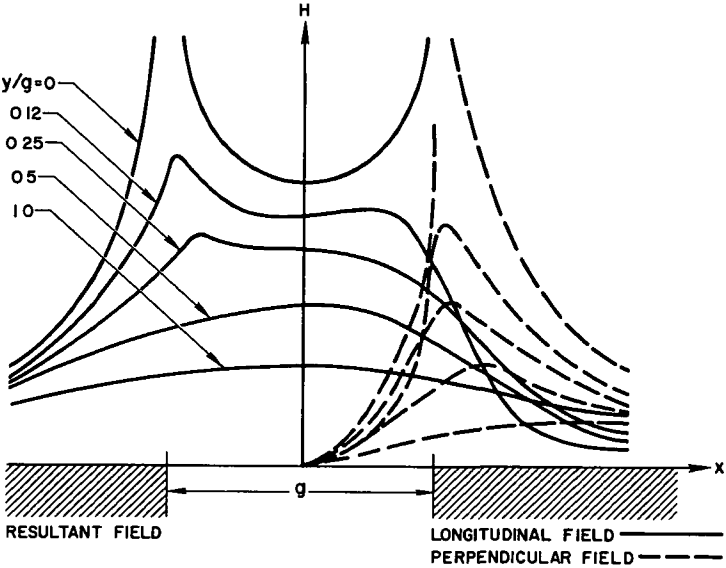
On reproduction, the flux fringing out from the tape, driven by the remanent permanent magnetomotive force originally developed by the recording fields, appears across the gap and the effective magnetomotive force across the gap drives flux through the pickup coils. If the gap is so small that the reluctance of the soft magnetic circuit and of the gap are about the same, much of the magnetomotive force drop appears along the magnetic circuit and is not available for inducing flux, and hence voltage, in the pickup coil. One way of looking at these gap dimension phenomena is to consider that the actual gap has a shunting effect on a theoretical gap of infinite reluctance. This shunting effect, and the effect of wear on gap depth, make the choice of the gap depth important in the design of a magnetic head. A deep gap will wear for a long time but will have high shunting and hence less output, all other things being equal.

It is generally accepted that the factor which determines the recording resolution of the record gap is not the gap length but the sharpness of the gap trailing edge. This is an indirect way of stating that the rate at which the recording flux falls off at the trailing edge of the gap determines the precision with which the record head locates on the tape the point at which a particular signal is recorded. The gap length has a secondary effect on the recording phenomenon. This secondary effect is related to the head-tape spacing and the recording medium depth. The practical effect of recording gap length is to influence the relationship between optimum bias for a particular test frequency and the tape thickness for linearized recording (McKnight [1961]). For pulse recording, the record gap length has little effect except on the amount of record current necessary to produce tape saturation. In any case, the record gap is always considerably longer than the reproduce gap.

The spacing between the head and the tape and the thickness of the active coating on the tape combine to form the third factor of head-tape geometry which influences the record/reproduce process.

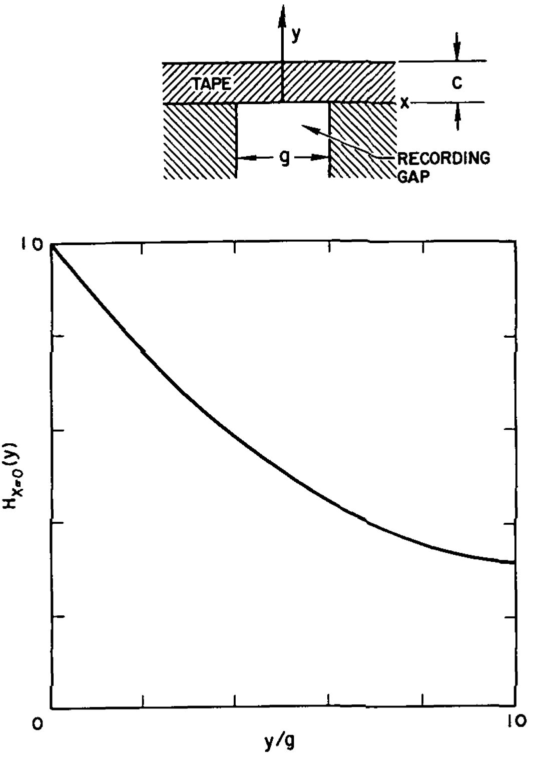
The same basic process is involved in determining the effect of the thickness of the medium and of the head-tape spacing. The effect of these geometric factors can be analyzed by inspecting an infinitely thin layer of medium and determining how the spacing of this layer from the record or reproduce gap affects the signals transduced by the gap.

Figure 5–6 shows the fields to which an elementary (infinitely thin) layer of tape is subjected as it moves past a recording gap at various distances from the gap. The parameter y/g, the ratio of the distance from the surface of the head to the gap length, obviously controls sharply the intensity of the maximum field to which the tape is subjected. Figure 5–7 shows the way in which the field intensity along the direction of tape movement in the center of the gap varies with spacing from the head surface. Assuming for the moment that the gap length is 1.0 mil and the tape coating is 0.3 mil thick (rather typical values), and that the coating lies actually in contact with the surface of the head, it is apparent that the intensity of the field in the center of the gap for the nearest layer of the tape is about 1.5 times that for the layer farthest from the head. For the field at the edge of the gap the ratio of near-layer intensity to far-layer intensity is almost infinite. It is thus quite obvious that the recording field intensity is sharply influenced by spacing.



(*after Dunker*)

Figure 5–6.—Fields surrounding the recording gap



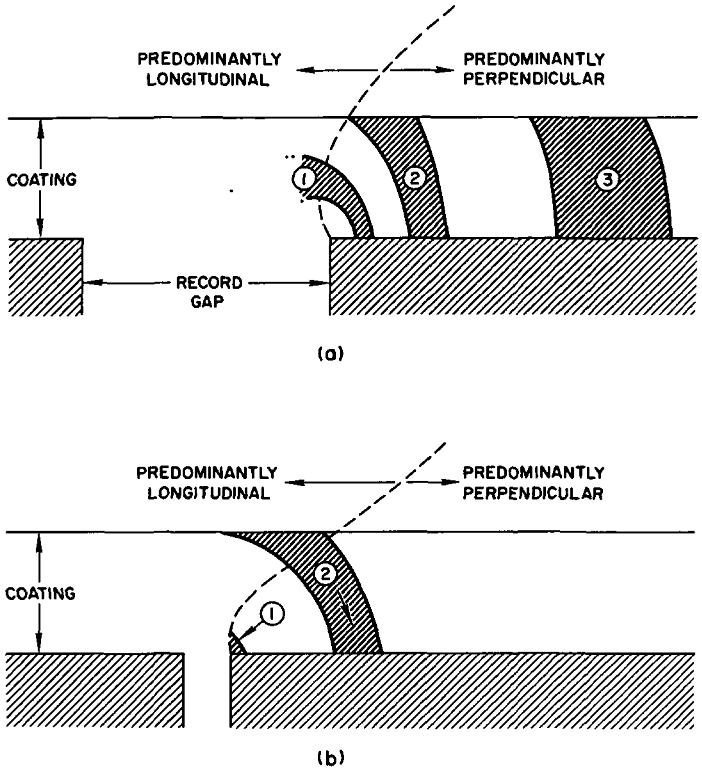
(*after Mee*)

FIGURE 5–7.—Dependence of field intensity in center plane of recording gap on distance from gap.

The relationship between the spacing effect and the medium thickness effect is, of course, that the overall field to which the tape is subjected is the integrated effect of the various fields through the thickness of the tape. The thicker the coating, the greater the range of spacing over which the effective field must be integrated, and as the field falls off with distance, the lower the average field. What is more important than absolute value of the field intensity is the steepness of the curve of field intensity in the direction of tape movement versus position at the edge of the gap. For linear ac-biased analog recording this steepness is the most significant parameter in determining the recording resolution. In a related way the same phenomenon occurs for digital recording. The plot of figure 5–6 shows that the steepness of this falloff is also sharply dependent on spacing.

It is apparent from figure 5–6 that the portion of the tape in immediate contact with the head is subjected to a field which is first in one direction along the surface of the head and finally in the opposite direction along the surface of the head, and that in the process of passing over the gap this section of the tape is subjected to a rotating magnetic field. Likewise it is apparent that there is an appreciable vertical component of the field in the vicinity of the gap. This figure further shows that the gap fields can produce high-resolution recording only in those portions of the tape very near the head. Close head-tape spacing is therefore essential to good short-wavelength recording.

Eldridge and Daniel have analyzed the process of ac-biased recording to evaluate the differences between the long-wavelength and short-wavelength conditions (Eldridge and Daniel [1962]). Most authorities would agree that a specific point at which the recording takes place can be identified for any recording process. This is the point at which the various parts of the tape encounter the last field which can affect its remanent magnetization as the tape moves away from the recording gap. Because the bias fields are always much stronger than the signal fields, it is also generally agreed that the record point for biased recording is that at which the bias falls below some critical value. Daniel and Eldridge show that the region within the tape at which the recording takes place is a function of the length of the record gap, the amount of bias, and the position of a particular particle within the tape thickness. They point out that since the fields in the vicinity of the head have both vertical and horizontal components, it may be that the recording point is such that a vertical rather than a longitudinal field tends to be impressed on a particular particle. Figure 5–8, which is adapted from their work, shows first, that at a, there are three possible conditions of biasing for a relatively large record gap. In region 1, recording takes place if the bias is quite small. This would give good resolution for short wavelengths but would leave most of the tape material under-biased with consequent poor long-wavelength response. If the bias were approximately doubled, the recording would take place in region 2, and under this condition the entire depth of the tape material would be used but the short-wavelength resolution would be relatively poor. Under condition 3, the entire tape would be fully used and the overbiasing would result in loss of sensitivity at long wavelengths and poor resolution at short wavelengths. At b of the figure, with the small gap, condition 1, for small bias, would give good short-wavelength resolution but essentially no recording at long wavelengths since very little of the tape would actually be used. Condition 2, with more bias, would effectively use the whole tape but, because of the long extension of the recording region, short-wavelength response would be poorer than for



(*after Eldridge and Daniel*)

Figure 5–8.—Recording zones for different applied fields and gap sizes: (a) wide gap, (b) narrow gap.

the wide-gap condition of a. A proper compromise is very difficult to come by for both short and long wavelength recording. Daniel and Eldridge proposed a two-gap technique which has not been widely used. The current approach for wideband recording is to attempt a compromise between these two conditions with the bias set, as much as possible, to emphasize the short-wavelength response.

The fields shown for the area surrounding the gap of the record head are based on the material of the tape coating having unity permeability, i.e., the permeability of free space. Tape permeability is not actually unity but there is remarkably little effect on the shape and intensity of the fields if the permeability is postulated at a value between one and four, which range probably includes the actual value of permeability for a practical tape (Westmijze [1953]). In the case of a reproduce head, the description of the field is not by any means as simple as it is for the record head but the general situation can be analyzed on the same basis as for the record head.

For the reproduce head, of course, the magnetomotive force which produces the reproduce flux lies within the tape proper. The head itself is not generating a field but is intercepting flux generated by this internal magnetomotive force within the tape. A quantity which might be plotted for a reproduce head would be the relative ability of the head to intercept flux at various points in the vicinity of the head. A plot of this ability would look quite similar to the plot of the record flux intensities. For all practical purposes short of a detailed analysis, this gives an adequate physical description of what goes on in the reproduce head. Quite a number of complex analyses of reproduce-head field patterns have been undertaken and at the moment there is only general agreement on how such patterns should be plotted (Fan [1961]).

A convenient figure for describing the way in which the spacing effect changes the sensitivity of the tape on record and reproduce was derived by Wallace some years ago (Wallace [1951]). This figure is that for every wavelength that the tape is spaced away from the head there is a loss of 55 db. This is often referred to as the "55 d over lambda loss." For example, if the wavelength is 0.5 mil, i.e., a frequency of 60 kc at a tape speed of 30 inches per second, a spacing of 0.1 mil would cause a signal loss of 11 db. When one considers that current wideband longitudinal recorders use wavelengths of 0.08 mil, it is obvious that a few microinches of spacing can cause severe losses. Wallace also derived a considerably more complex formula for describing the thickness loss, that is the loss at short wavelengths resulting from finite coating thickness.

By using the Wallace figure it is possible to determine that under normal recording and reproducing conditions tape does not appear to be actually in contact with the head. By using a large model in which very low relative spacings can be maintained, one can determine the absolute relationship between the wavelength and the actual amount of signal induced in the head or recorded on the tape. If this calculation is then scaled for practical record and reproduce heads and tested by arbitrarily adding spacers between the head and the tape, it will be found that the zero value of spacing of the practical tape appears to be about 40–55 microinches. It is probable that this figure will gradually be reduced as both heads and tapes are improved. The apparent spacing undoubtedly is made up of the effect of surface roughness on the tape and the fact that the last few microinches of the polished pole piece are not as magnetic as the bulk material of which the pole piece is made. To add to this factor, under normal operation, the tension in the tape places a considerable physical strain on the front of the pole piece and this strain may so affect the crystalline structure of the pole material as to reduce its magnetic effectiveness. Actual dynamic measurements of head-tape spacing have been made recently, using optical interferometric methods (Lipschutz) [1964]). These measurements roughly confirm the spacing figures quoted above.

To emphasize the importance of minimizing head-to-tape spacing as well as the uselessness for some applications of a thick coating on the tape, Eldridge and Daniel showed that at a wavelength of 1/8000 inch, 75 percent of the output signal from the reproduce head is derived from the first 28 microinches of tape material! (Eldridge and Daniel [1962]).

HEAD-TAPE GEOMETRY—PULSE RECORDING

Much the same influences are at work affecting the recording performance when pulses are involved as in the linear recording process just discussed. The details of the effects are modified because in pulse work the tape is usually magnetized to saturation in one direction or another and this, together with the basic nonlinearity of unbiased recording, prevents direct application of the linear recording analysis. One normally operates in the frequency domain in analyzing linear transmission systems and shifts to the time domain when analyzing pulse systems. In the same way, one shifts in magnetic recording from concern with frequency response, phase shift, and distortion to concern with rise time and position shift.

Only in the last few years have usable analyses of the basic mechanism of pulse recording on tape become available (Eldridge [1960]) (Barkouki and Stein [1962]). Currently, many investigators are undertaking intensive study in this field. To increase the basic understanding of the nonlinear processes involved, some analyses have even been made of sinewave unbiased recording to evaluate the elements common to both recording modes (Stein [1961b]).

Pulse recording is often described as the process of imprinting a flux reversal on the tape. This is exactly what happens with NRZ or NRZI recording. With RZ, RB, or phase-shift recording, several flux reversals may be involved in the recording of any single bit. FM recording, since it is usually performed with saturation signals without bias, also involves the same mechanism, although it is more difficult to describe in pulse terms. Performance of any of these recording processes can, in principle, be derived by superimposing the effect of several separate single flux reversals. The nonlinearity of the unbiased recording process prevents the superposition method of analysis from giving very quantitative results. The approach, nevertheless, gives good insight into the processes at work.

When the pulse current through the recording head is turned on or turned off instantaneously it effectively maps the external flux field of the recording head onto the tape (Eldridge [1960]). That is, the sudden current change leaves in the tape a "snapshot" of the instantaneous flux distribution at the moment of turn off or turn on. If saturation current flowed continuously in the head, the magnetic condition of any part of the tape would change from unsaturated to saturated as it moved into and through the external flux field of the head. If this current is suddenly turned off, the instantaneous flux distribution around the head is mapped onto the tape. If, with no current flowing through the head, the current is turned on suddenly, the opposite result is produced. On the tape which passed under the head when no current was flowing there would be no remanent flux, and on the tape which passed the head with the current turned on, there would be saturation magnetization. In the part of the tape which was directly under the head when the sudden current change took place the snapshot of the transition from zero flux to full saturation would be recorded.

The shape of the recording head field distribution would be closely related to the shape of the recorded pulse on the tape. If some kind of nonmagnetic flux probe were passed along the tape the probe would produce an output signal which described exactly the recorded flux. When the probing is done by an appropriate reproduce head, the same result is not obtained because the magnetic properties of the reproduce head affect the net voltage induced in it.

The Eldridge analysis referred to above points out that the ability of the reproduce head to produce a pulse output which accurately describes where a step function of flux is located in the tape is about one fifth as good on the average as the ability of a similar record head to define a flux transition in the tape. He found that this appeared to be a fundamental relationship more or less independent of detailed head design. Stein's analysis (Stein [1961 b]) supports the reasoning that the basic difference between the action of the record and reproduce head results from the differences of the magnetic material of tape and base. The transfer of the flux pattern from the soft magnetic material of the nonremanent record head to the remanent material of the tape defines a sharper flux transition than does the reverse process when the remanent material of the tape induces a flux in the nonremanent head on reproduction. Unfortunately, a head manufactured of remanent magnetic material is a confusion in terms! The analysis provides, however, a useful guide for those who would refine head designs to improve the overall pulse resolution.

The wide range of conditions and circumstances under which pulse recording may be done makes it difficult to describe in any detail in this survey the complex interrelationships between pulse resolution determining factors. Most analyses seem to show that the thickness of the medium and the spacing of the head from the medium are probably the crucial factors in determining the sharpness of pulse reproduction. The size of the reproduce head gap is less important than these factors. The size of the actual pulse, that is the total length determined by any one of a number of criteria, appears to be constructable from the response of the reproduce head to an ideal flux transition added in time to the length of the actual recorded pulse. The length of the record head gap, determines, as in biased recording, to a certain extent, the position within the thickness of the tape where the recording takes place and hence affects the sensitivity of the size of the recorded pulse to spacing and thickness effects. The presence of both vertical and horizontal components of the magnetic fields involved is particularly important in determining pulse shapes and there is some evidence that detailed modification of the shapes of the head pole pieces affects the overall resolution (Shew [1962]). (Pole shape may be more important for noncontact recording than for contact recording.)

FUTURE REQUIREMENTS

Along with every other user of high-performance tape recording equipment, NASA can well use improved data resolution on the tape and increased overall data storage density. Improvement in these characteristics can no longer be achieved, as it once could be, by isolated attempts to improve tape *per se* or heads *per se*. The current sophisticated knowledge of the characteristics of heads and tapes is so far advanced that significant improvement in either must be preceded by an increase in understanding of the processes involved in interaction between head and tape. Continued basic and applied research in the interaction areas which have been covered in the broadest outline in this chapter is therefore essential to progress in these important magnetic recording performance factors.

CHAPTER 6

Tape Moving Systems

Magnetic tape recorders are usually integrated into complex electronic systems and themselves contain many electronic elements. Recorder performance depends more on the state of perfection of the mechanical elements that are involved, however, than it does on corresponding perfection in electronics. The mechanical accuracy of construction of recording and reproducing transducers, the structural uniformity of the magnetic media and, more obviously, the precision with which the movement of the medium is controlled, are important aspects of mechanical perfection. Usually this last means translation of the medium past the transducers at a perfectly uniform rate. Intermittent tape motion for special applications will be mentioned later, but the emphasis here will be on the almost universal requirement for smooth motion.

In a practical sense, it is almost essential that maintaining really uniform motion of the medium requires providing separate functions of reeling and metering. By "reeling" is meant the task of supplying tape from a source and storing it after passing the transducers while maintaining as uniform tape tension as possible. The "metering" function is that of assuring that the tape moves past the transducer at a uniform rate, using tape supplied by the first half of the reeling function and delivering the tape to the second half of this function. The design of a recorder tape handling mechanism consists of optimizing the balance of tasks between these two functions, and at the same time maximizing the protection of the metering function from disturbing external influences.

Many tape recorder configurations have been proposed and used to perform and integrate these functions while providing adequate isolation. Tape moving systems will be analyzed by discussing first the various configurations, then the elements essential to these configurations and, finally, the relationships between these elements inherent in the configuration.

CONFIGURATIONS

Tape recorders may either be of the *reel-to-reel* or *endless-loop* type (fig. 6–1 a,b). Endless-loop recorders may be subdivided into those which use a relatively compact tape pack resembling a reel of tape

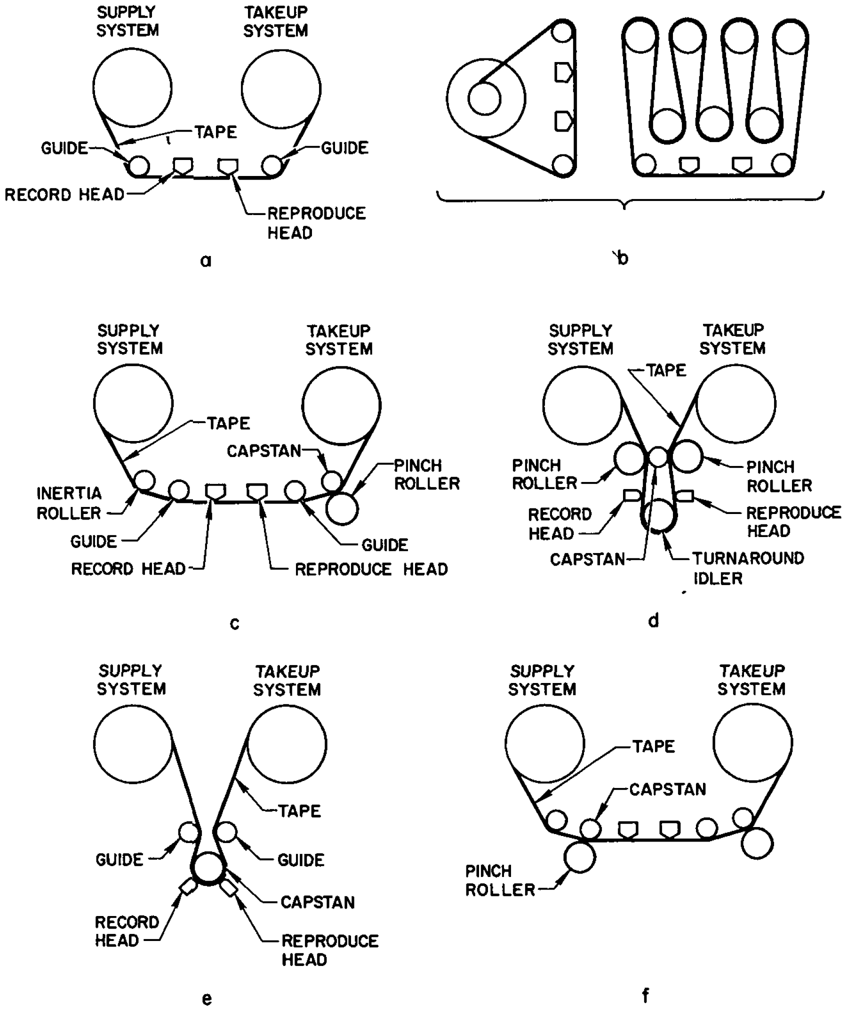


FIGURE 6–1.—Recorder/reproducer configurations.

(a) Basic reel-to-reel recorder/reproducer elements, (b) compact (on the left) and distributed (on the right) endless-loop recorder/reproducer arrangements, (c) elements of a complete open-loop recorder/reproducer, (d) elements of a complete closed-loop recorder/reproducer, (e) elements of a zero-loop recorder/reproducer, (f) addition of a second capstan/"pinch roller" combination to the elements of (a) results in a typical differential-capstan recorder/reproducer.

without hub or flanges and those employing an open loop wound on racks of separate rollers which are used in repetitive analysis of tape records. (There are further variations on the endless-loop arrangement which are covered in chapter 13.) Recorder configurations can be further classified in another way only indirectly related to the distinction between loop and reel-to-reel types, and that is on a basis of the tape arrangement in the region between the supply and takeup. This second classification is into *open-loop*, *closed-loop*, and *zero loop* types. The "loop" referred to here is that section of tape which is passing the transducers and which is under tension supplied by restraints of some sort at its ends.

In the open-loop configuration (fig. 6–1 c) the tape is pulled by a capstan which performs the metering function and back tension is provided solely by the supply source. Appropriate intermediate mechanical filtering devices are often provided. In an alternate version, the tape is pulled by the takeup device and is metered by being held back by the capstan. This is usually referred to as a "pusher" capstan. What is "open" about this loop is the fact that a metering device has control of only one end of the section of tape passing the transducers, the other being under control only at one reeling element.

In the closed-loop configuration (fig. 6–1 d) the section of tape passing the transducers is controlled by a metering element (usually through frictional contact) at both ends of this passage. The metering element may be a single capstan which the tape contacts twice or two separate capstans which are mechanically connected.

In the zero-loop configuration (fig. 6–1 e) the tape contacts the transducers while also in contact with the metering mechanism. The capstan or metering device must be made resilient in some way and/or the transducers must be spring mounted so that the tape is, in effect, sandwiched between the transducer and the metering device.

The first high-quality audio tape recorders were of the open-loop type. The first instrumentation or scientific recorders correspondingly used the same tape configuration. The single-capstan closed-loop configuration was introduced next and has persisted during most of the period in which magnetic recording has grown to its position of indispensability in scientific investigation. At about the same time, Ampex introduced a zero-loop recorder (the model 500) (Selsted and Snyder [1954]) which was of impressive performance but limited flexibility. (Recently there have been indications that the zero loop configurations will soon be reintroduced.)

The major development following the single-capstan closed-loop recorder was that of the differential-capstan recorder. A differential-capstan recorder has a capstan at the entrance and one at the exit of the metering area (fig. 6–1 f). The capstan at the exit is arranged to provide a higher velocity to the tape than that at the entrance. This may be accomplished by using capstans operating at different peripheral speeds or, in the case of one manufacturer, the use of a capstan which is so machined as to have different diameters for the exit point and the entrance point.

Beyond the terminals of these particular metering configurations (the capstan or capstans), the supply and takeup of the tape may be arranged in many different variations of both reel-to-reel and endless-loop forms. However, certain of the metering configurations fit best with certain reeling configurations. The subject is sufficiently complex that the entire tape handling assembly must be analyzed as a whole.

Figures 6–2 and 6–3 show examples of several open- and closed-loop instrumentation recorders for laboratory and general use on the ground. (No zero-loop recorders are currently being manufactured.) Miniature flight recorders of various configurations are shown in chapter 13.

THE OPEN LOOP

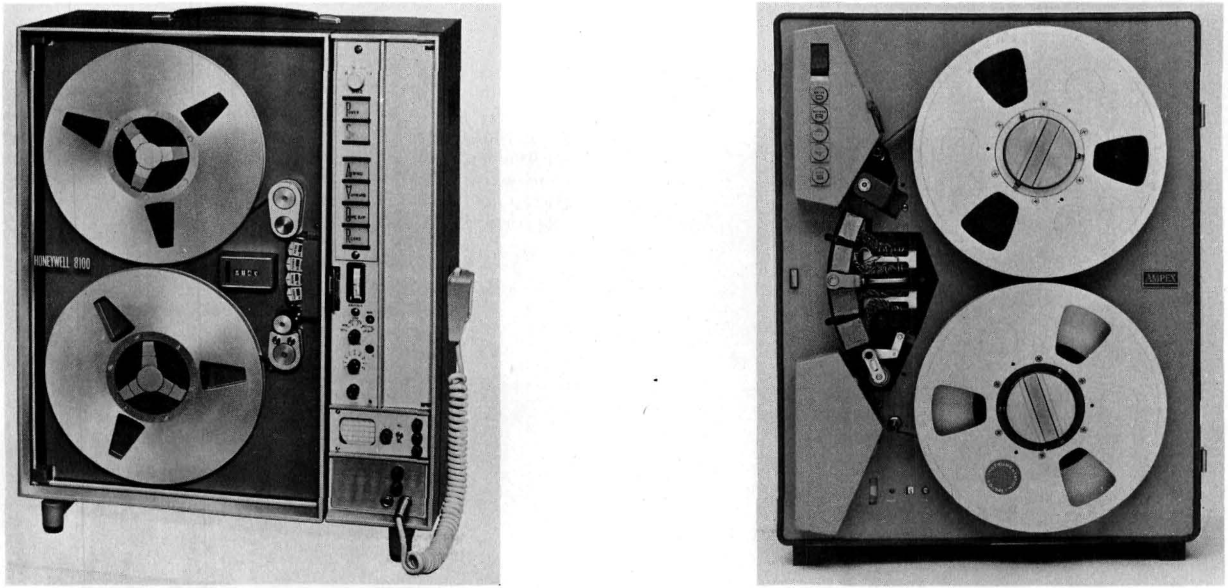
The basic elements of an open-loop tape handling system are shown in the accompanying illustration (fig. 6–4a). The illustration is rather complete in that essentially every element that may be included in such an array is included therein. Many perfectly practical and usable recorders omit many of these elements, although some of the most sophisticated include them all. The accompanying schematic diagram (fig. 6–4b) shows the equivalent mechanical circuit of this array. Both drawings are adapted from an article originating in a publication of the East German radio system (Wolfe [1960]). That this unusual source of information is used here emphasizes how little has been written on this important aspect of tape handling systems. This appears to be the only detailed reference and analysis of the open loop system published in periodical literature. The almost complete absence of definitive literature on the subject of flutter performance of all types of tape handling systems is in interesting contrast to the many dozens of quite distinguished papers which appeared during the period of development of film recording systems, where many of the same problems occurred.

Each element of this tape handling device is nominally assigned a specific function to perform. However, the practical element used in that location in a practical recorder fails to some extent, in some way or other, to perform the assigned function. The open loop configuration can now be analyzed by comparing the ideal and practical operation of its elements.

The ideal capstan rotates at a perfectly uniform rate of speed. It is ideally driven by a completely uniform transmission system from an ideal "prime mover." The ideal prime mover has zero internal mechanical impedance or infinite mobility, i.e., it provides drive of uniform velocity independent of any external influences. In the practical case, the drive is usually provided by either an ac or dc motor. The practical motor suffers either from cogging in the ac case (since the motor is usually synchronous) or commutator ripple in the dc case, which makes the rate at which rotational energy is produced nonuniform. At the same time, the practical motor has a relatively high mechanical impedance in that the rotor, although usually massive, is not of infinite mass, and for many applications has been deliberately reduced in mass to reduce the total weight of the recorder. The connection between the actual electromechanical conversion process in the motor and the practical rotor is also not infinitely stiff. This is somewhat easier to describe in the case of the ac motor, but a similar effect occurs in the dc motor.

The windings of an ac motor are so placed and so connected to its terminals that a rotating magnetic field is created. In the polyphase motor, the field generation is straightforward; in the single phase motor, phase shifting means produce a similar rotating field although in considerably less stable form. If efficiency and weight were no problem, a very spread-out "wave winding" technique could be used, such that the rate of rotation of the magnetic field would be almost perfectly smooth. However, in the practical case there is a limited number of slots into which the winding of the stator can be placed. The amount of smoothing of the magnetic field through spreading of the effective magnetic poles by distributing the winding that can be tolerated is limited in the interest of efficiency. The practical motor, therefore, has a magnetic field which rotates at a uniform rate on the average, but which has instantaneous rate variations associated with the structure of the magnetic circuit. This effect produces the phenomenon known as "cogging" when such a slightly nonuniform rotating field drags a rotor with it.

The rotor is moved along by the magnetic field and, to a great extent, stays in step with it. However, if a load is suddenly applied to the rotor, the rotor slows down for an instant and then continues to rotate in a slightly different position with respect to the rotating field. Under dynamic conditions, the rotor appears to be connected by an effectively elastic connection to the magnetic field. If a sudden shock load is applied to the rotor, the elastic connection will lengthen, and if the load is removed, the connection will shorten. This means that, under transient loads, the rotational inertia of the rotor and the elasticity of the connection between the rotor and the driving field can form a resonant circuit which will "ring" in angular velocity.



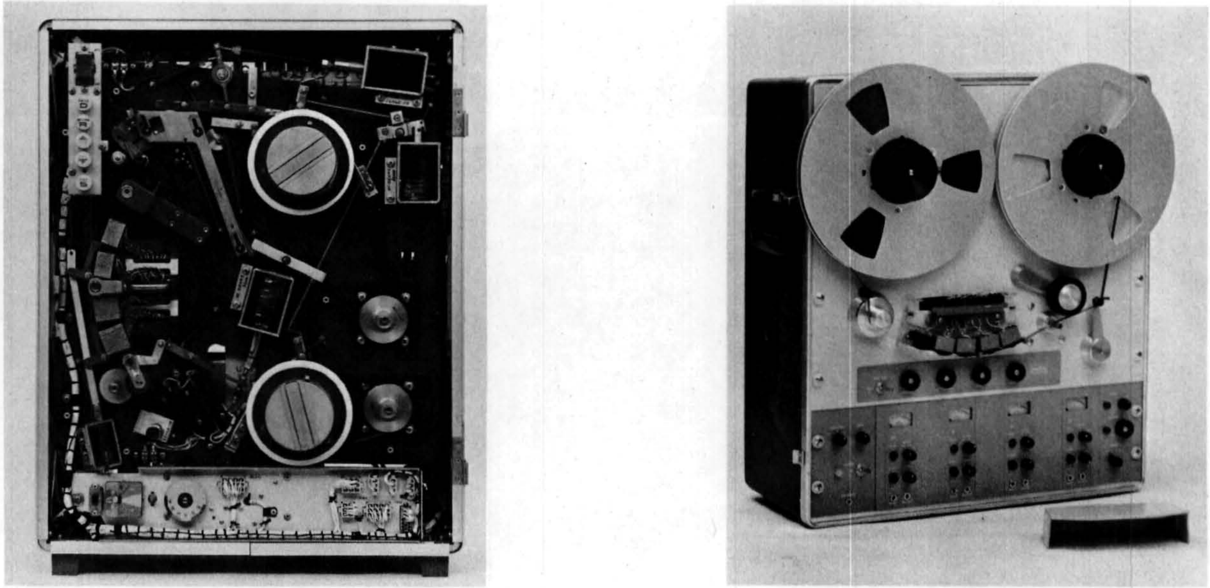
(*photo courtesy Honeywell Inc.*)

(a) A medium performance portable instrumentation recorder/reproducer—the tape path is apparent in the photograph, around an upper guide roller, over the heads, between the capstan and pressure roller and around the lower guide roller, past an end-of-tape sensor to the lower reel—dynamic reel braking is used in this unit, (Honeywell Model 8100).

(*photo courtesy Ampex Corp.*)

(b) The Ampex Model FR–1300, a medium-performance portable recorder, shown here with head cover removed to uncover tape path.

FIGURE 6–2.—Representative open-loop recorder/reproducers.



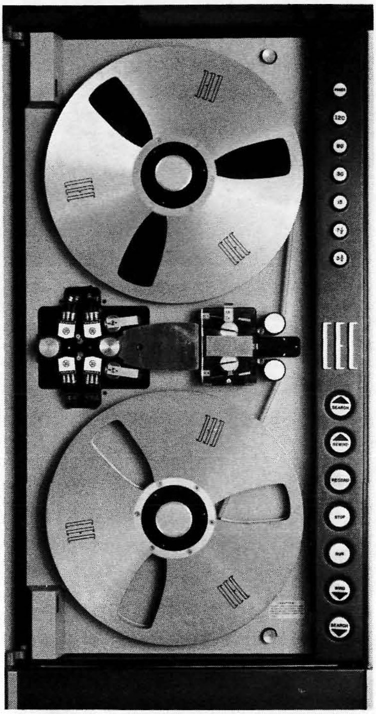
(*photo courtesy Ampex Corp.*)

(c) Mechanism of the recorder/reproducer of (b)—the servo holdback mechanism of this unit shown in more detail in figure 6–20—the unit is unusual in that mechanical access is through the front rather than the rear—tape lifters can be seen between the upper two and the lower two pairs of heads—a flutter-damping inertia idler is seen at the tape entrance to the heads, to the right of and slightly below the "Stop" button—the bearing of a roller designed to damp high-frequency flutter can be seen in the center of the head array.

(*photo courtesy Ampex Corp.*)

(d) The Ampex Model SP–300, shown here with the head cover removed to show the tape path—this instrumentation recorder is derived directly from an open-loop audio recorder by the addition of certain refinements—an inertia idler is visible to the left of the head group with a spring-loaded reel snubber-idler adjacent—the idler to the right of the capstan/pressure roller combination also acts as a snubber and end-of-tape sensor.

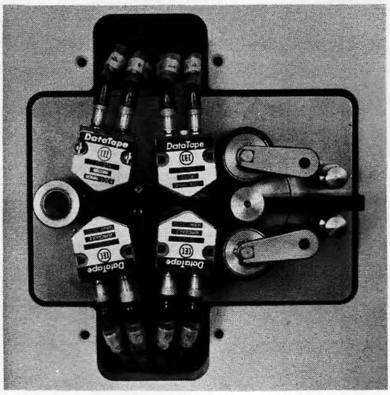
FIGURE 6–2.—Representative open-loop recorder/reproducers.



(a) The CEC Model VR–3600 recorder/reproducer—a high-performance unit featuring an electrostatic tape cleaner (the transparent rectangular box toward the right of the center, see text) and a vacuum compliance (the boat-shaped structure in the center, see figure 6–21)—the small rollers immediately to the left of the large turnaround rollers at the right center are spring-loaded tape tension sensors—tension is regulated by a magnetic-amplifier servo with input from these sensors, the turnaround roller at the left acts as an optically-detected tachometer to provide a signal when the tape has been brought up to the speed of the capstan and the pressure rollers can be closed, as well as to provide a speed signal for "search" operation—reel diameter is detected by a photocell system (boxes at extreme upper and lower left)—the rear of this unit can be seen in figure 7–2.

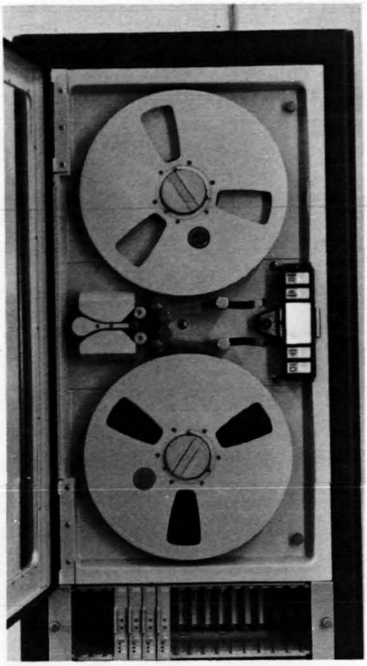
(*photo courtesy Consolidated Electrodynamics Corp.*)

(b) The "precision plate" area of the CEC Model VR–2800, a less refined version of the VR–3600—the tape is led between the capstan (center right) and the upper pressure roller, between the upper heads and the septum, around the turnaround roller, between the lower heads and the septum and between the capstan and the lower pressure rollers—the geometry produces a steady force between head and tape essentially normal to the gap—the mechanical precision of alignment of these elements and the tape guides on the extreme right determines the overall accuracy of the recorder and is established by mounting all the elements on a single plate of high precision, apparent here in rather pure rectangular form.



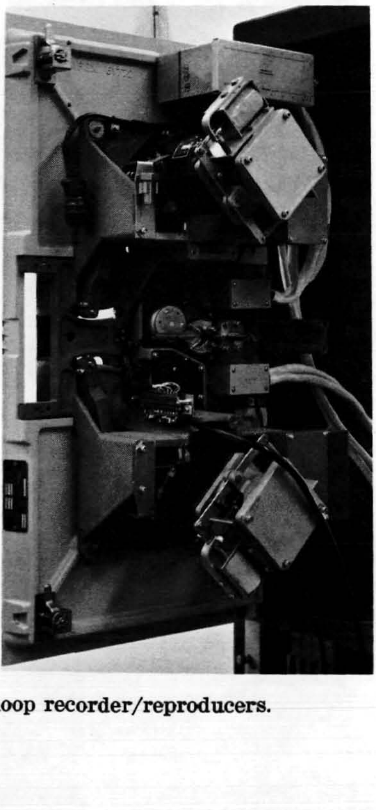
(*photo courtesy Consolidated Electrodynamics Corp.*)

FIGURE 6–3.—Representative closed-loop recorder/reproducers.



(c) The Ampex Model FR–1200—this is the modern version of the widely used FR–100—this unit employs open-loop tension sensing (see fig. 6–18) and employs the spring-loaded tension arms (operating through the arc-shaped slots) for slack takeup rather than for servo brake control (compare fig. 6–16)—the tape path in the head region is similar to that of (b).

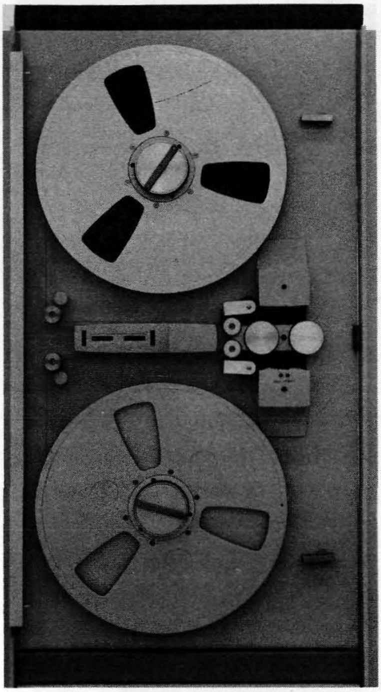
(photo courtesy Ampex Corp.)



(d) A rear view of the unit of (c) above—stopping of the reels is provided by the solenoid-operated brake assemblies seen attached here to the rear of the torque motors which control running tape tension. The capstan flywheel has been removed in this photograph to improve visibility.

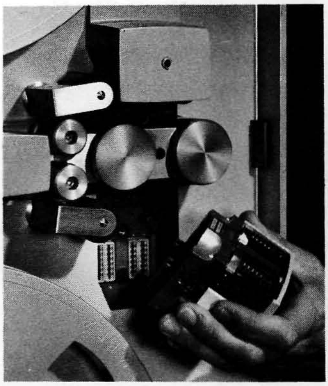
(photo courtesy Ampex Corp.)

FIGURE 6–3.—Representative closed-loop recorder/reproducers.



(e) The Ampex Model FR–1400 (the Model FR–600 resembles this very closely in external appearance despite internal differences)—the turnaround guides at the left are air lubricated (see fig. 6–17) and provide the tape tension servo input data—the turnaround roller at the extreme right carries a tachometer which provides pinch roller closing speed information and search speed control—the tape threading path is perfectly straight with the heads retracted as shown in this view.

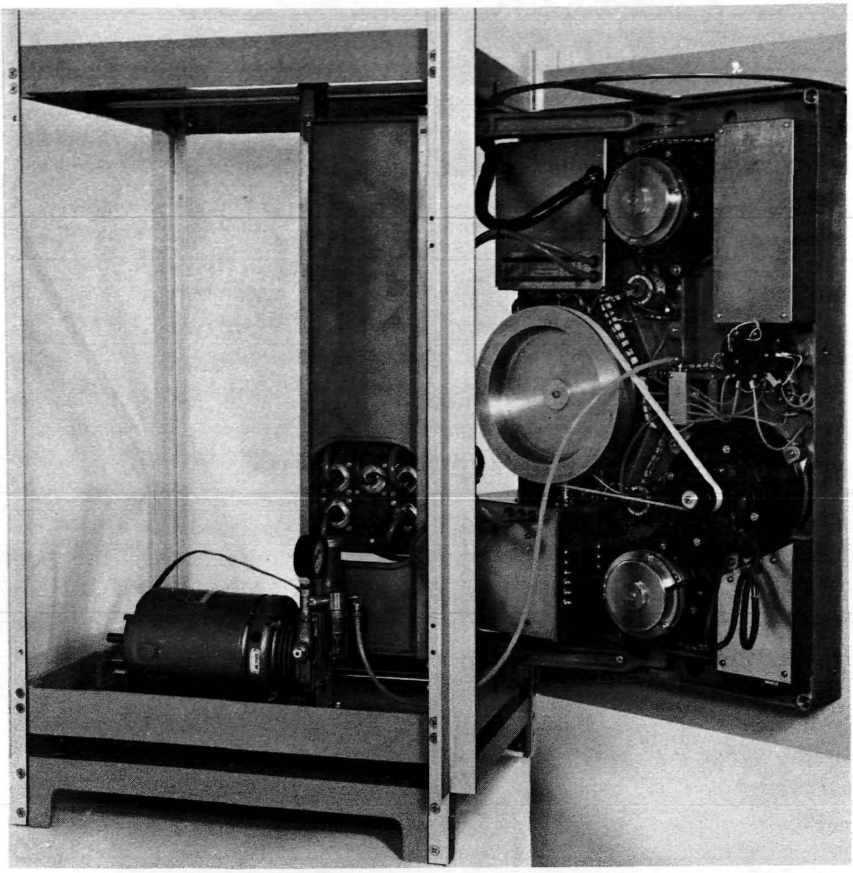
(*photo courtesy Ampex Corp.*)



(f) The head region of the unit of (e) above—plugin head mounts such as shown here are often provided in instrumentation recorder/reproducers—the retractable heads, as shown here in retracted position, provide tape threading simplification at the cost of extreme precision of head-retraction mechanism.

(*photo courtesy Ampex Corp.*)

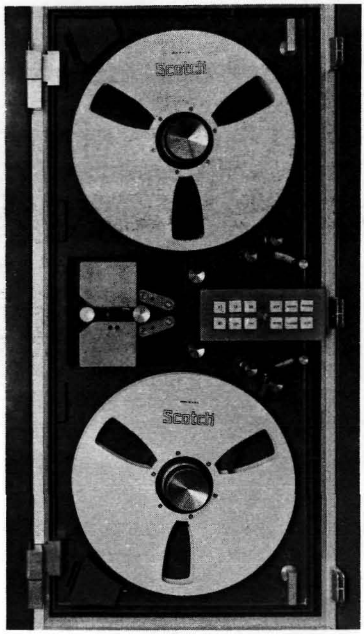
FIGURE 6–3.—Representative closed-loop recorder/reproducers.



(photo courtesy Ampex Corp.)

(g) A rear view of the Ampex FR–600, showing the air source at the lower left, the massive drive motor below center right, the equally massive capstan flywheel (an internally damped flywheel is provided in the FR–1400 version), the small stopping brakes (the flat circular units applied to the backs of the reeling motors, top and bottom) and the ball bushings (upper left center) and rotating link mechanism provided for easy access to the mechanism of this unit.

FIGURE 6–3.—Representative closed-loop recorder/reproducers.

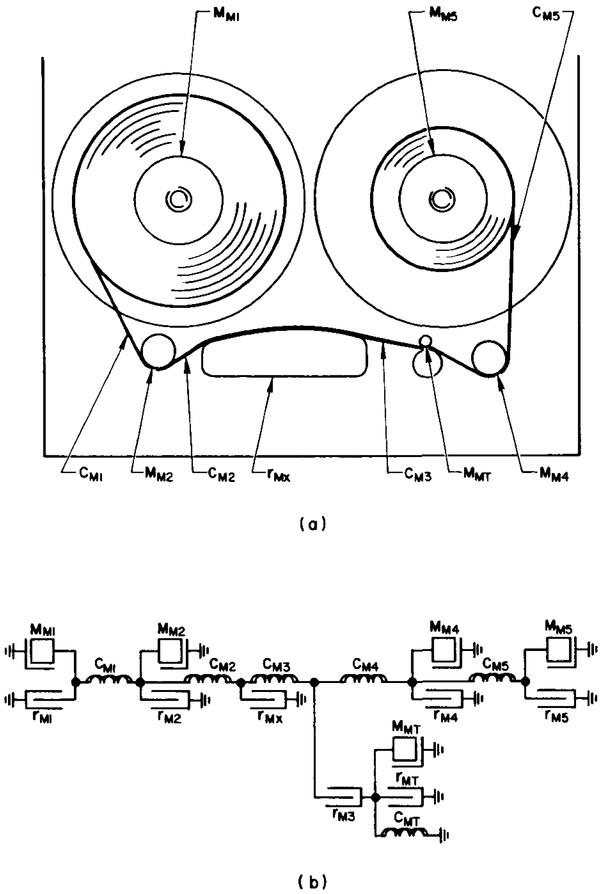


(h) The Mincom Ticor II, a low-mass-capstan, low-time-displacement-error recorder/reproducer—the complex tape path here provides a small amount of tape storage for start and stop transients—tension is maintained by a servo which detects the armature voltage of the series dc reeling motors to detect reel rotational velocity which, when combined with the steady tape speed, provides a signal to regulate tension through transistor amplifiers driving the reeling motors—a rear view of this unit is shown in figure 7–1.

(photo courtesy Mincom Division)

FIGURE 6–3.—Representative closed-loop recorder/reproducers.

The foregoing is necessarily oversimplified, since it is well beyond the scope of this section to discuss the action of synchronous motors in detail. The rather elementary synchronous motor which has been described has a typical salient-pole rotor. Such a motor typically has either a permanent magnet (or more rarely) a wound dc winding on the rotor. Many tape recorders still use such motors and they were practically the only motors available when the first audio and instrumentation recorders were built. The so-called hysteresis synchronous motor now has to a great extent replaced the salient-pole motor. In the hysteresis motor, which is actually a rather complicated device, it can be said that the rotating magnetic field creates its own poles in a magnetically uniform rotor. These poles then rotate in synchronism with the applied field. The hysteresis synchronous motor has the interesting characteristic that if it is overloaded the rotor poles will simply slip with respect to the rotor structure, and if the load is removed, the motor will continue to run synchronously, having dropped back in phase by the amount that it slipped. The salient-pole synchronous motor would be more liable to lose synchronism permanently and to slow down and stop if overloaded. The jerkiness with which wound or permanent magnet rotor poles move past the stator poles is considerably greater than is the case for the "isotropic rotor" of a



(after Wolf)

FIGURE 6–4.—Analysis of an open-loop audio recorder/reproducer.

(a) Schematic top view of the Model SJ–100 Studio Tape Recorder manufactured by Sander and Janzen in East Berlin—this is the unit analyzed in detail in Wolf [1960]—the designations given are from that paper—r_{MX}=mechanical responsiveness of the head assembly; M_{M1}, M_{M5}=equivalent masses of the reel motor + reel + tape pack; M_{M2}, M_{M4}=equivalent masses of the turnaround rollers; M_{MT}=equivalent mass of the capstan motor; $C_{M1}\cdots C_{M5}$=compliance of the respective tape sections.

(b) Mechanical schematic diagram of the transport of (a) in the "mobility" analogy—M_{M1}, M_{M5}=equivalent masses of the reel motor + reel + tape; M_{M2}, M_{M4}=equivalent masses of the turnabout rollers; M_{MT}=equivalent masses of capstan motor; $C_{M1}\cdots C_{M5}$=compliance of the respective tape sections; C_{MT}=equivalent compliance of the elastic connection between magnetic field and rotor of the capstan motor; r_{M1}, r_{M2}, r_{M4}, r_{M15}=viscous bearing frictions; r_{M3}=friction between capstan shaft and the rubber pressure roller; r_{MX}=dry friction between tape and heads and fixed guides; r_{MT}=equivalent electrical viscous damping of the rotor cage of the capstan motor.

hysteresis synchronous motor. Either type of motor demonstrates a certain amount of cogging. There is therefore always a small disturbance present in the rotational energy supplied to the rotor.

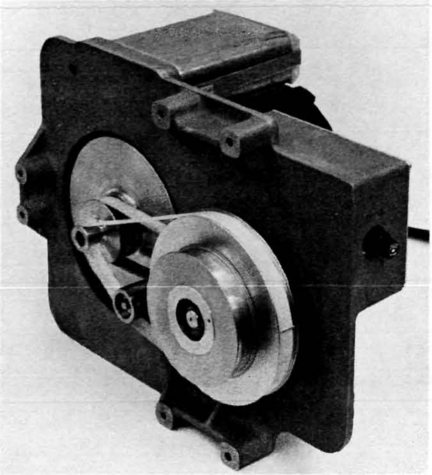
In the dc motor no such rotating field exists. One might say that the field momentarily looks as if it is about to lag behind the moving rotor, but the commutator switching arranges just in time to provide a new section of the rotor so placed as to be in a position to derive torque from the fixed field; the field does not actually ever have to rotate but essentially "pretends to rotate." The switching action which takes place at the commutator produces an effect closely similar to that produced by cogging in the ac motor. In a similar way, the connection between the stator field and the rotor field is not perfectly stiff, but is elastic, and the same kind of resonant system can be created within the dc motor.

Both motors can be so constructed as to minimize the effect of the resonances just described. This can be done by providing extra windings in the stator and rotor, such that when there is any tendency for the physical elements to move irregularly and rapidly, relative to the nominally smoothly rotating field, voltages are induced in these windings such as to create currents and hence magnetic fields which oppose the sudden motion. These windings are called "damper" or "amortisseur" windings.

In many applications, refinements such as damper windings and stator windings so designed as to smooth the torque available, are used with extreme reluctance by the motor designer, because they invariably reduce motor efficiency. For the satellite recorder, for example, a few percent lost in efficiency caused by damper windings would be accepted with great reluctance by the designer.

Further details of motor performance and choice of particular applications will be considered under "Mechanical Elements." Here, it is only important to note that the motor does not deliver perfectly uniform rotational torque, and that it does not deliver this torque from an "infinite source." If any disturbing influence is applied to the motor, it can in general be expected to "ring" in angular velocity. It has often happened that a massive element elsewhere in a tape handling system has been found to resonate with the spring constant of the coupling between the rotor and the magnetic field, even though the resonance between the rotor itself and its elastic connection was not of importance.

The transmission system between the motor and the capstan is also subject to variation and may itself create a variation in the torque available at the capstan. Rubber timing belts have been used for tape recorders but under most circumstances rotational irregularities are introduced at the belt tooth rate. Smooth belts which have been used to perform this transmission function were at one time almost exclusively assembled with a butt joint, and much ingenuity went into the design of a butt joint producing a minimum disturbance in transmission (fig. 6–5).



(photo courtesy Ampex Corp.)

FIGURE 6–5.—A motor-reducing-idler combination of a tape transport of the middle 1950's—the cloth belt and its butt joint are clearly visible.

Currently, the transmission between the capstan and the motor usually is handled by a Mylar plastic belt, constructed by a technique of warping a flat ring of Mylar into a short cylinder, to produce a seamless belt (Licht and White [1961]). Transmission irregularities in such belts result only from imperfection of manufacture, i.e., variations in thickness or in local stiffness. The seamless Mylar belt closely approaches an ideal transmission system. Few of the early open-loop recorders, however, had this effective a transmission system to help them.

Early recorders sometimes used a so-called "puck" drive. In a puck drive, a rubber tire is used to smooth the transmission at some point in the connection between the motor and the capstan. The typical construction is one in which the motor shaft itself is used as a friction roller pulley to drive the capstan flywheel through a rubber tire placed directly on the flywheel (fig. 6–6 a). In a variation, the driving element carries the tire and the driven element is made of solid material.

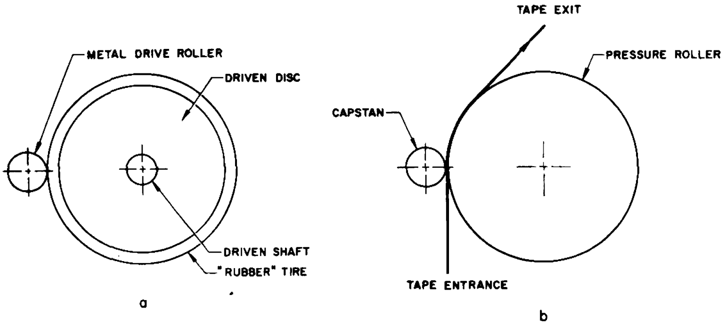


FIGURE 6-6.—Elastomer problems.

(a) A puck drive, (b) a capstan-pressure-roller-tape geometry in which irregularities in the pressure roller may affect tape motion—for a "puller" capstan, no problem would exist, but for a "pusher" capstan (see text) irregularities in the pressure roller would produce tape motion irregularities.

Puck drive schemes which depend on the characteristics of an elastomer are always subject to the possibility of variation in characteristics of the elastomer from point to point. Even if the elastomer itself can be manufactured in a perfectly uniform manner, at some time, in the application of the recorder, the puck and pulley combination may be left in contact for a period of time, and it is characteristic of the elastomers used for this service that some sort of a semipermanent dent will appear in the elastomer. This means that there will be an irregularity in transmission every time this deformation of the elastomer passes through contact with the driving mechanism.

At present the butt-jointed belt, the timing belt, and the puck drive are essentially obsolete, but many design features of current open-loop recorders are historical derivatives of the unfortunate characteristics of these three drive schemes.

To add to all the difficulties just described in providing uniform drive to the capstan, the capstan must also provide proper transmission of its drive to the tape. This drive is always provided by friction between the capstan and the tape. A pinch roller or capstan idler is usually employed to assure that the tape is placed into intimate frictional contact with the capstan. As positive as may appear the drive for a piece of tape sandwiched inexorably between the pinch roller and the capstan, in practice this drive is far from absolute. Many engineers believe that the capstan does not drive the tape directly. This school of thought says that the capstan drives the pressure roller where it overlaps the tape, and that the pressure roller then drives the tape. There is some evidence in modern machines that this is a true description of the operation of the capstan/pinch roller combination.

The coefficient of friction between the capstan and/or the pressure roller and the tape is other than infinite. Assuming the capstan does drive the tape, it would seem better practice to have the capstan contact the non-oxide side of the tape so that less damage is done to the important oxide side. Fortunately, the coefficient of friction of the base of most tapes is considerably higher than that of the oxide side of the tapes, particularly as modern tapes have been refined in surface finish on the operating side. Given a coefficient of friction between tape and capstan which is other than infinite, the driving force imparted to the tape by the capstan could be increased by increasing the roller pressure. There is, of course, an upper limit to how great this pressure can be, for the pressure roller may actually deform the capstan shaft or an excessive amount of power may be required to drive the loaded capstan bearings and to overcome the internal losses in the elastomer of the pressure roller. Roller pressures, therefore, must be kept within reasonable limits.

Another problem can be created by improper application of the pressure roller in that the metering of the tape can be performed effectively by the part of the pressure roller not in contact with the capstan. Figure 6–6b shows the geometrical situation in which this can occur. It is apparent that any irregularities in the mechanically less stable pressure roller could destroy the effect of the capstan precision if this situation were allowed to exist.

The type of mechanical finish on the capstan is important to the value of the coefficient of friction between capstan and tape. An investigation of the relationship between the actual effective tape drive and the roughness of the capstan surface usually gives evidence similar to that shown in figure 6–7. In this case the tape is driven by a capstan under a specified fixed roller pressure against a fixed holdback torque provided by the tape source. A tone recorded on the tape is picked up by a frequency meter and from the frequency indicated by the meter the actual tape speed past an auxiliary head can be derived. A curve of apparent tape drive speed as a function of surface finish of the capstan has the general shape shown. The tape recorder manufacturer tends to make his capstan surface finish fall at a point on the curve where the effective drive speed becomes almost asymptotic to the final maximum speed.

Control of the amount of friction between tape and capstan is essential to adequate performance in any tape moving system. In the open-loop recorder it affects the entire metering process, and in the closed-loop recorder it affects directly the degree of filtering and isolation provided by the closed-loop configuration.

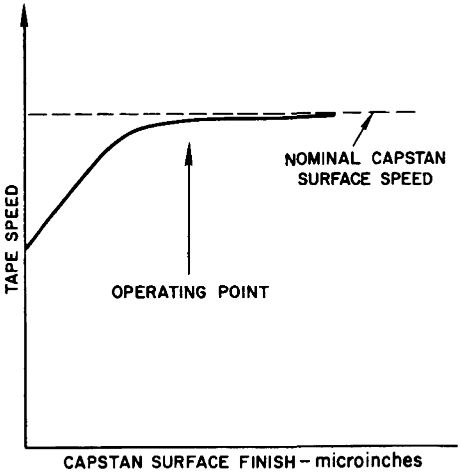


FIGURE 6–7.—Typical relationship between capstan surface finish and actual tape speed for constant roller pressure and holdback tension.

TAPE VELOCITY AT CAPSTAN AND HEAD

Whatever the actual velocity of the tape at the capstan, as affected by the influences just described, the important tape motion is that at the transducer or head. Two influences other than those just described can affect the velocity at the head. One of these is that a nonuniform drag operating on the tape at its supply source may act to place nonuniform torque loads on the capstan and hence cause the capstan to rotate non-uniformly. The other is stretching of the tape between the transducer and capstan, so that whatever the tape velocity may be at the capstan it is not the same at the transducer.

Even if the tape were not elastic and could not be extended under stress, there could be many disturbances that could be propagated from the supply source through the tape to the capstan, and hence affect the capstan's speed. If the supply-holdback mechanism is a mechanical clutch or brake, the braking torque may not be perfectly uniform with rotation of the supply reel. Since the supply reel is often not a precision mechanism, its irregularities can produce variable drag on the tape. In addition to such variable drag effect, deliberately introduced idlers or rollers which guide the tape may not rotate with perfectly uniform torque. Typically, a massive roller connected to a flywheel is driven by the tape at some point between the supply reel and the heads. The mass of this so-called inertia flywheel and the perfection of its bearing will affect the tension and stress on the tape at this point.

All these phenomena produce relatively low-frequency effects on the tape velocity. A completely different kind of effect is caused when the tape medium, which is other than perfectly smooth, rubs past the polished, but nevertheless also not smooth transducers and fixed guides in the tape path. These rubbing contacts produce longitudinal forces in the tape which are closely equivalent to noise in their effect. These rubbing forces have a broad "hashy" spectrum and produce serious effects on the overall performance of the recorder, although the actual forces and amplitudes involved may be quite small.

If the tape were inextensible and the capstan drive to the tape were perfect, there should be perfectly uniform tape motion. But what happens, of course, is that the disturbing influences are propagated through the elastic and (somewhat) massive tape to a driving capstan with other than zero impedance, and complex mechanical disturbances are introduced into a complex mechanical network. An analysis of these disturbances is given under "Tape Motion Disturbances." It will suffice for this section to show the sources of the disturbances and to show schematically where they appear in the mechanical circuit.

Sophisticated open-loop machines are currently being introduced in the market, both for professional audio use and for medium-cost instrumentation use, which add to the elements of the original diagram certain damping elements either at the capstan flywheel or at the so-called inertia idler. This resurgence of interest in the open-loop device for instrumentation recording comes after a long period of rejection of this configuration for new designs; it was generally accepted by recorder designers that no open-loop machine could give performance equivalent to a closed-loop unit. Current applications of conventional open-loop technique are primarily to recorders which are not intended to be of the highest performance. A more refined version of open-loop drive has, however, been offered recently in a recorder which delivers excellent performance in a completely different price range from that of most available closed-loop machines (Selsted [1965]). Another very unusual open-loop machine which is soon to be available is discussed later in this chapter.

CLOSED-LOOP RECORDERS

In the closed-loop recorder, the metering function is performed in such a way that the tape is under control of a positive (usually massive) drive element at both ends of the section of tape moving past the transducers. The majority of closed-loop machines actually contain a closed tape loop, i.e., one can see a loop of tape which appears to return to itself. The effect of a closed loop can be obtained with separate elements controlling the two ends of the significant tape section, i.e., by the use of two capstans, if these capstans are coupled closely together mechanically.

The important features of the closed-loop tape configuration can be summarized as: (1) The disturbances generated in the vicinity of the transducers tend to be confined to the section of tape between the terminals of the closed loop because of the very high (true or electrically-coupled) mechanical impedance of the elements terminating the loop, and (2) the part of the tape in the vicinity of the transducers, as a subsection of the tape moving from the tape supply to the tape takeup, exists in a sort of "backwater" and is therefore less easily disturbed by reeling effects. Take up or supply disturbances tend to be "passed on" from one reeling element to the other without affecting the metering elements very much.

MAINTAINING TENSION IN THE CLOSED LOOP

The original closed-loop recorders had tape configurations very much like that shown in figure 6–8. The only elements which could apply tension to the tape were outside the closed loop. There was a certain hold-back tension supplied by the supply reel and a certain take-up tension provided by the take up reel. Within the closed loop itself all the elements were fixed in position and there was no spring loading or other provision for maintaining tension between the two points of contact of the tape and the common capstan. In so-called tight-loop motion picture sound recording mechanisms, from which one might assume that the tape recording closed-loop concept was borrowed, there is no problem about maintaining such tension if a spring element is introduced somewhere. With film, the presence of sprocket holes makes it easy to insure that the amount of tape that arrives from the supply source is the same as the amount of tape that leaves toward the takeup source. If one of the rollers or guides within the loop is spring loaded, the tension of that spring can determine completely the tension within the loop.

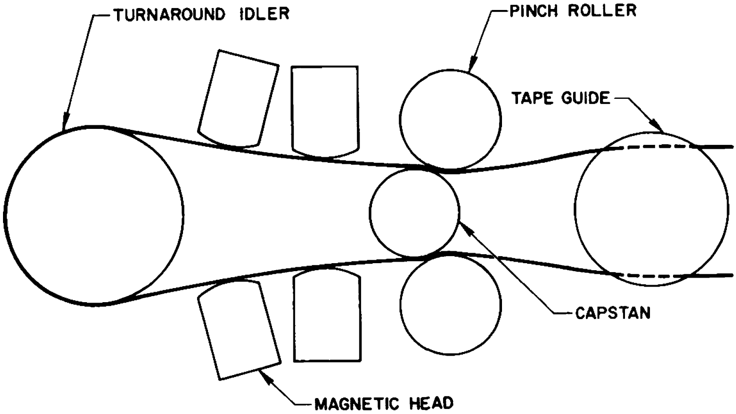


Figure 6–8.—Elements of a typical closed-loop tape metering system.

Without a positive device for metering tape in and out of the loop in the tape recorder, some other means must be provided for establishing tension. Actually, if a spring-loaded element were placed within the tape recorder loop, creep of the tape on contact with the capstan could easily result in a gradual movement of the spring loaded element to the point where the limit of movement of the spring was exceeded and tension would disappear. To maintain tension within the closed-loop tape configuration, the contact between the tape and the capstan cannot be 100 percent positive. A small amount of creep of the tape past the capstan must be permitted to assure that tension is maintained in the loop by the reeling mechanism.

Because this creep is essential to tension maintenance, it was early established that the capstan rotational speed was not the most positive possible measure of the actual surface speed of the tape; the turnaround idler, which has nothing to do with tape drive or maintenance of tension, can be charged with determining the tape surface speed and it is currently fitted with a tone wheel or other tachometer means.

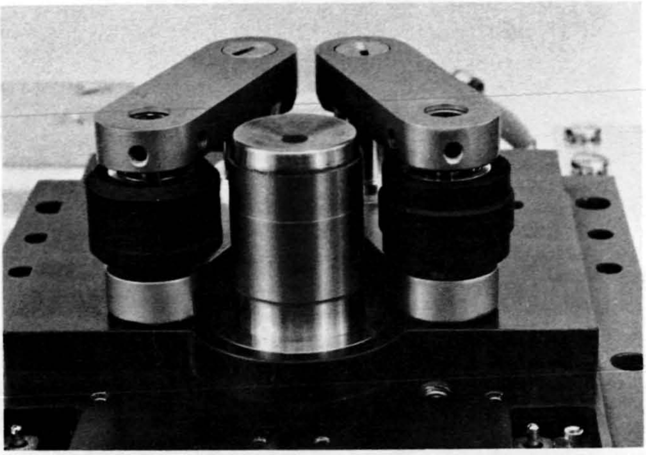
Although some of the advantages of isolation from reeling disturbance mentioned in an earlier paragraph were achieved with the closed loop, maintaining tension within the loop required that the reeling system do its job correctly. If the supply or take up causes uneven or varying tension in the tape, the amount of creep that takes place at the capstan will likewise vary. Under these circumstances, the loop tension and, of course, the tape speed will also vary. In effect, the existence of the large capstan which must be driven (though not absolutely positively) by the tape, and hence "connects the tape back to itself," affects the operation of the closed-loop machine relative to that of the open-loop machine more than any other part of the mechanism. Although some creep is necessary to maintain tension, it may be very small in relation to the ability of the friction between the capstan and the tape to pass on to the capstan any attempts to produce irregular motion by the reeling mechanism. The take-up reel, for example, must pass a jerk on to the relatively massive capstan in order to jerk the tape within the metering loop. The tape creep at the capstan which maintains tension will not seriously affect the coupling between the capstan and the tape in suppressing reeling disturbances. Even with the other than perfect coupling between tape and capstan, the reduction in transmission of irregularities and motion from reeling to metering sections is quite effective.

However, the conflict between the requirements of allowing enough creep to maintain tension and yet coupling the tape tightly to the capstan to transfer as much of the smooth capstan motion as possible to the tape causes designers to look for alternatives to the simple closed-loop configuration. The most successful approach along these lines, and one now widely used, is the differential capstan. The differential capstan is simply a mechanism which provides that the tape is metered into the loop a little bit more slowly than it is metered out. This differential action assures that while the tape is inside the metering loop there is a continuing force attempting to stretch it. The mechanical properties of polyesters like Mylar with their rather long linear range of stretch reaching a yield point, and then stabilizing after yielding at a new elastic stretch point, have lent themselves particularly well to this kind of tension maintenance.

Although the differential capstan provides only something of a refinement from the conventional and initial closed-loop configuration for the ground-based instrumentation recorder, there are applications in severe environments for which the differential capstan has become the invariable choice of the designer. Particularly in the case of the endless-loop recorders where supply and takeup tension must be quite low, and are very difficult to control, the differential capstan is now almost universally chosen.

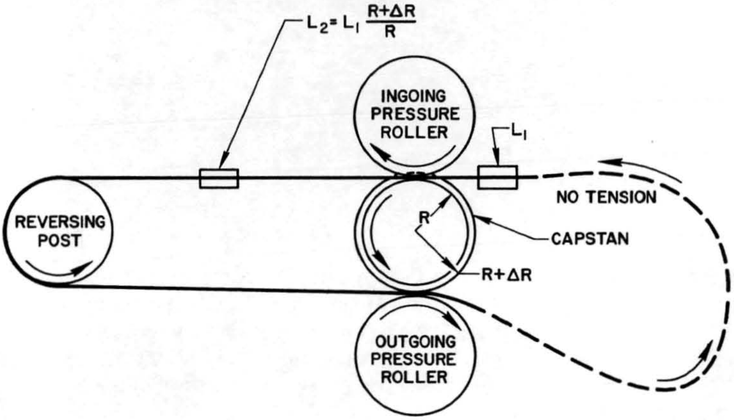
Differential capstan action is obtained by providing two capstans which move at slightly different surface speeds. These may be two capstans of the same diameter turning at slightly different speeds, or two capstans turning at the same speed but of slightly different diameter. One manufacturer provides a modification of this last arrangement to provide two diameters on one capstan and thereby produces a differential capstan action involving only a single shaft and bearing pair. The mechanical simplification and hence more easily maintained precision of the capstan is purchased in this case at the cost of some complication in construction of the capstan proper and of the pressure roller arrangement.

Figure 6–9 shows a close up of such a capstan/pressure roller combination and figure 6–10 shows schematically the action of this two-diameter capstan. The supply pressure roller is relieved over its center section so that the roller touches the tape and forces it against the capstan only at the outer edges of the capstan. This outer section of the capstan is a few thousandths of an inch smaller in diameter than the center section. As the tape is supplied to the capstan and passes into the metering loop, the center section of the capstan with its slightly greater surface velocity is allowed to slide past the tape; it can do so because there is no forced contact between capstan and tape at this point. At the exit of the metering loop, a relatively narrow pressure roller contacts the tape opposite the center portion of the capstan where the diameter is slightly larger than at the outside. The result, shown in the schematic drawing, is that tension is generated because of the difference in diameter and hence difference in surface velocity of the entering and leaving sections of the tape.



(photo courtesy Mincom Division)

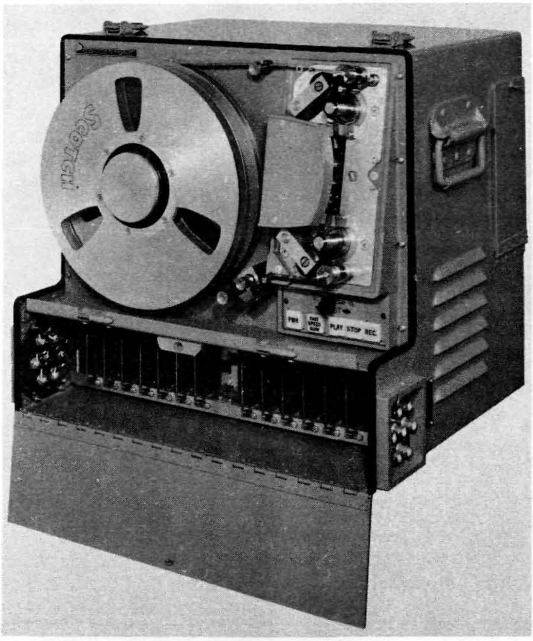
FIGURE 6–9.—The Mincom two-diameter differential capstan.



(drawing courtesy Mincom Division)

FIGURE 6–10.—Schematic indication of the source of loop tape tension in the Mincom two-diameter differential capstan system.

A typical example of a two-capstan differential-capstan unit is shown in figure 6–11. In this case the two capstans are of the same diameter with flywheels slightly larger for one capstan than the other, both flywheels being driven by a single polyester belt. This arrangement is found in many airborne and severe-environment recorders and, in fact, was used in a modification of the recorder shown (basically a ground-based unit) for use aboard an aircraft under moderately severe environment. The two-capstan differential-capstan system operates on the same principle as described above to provide the necessary metering-loop tension.



(photo courtesy Astro-Science Corp.)

FIGURE 6–11.—**The Astro-Science (Concertone) M–101 portable instrumentation recorder/reproducer, a differential-capstan unit—the tape path and the two capstans are clearly shown—the coaxial-reel geometry requires some tape twisting and the tilted post at the extreme lower left of the raised "precision plate" is provided to avoid excessive twist (see this chapter under "Tape Housekeeping" and chapter 11 under "Guides").**

At this point a relatively controversial subject, the mechanism by which the tape is driven by a capstan, should be discussed. From the elementary point of view, the friction between the tape and the capstan seems to be maintained by physical pressure of the pressure roller. The function of this roller is thus considered to be simply that of providing enough force normal to the surface of the tape and the capstan so that the coefficient of friction between the capstan and tape can cause the tape to be driven by the capstan. Studies of the importance of the surface finish of the capstan (and hence of the effective coefficient of friction between tape and capstan) seem to follow the same line of reasoning—that the drive force exists between the capstan and the tape. There is, however, some well-documented support for the thesis that under normal circumstances the drive is actually transferred to the tape by the pressure roller. According to this way of analyzing the drive, the pressure roller, which typically overhangs the tape and therefore touches the capstan beyond the edge of the tape, is driven by the capstan at exactly the same surface speed as the surface of the capstan. (This modifying phrase is necessary to provide for the fact that the pressure roller is typically of an elastomer and is deformed at the point of contact with the capstan. The deformation is such that the peripheral speed at the point of contact, except for a certain amount of scrubbing action which takes place as the effective radius of the pressure roller is changed during contact, is exactly the same as that of the capstan. The peripheral speed of the roller is higher where undeformed.) The reasoning mentioned above carries on to say that the pressure roller then applies the drive to the back of the tape, having received its own drive from the capstan beyond the edges of the tape. In many cases this might be an academic argument, since it is difficult to see how one can separate the drive from the pressure roller and the friction drive from the capstan in an analysis. However, there are situations where the overhang of the pressure roller to drive it does not exist. This happens with the two-diameter differential capstan discussed above. Although the outer two sections of the input pressure roller may be able to contact the capstan beyond the edge of the tape, the inner pressure roller section at the exit of the metering loop cannot, by definition, touch the capstan. There is evidence that supports the pressure-roller-drive theory in observing the action of a tape recorder using this dual-diameter capstan. Nominally a differential-capstan recorder should maintain essentially uniform tension within the metering loop independent of supply and takeup tensions. However, some engineers claim that inhibiting the takeup drive manually can cause the dual-diameter-capstan recorder to lose the metering loop.

At present the products of a single manufacturer use the dual diameter differential capstan. The dual-differential-capstan approach is used only in medium performance ground-based recorders and in some portable and semiportable recorders at present. The single diameter nondifferential-capstan closed-loop drive can therefore be described as the most common drive currently in use for ground-based equipments. Although no specific figures are available to compare performance of the differential-capstan and the nondifferential-capstan approach to the closed-loop drive, it is apparent from the commercial pattern at present that proper engineering of either type of metering tension control can be made to produce a satisfactory recorder. Modern reeling mechanisms have become quite sophisticated and many of them provide very exact controls of the tensions, so that the actual structure of the metering loop is less important than it may have been in the earlier development of ground-based recorders.

ZERO-LOOP CONFIGURATIONS

At one time in the development of instrumentation magnetic recorders one manufacturer brought out a so called "Zero-Loop" machine which had very impressive performance for its period (Kinney [1953]). This recorder used a very large capstan around which the tape was wrapped in a normal manner but no pressure roller was used. Grooves were provided in the capstan and connected through a complex manifold to a vacuum pump so that the tape was maintained in contact with the capstan by the vacuum. The grooves from which the air was evacuated to produce the gripping force between the tape and capstan were very precisely machined and were located directly opposite the protruding pole faces of the individual head structures of the multi-track record and reproduce head assemblies. The heads were spring-loaded into contact with the tape, pressing the tape between transducer and capstan. The grooves and the protruding pole pieces were so arranged that the tape was pressed slightly into the grooves by the pole piece and the natural elasticity of the tape, stretched on a cylindrical surface, provided a restoring force to keep the tape in close contact with the pole piece. This recorder had a basic disadvantage which is perhaps responsible for the fact that it is no longer manufactured. The particular marriage between the pole piece structure and the precise grooves in the capstan had to be changed to change the number of tracks; this made the recorder extremely inflexible. If a unit were designed as a four-track recorder using half-inch tape, that is all the recorder could be used for without replacing the most complex mechanical parts.

The superior performance of this recorder was based, of course, on the fact that the properties of the tape were relatively unimportant in determining the fine detail of the quality of motion of the tape past the head. The tape was constrained to operate directly in contact with the capstan at the time of recording and reproducing and hence the motion of the capstan rather than that of the tape was the significant element in determining the quality of the produced recording. The tape mechanical properties of elasticity, yield strength, propagation of longitudinal vibrations, etc., which cause major problems in any type of loop recorder were essentially overcome in the case of the zero-loop machine. The quality of tape movement produced by this machine was most remarkable, considering when it was developed. Zero-loop recorders are now being considered quite seriously by several manufacturers, and it may be expected that they will appear very shortly. One manufacturer has informally announced such a recorder to his major customers, although the device has not yet officially appeared.

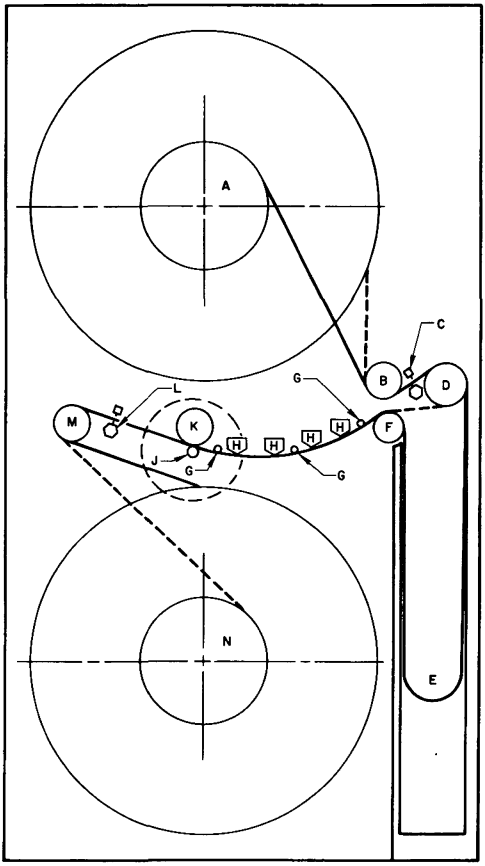
RECORDERS OF UNUSUAL CONFIGURATION

Several recorders that employ unusual reeling and metering techniques have recently been introduced to the market or have been announced. Little detailed information was available on them at the time of obtaining the data for this survey, and devices as recent as these cannot, as yet, have had any impact on the current state of the art.

One of these units, offered by Winston Research, employs the "Iso-elastic" principle of belt drive to the reels. This principle is discussed in detail in the chapter on "Miniature High-Environment Recorders." The unusual thing about the Winston recorder is that it is a full scale instrumentation recorder using this principle.

Another recorder of considerable interest is being introduced by Honeywell, Incorporated. This recorder is effectively an open-loop machine but achieves the open-loop operation in a very unusual manner. It thereby attempts to obtain a particularly effective degree of isolation of the metering function. Figure 6–12 is a schematic drawing of the tape path of this recorder. The unusual features of this unit are the two tone wheel idlers which contact the tape as it leaves the supply reel and as it approaches the takeup reel, and the vacuum column. In addition, the unit is unusual in that two air-bearing turnarounds are used at the terminals of the vacuum column. In addition to the unusual features visible in the schematic, this recorder employs a low-mass capstan drive and a very tight servo in the reproduce mode to achieve low time displacement error.

A feature of the particular configuration used is said to be that the long extension of the tape in the vacuum column provides very effective tape guiding. However, the most unusual feature of this recorder is that the tension is determined entirely in the vacuum column. The tone wheel idlers are used to derive speed signals to control the operation of the supply and takeup reels during fast reeling. This recorder appears to have the possibility of extremely good tape motion. Because the capstan isolates the significant part of the tape from influences of the takeup reel, and the vacuum column insulates this part from disturbances originating in the supply reel, the operation of this recorder is quite unlike that of others presently used for instrumentation. It is not known, however, how the performance of this

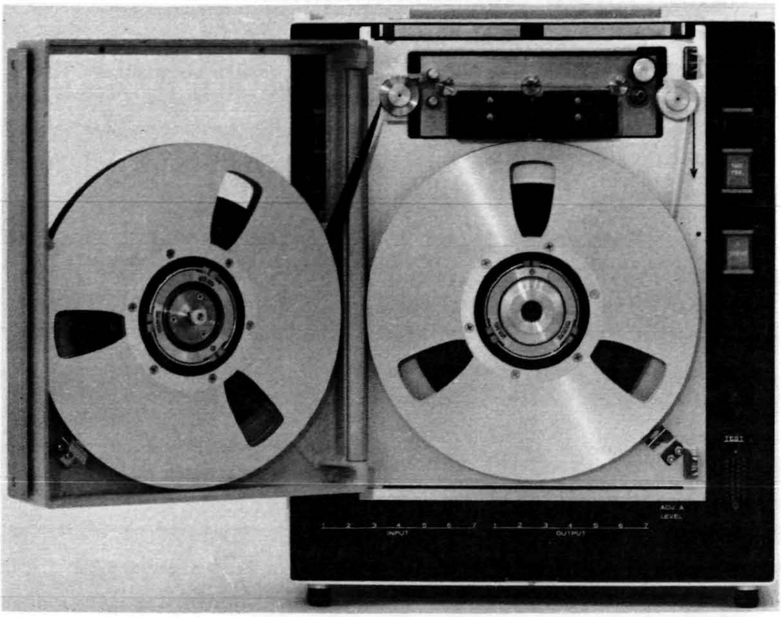


(*drawing courtesy Honeywell Inc.*)

FIGURE 6–12.—Outline schematic drawing of the tape path of the Honeywell Model 7700 recorder/reproducer. B and M are input and output tachometer rollers (tone wheel idlers), D and F are air bearing turnarounds, E is the vacuum column tape tension source, J and K are the capstan and pressure roller, the G's are tape lifters, the H's are heads and C and L are tape-break and tension sensors—see text for description.

recorder will compare with machines of the more conventional designs described elsewhere.

In order to reduce the overall size of the ground-based instrumentation recorder for portable or semi-portable use, a coaxial reel configuration is sometimes used. The practical achievement of a recorder with this configuration requires an ingenious mechanical design particularly if, as in the unit illustrated in figure 6–13, the feature of placing both supply and takeup reels together in a cartridge is included.



(*photo courtesy Precision Instrument Co.*)

FIGURE 6-13.—The Precision Instrument Model PI-200 recorder, a widely used coaxial-reel portable instrumentation recorder/reproducer which features handling of the two reels as a package in a removable cartridge.

However, the operating characteristics of such a recorder do not significantly differ from those of the conventional "reel-over-reel" configuration.

TAPE REELING MECHANISMS

There are quite a few ways in which tape may be supplied to and extracted from the point at which the recording and reproducing takes place. This discussion will be limited to systems in which the tape is supplied from a reel and taken up on a reel. The endless-loop recorder in its several forms will be discussed under the heading of its field of principle application, "Miniature High-Environment Recorders."

The first task of the supply and takeup mechanisms in the recorder is to provide tension while allowing the tape to move freely. In any recorder, the stability and uniformity of the supply and takeup tension are important to the overall performance of the recorder no matter how elaborate the isolation provided in the metering loop may be. Uniform tension is therefore the first task of the reeling mechanism.

The most straightforward way of providing uniform tension to a tape being unwound from a supply reel is to provide a brake or holdback clutch of some sort and to adjust the force of the clutch to compensate for the fact that, as the tape unwinds from the reel the effective diameter at which the tension is applied to the tape changes. The first recorders of many types actually used such brake holdback and elementary recorders such as dictating machines and some home recorders do up to the present time.

Several relatively low cost instrumentation recorders of reasonably high performance also use such brake mechanisms. The first professional audio recorders used torque motors for this purpose, however, and this practice was eventually taken over in the instrumentation recording field. Strangely enough, in the early stages of instrumentation recording, some high-performance machines went back in history to use brakes rather than torque motors to provide supply tension.

REELING MOTORS

When tape is being wound onto or off of a roll at a constant linear velocity, the rotational velocity of the roll is inversely proportional to the diameter at which the tape is being wound. If, at the same time, a constant tension is to be maintained in the tape, the torque applied to the shaft turning the roll must be directly proportional to the diameter of the roll. Maintaining constant tension requires that the product of speed and torque of the reeling motor be a constant, or, in other terms, that the plot of speed versus torque be a rectangular hyperbola (fig. 6–14).

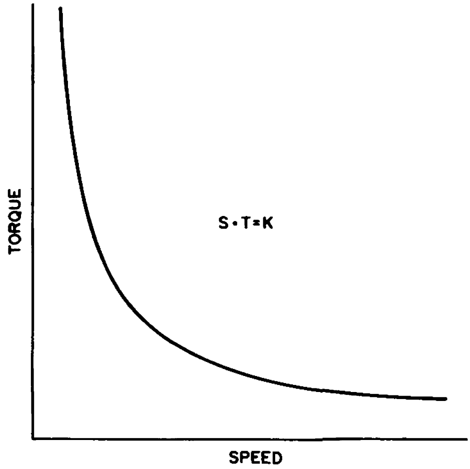


FIGURE 6–14.—Idealized speed-torque relationship of a reeling device.

An ideal series motor (no losses in brushes or internal resistance) has a rectangular hyperbola as a speed-torque curve. Such a motor therefore appears to be ideal for reeling service. Both ac and dc series motors have been used for reeling devices in special applications, but this use is limited by the desire of the designer to avoid the problems inherent in the commutator of such a motor. Series ac motors have extremely high efficiency, but for reeling service the disadvantages of the presence of the commutator have almost eliminated such motors from serious consideration.

The ac torque motor is another kind of motor which has approximately the characteristic desired for reeling service. Essentially, the torque motor is an induction motor which has been designed to have a rather steep slope of the speed-torque curve. A typical high-efficiency induction motor has a speed torque curve such as that shown in figure 6–15a, a shape useful for constant-speed running but useless for reeling service. Such a typical induction motor can be arranged to provide for the insertion of resistance in its armature. The effect of inserting this resistance is to move the peak of the speed torque curve toward lower and lower speed. For resistance which moves this peak to zero speed, or even to slightly below zero speed, the resultant speed-torque characteristic, shown in figure 6–15b, has a rather steep slope from high torque at zero speed to low torque at synchronous speed. Such a speed-torque characteristic matches fairly well the desired rectangular hyperbola of the reeling analysis given above. The design of the magnetic structure and windings can be conditioned toward optimizing this particular shape of speed-torque

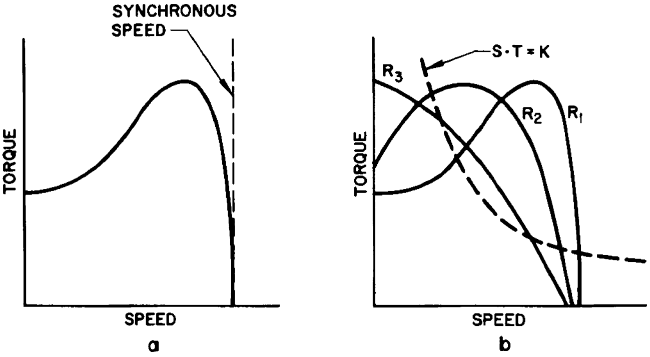


Figure 6–15.—Induction motor characteristics.

(a) Typical speed-torque relationship of a low-slip induction motor, (b) variation of speed-torque relationship of induction motor as rotor resistance increases from R1 to R3—the required speed-torque relationship for a reeling motor is superimposed in dotted lines.

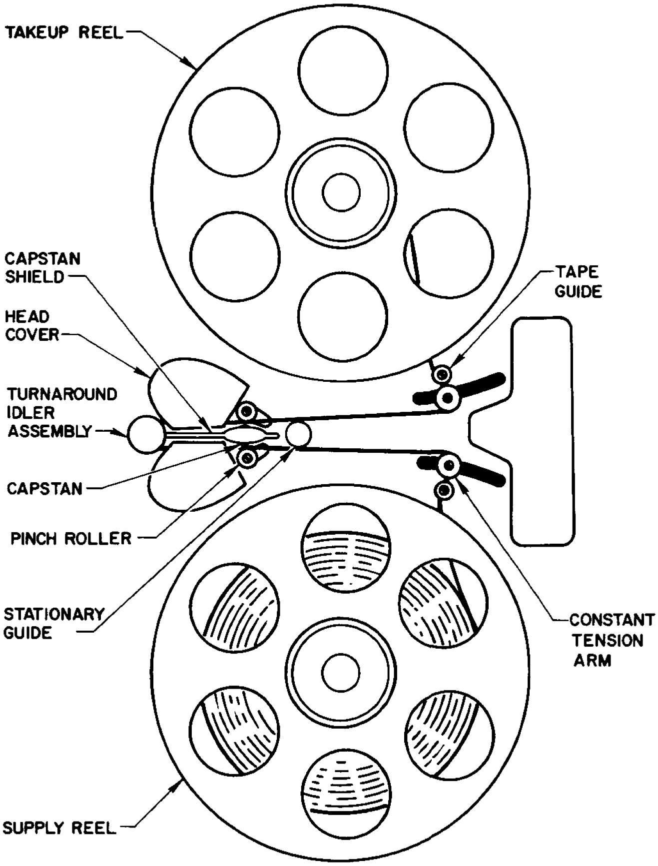
characteristic. Nevertheless, the torque motor does no more than approximate the desirable constant product of speed and torque.

It therefore appears that no reeling motor is available which gives precisely the most desirable correct speed-torque characteristic. One way of dealing with this situation is to design the motor and its associated mechanical elements so as to approximate within an acceptable degree the speed-torque characteristic desired, and accept the variation in tape tension resulting from this other than optimum design. An alternate way of dealing with the other than perfect speed-torque characteristic is to provide some kind of servomechanism control based on feedback from a measurement of the effective tape tension or some quantity related to the tension.

An open-loop servo control of reeling tensions is managed by detecting by some means the radius at which the tape is being supplied to or unrolled from the reel in question. From a "knowledge" of this radius, the servo calculates what drive torque should be supplied by the motor and arranges to have this torque supplied. This is an open-loop system in that the torque provided is determined from a prior knowledge of what should be supplied for the radius condition detected. Such a servo cannot deal with unusual conditions, nor does it have any feedback features which are self-correcting by automatic means. Closed-loop servos are more complex and raise many additional problems but they are currently preferred for the most sophisticated recorders.

In a closed-loop servo machine, the tape tension is detected by some means and torque is supplied to the reeling motor on the basis of maintaining that tension within a certain narrow range. Several controls of this kind have also been used for brake systems, rather than torque motor systems. The two major methods for obtaining the tension information are by the use of spring-loaded tape idlers and by differential pressure measurement in air-lubricated turnaround or guide posts.

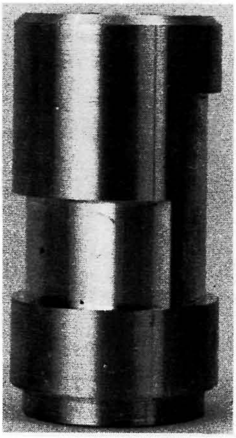
If the tape is directed between two guides in some fashion and a third guide is provided between these two, which guide is allowed to move, usually rotating around a fixed post under control of spring pressure, the steady position which is taken by the moving guide is directly related to the tension with which the tape passes through the guide array (fig. 6–16). In effect, such a guide system is a tensiometer such as is used to determine tension in belts and pulley systems. A device which detects the position of the moving guide will then give a direct measure of tape tension. Often, this information about tape tension is extracted either by allowing the guide to derive an electrical signal from a potentiometer or a multi-step switch which signal is used directly in the tension control system. Another common way of extracting the tension information is to have the moving guide control a shutter in a lamp-shutter-photocell system, so that the light falling on the photocell varies with guide position. An electrical signal can be derived from this array and it has the feature that no mechanical load need be placed on the guide as would be the case in the use of a potentiometer or step switch.



(from an Ampex Corp. drawing)

FIGURE 6–16.—Mechanical elements and tape path of a transport using a "tensiometer" tape tension sensor.

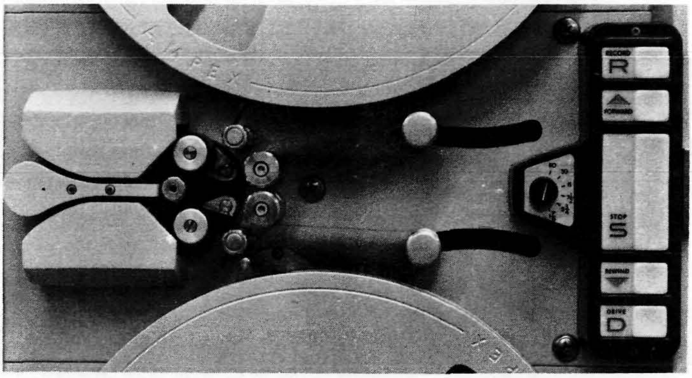
The moving guide has a certain amount of friction and some mass which are coupled to the tape. These elements therefore become part of the loop of the servomechanism controlling tension and must be included in the performance design of such a servo loop. The mass is particularly liable to create servo problems, and for that reason designers have looked toward a massless tension-determining mechanism. In some sense they have found this in the air-lubricated guide technique of determining tension. In this scheme, the tape is passed around a fixed guide in which are provided holes leading to an air supply manifold. Air is blown through these holes and allowed to escape between the tape and the guide so that in effect the tape rides on a film of air rather than on the surface of the guide itself (fig. 6–17). This produces a guide of extremely low friction, with its consequent advantages. If a sensitive pressure transducer is placed in the supply to the air-lubrication holes in the guide and the supply pressure is compared with the atmospheric pressure surrounding the equipment, the difference in pressure will be found to depend on how tight the tape is pulled around the guide. This pressure differential can then be converted by a transducer to an electrical signal which is a measure of tape tension. In theory, the air involved in this tension measuring scheme is massless and the detection should be free of inertia. In practice, the pressure transducer always has some mass, and in a transducer simple and reliable enough for use in a tape recorder this mass may be as important as the mass of a moving guide.



(photo courtesy Ampex Corp.)

FIGURE 6–17.—The air-lubricated tension-determining tape guide of the Ampex FR–600/1400 series—the guide is designed for both ½-inch and 1-inch tape.

The methods used for determining the instantaneous reel diameter for open-loop servos are very similar to those used in determining tape tension for closed-loop servos. In some very simple designs a follower is allowed to rest on the surface of the tape to indicate the amount of tape on the reel. A more sophisticated version involves shining a light past the roll of tape so that it falls upon a photocell on the far side of the roll. Either by using an extended collecting system for the photocell or an extended light source, a photocell signal related to the amount of tape on the reel can be obtained. Another reel diameter detector involves a spring-loaded tape guide roller operating under extremely light spring pressure, such that it scarcely deflects the tape at all when the tape is under normal tension. Such a roller is so placed that the variation in the angle with which the tape departs from some fixed guide to be wound up onto the reel varies the position of the spring-loaded guide as the reel fills up. One version of this technique is shown in figure 6–18.



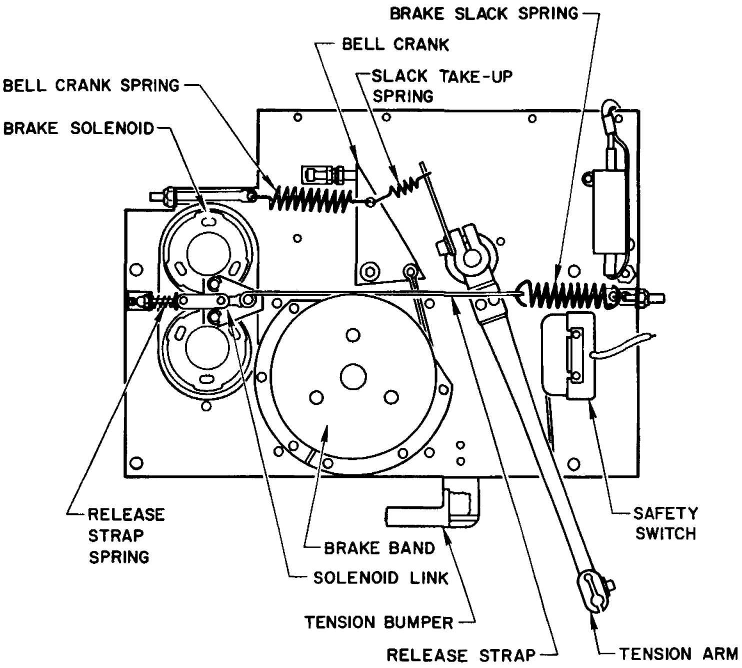
(photo courtesy Ampex Corp.)

FIGURE 6–18.—Reel-fullness detector.

The smallest roller visible here, just above and to the left of center of the lower reel, detects the angle of departure of the tape from the larger roller next above it, to the reel and hence, determines reel fullness (this is an enlarged view of the center of figure 6–3c).

BRAKE TENSION CONTROL

The first true closed-loop servo-controlled tension mechanisms were used to control brakes on supply reels. A brake could not be used on the takeup reel and the tension at this point was adjusted by adjusting the overall torque on the takeup torque motor. However, a genuine servomechanism was used to determine the supply tension. A typical example of such a servo brake is shown in figure 6–19. The brake itself cannot be seen in this drawing, but is actually a strap brake wound around the drum which is concealed under the circular housing in the center of the picture. The servo action of this brake was quite straightforward. The threading path of this tape recorder is shown in figure 6–16; the roller marked "constant tension arm" is at the end of the long arm labelled "tension arm" in figure 6–19. The following slightly edited quotation from the manufacturer's handbook explains how this particular brake worked:



(*from an Ampex Corp. drawing*)

FIGURE 6–19.—A controllable-holdback brake mechanism used as part of a tension servo (see text—this is the basic mechanism of the Ampex FR–100 servo brake).

"The assemblies consist basically of a *turntable* driven directly by an *induction-type motor*, and a *mechanical servo brake.* A *brake band* is wrapped around the braking surface of the turntable. The brake band is connected on one end to a *brake slack spring*, and on the other end to a *spring-loaded bell crank*, to which is connected a *slack take-up spring* and *bell crank spring.* The slack take-up spring is controlled by the position of the constant tape tension arm. The position of the arm is determined by a balance between the tape tension and a combination of the tension bumper and the brake force and causes the arm to increase or decrease the brake application by physically moving brake band release strap on the trailing turntable so that constant tape tension is maintained. If tape should break or if a loop should form, the slack take-up spring causes the tension arm to move in a direction to actuate the *safety switch* and stop the machine.

"When the DRIVE pushbutton is actuated, the sequence of events is as follows:

"1. The brake solenoids are actuated, and the release strap releases the brakes on both the take-up and rewind assemblies.

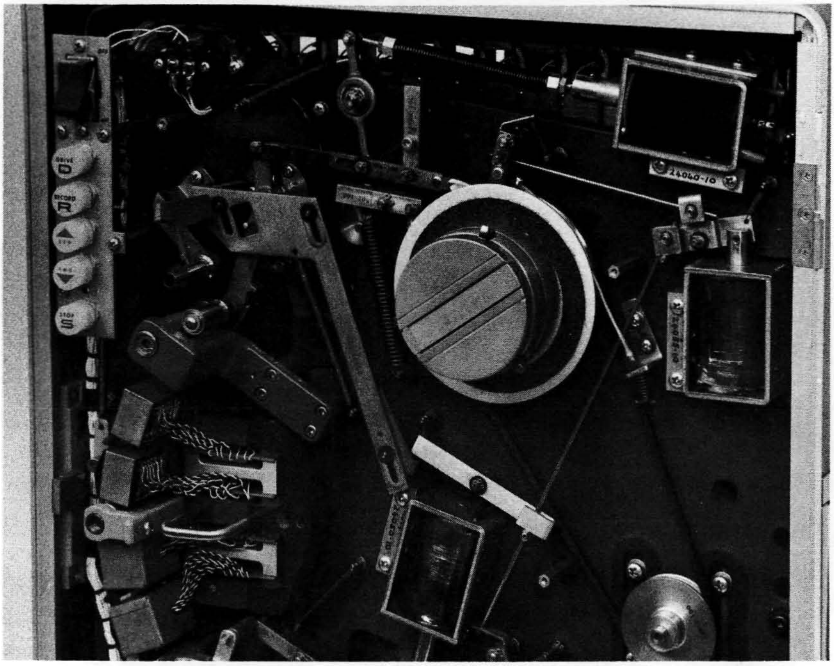
"2. An overvoltage is applied to the takeup motor for 0.1 second to cause the takeup turntable to move sufficiently fast to take up the tape supplied by the capstan.

"3. The capstan pinch roller solenoid is energized, causing the pinch rollers to clamp against the capstan.

"4. Tape is pulled from the supply reel by the capstan at a constant tension controlled by the brake and tension arm position. If tape tension tends to increase (tape not supplied at sufficient rate) the tension arm moves in a manner to position the brake so that braking pressure is decreased. Therefore, the turntable rotates at a higher rate, tape is supplied at a higher rate, and the tension arm moves to a position to increase braking pressure. If tape tension tends to decrease, the brake pressure is increased and the turntable rotates at a lower rate."

Brake holdback in the form of a string or wire brake as shown in figure 6–20 has recently been reintroduced for use in medium-performance recorders. It offers the advantage of a servo tension control of minimum complexity, but it is difficult to make such a mechanism perform at better than a certain level since the brake has certain inherent limitations compared to the completely electrical control possible with torque-motor holdback.

The string of the brake can be seen leaving a bracket just to the left of the rightmost solenoid and wrapping counterclockwise around the reel turntable, the other end being attached to an almost horizontal linkage. This linkage is connected to one end of an arm the other end of which carries a roller visible directly to the right of the "Stop" button, which roller detects tape tension. The normal tape path is from the conical-topped roller immediately to the left of the "Fwd" button, to the inertia idler (the upper bearing of which can be seen fastened to the heavy bracket immediately above the heads), passing also to the right of the roller attached to the servo brake arm, which roller normally rests to the left of its present position (see figures 6–2b and 6–2c). The roller attached to the servo arm seeks its present position driven by spring tension against the tape tension and thus provides a tension-sensing element.



(photo courtesy Ampex Corp.)

FIGURE 6-20.—A modern servo-controlled string brake.

SERVO REELING DEVICES

In the modern ground-based instrumentation recorder a reel of tape, usually 14 inches in diameter and a half or 1 inch wide, must be controlled smoothly during acceleration and deceleration, as well as during steady tape motion. The inertia of such a reel turning at 120 inches a second is adequate to snap the strongest tape if the total kinetic energy of the rotating reel is, through mishap, caused to exert force directly on the tape. Considering the fact that the data collected by such recorders is of extremely great economic value, a major consideration for the recorder designer is to provide that this tape be handled gently enough by the tape moving mechanism so that it cannot be damaged. The inertia forces described are those which are more liable to damage the tape than almost any others.

The basic problem here is to accelerate the empty take-up reel and the full supply reel smoothly and rapidly while maintaining a relatively constant tape tension without any sudden jerk or transient tension which can damage the tape. One would ordinarily assume that the maximum risk of damage would occur on starting and stopping the tape since large transient forces are involved. However, it is also necessary to consider possible damage to the tape when it is running smoothly. A resonance can exist between, say, the spring constant of the rotating magnetic field of the capstan drive motor and the mass of the supply reel, and this resonance can be excited at certain tape speeds by irregularities elsewhere in the equipment to the point where the tape can be pulled out of shape and broken under what appears to be a stable condition.

In the ground-based, controlled-environment situation, it is possible, of course, to protect the significant data on the tape from start/stop damage by starting the recorder well in advance of the arrival of the data and stopping it well after the data has been received. However, the kind of instability under steady running conditions just described can occur while important data is being recorded. It cannot be overemphasized how concerned the typical user is with the safety of his data and therefore with the gentleness with which the recorder handles the tape carrying this data. There is a corollary situation in the satellite recorder where start/stop is often a requirement of the necessary operating modes. Under these circumstances the start/stop action of the recorder must be essentially perfect and start/stop considerations may affect its design more than any other part of the performance specification. The avoidance of excessive tape stress may therefore be the primary goal of the tape mechanism designed for this application.

In addition to starting and stopping the tape motion gently, the tape transport must carry out its primary function of traversing the tape smoothly past the heads. One of these aspects of transport performance is sometimes emphasized to the disadvantage of the other; it may be that, at present, smooth tape motion, that is, the absence of flutter, has been overemphasized in recorder design. A complete recorder must, however, perform all its functions properly and the overall mechanical design must be made with full consideration of the relationships between motion disturbance and tape handling damage.

In open-loop tension control, the mechanical perfection of the reeling elements is about all that is directly involved in the uniformity of running motion. This might be summarized by saying that the function which relates the fullness of the reel and the force acting on the reel must be generated smoothly. Irregularity in this function may easily be propagated into the tape metering system. Only very indirectly, however, can these disturbances be propagated in the other direction; a reaction from the metering system against the reeling system cannot produce any major disturbance in the reeling system since its information is coming, not from tape tension, but from reel diameter itself. In some reel diameter detectors, of course, there may be transient defects, particularly in the case of the one which observes by a spring loaded guide the angle of departure between the tape and the fixed guide.

In the closed-loop servo, however, the entire situation must be dealt with at once. The reel mass must be smoothly accelerated while maintaining uniform tape tension, and under steady operating conditions any disturbances introduced through mechanical imperfection in the reeling system must be prevented from disturbing the tape metering. The tension servo requirements therefore must fall somewhere between the long term requirements of smooth acceleration and the short term requirements of reacting to disturbance. Under smooth operating circumstances the tape-metering mechanism is fairly tightly coupled to the reeling mechanism and the overall steady state stability of the combination, therefore, must be considered. The example cited earlier shows a situation in which ignoring this relationship can produce trouble.

No analysis covering this entire mechanical interacting system has been published to the writer's knowledge. Internal studies within the larger companies have been made on this subject but nothing has been published so far. It is well beyond the scope of this survey to perform any specific analysis beyond the general remarks which have been introduced at this point.

REELING IRREGULARITIES

It is probably not too much to say that the main trouble with reeling is reels. The mechanism of the tape recorder itself is usually constructed with great precision, good tolerances and fine fits. However, a reel with a history not completely under the control of the recorder user is then brought up to this recorder and attached to it. The irregularities of the reel and the problems raised by taking a separate unit, such as the reel, and connecting it in a mechanically satisfactory manner to the transport are some of the most difficult to solve. In one company there is an expression that "one does not succeed as a mechanical designer until one has designed at least one reel holddown mechanism." At the same time many tape recorder manufacturers make what they call "precision" reels, as do many of the tape manufacturers. Such precision reels attempt to supply the tape on a holding mechanism of a precision related to that of the recorder on which it will be used. In actual practice, however, reel deformation resulting from rough handling or improper storage can easily defeat the most sophisticated design of the mechanical engineer. The reel attachment must be such that it can be used relatively quickly and easily by a relatively untrained person; it must also guarantee that the reel is rigidly and firmly fastened without runout or wobble to the appropriate shaft.

It is again beyond the scope of this survey to discuss the various types of reel holddown other than to mention briefly the approaches that have been used.

The simplest reel holddown is one in which the reel fits over a relatively large hub which is essentially an enlargement of the reeling shaft and which has a turntable or other flange against which the reel is seated. The problem of holding the reel against this seat is solved in many different ways. One approach is to screw a large holding knob down on a threaded center post. The tape transport provides pins in the turntable which fit into standardized semicircular slots in the reel hub to provide positive drive. A popular modification of this approach is to retain the turntable and the drive-pins but replace the center shaft hub with a large rubber slug. This slug is arranged in such shape and size that when an external flange is screwed down on it, it is forced to expand; in so expanding, the slug grips the reel hub from the inside. With such a hub structure the rubber must be so shaped that there is a net force pushing the reel against the turntable; if not, the reel will be gripped firmly but will not necessarily be seated against the guiding turntable surface. Various other forms of dogs and driving mechanisms have been used to provide reel drive while still permitting easy removal.

The reel must not only be relatively precise if it is to avoid causing tape motion irregularities, but under many circumstances, it must be extremely strong. Tape is usually wound on the reel as smoothly and under as uniform tension as possible in order that the tape pack be quite stable. This means that the tape pack should be sufficiently strong to withstand sudden accelerations such as it might receive from the box of tape being dropped or roughly handled. A smooth, uniform tape pack is an essential requirement in any first class instrumentation recorder and it is purchased at the price of rather high stresses on the reel hub. As tape is wound smoothly onto a hub under uniform tension, there is a compressive force on the hub which derives directly from the geometry of the hub and tape and the tension of winding. As successive layers are wound on, the forces trying to compress the hub gradually increase. They do not increase indefinitely, i.e., every layer of tape does not add the same amount of compressive force on the hub but there is a net buildup of this force. Under normal circumstances, this hub compression force may not cause problems but if the reel is subjected to wide variation in temperature, the change in dimensions of both tape and hub may produce forces large enough to collapse the hub.

The precision of construction of the reel rather than its strength determines how well the tape pack withstands acceleration forces.

Actual operating accelerations may damage the tape pack in a fast start/stop digital tape handler. The tape pack of a ground-based instrumentation recorder suffers damage only when the reel itself is dropped or roughly handled. In the miniature high-environment recorder, the recorder itself may be subjected to accelerations adequate to damage the tape pack (chapter 13).

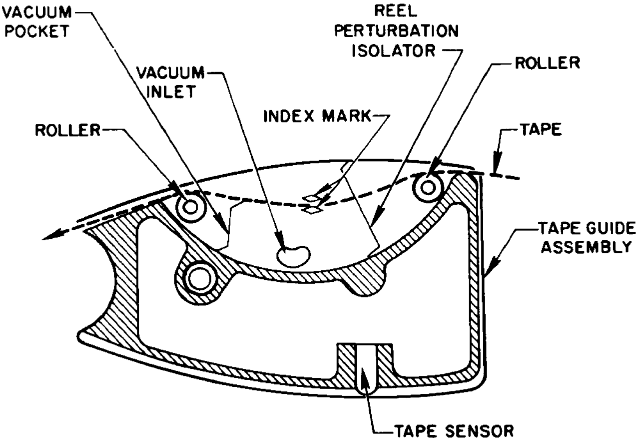
TAPE HOUSEKEEPING

Under tape housekeeping is included all the functions aside from reeling and metering the tape which must be performed by the tape transport. This includes guiding, end of tape sensing, tape-break sensing, and related functions. Of these functions, tape guiding is the only one which requires specific discussion at this point.

The tape guide may be either fixed or rotating. Obviously fixed guides have higher friction which may lead to higher tape tension, but they also provide damping forces on vibration and other potential sources of tape motion irregularity. In the special case of the air-lubricated guide, the fixed guide has no real frictional contribution and does not contribute any moving mass to the tape. The rotary guide, on the other hand, although lower in friction, does become coupled to the tape and the mass of the guide becomes part of the total vibratory system which may be involved in tape-motion irregularities. These elements are discussed in further detail under "Disturbances to Tape Motion" and "Mechanical Components."

In guiding tape from reel to reel in ground-based machines, it usually is kept in a flat configuration. That is, one edge of the tape lies in one plane at all points. In the so-called coaxial reel recorder (Figure 6–13) the tape must somehow be guided between the planes of the two reels. This is a very common function in light airborne recorders and is discussed in some detail in chapter 11. One matter is, however, of considerable importance here and that is the extra stresses on the tape provided by tape twisting. When the tape, in passing from one plane to another is twisted around its own axis, the edges of the tape are stressed more than the center of the tape. This results from the basic geometrical relationship that the generatrix of a cylinder is the shortest line of descent between the two ends of the cylinder. Any diagonal or twisting descent line from one end of the cylinder to the other must necessarily be longer. The edges of the twisted tape lie on the surface of such a cylinder and the tape axis along the cylinder axis. When the tape is under tension, the edges representing these longer descent lines therefore are stressed more than the center which is parallel to the cylinder generatrix.

An interesting example of specialized tape "housekeeping" is the special vacuum tape guide shown in figure 6–21. The mechanism of this drawing is that visible immediately to the right of the head and capstan area of the recorder shown in figure 6–3a. This particular guide contains a vacuum chamber which serves to deflect the tape from a straight path through the guide in accordance with the differential pressures on the two sides of the tape. In effect this is a small compliance placed in the tape path ahead of the capstan to perform the function with which it is labeled as a "reel perturbation isolator." It is intended to remove the resonance between supply reel mass and the compliance of the tape between supply reel and capstan. This resonance occurs in most such tape transports and has a frequency near the supply reel rotational rate.



(after a Consolidated Electrodynamics drawing)

FIGURE 6–21.—The reel perturbation isolator of the CEC Model VR–3600.

The vacuum connected to the point marked "vacuum inlet" causes the tape to deflect as shown and hence acts as a low-mass compliance against certain tape tension irregularities resulting from resonances driven by "once-around-of-the-reel" forces.

In addition to this special vacuum guide, another housekeeping function performed in this recorder can be seen in figure 6–3a in the form of a tape cleaning station between the reel and the heads. In this tape cleaning station, the tape is twice bombarded by ions generated by a combination of polonium radiation and a high electric field, being drawn past brushes between bombardments. The ions release the static charge binding dust to the tape and the brushes, plus a small vacuum maintained in the area, remove the dust.

Included in the housekeeping function is, of course, every aspect of the mechanical relationship between the heads and the tape. Rollers and guides are provided in order to guide the tape properly past the head but in turn the accuracy of mounting and the internal precision of the head itself are very important. Usually a high-performance recorder employs a so called "precision plate" on which all the elements which determine the relationship between the head and the tape are mounted with great accuracy. By tying these elements together with care, the requirement of high precision may be lifted from elements external to the precision plate. The precision plate can be clearly identified as such in figure 6–3b.

In tape housekeeping the possible generation of static electricity must also be considered. Wherever there is a rubbing contact of the tape, static may be generated and may cause unwanted effects on the tape motion. This problem is, however, mainly confined to rapid start/stop computer machines and to the internal problems in the tape pack of endless-loop recorders. Static problems are further discussed in chapters 13 and 9.

REWIND, FAST-FORWARD, AND SEARCH

In addition to the conventional function of recording and playing back at a controlled speed, any recorder must be able to rewind the tape rapidly and also to run forward at rewinding speed. The "fast-forward" and rewind functions usually are performed at several times the normal recording speed and it is under such conditions that tape damage may quite often occur since heavy accelerations and high velocities are involved. The difficulties involved in implementing these functions are similar to those involved in starting and stopping the tape at normal running speed and are considered under the reeling function elsewhere in this chapter. The emphasis in fast-forward and rewind is simply on careful control of tape tension so that no damage occurs.

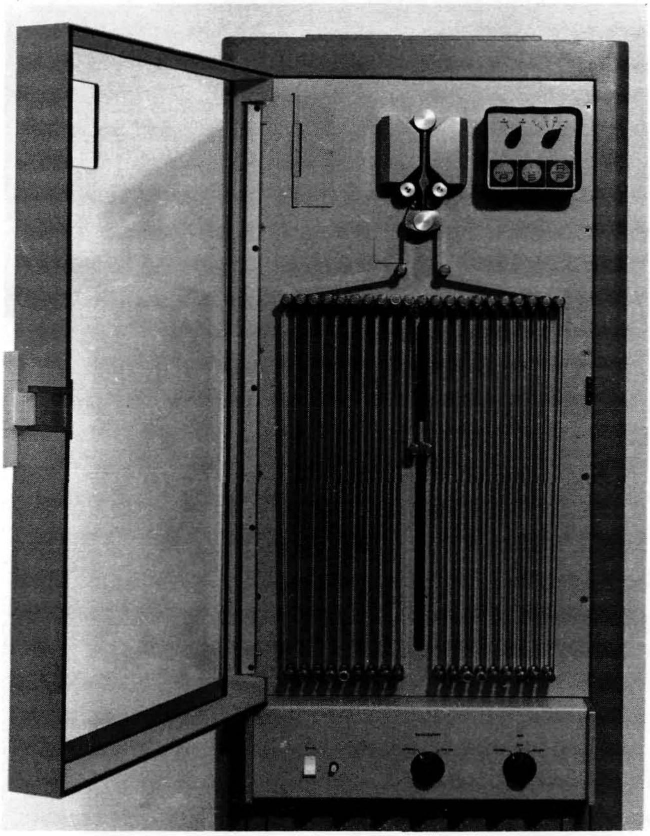
In many tape applications, particularly for data reduction, the fast-forward or rewind function may be performed at the same time that a signal is being reproduced from the tape. This is done in order to search out in a hurry some particular part of the tape. Typically a tape will have recorded on it some sort of clock signal which indicates the precise time corresponding to the recording of any data. It therefore is possible to give a modern recorder an instruction to seek out a particular hour, minute and second and to run fast-forward until it locates this moment and then stop. This process may be completely automated; the reel is placed on the recorder, the data address is punched into a register and when the recorder is started, it runs fast-forward until it finds the data and then operates at normal reproduce speed. The search function may include "shuttle"; two signal markers are established on the tape between which the tape shuttles back and forth rapidly. This simulates many aspects of the continuous-loop data-reduction function mentioned below. The mechanical problems of search are the same as those of fast-forward and rewind but they also involve control of the rapid deceleration when the desired point is located. The tape is usually separated from the heads, in fast-forward or rewind, to avoid excessive tape wear. The simple address signals are fairly clearly reproduced at the fast search speed even with large head-tape separation. A special "search" function must be provided in the reproduce channel to deal with the rather peculiar signal that is received under these circumstances but otherwise the search operation is straightforward.

DATA REDUCTION FUNCTIONS

In addition to the conventional processes of recording data and playing it back, the two operations sometimes performed at different speeds, there are more complex functions required in data reduction. Some of these are suggested in chapter 14 although the broad subject of data reduction is well beyond the scope of this survey. Two data-reduction functions, which, however, require special characteristics in the recorder tape moving mechanisms will be discussed here.

The simplest of these functions is that of providing a loop for continuous data analysis. Often a spectrum analysis of a piece of analog-recorded data must be undertaken. The pertinent section of tape is cut out of the reel or a copy of the section is made and the ends are joined to form a loop. The loop is then strung in a loop rack and run continuously past reproduce heads as the spectrum analysis is performed. Often the analysis must be done slowly or in steps and the tape may have to run for many passes. The loop function is fairly simple and is usually provided by a continuous loop recorder such as that shown in figure 6–22. Many recorders which normally have the reel-to-reel configuration can be modified for a loop operation.

A more sophisticated kind of loop operation may be necessary for such functions as cross- and auto-correlation. It may be desirable to compare data taken at two times separated by anywhere from a few milliseconds up to many seconds or even minutes. In order to perform this kind of specialized playback function at least one manufacturer equips his recorder with "delay bins." In such an arrangement the tape may be run off a reel, past a reproduce head, allowed to fall randomly into a bin which may hold anything from one to several hundred feet of tape, and then run past another reproduce head. The recorder must be carefully servo controlled so that the amount of tape



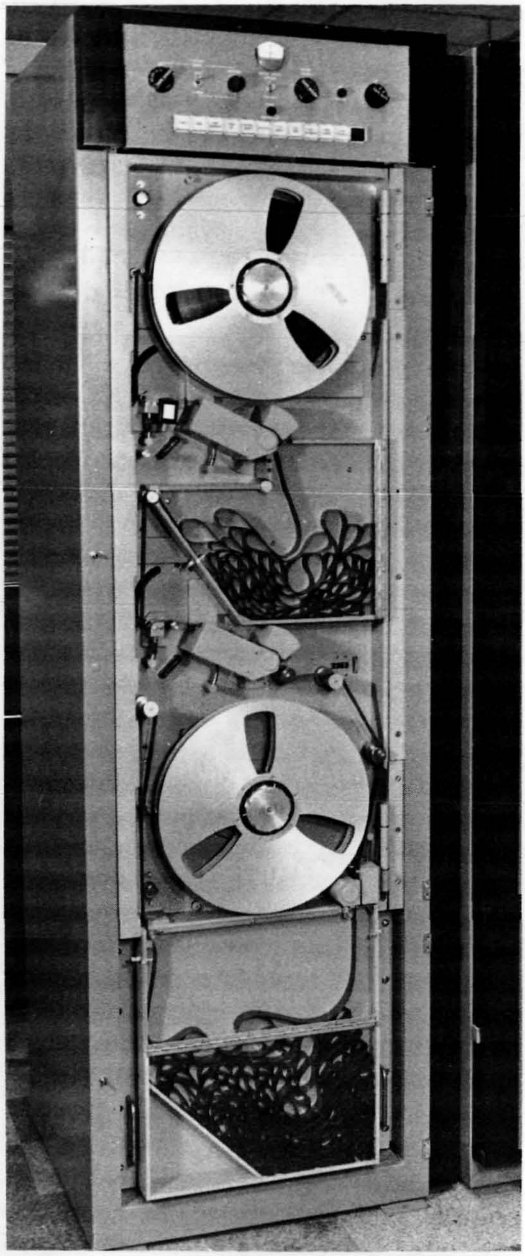
(photo courtesy Ampex Corp.)

FIGURE 6–22.—A typical endless-loop recorder for repetitive tape data analysis. Ampex Model FL–300.

stored in the bin between the two head passes is precisely controlled and hence the delay between the *recording* times of the data being correlated simultaneously is likewise controlled. In a further extension of this function, the entire delay operation may be performed on a section of tape which has been formed into a loop. The recorder shown in figure 6–23 is one which performs this operation using a tight-loop servo to control the playback speed and position with precision.

TRANSVERSE RECORDERS

The transverse method of recording, first introduced for the broadcast video signal recorder, involves moving both transducers and tape at the same time. A relatively wide tape is driven, usually in a fairly

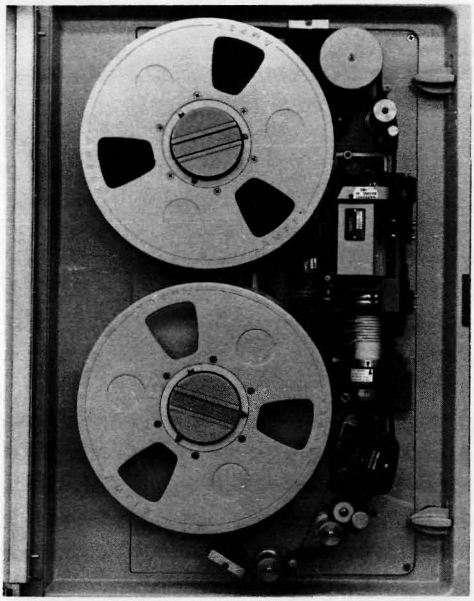


(*photo courtesy Sangamo Electric Co.*)

FIGURE 6-23.—The Sangamo Model 480 Bin-delay recorder/reproducer.

This model is fitted also with a second delay bin to provide repetitive data analysis as well as the controlled data-point-to-data-point delay of the first bin (see text).

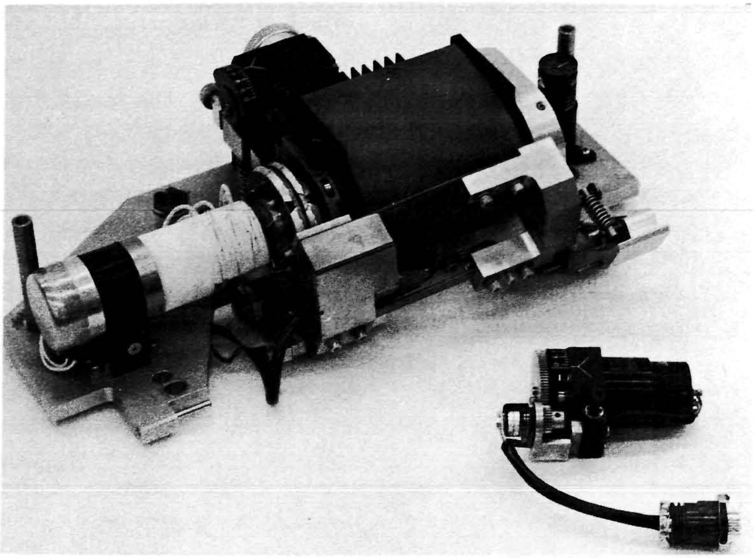
conventional open-loop drive, past a rotating head wheel or drum which traverses the actual transducers at a high speed across the tape. The tape path is essentially a portion of a long spiral. With a tape speed of 15 inches per second, the head speed, and hence the head-tape velocity, may be as high as 1500 ips. This drive scheme introduces a whole new set of interrelationships and parameters into those already present in a conventional longitudinal tape transport scheme. A transverse-scan instrumentation recorder is shown in figure 6–24 and the head-drum mechanism is shown in greater detail in figure 6–25.



(photo courtesy Ampex Corp.)

FIGURE 6–24.—The Ampex Model AN/GLH–3 Laboratory "video-instrumentation" recorder/reproducer.

The longitudinal drive of the tape need only be good enough in a transverse recorder to assure that auxiliary tracks recorded longitudinally on the side are reproduced with adequate fidelity and that the spiral traced by the reproducing head is the same as the spiral traced by the recording head. Signals are derived in playback from a special longitudinally recorded and reproduced synchronizing track to guarantee that the "threads" of the two spirals fit together. This is done by adjusting the speed of the head rotating motor so that the spiral it generates is in phase with that laid down on recording. This servo is of the closed-loop type and, although nominally of rather simple design, the time stability of the rotating head mechanism



(*photo courtesy Ampex Corp.*)

FIGURE 6–25.—The rotating-head assembly of a two-channel "video-instrumentation" recorder/reproducer.

A manual female-guide control is shown installed and the servo-operated guide control which can be substituted for it is shown to the right and below.

and the output signal it generates depend on the head-servo stability.

Since the rotating head drum usually operates at about 15,000 revolutions per minute, its high rotating inertia should make it rotate quite smoothly. There may be irregularities in this rate, however, brought on by instability in the drum synchronizing servo. There are also a whole new set of motion irregularities which are created by the peculiar geometry of this drive scheme.

As the head drum sweeps across the tape, the head itself protrudes slightly from the drum and deforms the surface of the tape locally. This guarantees good head/tape contact and indirectly makes it possible so to construct the transverse recorder as to compensate for many effective speed irregularities. As the head sweeps across the tape it deforms the tape into a so called female guide which is a cylindrical guide grooved or relieved to accept the head protrusion. The position of this guide relative to the head drum has an important effect on the relative speed of the head and the tape. The center of rotation of the drum and the center of generation of the female guide can be displaced from each other and may be deliberately so to compensate for differences in wear between the record and reproduce head. This subject has been intensively discussed in the literature, particularly with reference to broadcast practice and will not be considered in detail here (Kietz [1963]). The broadcast problems exist, of course, in instrumentation use of this drive.

In the broadcast application of the transverse recorder, it is desirable to maintain extremely accurate phase coherence in order to be able to deal with the color television subcarrier. Elaborate techniques have been worked out for maintaining the necessary phase accuracy. The methods first applied were dependent on the existence of the synchronizing pulses within the television signal for successful operation. The absence of such pulses in instrumentation input signals has limited the application of these compensation techniques. Recently, however, refinements of equipment have led to the point where ±25 nanoseconds is the time stability that can be maintained by such a recorder. This is discussed further under "Disturbances to Tape Motion" in chapter 7.

UNUSUAL DRIVE SCHEMES

Several tape drive methods for specialized recorders have been developed recently which differ fundamentally from the methods described elsewhere in this chapter. These include the "Iso-elastic drive," the "Cobelt drive," and a variation on the "Cobelt drive" in which a Mylar belt is used to provide the function of the pressure roller. These drives, except for one specific case referred to earlier in this chapter, are confined to use in small high-environment recorders and therefore are discussed in chapter 13.

Because endless-loop recorders are limited for scientific application to the miniature high-environment class, the problems of endless-loop tape packs, friction and motion irregularities are discussed under the "Miniature High-Environment Recorder" and are not considered further in this chapter.

The discussion of this chapter and of chapter 7 is concentrated on devices which, if operating properly, move the tape forward in a uniform manner. For some applications it appears desirable to move the tape in steps rather than in uniform flow. This is particularly useful for recording digital information and has the great advantage that if the information arrives in a very irregular manner the amount of tape required to record a given amount of information is greatly reduced by intermittent operation. Tape is only consumed when the information is being received and is at rest at all other times. The action of such intermittent mechanisms for ground-based data handling is for all practical purposes limited to computer digital storage and, as such, is well beyond the scope of this survey. A preliminary experiment looking toward the application of intermittent recording technique for space probe use is referred to in chapter 13.

CHAPTER 7

Disturbances to Tape Motion

A fundamental difference between any data handling system which contains a tape recorder and any system not containing such a storage mechanism is that in the first the time scale of a transmitted signal can be distorted. Although the literature contains few analytic discussions of the causes and effects of this time scale error, Davies (Davies [1961]) gives an excellent general survey of the subject. This chapter will be limited to a general introduction to tape motion irregularity with emphasis on methods of compensating for and minimizing it. The kinds of irregularity which hold little promise of ever being completely eliminated will be considered as well as some which newer recorder designs have eliminated. This discussion should serve as a background for the subsequent chapters on "Mechanical Components," "Miniature High-Environment Recorders" and "Complete Recording Systems."

Besides Davies' general survey of the subject of recorder speed errors little has been written on this subject. Sweeney (Sweeney [1952]) has discussed a method of time displacement error measurement, as has Cox (Cox [1962]). In a discussion of this last reference, McKnight (McKnight [1962]) emphasizes some of the confusion that exists between time displacement error and flutter in audio applications. Some differences in methods of specification of time displacement error and their meaning for instrumentation recording have been discussed by Brenner (Brenner and Meyer [1964]). Wolf (Wolf [1960]) gives a detailed analytic study of audio recorder flutter and, of particular interest, of methods for measuring the mechanical elements of a complex recorder mechanical system to make quantitative the filter analogy approach to minimum-flutter design. The only available analysis of instrumentation recorder flutter appears to be that of Pear (Pear [1961]). Schulze (Schulze [1962]) discusses the way in which the first commercial "low-mass servo" recorder developed by D. G. C.

Hare operates. No discussion of some of the more sophisticated low-mass-servo controlled machines has appeared in the literature. Discussion of these machines is also deliberately omitted from this survey because methods of designing such servos have been the subject of recent extended litigation which is not known to have been resolved as yet. So that it will not appear that a conspiracy of silence is responsible for this omission, the low-mass-servo recorders currently offered include the following: The Mincom Division of the 3M Company introduced in 1964 the Ticor II which is understood to be a low-mass-servo machine with a printed-circuit capstan motor delivering an advertised absolute time base stability of 0.5 microsecond; Winston Research, a division of Fairchild Camera and Instrument Company, is understood to have offered recently a low-mass-servo recorder with comparable performance, and Honeywell, Incorporated has announced an unusual form of open-loop recorder which appears to be designed to accomplish the same low-time-displacement-error objective. The latter machine is discussed in chapter 6 because it is the only one of the three about which information is currently available. It is expected that other machines of this type will shortly become available.

FLUTTER

The term flutter used in connection with a recording and reproducing device refers to the instantaneous variations of speed in the recorder and reproducer. The term is sometimes extended to include "wow"; the descriptive term becomes "wow and flutter." Wow is of relatively low frequency and flutter is of relatively high frequency.

The term wow originated with the disc record when a speed variation at a rate of once around for the record produced an effect on sustained tones that was graphically described as "wow." Currently it refers to relatively smooth speed variations at rates in the order of a few cycles per second and below, primarily for audio recorders. Instead of using this term here we shall refer to low-frequency and high-frequency flutter as appropriate.

Flutter is expressed as a percentage variation in steady speed. For example, flutter of one percent, peak-to-peak, means that the instantaneous speed of the recorder or reproducer varies from the steady speed plus or minus a half percent at a fairly rapid rate (flutter does not include any long term speed error). A frequency modulation detector of suitable response can be modified and calibrated to indicate flutter directly from the signal reproduced from a recorded steady tone. Flutter expressed as a percentage seems to correlate with audible sound disturbance in an audio recorder and, of course, is a direct measure of the FM noise produced in an instrumentation recorder operated in the FM mode. It is sometimes useful, however, to consider the instantaneous speed variation on an absolute rather than a percentage basis.

INSTANTANEOUS TIME ERROR

When a recording is made and the recorder does not operate at a perfectly uniform speed, one might say that the clock recorded on the tape has instantaneous time errors when compared to the clock of the original signal. An actual clock signal could be placed on the recorded track by using pulses timed by a local accurate crystal oscillator for the input.

When the recorded tape is reproduced, further instantaneous speed variation takes place and the reproduced clock differs even more from the recorded clock. This error could be tested, for example, by using the same crystal-controlled oscillator to provide an accurate series of local pulses with which the reproduced pulses could be compared for time stability. There is, of course, a large "dc" component of time which is ignored, that is, the delay between the time of making the original recording and of reproducing it.

If one considers the performance of the recording process by comparing the reproduced time scale with an absolutely correct time, it is apparent that there is a net uncertainty of time introduced by the recording and reproducing process. This net uncertainty is seldom expressed as such in writing the specifications of a recorder/reproducer. It may, however, be of even greater significance in determining the utility of a recorder than the amplitude signal-to-noise ratio, the only specification of uncertainty normally given. A signal-to-noise ratio of 100 to 1 implies that the instantaneous value of a recorded variable is not known to better than 1 part in 100 because of random variations in amplitude in the recording/reproducing process. Knowing the value of the variable to this accuracy is of little significance if the time at which the variable has this value is not known to corresponding accuracy. The direct correlate to amplitude signal-to-noise ratio in terms of time is flutter. Because the absolute frequency of a signal may not be handled directly by the recorder because of heterodyning and frequency multiplication, the concept of flutter does not deal with time errors in the same way that signal-to-noise ratio deals with amplitude errors. For many applications, the absolute time error may thus be of more significance than the percentage time error.

The absolute time error can be derived from the percentage time error, i.e., the instantaneous time displacement error can be derived from the flutter if enough information is available about the nature of the flutter. If the flutter is of a cyclic type, it is particularly easy to connect the two errors since cyclic flutter implies that an analytic function describes the variation in speed; such an analytic function can easily be integrated to give the net time displacement. The same relationship exists for complex flutter but is usually almost impossible to compute in analytic or usable mathematical terms. Something may be learned, however, from the integrating process involved. In integrating a conventional function containing sinusoidal terms, the frequency of a particular term appears in the denominator of the integral. This means that for a given percentage variation in speed, i.e., flutter percentage, the higher-frequency flutter components have less and the low-frequency flutter components more effect on the total time displacement error. The low-mass-servo controlled recorders are therefore able to provide low time-displacement error by removing flutter components of frequencies up to a few hundred cycles per second by "brute force."

FLUTTER SOURCES

Flutter effects in a tape recorder fall roughly into two groups. One of these originates in the mechanism proper of the recorder and the other in the tape as it reacts to interaction with the elements of the recorder mechanism. Flutter sources within the mechanism are primarily low-frequency irregularities in movements of the elements responsible for moving the tape; as the largely unsupported tape comes into frictional contact with other tape elements or is subject to irregular moving forces, the particular mechanical characteristics of the tape itself are involved in generating high-frequency motion disturbances.

Flutter sources within the mechanism include the relatively high-frequency group which come from irregularities in tooth mesh of gears or from cogging in motors. Irregular high-frequency sources include ballbearing roughness and ball interference. The low-frequency sources are primarly found in once-around variations in roundness or drag torque of the rotating elements. The once-around irregularities may be runout in one or two dimensions or they may be variations in surface finish of an item such as a capstan. They also may come from nonuniformity or drag of clutches or other slipping devices. The lowest-frequency flutter in a reel-to-reel tape recorder usually originates in rotation of the supply and takeup reels. As well as being the lowest frequency source and therefore most difficult to deal with mechanically, the once-around of the reels is less under control than any other rotational movement within the recorder. This results from the lack of control by the recorder designer of the reels themselves (chapter 6). The irregularity of the sides of the reels, the degree to which the tape rubs against the sides, and the overall tolerance with which the reels are made may be specified in achieving performance limits in the recorder; the utility of this specification may be destroyed by reel damage resulting from rough handling.

In the same frequency range and in many ways as difficult to deal with are supply and takeup tension devices using friction clutches. It is almost impossible to maintain absolute uniformity of torque during a complete revolution in a slipping device. The use of slipping devices for holdback and takeup tension adjustment has therefore been sharply limited.

The tape recorder contains many rollers which guide the tape or are driven by it to couple filter elements to it or to control its motion. These rollers are all potential sources of intermediate-frequency flutter, as is the pressure roller which forces the tape against the capstan. The pressure roller is a relatively slowly rotating device made of a relatively soft material. Irregularities in the softness of the material, i.e., in durometer of the rubber typically used, may produce gross irregularities in tape contact against the capstan. The capstan itself is often of small diameter and can therefore generate flutter of relatively high frequency. In the case where the capstan is large, and must therefore be driven through a reduction mechanism, any irregularities in the belts or gears of the reduction mechanism can be sources of high-frequency, mechanism-induced flutter.

If one were to plot the frequency modulation signal produced by most of these sources within the mechanism, it would be a smooth function, often almost sinusoidal. Such flutter should be easy to filter out by using mechanical filters designed by analogy. This has seldom been done in the design of United States tape recorders, and it has hardly been discussed in the literature. Relatively simple principles of mechanical analogy may have been used to determine, for example, that a flywheel should be doubled in mass or that a severe flutter source is a resonance between the effective spring coupling of the air gap flux of a motor and a flywheel driven through a double reduction. Sophisticated analysis of flutter and its removal by complex filter techniques is, however, rare.

The other important source of flutter is within the tape itself. Tape is an elastic material which is in various frictional contact with elements of the recorder and is continually under tension. Irregularities of tension and in torque generated within the mechanisms are propagated from one part of the mechanism to another via the tape. The tape is typically shock excited by such internal irregularities. A major source of tape motion excitation is at the head itself where the tape must necessarily be dragged in contact with a surface that is not perfectly smooth. Polyester tape, which is now almost universally used, adds the further complication of having very nonlinear mechanical properties. These nonlinear properties are responsible for the curious strength of Mylar but they also result in some very difficult mechanical behavior of the tape when interacting with other elements of the tape recorder mechanism.

Almost all the irregular forces applied to the tape are longitudinal. The tape can, of course, vibrate longitudinally and longitudinal disturbances can be propagated along the tape from point to point. Because, however, much of the tape is unsupported between the mechanical elements of the tape mechanism and the tape is always under the influence of gravity as well as the longitudinal tension, there is a continual conversion of longitudinal forces and vibration into lateral vibration. Such lateral vibration is propagated differently from longitudinal vibration and interacts in a completely different way with the rest of the mechanism elements and is easily converted back into longitudinal vibration. The interaction makes filter analysis of tape flutter particularly difficult. The type of flutter resulting from such tape vibration is, unfortunately, the most serious in many tape applications. The ultimate limit to the signal-to-noise ratio of an FM recording system is set by the "hash" flutter originating in frictional scraping excitation of the tape. The spectrum of such flutter, although broad, is not smooth and produces FM noise with a similar spectrum. Such an irregular "hashy" spectrum of speed disturbance is, unfortunately, the most difficult for the designer to control of any encountered in the tape recorder. It is almost always observed that as FM noise is measured over a progressively wider band in a particular recorder channel, the noise increases faster than in proportion to the increased bandwidth. This increased FM noise is apparently due entirely to the hash flutter produced by scraping contact in the recorder.

FLUTTER REDUCTION

There are in practice two basically different approaches to direct methods available for reducing mechanism flutter. One of these tends toward increasing the mass of critical elements so that the flutter sources are unable to disturb the motion at the point of the heavy mass. Such an approach is effective in reducing mid-frequency flutter but becomes progressively less useful as the flutter becomes lower in frequency. The alternative is to use extremely light elements at the capstan and the other critical points and to maintain uniform motion at these points with a very tight powerful servo. This approach reduces the low-frequency flutter but leaves the mid-frequency flutter little affected. Both leave high-frequency (hash) flutter almost unaffected.

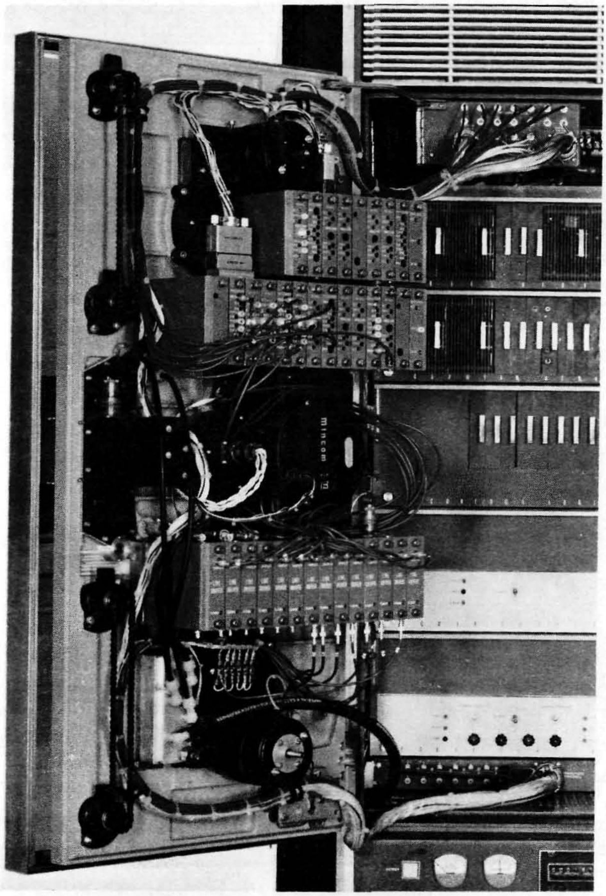
The significance of the difference between the effects of high-mass and low-mass filtering may not be apparent when measuring overall flutter by some averaging method. The difference is important, however, in dealing with time displacement error. As noted earlier, low-frequency flutter produces proportionately greater time displacement error. A low-mass filtering system combined with an active servo mechanism can sharply reduce the low-frequency flutter. When carried out properly, this technique produces a machine with an extremely low time displacement error. However, the overall flutter of such a machine is reduced in the process little below that of a high-mass machine with considerably worse time displacement error.

The high-mass approach to flutter reduction is really misnamed. It includes all methods of reducing flutter by attempting to isolate its sources and reduce its transmission to critical areas through analogy filter techniques. The term "high mass" has been applied to this approach because the design almost invariably ends up with a relatively massive structure as filter elements in the capstan or tape-metering area. For example, in the standard single-capstan closed-loop recorder configuration the tape is locked as tightly as possible to a single capstan as it enters and leaves the metering loop. Clearly, if the tape-capstan adhesion is high enough in order to move the tape within the metering loop, any disturbance from outside that loop must move the capstan as well. A massive capstan is obviously harder to move and until the advent of the low-mass servo, capstan assemblies were always heavy.

Weight alone may not be the most important part of the capstan since it is part of a complex mechanical filter network. Many machines produced in the last few years have substituted for the straight capstan flywheel a damped flywheel copied in principle from the rotary stabilizer of film recording practice. With such a flywheel the capstan drives a relatively light cylindrical can inside of which the flywheel proper is supported on extremely good ball bearings. The space between the flywheel and the can is filled with an oil of controlled viscosity. The effect is to couple the capstan to the flywheel through a mechanical resistance. Considering the existence of the rotary stabilizer type flywheel in motion picture use since the late 30's, it is interesting to note the number of tape recorder designers who appear to have discovered its utility within the last 3 years.

The mass alone is therefore not the significant thing here. The idea of the large mass being hard to move is a subjectively satisfactory way to look at the action of the closed-loop isolation between metering and reeling function. However, all the elements of the recorder are part of the closely coupled mechanical network and only with detailed filter design can one accurately predict the effect of changes in the elements of such a system. Very little has been written on filter design of closed-loop systems, possibly because it is a somewhat difficult subject and possibly also because many manufacturers consider this a region of considerable proprietary interest (Pear [1961]).

Although the use of the term high-mass has been objected to on fundamental grounds, it is interesting to compare figures 7–1 and 7–2 with respect to this term. Figure 7–2 is the rear view of the mecha-

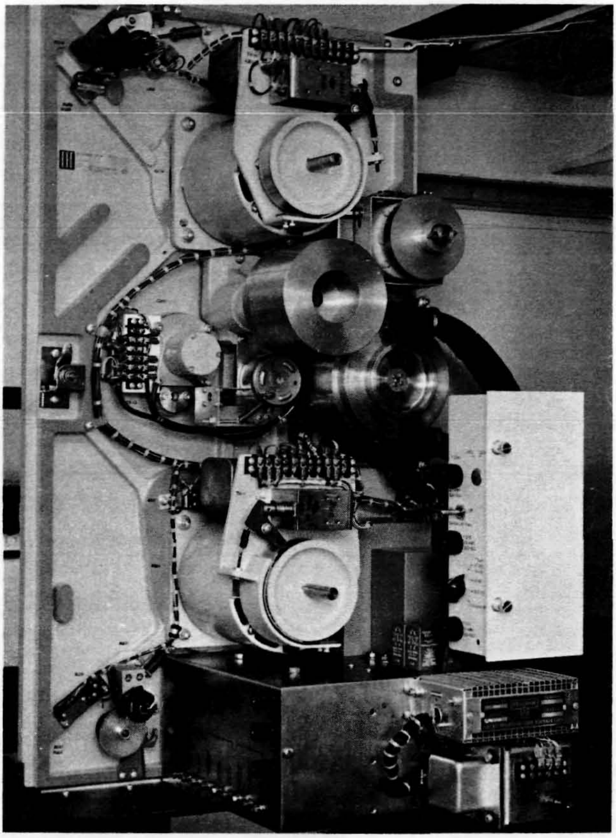


(photo courtesy Mincom Division)

FIGURE 7–1.—Rear view of the Mincom Ticor II transport.

The presence of the large number of electronic modules directly mounted on the transport base emphasizes how few massive elements are used in this tight-loop servo-controlled transport.

nism of an instrumentation tape recorder which employs conventional analog filtering techniques to reduce its flutter. No tight servo is employed here. Figure 7–1 shows the rear view, although admittedly in not very much detail, of a low-mass servo controlled machine. The difference in mass between the rotating elements in the two cases is quite impressive despite the lack of detail in the second picture. The specifications indicate that the overall wideband flutter of these two machines is quite similar. The time displacement error, however, is about a quarter-millisecond in one case and a half-microsecond in the other.



(photo courtesy Consolidated Electrodynamic Corp.)

FIGURE 7–2.—The rear view of the CEC Model VR–2800 transport.

The large flywheels visible here clearly illustrate the results of the "high-mass" approach to tape transport design (although this unit differs in some respects from the higher-performance Model VR–3600 shown in front view in figure 6–3a, little evidence of the difference is apparent in this view).

The Sangamo recorder developed by D. G. C. Hare was perhaps the first low-mass-servo unit. Figure 7–3 shows a closer view of the motor-drag-disc combination of this recorder. At one time the Sangamo machine used several small dc motors coupled to the capstan to reduce the overall moving mass. These motors, which were small in diameter but relatively long, produced a minimum rotational inertia for the power developed. The current model of the machine uses a high-mass motor but couples it resiliently to the drag disc which can be seen in the picture. Assuming that the resilient coupling does its job, the only elements of the mechanism which must be tightly servo-controlled are the relatively low-inertia drag disc and the capstan itself.

(photo courtesy Sangamo Electric Co.)

FIGURE 7–3.—The motor-drag-disc combination of the Sangamo tight-loop-servo transport.

The rather massive motor on the left is connected to the very light eddy current drag-disc on the right through a resilient coupling which essentially makes the controlled element light in mass.

DISTURBANCE COMPENSATION TECHNIQUES

The technique called "flutter compensation" has been used to improve the signal-to-noise ratio of FM recording channels for quite a few years (Peshel [1957]). A flutter compensation system operates by recording a reference sinewave signal along with the desired data signal and detecting the reference in a discriminator system, the output of which describes the tape motion irregularities that are disturbing the data signal. The reference signal may either be placed on a separate track or be multiplexed on the same track with the data.

In one approach to flutter compensation the so-called reference discriminator signal was simply added electrically to the disturbed data signal in such phase as to tend to cancel the noise produced by the disturbance. In another compensation method the signal representing the disturbance was inserted directly into the data discriminator. Originally this was done in a pulse counting discriminator by varying the area of the nominally equal-energy pulses feeding into the counter in accordance with the disturbance signal (chapter 10). In the phase-locked-loop discriminator, now widely used, the correcting signal is introduced into the feedback loop of the discriminator.

A detailed analysis of the action of this flutter compensation is beyond the scope of this survey. However, Davies (Davies [1961]) analyzes the spurious signals produced by flutter in the recorder. By examining these signals and what compensation can do to change them an evaluation can be made of the overall gain to be derived from compensation.

Davies points out that in the flutter-distorted FM system output there are several undesired terms. One of these is the actual noise signal produced by the flutter, and there is also both amplitude and frequency modulation of the data signal. His analysis also shows that any FM recording system is plagued by what has been called the "noise multiplication" effect. With a given flutter percentage, the ability of flutter noise to interfere with the signal is dependent on the deviation ratio of the signal; in a sense, the percent flutter must be multiplied by the ratio of the FM carrier frequency to the peak data deviation frequency to determine the peak signal-to-noise ratio.

In practice, the flutter noise compensation can only be adjusted to be most effective at one particular instantaneous signal level. The adjustment is usually optimized for zero signal, although for certain applications it may be desirable to adjust it for some other signal level of importance. The technique of varying the area of the pulses in a pulse-counter discriminator and the corresponding process in the phase-locked-loop discriminator can also remove the amplitude modulation of the desired signal. However, any of these systems leaves the flutter of the data itself unaffected by compensation.

It is quite probable that much tape stored in warehouses for possible future data reduction contains data that is useless because there is flutter in it. However, an influence at work at present may make the issue of data flutter compensation academic. The practice is steadily growing of analyzing all data received from research and development tests, whether for NASA or for the military services, by digital means; and those signals which are not digital are converted to digital form. Elaborate slow-speed and high-speed digitizing installations have been built in many centers and in the plants of many contractors. They provide tools for compensating completely for the flutter in any data. If the 100 kc or other reference signal which is used to drive the flutter compensation discriminator is fed to the digitizing equipment, the digitizing process can be slaved to this reference frequency. When this is done any flutter in the reference frequency is reproduced in the digitizing timing and hence the data itself is digitized in an accurate flutter-free manner.

Davies also discusses, in the reference cited, the instantaneous time errors between various channels. Many such timing errors, if systematic because they result from mechanical irregularities in the recorder, are relatively easily removed. However, the kind of broadband "hashy" flutter which causes flutter noise problems can cause instantaneous track-to-track uncorrelated time deviations. The compensation of this kind of deviation is very difficult to accomplish. Recently, however, by the use of wideband variable delay lines, commercial devices have been made available which can reduce the track-to-track skew timing error to an extremely low value (Jorgensen and Moskovitz [1962]). These devices work by controlling the relative delay between the two tracks according to information derived from a reference frequency.

The same basic technique makes it possible to remove the bulk of speed variations from the rotary-head recorder. In early applications of the rotary-head recorder, two fundamental timing and amplitude errors were always present. The amplitude error came from lack of perfect match between the signals from two heads reading overlapped data on the tape at the time of shifting from one head to the other. So-called "slow switches" have now been introduced which move smoothly from one data level to another if the two levels (which should be identical) differ, and disturbing signals resulting from abrupt switches between incorrect levels have essentially disappeared. The timing error, which also exists at the switching time because of inaccurate fit between the recording and playback geometry, can be little improved until the geometric errors are brought down to within a microsecond or less. In the original television application of the rotary-head recorder the synchronous nature of the television signal with its inbuilt timing signals made it possible to compensate for these timing errors by more or less slaving the local electronics which processed the output signal to a corrected reference time. In the absence of such synchronizing information within the conventional instrumentation data signal, these time deviations were originally a big problem. However, improved mechanical accuracy in the recorder has resulted in consistent switching errors being reduced below a microsecond. When this has been done, a variable delay line, controlled either by a recorded reference tone or some other local reference, can remove the residual timing errors. It is now possible to obtain commercially an instrumentation recorder which has a total gross time displacement error of ±25 nanoseconds (Ampex [1964]).

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CHAPTER 8

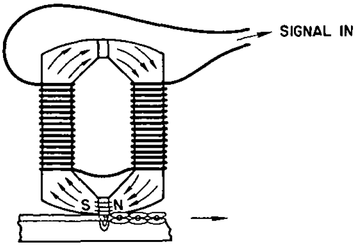
Tape Recorder Heads — Structure and Function

In the development of magnetic recording to its present state of art many geometrical arrangements of the remanent fields in the magnetic medium were tried. Early recorders used perpendicular magnetization, that is the field applied to the tape and the resultant remanent magnetization was normal to the surface of the tape; current recorders almost universally use longitudinal magnetization. Longitudinal magnetization, that is, magnetization parallel to the direction of tape movement, can be induced in the tape in several different ways. Each way induces a magnetic flux to leave one pole piece and to travel along the tape and enter another pole piece. In early trials pole pieces were sometimes located on opposite sides of the tape. At present all recorders use pole pieces on the same side of the tape.

HEAD TYPES

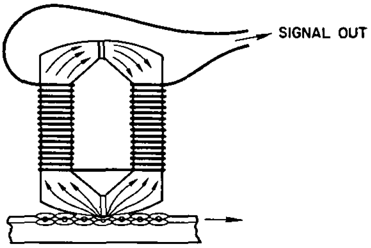
Two main types of reproduce heads and one type of record head are in current use. Essentially all heads use the fringing effect that occurs at a well-defined gap in a soft magnetic structure as the primary mechanism of inducing magnetomotive force into the tape or for extracting flux from the tape.

The form of record head in most common use is effectively a ring of soft magnetic material, interrupted by a narrow gap of nonmagnetic material, with windings placed somewhere around the circumference of the ring. When current is passed through the windings, most of the magnetomotive force produced in the magnetic circuit by the windings appears across the nonmagnetic gap and the fringing fields at this gap are relatively strong. These fringing fields are the means for producing a magnetomotive force in the tape (fig. 8–1). Although the foregoing states the principle on which such heads work, the current use of shorter gaps and the trend to recording higher and



(*from an Ampex Corp drawing*)

FIGURE 8–1.—Stylized representation of typical C-core recording head



(*from an Ampex Corp drawing*)

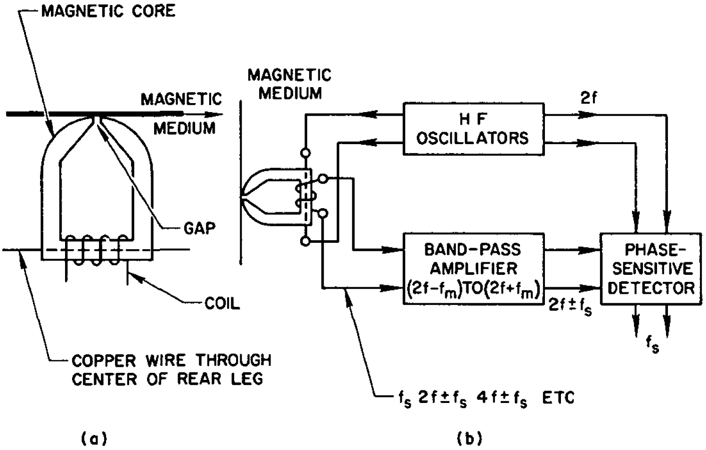
FIGURE 8–2.—Stylized representation of typical C-core "dϕ/dt" reproducing head

higher frequencies, for which the effective permeability of the magnetic material of the head may be low, invalidate the statement that most of the magnetomotive force appears across the gap. It is more accurate to say that a controlled amount of the total magnetomotive force appears across the gap (chapter 5).

The two basic kinds of reproduce heads are the so-called "dϕ/dt" and flux-sensitive heads. The dϕ/dt head is almost identical in construction to the record head just described and "obtains its information" about the flux in the magnetic tape by determining the voltage induced in the reproduce head winding as the flux intercepted by the gap and passed through the head changes with time (fig. 8–2). The output of such a head is effectively the time derivative of the flux intercepted. The remanent flux induced in the tape by the record head is almost linearly proportional to the record current. The overall transfer characteristic of a record/reproduce system using the dϕ/dt head is therefore differentiated. In a particular record/reproduce system, such differentiation may be a disadvantage or an advantage.

When the rate of movement of tape is extremely slow, the dϕ/dt output is correspondingly low. For such applications, heads of a different basic operating mode are often used. These are so-called flux-sensitive heads, of which there are two basic types. In one type, the flux intercepted by the head from the tape is introduced in the same magnetic circuit as the flux induced by an auxiliary signal applied to some auxiliary windings. A pickup winding detects changes induced in the auxiliary signal as the tape flux modifies the magnetic characteristics of the nonlinear magnetic circuit used. This is the so-called "modulator head" (fig. 8–3). A variation of this type is one in which the tape flux is caused to vary the reluctance of a magnetic path where the reluctance is externally measured by some method other than the carrier technique described.

The second type of flux-sensitive head employs the so-called "Hall effect." The Hall effect occurs when a steady current and a magnetic flux are applied orthogonally to a material exhibiting the Hall phenomenon. The Hall effect occurs in most of the common semiconductors, and is especially strong in gallium arsenide. The "Hall voltage" appears across electrodes orthogonal to the current and flux directions and is proportional to the product of the flux intensity and the steady current intensity. Although very simple and quite effective in many applications, Hall effect heads suffer from thermal sensitivity and many other complicating properties which have been discussed in the literature (Stein [1961a]).



(*after Daniel*)

FIGURE 8-3—A flux-sensitive reproducing head

(a) Mechanical schematic, (b) electronic schematic—a wave of frequency F is directed through the copper wire through the center of the magnetic core as shown at (a) and a wave of twice that frequency is delivered to the phase-sensitive detector—the signal frequency recorded on the tape causes the frequencies shown to be generated and in the phase-sensitive detector the signal frequency is recreated (Daniel [1955])

HEAD MATERIALS

A basic problem in the design of magnetic heads is achieving the required mixture of magnetic and mechanical properties. The head structure must be so fabricated as to form a precise gap in the magnetic pole materials, which must also form a smooth front surface for the tape to contact intimately. At the same time, the material so fabricated must have adequate magnetic susceptibility to provide control of the induced or driven flux.

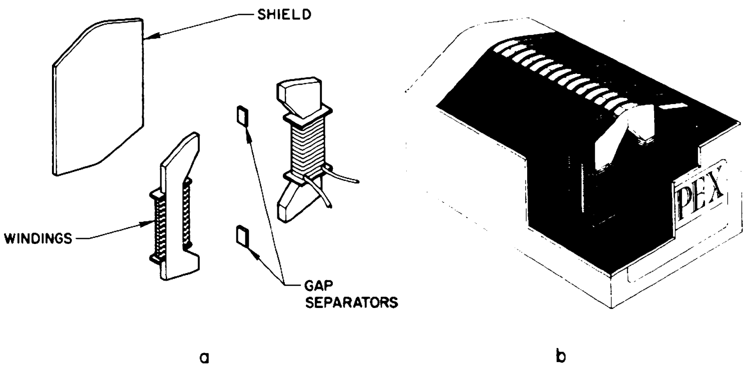
Classically, laminated soft high-permeability materials have been used for head structures (Permalloy, Hi-Mu 80, etc.). The polishing and forming of heads made of these materials is quite an art since it is inherently difficult to polish a very soft material. At the same time, those properties of the soft material which make it difficult to polish tend to make it wear rather rapidly. A class of magnetic materials was introduced in the 1950's which is somewhat harder mechanically while retaining many of the mechanical and magnetic properties desirable for heads (Alfenol, Silconol). These materials have almost displaced the earlier favorites in critical, long-life applications.

Many early attempts were made to use ferrite for recorder heads but most of them foundered on the peculiar mechanical properties of ferrite. Ferrites are extremely hard but are bad thermal conductors. At a fine edge, such as occurs at the gap in a magnetic head, considerable frictional heat may develop and, with the poor thermal properties of the heads, very high local temperatures may exist. Under these circumstances, ferrites tend to erode at the gap. Only recently has a technique involving the use of sintered glass bearing metallic salts, formed at high temperature in the gap between the two halves of a ferrite head, made it possible to produce working ferrite magnetic heads (Duinker [1960]) (Peloschek and Vrolijks [1964]) (Bakos [1964]).

The gap-forming material of magnetic heads must have rather special properties, particularly since gap lengths as short as tens of microinches are now common. Spacers for half-mil or quarter-mil gaps are usually made of some metal such as platinum which can be accurately rolled to a thin foil of controlled gauge. For very small gaps, materials such as silicon monoxide are evaporated in controlled layers onto the faces which meet at the gap.

HEAD STRUCTURE

Many different physical assembly techniques are used in the manufacture of modern recording heads. The mechanical and magnetic properties of the materials of the head and the physical conditions and dimensions required by the task to be performed determine the actual head structure. The head form currently most widely used is that made up of two halves, each assembled from sets of thin metal laminations of roughly the shape of the capital letter "C" (C-core head). These laminated assemblies are lapped on the tips of the arms of the C to an extremely smooth, fine finish, and are then joined together, usually with close contact between the mating faces at the back gap and with some sort of a gap-determining spacer at the front gap. Coils are usually wound on spool-like assemblies or directly on the C-cores themselves (fig. 8–4a). Where space or other problems do not permit this head structure, many variations are allowed. The video recording head is an example of such a variation. In this head, a ferrite of good high-frequency magnetic properties and of an almost-closed C form is used for the bulk of the magnetic circuit. On this core are wound the record/reproduce coils. Tightly pressed against this ferrite core are two extremely small Alfenol metal pole-tips which actually determine the gap and contact the tape (fig. 8–5). In the video recorder, the high-frequency losses in a complete Alfenol core structure would be too high, but since no ferrite head structure involving contact of the ferrite with the tape had been successful up to the time of introduction of the video recorder, the more dependable Alfenol metal was used for tape contact. The amount of Alfenol is minimized to reduce the high-frequency losses in this part of the magnetic circuit.



(*drawing courtesy Ampex Corp.*)

FIGURE 8–4.—Typical multitrack head elements and assembly: (a) elements, (b) assembly.

Conventional recording heads and $d\phi/dt$ reproduce heads are almost identical in construction. Reproduce heads usually have much smaller gaps than record heads and there are differences in the windings on the core structure for the two types. For each head application there is an optimum number of turns and size of wire for the winding.

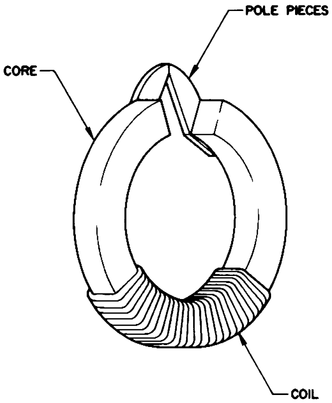


FIGURE 8-5.—Stylized rendering of the elements of a video recording head (see text).

For a record head the wire is usually heavier and the winding is designed to induce as many ampere-turns in the head as possible with the recording amplifier available. In the corresponding reproduce heads, the wire may be finer and more turns may be desirable to obtain as much induced voltage as possible, but the winding is also optimized for the reproduce amplifier chosen (chapter 10). For multitrack record heads the winding size required may lead to serious space problems.

Cross-talk between the tracks of a multitrack head poses a continual problem. In recording, there is, of course, simple transformer action between the adjacent magnetic structures with their windings. The bodies of the heads themselves may be shielded from each other but the fringing flux at the gap may result in a transfer between adjacent cores which resembles transformer action. This may be influenced by the presence of the magnetic material of the tape as it moves past the head. For the reproduce head, there is, of course, also transformer pickup, but because of sensitivity of the head, it is also possible for one track to pick up the signal directly from the adjacent track. The flux source in this case is in the track rather than in the core structure. In pulse recording there is relatively little flux available in an adjacent track from the record current in a given track, but in carrier or FM recording, where there is always a large signal present in every track, a small cross-talk flux can produce a detectable recording (Davies [1961]). On reproduction, the transformer action cross-talk is usually limited to relatively high frequencies since these are the hardest to shield. Adjacent-track flux pickup in the reproducing process is usually limited to long-wavelength and hence low-frequency signals. An array of pole tips and gaps in a multitrack head is a fairly sophisticated magnetic structure and quite unusual means are sometimes needed to provide adequate shielding between tracks at the pole tips, both for record and reproduce (fig. 8–4b).

Because flux-sensitive heads are used in specialized applications, their construction is likewise specialized. Modulator and variable-reluctance heads may resemble conventional dϕ/dt heads quite closely except for extra windings and additional applied magnetic circuits.

The Hall-effect head can take basically two forms. In one of these, the Hall materially itself is placed in close contact with the tape. The Hall material itself is not magnetic and, as a result, it is unable to resolve finely the detailed structure of short-wavelength recordings. Two methods are currently used to improve the resolution of the Hall effect head. One of these is to surround the head material itself with a magnetic structure of some sort and to make the Hall material extremely thin (fig. 8–6). If the magnetic material is a typical recording-head metal, this method works fairly well. There has been interest in using the Hall material for extremely high-frequency reproduce heads, since the Hall effect is essentially independent of frequency. In order to accomplish this high-frequency application, it is necessary to use ferritic materials as the defining magnetic structure, and the wear limitations of ferrites limit the use of this technique.

The more commonly used method of defining the reproduced area for the Hall effect head is to place it in the back gap of a conventional C-core reproduce head. This leads to all the typical difficulties of the standard reproduce head, including high-frequency losses in the

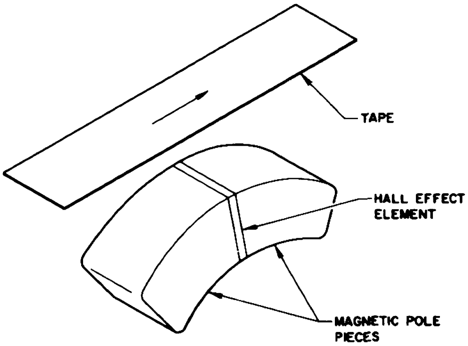


FIGURE 8–6.—A Hall-effect reproducing head with pole pieces to increase resolution.

head metal itself, but it does give as good resolution as a conventional head. At the same time the head is flux sensitive and can be used at an extremely low tape speed (fig. 8–7).

The front surface of any magnetic head must be extremely smooth. This is essential for good head-tape contact, and for low head and tape wear. Since the typical recording head material is mechanically soft, it is difficult to produce a very high finish on such a surface. Since this soft material carries a very small gap which must be clearly defined, the process of polishing the head metal must avoid "smearing" the gap. The head lapping process is thus often a magnetic head manufacturer's most closely guarded secret. Most manufacturers have, by now, managed to work out individual processes which produce reasonably uniform results.

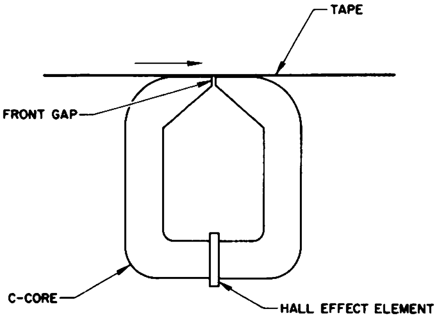
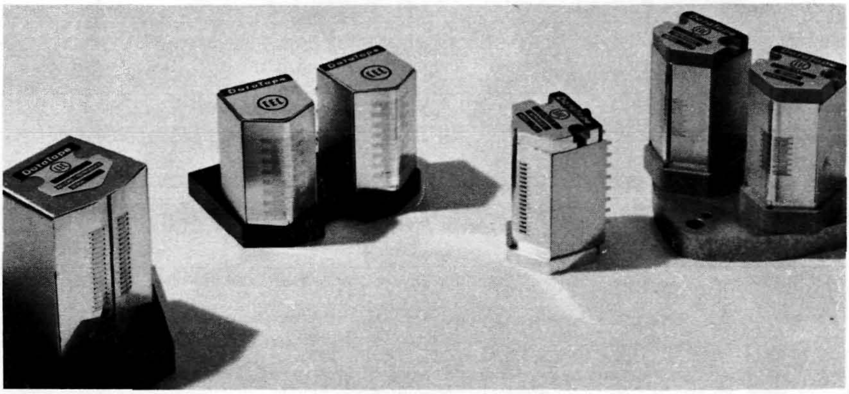


FIGURE 8–7.—A "back-gap" Hall-effect head.

The magnetic head is, however, not all gap and pole pieces. Except in the simplest application where a full width track is recorded on the tape the actual operating magnetic head is surrounded by an inactive surface against which the tape bears. One way of dealing with this surface is to eliminate it (fig. 8–8). That is, the individual heads of a multitrack structure are allowed to project from the supporting mechanism and the tape is permitted to bear against the pole pieces only. An alternate approach is to fill all the spaces between the poles with plastic, and the so-called "all-metal head" has also come into use recently. The all-metal head is arranged so that the active magnetic pole pieces are surrounded, except for microscopic gaps, by a uniform metal surface against which the tape bears. Figure 8–9 shows representative examples of heads employing these different constructions.

(*photo courtesy Ampex Corp.*)

FIGURE 8-8.—Typical multitrack heads with relief between pole pieces.



(*photo courtesy Consolidated Electrodynamics Corp.*)

FIGURE 8-9.—Typical metal-faced heads.

On right and left of center, narrow- and wide-tape interleaved head stacks and, on left, a digital read/write head combination.

In these complex head structures, nonuniform wear of the various head elements can result in excessive overall head wear, excessive loss of tape-head contact and excessive tape wear. Head wear is further involved in maintaining head cleanliness and the corresponding relationship between maintenance and reliable head and tape life. This is discussed further in chapter 5, but one factor should be emphasized here as a complication of the entire question of head structure. This factor is the change in the cross section of the gap in the head as the head wears and the corresponding change in the fraction of the available flux that appears across the gap. The degree to which the gap is an interruption in the low-reluctance flux path is therefore dependent on the amount of head wear. The cross section of the gap also affects the eddy current and hysteresis losses that take place in the head at high frequencies. It is therefore important in head design to determine how head wear and gap performance must be balanced. As much as any other consideration this is the reason for the continuing search for better magnetic and gap materials for magnetic heads.

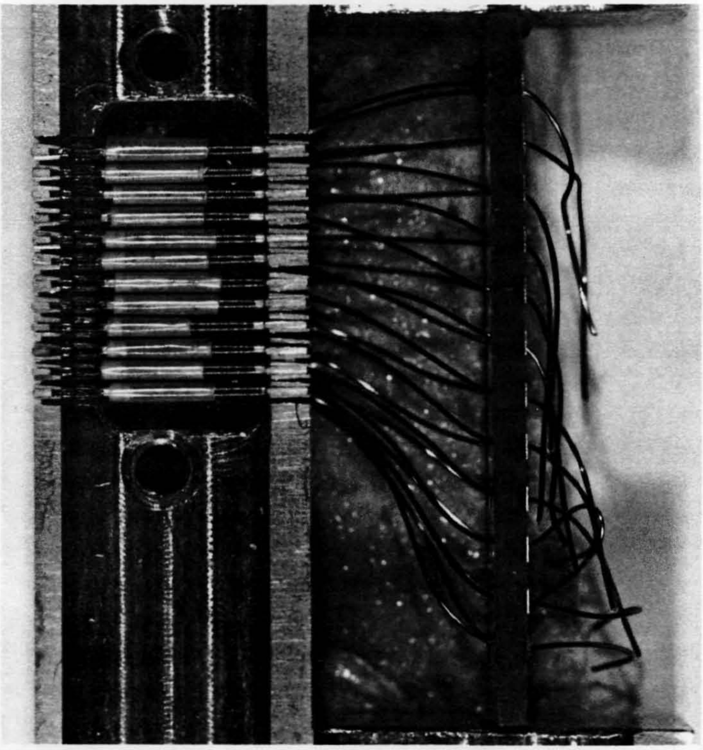
The tape recorder head defines the record and reproduce point on the tape with great precision in the direction in which the tape is moving. In the direction at right angles to this, across the tape, the head defines the recording location with considerably less precision. The head width, which varies from about 10 thousandths of an inch to 30 or 50 in most high-performance recorders, effectively determines the lateral resolution of the data on the tape. The contrast is marked between 12,500 cycles per inch along the direction of tape motion and 14 or perhaps 32 tracks per inch across the width of the tape. The low lateral density is often cited as an argument for trying some other method of recording than magnetic for a particular application. The argument holds, for example, that optical systems are able to focus an image point in two dimensions whereas magnetic recording seems limited to detailed focusing in one dimension only.

There have been many attempts to increase the number of tracks per inch across the tape with a view to using the tape surface more efficiently for storage. There are theoretical limits to how narrow a track can be used but these limits are seldom approached in any practical head. There is therefore considerable justification for attempting to increase the lateral track density.

A specific investigation of what can be done by straightforward methods to increase the track density was undertaken in 1964 by Jet Propulsion Laboratory (Clement [1964]). The investigation so far has concerned itself with determining the performance obtainable using commercial techniques to provide a large number of tracks per inch. The first successful experimental heads built under this program are shown in figures 8–10 and 8–11. Twelve tracks are fitted in this head onto quarter-inch tape which, when interleaved, would produce 24 tracks per quarter inch or 96 tracks per inch. Each track is 0.006 inch wide and the track-to-track pitch is 0.020 inch.

(*photo courtesy Jet Propulsion Laboratory*)

FIGURE 8–10.—A 24-track interleaved head combination for ¼-inch tape, general view, showing guides closely adjacent (see text).



(*photo courtesy Jet Propulsion Laboratory*)

FIGURE 8–11.—Cutaway view of one 12-track unit of the heads of figure 8–10.

When head elements are spaced this closely, interaction between heads becomes a severe problem as does the physical task of fitting the large number of coils and windings into the small space available. The results so far of the investigation show that at this track density reasonable cross-talk values (down 34 db) can be obtained for pulse recording, presumably at about 1,500 bits per lineal inch. The results show promise that the final goal of the program, which is to record at 100 tracks per inch at a density of 10,000 bits per lineal inch, may well be achieved.

HEAD PRECISION

The physical construction of individual heads varies from application to application and manufacturer to manufacturer. Although the general principles are the same, different manufacturers succeed to a different degree in providing adequate precision and rigidity. As mentioned above, the typical C–core head is fabricated by lapping the pole tips of the two "C's" to an optical finish and placing them together with a gap spacer in the form either of a shim or an evaporated coating.

In the multitrack head it is essential that all the gap planes align with each other. A typical "gap scatter" specification, that is, for the total distance between the extremes of the center lines of the gaps relative to the nominal common center, is a total of 100 microinches. The center lines of all the gaps in a multitrack head should thus be included between two parallel lines 100 microinches apart. Great precision is obviously required in head manufacture and, as mentioned in chapter 6, it is important that the head be aligned accurately with the rest of the mechanism.

At one time, most heads were mounted by potting them in plastic; this is still the practice for most audio heads. However, a gap-scatter tolerance as tight as that given above is easily exceeded if a head made of any conventional plastic is subjected to external forces—it will simply bend. Therefore ceramic and metal stiffening structures are included in modern heads. At present, heads are widely available which meet the gap scatter and other precision requirements of instrumentation recorders. However, meeting these mechanical requirements and at the same time maintaining the electrical and magnetic properties of the head is not yet under complete manufacturing control. The manufacturer can invariably make heads which meet all the specifications, but his yield of such heads is low. The sometimes extraordinary cost of precision multitrack heads is primarily the result of this situation.

ERASE HEADS

The heads on which this chapter has concentrated are those which record and reproduce the signal. It is usually necessary to perform also the function of erasure of the tape. This is particularly important in audio recording but the erase function is often omitted in the instrumentation recorder. It is generally considered somewhat more satisfactory to erase instrumentation in bulk by passing it through a saturating ac magnetic field which is slowly reduced to zero and thereby leaves the tape in an essentially unmagnetized condition. In pulse recording, the recording current usually saturates the tape and no erasure is needed because the previous tape history has only a minor effect on the record left on the tape by a saturating signal. Only in direct analog or FM recording is the erase function significant to the recording tasks covered in this survey. For example, in the OGO and Nimbus satellite recorders described in chapter 13 a special three-stage permanent-magnet erase head performs the erase function without the use of any power. This is accomplished by passing the tape past three successive permanent magnets, one of which is intended to saturate it in one direction and another to demagnetize it and to magnetize it slightly in the other direction. The third magnet is so arranged that as the tape passes, its field, combined with the field of the next proceeding magnet, subjects the tape to a net field which decreases gradually to zero. In this way essentially complete demagnetization of the tape is provided without using any power. The erase function as normally performed by applying a strong high-frequency current to a head requires large amounts of power since erasure cannot be guaranteed unless the initial record magnetomotive force is adequate to saturate the tape.

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CHAPTER 9

Magnetic Tape

The first magnetic recording media were flat steel bands and much work was done on improving the properties of the magnetic material from which the bands were produced. Just before World War II, plastic tape employing a dispersed magnetic powder as the storage material became available. Some of the early powder tapes contained integral magnetic material, that is, the tape was a homogeneous mixture of plastic binder and magnetic particles. This tape introduced a whole new series of recording parameters, but suffered from the inseparability of mechanical and magnetic properties. To give the tape reasonable strength it had to have a certain minimum thickness. Although in the early days, the importance to the recording process of the thickness of the magnetic layer was not fully understood, it was realized that the thick tape required for adequate strength did not work too well.

Modern magnetic tape began with the introduction of a plastic film base on which a dispersed magnetic particle mixture was coated. This type of tape has undergone continuous refinement since its introduction. A steady improvement has been seen in many parameters such as, for example, an increase in the shortest wavelength which can be recorded. The improvement in audio short wavelength performance, which is now, of course, even more important for scientific recording, has resulted from improvements in several aspects of tape structure. The surface smoothness and the uniformity of dispersion of the magnetic particles has been improved, and both of these factors affect the signal-to-noise ratio. Better oxides have provided adequate performance with thinner coatings and permit tighter packing of information. Perhaps more important than anything else, the uniformity of tape has steadily been improved.

The properties most desirable in magnetic recording tape for scientific use may be summarized as follows

1. The tape must reproduce a signal of adequate amplitude and signal-to-noise ratio.
2. The tape must be capable of packing information at as high a density as possible.
3. The output of the tape must have short term and long term uniformity.
4. The tape must be physically durable, with one set of standards for normal environments and another set for severe environments.
5. The tape must be compatible with the mass of tape already in use on the basis of which most recorders have been designed.

Optimization of the above characteristics are important for NASA's space and other research programs as well as for the applications of almost all tape users in the scientific field. The specific characteristics of magnetic tape which affect the above performance parameters will be briefly discussed.

MAGNETIC PROPERTIES OF TAPE

The first five pages of chapter 5 of "Physics of Magnetic Recording" by C. D. Mee give an excellent brief summary of the significant magnetic criteria and properties of magnetic tapes (Mee [1964]). In this brief section, Mee makes a synthesis of all the important magnetic properties in the clearest terms and it would be inappropriate to attempt to improve on his analysis. It is appropriate to note, however, that his brief introduction is the opening section of a 96-page chapter on a detailed analysis of the properties of magnetic tape. In the material which follows here, the magnetic properties of tape will be discussed only to the extent that they interact with the other properties of tape.

Since the introduction of coated-plastic tape, the magnetic medium used has almost invariably been some form of iron oxide. The early recording oxides differed little from those occurring in nature. They were basically of cubic structure, with little shape anisotrophy; the net coercivity was quite low and the remanent magnetization was little more than half the saturation magnetization. Low coercivity usually means relatively poor packing density on the tape and a low remanent-to-saturation ratio means low output. Later, it became possible to produce and control acicular or needle-like magnetic particles with higher coercivities and better remanent ratios (~ 0.8). Since then, the refinement of acicular particles has resulted in a steady increase in practical packing density.

Gamma ferric iron oxide has been the workhorse material for magnetic tape for fifteen years. Variations in production of this oxide have resulted in some differences in shape and some slight changes in magnetic characteristics. One manufacturer is said to have tried one thousand different ferritic materials without succeeding in turning up one magnetic material which was clearly superior to gamma ferric iron oxide as a magnetic recording medium. Cubic particles of coercivity and other properties comparable to those of the acicular particles have been developed by "doping" the basic gamma ferric iron oxide with cobalt. The lower shape anisotrophy along with the tendency to instability usually associated with cobalt ferrites appears to produce the unfortunate effect of making short-wavelength recorded material subject to thermal and mechanical erasure. However, if the same net remanent magnetization can be obtained with smaller particles, a better signal-to-noise ratio results because there are more particles per signal sample than with conventional oxides.

One oxide material other than the familiar gamma ferric iron oxide has shown some signs of becoming a useful magnetic material. This is chromium dioxide, which is now being examined by both American and European manufacturers for tape use. At present, its manufacture is more accurately controlled but much more involved than the slight variation on paint pigment manufacture which has been used for iron oxide production in the past. It is, therefore, a more predictable but more expensive material than iron oxide.

At least one Japanese manufacturer has used a magnetic metal powder in place of the oxide and others have tried similar variations on a small scale.

It is probable that metallic coatings may shortly begin to play an important part in the magnetic tape field. By a metallic coating is meant a more or less monolithic sheet of metal with magnetic properties, plated or otherwise fastened to a plastic base. Cobalt-nickel plated on beryllium copper has been used by Univac in computer tape transports in the interest of ruggedness. Thin, high-coercivity, uniform magnetic platings on plastic bases may, however, become quite important in the near future as several manufacturers have demonstrated considerable interest and effort in developing such tapes.

Several tape manufacturers have brought out high-resolution wideband tapes within the last few years. These tapes have thinner coatings than those typical 5 years ago and yet have approximately the same output signal level on conventional recorders. The exact basis of the improvement achieved is a manufacturing secret. The 1.5 megacycle, 120 inch-per-second recorder would not exist, however, were these tapes not available, since marginal performance is obtained from such recorders when using the best high-resolution tapes of 5 years ago. Similarly, other properties of tapes have occasionally been optimized for a particular application. At the time the 3M Company introduced a line of tape recorders and prerecorded tapes which provided a 15 kcps bandwidth at 1⅞ inches per second (8,000 cycles per inch), it was quite apparent that the success of this new process was in great part due to a lower noise tape (Goldmark et al. [1960]). Since that time this tape has been described in the literature but its use for audio frequencies has been emphasized (von Behren [1963]). Other manufacturers have brought out, however, what they describe as lower noise tape. It is expected that gradual improvement in tape noise will be made during the next few years. Newer oxides may be coming into use, since a better signal-to-noise ratio would imply that a larger number of particles were being used.

TAPE BASE MATERIALS

Current magnetic tape has a base of some acetate plastic or of one of the polyesters. Acetate is limited at present almost entirely to home audio use, since it has inferior mechanical properties. Polyesters, of which DuPont Mylar is certainly the most widely used, are employed for the tape base in a wide range of thicknesses, depending on the relative importance of mechanical strength or of compactness of storage. For severe environments, special treatments are given the tape base to enable it to withstand mechanical and thermal stresses. One treatment involves passing the tape through a thermal cycle at the same time that it is being stretched slightly, mechanically. Such tape has been popularly called "Sanforized" tape.

To withstand such temperatures as are involved in a sterilization process for interplanetary probes, the tape must not be seriously effected by being retained at a temperature of 145° Centigrade (295° Fahrenheit) for 36 hours. At these temperatures the polyesters have a tendency to "block." Blocking is a rather graphic way of saying that a roll of tape after passing through a temperature cycle no longer resembles a roll made out of a wound-up strip but rather a solid cylindrical block of somewhat the same shape as a hockey puck. Part of the blocking is caused by increased adhesion by the binder from layer to layer but the basic problem is that the polyester tape base tends to change properties at these temperatures. The only material currently available which shows promise of replacing the polyesters as a tape base is H-film, a new material manufactured by DuPont. H-film is described as a polyimide and has recently been renamed Kapton. Its properties closely resemble those of the polyesters but it is able to withstand considerably higher temperatures. H-film tape has successfully withstood such sterilization temperatures. The limitation to the use of H-film at present appears to be that it is still classed as an experimental product and mass production facilities are only now being completed. It was expected to be available in quantity in 1965.

TAPE BINDERS

The oxide is dispersed as completely as possible in a plastic binder. Until about 1960, most tape binders were polyvinyl plastics like "Saran," and were fully thermoplastic. Recent development effort has resulted in the availability of binders able to produce smoother surfaces, to maintain a better dispersion of the oxide particles, and to withstand the thermal stress of tape use better. Tape wear is largely dependent on the interaction between the binder and the oxide in the final tape coating. Since the oxide is a poor thermal conductor, much local heat is often generated in the tape and cannot be conducted away. Tape wear often results from this localized heating. At the tape speeds involved in rotary-head recording, which may reach 1,500 inches per second, the thermal characteristics of the binder are particularly important. Only recently has more than one manufacturer been able to produce a tape adequate for rotary-head recorder service.

Many current binders for high-performance tape appear to be related to the polyurethanes. The chemistry of these binders is such that almost the full range from completely thermoplastic to almost completely thermosetting can be covered with basically the same type of material by changing the number of crosslinkages developed between molecules in the polymerization process. Because the binder deterioration which occurs in high-temperature sterilization differs from that which occurs when the heat is generated from local friction as in the rotary-head recorder, the higher-temperature binders developed primarily for high-speed recording are not necessarily successful with high-temperature sterilization.

One company has recently announced a 600°(F) tape (Parkinson [1965]). This tape is understood to have a metallic magnetic coating deposited on a nonmagnetic stainless-steel base. A tape usable at such high temperatures is, of course, attractive for use on board a spacecraft that must be sterilized. However, the metallic base may be expected to give the tape handling properties sufficiently different from those of plastic-base tapes as to require fundamental changes in the mechanical design of the recorder. The difficulty of accommodating such changes in the carefully-balanced designs of flight recorders may slow the acceptance of this tape for this service.

Since head-to-tape spacing is all important in high-density and high-performance recording, the physical smoothness of the tape surface is an important parameter. In this area, as much as in any other, tremendous strides have been made in the last few years.

TAPE MANUFACTURING PROCEDURES

No matter how good the properties of the magnetic material, the base material and the binder of the magnetic tape, the way in which it is constructed determines whether it is a satisfactory tape or not. Tape properties which are dependent on the method of construction include uniformity of output, "ac" signal-to-noise ratio, dc and modulation noise and number of drop-outs. The uniformity of thickness of the coating as well as the uniformity of the properties of the magnetic materials obviously affects the uniformity of output of the tape. If there are holes in the coating, or if nodules appear in the finish, tape drop-outs are produced. Drop-outs are temporary sharp reductions in signal level occurring when magnetic material is missing locally on part of the tape or a nodule lifts the tape away from the transducer.

Until recently most tape was coated with a knife-coater in which a rigid smooth blade, wiping across the top of the wet coating material at a fixed distance from the base, determined the amount of coating material placed on the tape. To improve the uniformity of application of the coating for specialized applications, gravure coating has been introduced. In gravure coating, a thin uniform layer of coating material on a smooth roller is transferred onto the base material in a manner analogous to gravure printing. The uniformity of the layer on the coating roll may be established either by having it run at a very precise distance from a supply roll or by actually forming either the supply roll or the coating roll with an incised pattern similar to that of rotogravure. This incised pattern becomes filled with the coating which is then wiped off of the surface of the roll with a blade similar to that used for knife coating. The amount of material left in the incised pattern is very precisely determined by the depth of the pattern and when the roller is brought in contact with another surface the wet coating material is lifted out of the pattern. This elaborate procedure is sometimes used to guarantee that a perfectly uniform coating is produced.

The number of drop-outs produced in the tape is almost entirely dependent on the cleanliness of the tape coating operation. The handling of the coating material and the base material and the wet tape must proceed under essentially "white room" conditions in order to guarantee few drop-outs. In the production of computer tape, where drop-outs are crucially important, 100 percent inspection of the tape is the only current method of guaranteeing that a tape will be free of drop-outs. For space applications and for crucial telemetry recording, drop-outs may be just as important as they are in computer application, and tape inspection is used to guarantee absence of drop-outs.

The signal-to-noise ratio of a tape recorder is usually measured by recording as intense a signal as can be reproduced with a given maximum amount of distortion, noting the level of this signal, and then noting the level of the residual tape noise when the signal has been turned off. This could be called the "ac" signal-to-noise ratio and is largely dependent in a magnetic tape on the number of particles in the coating. That is, if a given output signal which, in effect, means level of remanent magnetization, can be obtained with either a large or a small number of magnetic particles per unit volume in the tape, the tape with the larger number of particles will have the better signal-to-noise ratio. Another important noise source in tape is that which is called "modulation noise." This is a noise which appears to "ride with the signal" and to increase with the intensity of the reproduced signal. It is essentially a modulation of the desired signal by noise. It broadens the spectrum of the signal and limits the utility of tape recorders for many applications. It appears that modulation noise is not dependent so much on the number of elementary magnetic particles as on the number of particle clumps. It is therefore a basic problem of tape manufacture that the coating material, when it is placed wet on the tape, be constituted of magnetic particles which have been allowed as little as possible to clump into small aggregates. This is spoken of as having a good dispersion. No matter how good the dispersion at the moment of application, if particle clumping increases as the coating dries, the final dispersion will not be good. Obtaining and maintaining a good dispersion is a manufacturing procedure essential to low modulation noise in a tape. So-called "dc noise" is actually the low frequency component of modulation noise. This is the noise which is observed when the tape is slightly magnetized and then reproduced. Dc noise, as a special case of modulation noise, is important in certain nonlinear recording processes (Eldridge [1963]) (Daniel [1963]).

The density capability of the magnetic tape is dependent on the particle dispersion and the coercivity of the particles as well as other magnetic properties, but it also depends heavily on the smoothness of the tape surface. In the chapter on "Head-Tape Interaction" the importance of a close approach of the magnetic material to the head for good short-wavelength response, and hence, for high-density recording, is emphasized. The quality of the surface finish depends on a very large number of manufacturing factors. The short wavelength performance of the tape is therefore almost entirely dependent on the way in which the surface quality is established in manufacture.

It is currently a practice in tape manufacture to subject the tape to a strong magnetic field while its binder is still wet. The purpose of this field is to produce a partial magnetic orientation of the particles of the surface. The effect of this orientation is to increase slightly the peak signal amplitude available for recording with fields oriented along the preferred direction. It is usually observed that measuring an oriented tape along the preferred direction will give about a 6 db signal improvement over the other direction. (This is actually only a 3 db improvement over an unoriented tape.) The advantages of orientation are considered to outweigh the disadvantages of the occasional application where the available tape is orientated the wrong way. For example, 2-inch-wide tape designed for a special longitudinal instrumentation recorder would not work very well in a rotary-head recorder where the head path is at right angles to the long axis of the tape.

OTHER TAPE PROPERTIES

Physical durability of tape is dependent, again, on the mixture of many different factors. The loss of oxide from the surface under tape wear may be related to poor thermal properties of the binder or to improper relationship of binder to oxide volume. Actual shedding of flakes of magnetic material from the tape may come from other forms of binder failure. As with most other aspects of tape manufacturing detail, the way in which the manufacturer provides for frictional durability of his tape is usually a proprietary process.

The ability of the tape to withstand jerks or accelerations depends simply on the mechanical properties of the base material. The choice here is quite limited since one of the polyesters will almost invariably be used in any high-performance application.

As Mee points out in his summary of the properties of tape referred to earlier, good contact between head and tape requires that the tape be quite limp. Combining limpness with strength can be difficult, and it is remarkable that current tape bases perform as well as they do in this respect. Tape base materials that have desirable mechanical properties for a severe environment often can not be used because they do not conform well enough to the contour of the head. The use of metallic tape bases, for example, has been inhibited by their inherent stiffness.

In order to improve the wear life of tape used in computer transports a type of tape called "sandwich tape" was introduced some years ago. At the price of spacing the tape a certain distance away from the transducer a protective coating was placed over the active surface to minimize wear on the surface. For the relatively low-density recordings of conservative computer applications, this appears to be a very successful mechanism. It has been suggested that the same kind of construction might be useful in certain high-environment tape applications for space and other experimental use where the losses inherent in the separation caused by the protective layer would be more than compensated by protective properties that could be put into the layer.

When tape is tightly wound up onto a reel the magnetic coatings of adjacent tape layers are brought quite close together, being separated only by the relatively thin base material Where extra-thin base has been used to permit recording more information on a reel, the approach of the two magnetic materials may be extremely close. Under these conditions there is a tendency for intense signals recorded on one layer of tape to imprint weak copy signals onto an adjacent layer. If the adjacent layer happens to have a very small signal recorded at the point of printing, the printed signal is clearly apparent as a spurious element. In audio recording where the signal-to-noise ratio may approach 65 to 70 db, the presence of a very weak printed signal can be quite annoying. For instrumentation recording, the problem is not as serious because the signal-to-noise ratio seldom is as great as it is for an audio recorder and the printed signal is easily lost in the noise. However, there is at least one circumstance under which "print through" may become a problem.

For some applications, double-coated tape has been used to provide additional recording time. For example, the inertia-compensated recorder discussed in chapter 13 uses a so-called "Moebius strip" tape loop to give twice the playing time of a single-sided tape. With coating on both sides, there is no separation between adjacent magnetic layers and the printing may become severe.

Printing has been investigated not only because it is an annoying problem in audio recording but because it gives insight into some of the fundamental processes governing tape action. An elementary theory of print action says that since there is a distribution of coercivities in the particles of the tape, the high coercivity particles are able to magnetize some of the low coercivity particles in an adjacent tape layer. A technique for reducing the print-through, successfully used in audio recording, involves passing the tape through an extremely weak erasing field. This removes much of the printing without removing the desired signal. The implication of the success of this technique is that there are some low-coercivity particles which can be erased with this weak field, but the bulk of the particles have high enough coercivity so that they are not disturbed by the field.

Print-through appears fundamentally to stem from the same factors which lead to thermal instability of tape. It may be considered to be under control as far as most instrumentation tape applications are concerned except for the limited one of double-sided tape. For such extreme applications, however, pulse recording is usually used and the weak printing action is not very effective in disturbing the data on the adjacent layer.

SPECIAL TAPES

For ground-based recorders the tape used by NASA, as by other customers, must have proper mechanical and magnetic properties for the particular recorder application and be extremely consistent from reel-to-reel and within the individual reel. There are no special requirements for ground-based recorder tape beyond meeting the above specifications at a commercial level.

When the tape is used in a flight recorder, however, the properties of the tape become extremely important and are often quite difficult to achieve. It has been very difficult for NASA as well as for other government agencies to obtain tape for many specialized requirements. This is because tape is best manufactured in a massive continuous process. The tape manufacturing companies who are best equipped to do specialized work, i.e., those who deal best with the detailed properties of conventional tapes and have them well under control, are relatively large organizations. For the extremely small market represented by, say, the flight recorder field, it is not economically and physically feasible for these manufacturers to do the amount of complex development needed to meet the special requirements. There is therefore little incentive for these manufacturers to divert their efforts to flight recorder tape. Lacking the assistance of such manufacturers, the complex nature of the tape problem has prevented NASA from making a major internal investigation of the subject. In this region of tape properties as much as in almost any other, extensive improvement will be required shortly if the flight recorder art is to continue to advance. Some of the specialized tape needs of flight recorders are noted below.

A property of magnetic tapes which is of particular importance for the flight recorder is the lubrication of the tape surface. Lubrication is of critical importance in endless-loop tape machines where almost any configuration requires continuous slippage of one layer of tape past the other in the tape storage device. No completely satisfactory solution has yet been developed for providing adequate lubrication for such loop operation, although graphite applied to the tape surface has been extensively used.

Another important semimechanical property of magnetic tape is its surface conductivity. Since tape is primarily used in devices which cause it to rub against surfaces, it is quite possible, with both the base and coating being insulating materials, to generate a considerable static charge. Computer-type tape transports in perfect mechanical order have been caused to fail catastrophically by the severity of the attractive forces created by such static charges.

Clearly, in an endless-loop satellite flight recorder, any tendency to build up static charge, with its consequent tightening of the pressure between the layers of the tape loop, could likewise produce a catastrophic effect. Therefore essentially every tape used for severe application has its surface conductivity artificially increased by application of a surface coating or by incorporation of a conducting material into the binder.

At one time a major commercial barrier to improvement in tape characteristics was compatibility. Many thousands of tape recorders presently in use in science and industry have inbuilt limitations on available record signal current and bias current. If a tape manufacturer were to introduce tape which provided great improvements in signal-to-noise ratio or short wavelength response he would encounter considerable resistance from the owners of such tape recorders if the new tape required that, say, twice as much bias and four times the record current be used. Admittedly, such a change in recorder characteristics would be disastrous in the home entertainment field. However, in the instrumentation field any development which offers real performance improvement would, although it might encounter resistance, eventually force the recorder manufacturers to move along with the requirements of the new medium. It may well be that reluctance to use tapes with incompatible properties is gradually disappearing. It is in any case almost becoming academic because many modern recorders have been so designed as to have considerably greater capabilities than are exhausted by present day tape.

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CHAPTER 10

Recorder Electronics

Although the tape recorders considered in this survey are always associated with complex electronic data handling systems, the actual electronic elements of the recorders themselves are neither complex nor unusual by modern standards. Compared to the difficult mechanical problems that have had to be solved to provide superior tape moving performance in the recorder and the chemical process refinement needed to produce superior recording media, relatively little electronics sophistication has been required in reaching current recorder performance levels.

Electronic elements appear at two points within the recorder proper: in the paths of the data signals between the input of the recorder and the output of the reproducer, and as elements of mechano-electrical systems controlling tape motion. Within the signal path, the primary electronic problems relate to dynamic range. In recorder electro-mechanical systems, the requirements laid on the electronic elements are quite conventional. The real problems in mixed systems lie in the areas of mechanical elements and electro-mechanical transducers rather than in electronics.

SIGNAL ELECTRONICS-DYNAMIC RANGE

The noise in the output of a magnetic reproducer originates in the electronics of the reproducer as well as in the tape itself. In the present state of the art, the design of a reproducer input circuit with noise low enough so that the system noise originates primarily in the tape is difficult (Skov [1964]). The difficulty lies primarily in the smallness of the signal available. At the low-frequency end of the useful recorder spectrum a typical reproducer head produces a small signal because the low frequency means a slow rate of change of the flux. At the high end of the frequency range, the shortness of the wavelength on the tape results in relatively little flux being available to generate voltage in the playback head.

When a head of a given design produces a given signal when reproducing a particular prerecorded test tape, increasing the number of turns on the head increases the output voltage from the head. All other things being equal, increasing the number of turns would also increase the inductance and the stray capacity of the head. The stray capacity added to the input amplifier capacity would cause a falling off of response for high-frequency signals, and beyond the frequency at which the inductance and the combined capacity resonated, response would fall off catastrophically. A balance between high-frequency response or, in practical terms, bandwidth, and low-frequency signal must therefore be made. For good high-frequency response, the head gap must be made very small because of the short wavelength of the signal on the tape. The low reluctance of the narrow gap tends to shunt some of the flux from the tape which would otherwise be available to pass through the windings of the head and help produce its output voltage. Reducing the gap depth decreases this shunting but gives the head a very short wear life. The interaction between these factors gives the electronics designer less output signal from the head than he would want if he were free of these design limitations.

In tube-equipped playback amplifiers, which were almost universal until fairly recently, the designer's primary interest was in the maximum possible induced voltage in the head windings. With the current almost universal application of transistors, the situation is somewhat different Not being an open circuit device the connection of the transistor to the reproduce head involves optimizing the power transfer into the transistor impedance. At the same time, the relatively unusual internal noise mechanism of the transistor results in minimum-noise operation being obtained for some particular source impedance (in this case, head impedance).

The primary noise sources in the input circuit of a tape reproducer are the thermal agitation noise in the reproduce head and other elements in the input circuit, and shot and so-called "1/f" noise in the input tube or transistor. Each of these noises has its individual peculiarities and the sum of all of them determines the overall system noise base.

The inductive reproduce head has an output impedance which rises with increasing frequency up to the frequency at which the self inductance of the head and the stray capacity of the winding and attached circuits resonate. Above this frequency the impedance of the head will fall rapidly as viewed from its output wiring. The usual design procedure involves placing the resonant frequency near or above the upper frequency which is to be reproduced. (For extreme bandwidths and certain other conditions, other arrangements may be used.)

Although primarily inductive the impedance of the head does have a resistive element, part of which is the ohmic resistance of the winding wires and part of which represents losses in the magnetic structure. The thermal agitation noise produced in the head therefore has a spectrum which corresponds to the resistive element of the equivalent parallel head impedance.

In vacuum tubes, much of the noise derives from the particulate nature of the electron stream. This includes partition noise, induced grid noise, and others, but that of greatest importance is usually described as "shot" noise and has a fairly uniform spectrum. Vacuum tubes also have flicker noise, so-called primarily because it is mainly apparent at low frequencies. It has the same 1/f (power) spectrum characteristic of the so-called "1/f noise" of transistors. These two phenomena are essentially identical but the 1/f noise usually appears at such a low frequency in vacuum tubes that it is often ignored. With semiconductor devices, particularly earlier ones with high noise levels, the 1/f noise was quite apparent and often crippling in effect. The subject of active device noise is too complex to discuss further here; the essential aspects for tape reproduce input circuits are those discussed here.

In the reproduce input circuit is found thermal agitation noise with a generally rising spectrum originating in the resistive elements of the head impedance, fairly flat-spectrum shot or equivalent noise, and 1/f noise with its rising low frequency characteristic. The relative sizes of these noise sources depends in part on the transistor, tube, or particular circuit chosen and in part on decisions made by the head designer. The detailed shape of the input noise spectrum depends also on these relative sizes, but is in any case a plot which is concave upwards.

Competing with the noise in the input circuit is the maximum signal which can safely be recorded on the tape. This recorded signal may have any one of a number of different spectra depending on whether the recording is analog, FM or pulse and further on the detail of the pulse mode chosen. The recorder designer usually attempts, however, to fill the tape spectrum as fully as possible and the signal from the reproduce head must be considered to have the spectral shape that would be received from fully saturated tape.

If the flux intercepted from the tape is the same at all wavelengths, the output from a conventional reproduce head is, of course, differentiated and has a sinewave frequency response with an upward slope with frequency of 6 db per octave. At the same time, the various high-frequency losses (basically short-wavelength losses) are also present. Both recording head resolution and playback scanning losses cause the signal to fall off with frequency. Other influences, including reduced depth of flux penetration and increased self demagnetization at short wavelengths, also tend to cause the signal to fall off at high frequencies.

By comparing the potential signal spectrum with the noise spectrum just discussed, an overall signal-to-noise spectrum for the recorder is obtained. This spectrum is determined at the input of the reproduce amplifier and cannot be improved on at any later point in the amplifier system. The input amplifier will be followed by equalization intended either to give uniform frequency response for analog recording or to optimize certain signal characteristics of digital recording. The output signal-to-noise spectrum of the reproducer will be shaped by this equalization and the overall signal-to-noise ratio figure will be determined by the net noise power and the net signal power at the output after equalization.

The recorder electronics designer always has a standard against which the noise performance of his input design will be measured. The noise originating in the tape will always be present and, in any properly designed system, it alone should limit the overall signal-to-noise ratio. The electronic elements of the system should therefore make no contribution whatsoever to the system noise. This can be done if at all points in the spectrum, or at least when averaged over the whole spectrum, the electronics noise is sufficiently low (say, 6 to 8 db below tape noise). This must be accomplished in the presence not only of the noise spectrum described above but also in the presence of the competing tape noises which have a basically flat input spectrum shaped by the equalization following the input amplifier.

Recorder users take the attitude that the tape noise should be the basic system noise. The electronics designer is thus in the unenviable position of having to conceal his presence by continuously staying ahead of the development of improved low-noise tape. The utility of new low-noise tape has been entirely lost on some users because their equipment had such high circuit noise that tape noise improvement resulted in no overall system noise improvement. The other aspect of the signal-to-noise ratio problem is, of course, that the maximum signal must, of course, not overload the input amplifier. Although it is not obvious that this should be much of a problem with modern electronic techniques, it has been one of the influences for retaining tube electronics in input circuits as long as they have been. The difficulty arises because, particularly with transistors, the optimum source impedance match and set of operating currents and voltages for minimum noise seldom results in adequate output capability. The input transistor circuit design therefore must often be a compromise between low noise and adequate dynamic range (or enough output).

Another point at which the recorder electronics designer must deal with the high end of the dynamic range is in the record amplifier. The record amplifier is actually a pretty straightforward piece of equipment, being unusual only in having to feed the inductive load of the record head. However, in digital or high-frequency analog recording it is often necessary to drive currents with very short rise times into this inductive load. Specialized circuit design may be necessary in order to accomplish this. In direct analog recording another very serious overload problem arises in that high-frequency bias must be added to the signal in the record head. The bias has typically 10 times the amplitude of the peak recording signal. If it is allowed to flow in the record amplifier circuits along with the signal, the circuits must be designed not to produce overload with 20 db more dynamic range than would be needed for the signal current alone. Ingenious techniques have been developed to isolate the bias from the record amplifier circuits while permitting the two currents to be mixed in the record head.

SIGNAL EQUALIZATION

In the chapter on "Head-Tape Interaction" an elementary magnetic recorder was described to show the importance of the various elements of the complete recording system. The statement was made in that chapter that by adding a simple RC feedback or resonant equalizer, the frequency response of the test recorder could be made flat. This is exactly what has been done for audio recorders and was originally done for instrumentation recorders. However, although the frequency response of the recorder-equalizer combination may be made flat, the phase response, characterized by delay distortion, is very far from flat. To oversimplify only slightly, one might say that the thickness loss and spacing loss and demagnetization loss in the recording and reproducing processes produce a fall-off at high frequencies with very little phase shift. The complex scanning process which is going on in producing these losses is quite different in its relationship between phase and amplitude response from the typical electrical transmission circuit. Were the high frequency fall-off to be caused, for example, by reactive circuit elements, an RLC or feedback RL equalizer would do a fair job of restoring phase response at the same time that it restored the amplitude response. However, in the absence of much phase shift in the scanning loss at high frequencies, the simple equalizer would introduce phase distortion.

In many applications of instrumentation and scientific recorders the phase response is extremely important. For example, in the standard multichannel FM/FM telemetry system the phase response across any one of the telemetry channels must be essentially flat if undistorted data is to be obtained from the FM system in that channel. Similar requirements apply to pulse recordings and other analog recordings. To assure proper phase response all-pass phase correcting filters are added to simple RLC equalizers or equalizers with special phase characteristics are used. Perhaps the commonest way of achieving this limited phase shift equalization process is by the use of delay line equalizers (Jorgensen [1961]).

The preceding discussion emphasizes that considerable equalization is necessary in order to produce uniform frequency response in a tape recorder. The discussion has emphasized the spectrum problems resulting from concentration of the equalization in the reproduce part of the equipment. This corresponds to the normal practice of attempting to produce a constant-amplitude recording in the tape and to correct the inherent frequency response in the reproduce process. Constant amplitude, however, is now usually interpreted to mean constant flux. That is to say, it is the intent of the recorder designer to produce uniform flux at all frequencies in the tape. To guarantee this in wideband systems a certain amount of record equalization is also required. About five to ten years ago there was a general change in policy from constant record current to constant flux in the tape. This change corresponded roughly to the gradual increase in recorded bandwidth. There is therefore now a certain amount of high-frequency record preemphasis required (free, of course, of phase error) to compensate for various losses in the recording system. There are many wavelength dependent effects at work to reduce the effective flux in the tape from the point of view of the reproduce head but these are not considered to be properly compensated by record equalization. The record equalization is limited to compensating for high-frequency losses in the magnetic material of the record head itself and therefore this equalization does not exceed, at the maximum, a few db. With this record equalization, a particular recorder is referred to as a "constant-flux" recorder as distinguished from a "constant-current" recorder.

IMPLEMENTATION OF RECORDING FUNCTIONS

Considering all the possible recording modes discussed under "Recording Methods" and "Head-Tape Interaction," recorder electronics have a wide range of specific signal conditioning or conversion functions to perform. These processes are, on the whole, quite straightforward and resemble closely the same processes as applied to other electronic devices (Davies [1961]). Pulse shaping, pulse stretching, limiting and amplitude and frequency modulation and detection, all are performed with fairly conventional techniques. Such standard techniques are beyond the scope of this survey but a few specialized methods which have been particularly adapted to tape recording will be mentioned.

In the chapter on "Recording Methods" the basic processes of FM demodulation via the pulse counting method are described. Each manufacturer has his own individual way of doing this particular job and most of them use the same method for compensating for flutter in FM systems as discussed under chapter 7 on "Disturbances to Tape Motion." Such flutter compensation schemes almost always involve, with the pulse counter discriminator, introducing the correction by changing the area or charge content of a pulse that is nominally supposed to have constant area or constant charge. Considerable ingenuity is brought to bear on this technique since it adds further complications to those inherent in any pulse-averaging system. Problems arise when the pulses are changed in area because the change adds a whole new set of frequency components to those already present in the FM signal. As pointed out under "Disturbances to Tape Motion," this is related to the proposition that it is almost impossible to compensate completely for flutter in a tape recorder. The practical problem arises because the presence of these new frequencies complicates the design of the filter which follows the averaging circuit. Without getting into the details, it is sufficient to point out that most manufacturers, therefore, when providing flutter compensation for a particular system deliver with it a different FM output filter. With the rarer phase-locked-loop discriminator, flutter compensation raises different but related problems.

The modulators used in FM tape systems often operate on quite different principles from those used in FM communication systems, since the characteristics of an FM system designed to work with a tape recorder differ from those designed for most transmission systems. A particularly elaborate and very specialized art has grown up around the modulators needed for rotary-head recorders. Since the FM system of rotary-head recorders violates conventional rules of FM design, considerable ingenuity had to be expended to bring this transmission system down to a level of distortion which would allow it to be used for other than simple video for entertainment purposes (Kietz [1963]). Although not as wideband as the typical transverse recorder, FM recording systems designed for bandwidths of 200 or 400 kilocycles have been introduced to instrumentation service recently. These require rather specialized modulators and a small literature is growing up describing these techniques (Price [1963]).

OTHER SIGNAL PROBLEMS

In the rotary-head recorder, various additional electronic problems arise because the head is rotating. In the typical four-headed recorder as originally used for broadcast work and now also used for instrumentation recording, the record drive must somehow be fed to the four heads. The standard method of doing this is to feed the heads through slip-rings and to do the switching between slip-rings in the record amplifier. Various schemes have been proposed for doing partial commutation, or for carrying solid state switches with the rotary head and causing the switching to take place in the head through a drive obtained through slip rings. Such a remote switching scheme avoids some of the slip ring noise problems and the corresponding mechanical complication. The same sort of thing happens on reproduce and the common practice has been to switch after the signal is picked off by slip rings. To reduce some of the slip ring noise problems in some modern machines, preamplifiers ride on the rotary head so that the slip rings will deal with a signal of higher level than the direct head output.

Although some one-head rotary machines have been used for instrumentation work, the two-head machine is by far the most commonly used variation of the standard four-head machine. Although the switching problem in the two-head machine is not as great as in the four-head machine, it exists nevertheless. The problem is not as severe in the two-head machine because the angular rate of head rotation is lower.

A major rotary-head recorder performance problem is that of time and amplitude error introduced at the head switching. Slight electrical and mechanical variations between heads will produce amplitude discontinuity, and slight variations in radius of rotation of the head gap or stretch of the tape or of relative position of head and tape can produce time discontinuities. Automatic gain control systems and slow switching systems are now able to eliminate almost all of the amplitude discontinuities. The time discontinuities can likewise be almost completely eliminated by the use of electrically variable delay lines adjusted by standardized signals to correct for the time error (chapter 7).

The circuit design of the balance of the electronic equipment in and around the tape recorder is quite straightforward. For ground installations, modular mechanical design is usually employed to provide flexibility. In tracking stations or large data reduction plants the function of the individual track of a multitrack recorder must often be changed rapidly. Duplication of electronics (as well as duplication of the entire recorder installation) is often employed to guarantee the safety of the valuable experimental data through redundant data acquisition.

For the small recorder in a satellite or space probe, the electronic design must be efficient, mechanically rugged, and extremely reliable. Simplicity of circuit design is usually emphasized even if it is obtained at the cost of reduced circuit performance. Certain specific aspects of satellite recorder electronic design are discussed in chapter 13. Figures 10–1 and 10–2 show representative examples of the packaging of ground-based and satellite recorder electronics.

PULSE TECHNIQUES

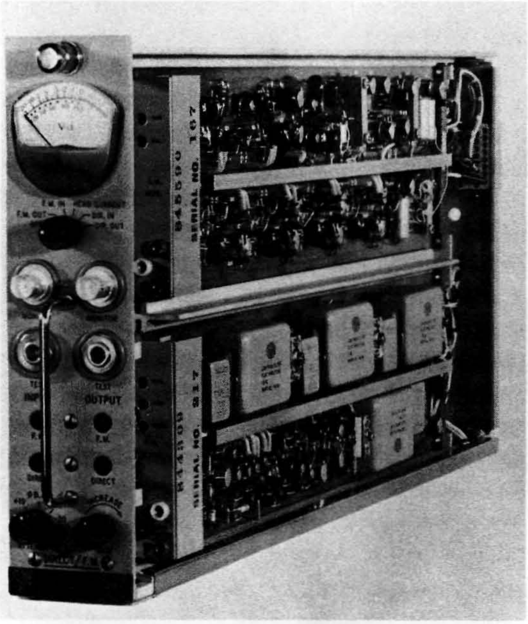
In the discussion of equalization earlier in this chapter the tacit assumption was made that the input signal is to be reconstructed and that therefore the equalization is designed to produce a uniform frequency response. This is naturally the case for analog recording. However, for pulse recording, two different approaches to equalization are possible. One may attempt, as in analog recording, to reconstruct the original signal. The output wave form is then, within the limits of linearity of the recording process, the same as the input signal. This signal may then be acted on by auxiliary circuits as if it were an only slightly damaged version of the input signal. Alternately, however, the differentiating action of the recording process may be deliberately preserved and equalization to remove it may be omitted. In this case, instead of reconstructing the flux transitions on reproduce, one simply observes the "spikes" which occur at the output of the reproduce head for each of these transitions and the signal detecting equipment is designed to operate on these spikes rather than on the basic wave form. Both approaches are presently used sufficiently widely that there are almost two completely separate schools of thought. The subject is discussed by Hoagland under "Readback Detection Techniques" (Hoagland [1963]).

A special "automatic equalization" technique has been proposed to simplify the electronic elements of a flight recorder (Cole [1963]). In this technique, which is primarily applied to phase-shift digital signals, the playback gap length is tailored to the planned recording density. For split-phase or phase-shift coding, the gap length is made equal to the pulse length for the high-frequency pulse (chapter 4). On playback, this gap automatically produces an integrated wave form which closely resembles the recording current wave form. By so matching gap length and planned packing density, a mechanical equalization takes place; it is possible in principle to follow this head only with an amplifier and the necessary pulse detecting means. This technique, of course, uses a much wider reproduce gap than would normally be used for a low packing density but holds the promise that extremely high packing densities may safely be reproduced with a better signal-to-noise ratio than would be obtained with a narrow gap and equalization.

CONTROL ELECTRONICS

Electronic equipment performs a control function for tape recorders in two major areas, those of tape-tension and speed-control servos. The major problems of tape tension servos originate in the tension determining elements and in the servo motors themselves, in that these elements usually have mechanical properties somewhat at variance with their required control function. The important servo problems, which therefore are not electronic, are discussed in the chapters on "Tape Moving Systems" and "Disturbances to Tape Motion."

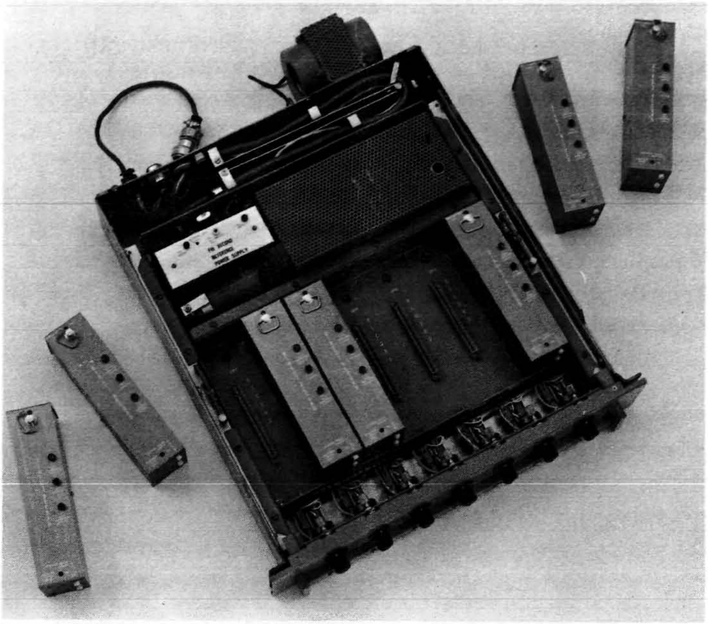
Speed control servos operate at two completely different levels of sophistication. Since the beginning of the application of instrumen-



(photo courtesy Sangamo Electric Co.)

(a) A combination FM and direct record/reproduce module for rack mounting, all solid state.

FIGURE 10-1.—Typical electronics assemblies for ground-based instrumentation recorders.



(photo courtesy Ampex Corp.)

(b) Modular rack tray and typical plug-in electronic elements for same in a solid-state instrumentation recorder.

FIGURE 10–1.—Typical electronics assemblies for ground-based instrumentation recorders.—Continued

(photo courtesy Ralph M. Parsons Co.)

FIGURE 10–2.—A miniature modular recorder electronic unit for flight service, typical in volume and degree of modularization of many such elements currently in use.

tation recording, rather simple servos for maintaining the average recorder speed constant have been in use. The standard practice is to record on a carrier of 16 to 18 kcps a modulating signal originating in the 60-cycle mains power which drives the recorder in the recording operation. On reproducing the tape, the 60-cycle signal is demodulated from the carrier and is usually introduced directly into the reproduce drive motor so that the power frequency recorded on the tape is locked into the power frequency at the reproducing point (Selsted [1950], Hare and Fling [1950]). Recently, however, recorder manufacturers have introduced tighter, more sophisticated servos which attempt to maintain instantaneous rather than average control of the reproduce speed. Instead of modulating the 60 cycles onto a carrier, a reference signal, usually of 100 kc or a multiple thereof, is recorded on the tape along with the data. On reproduction, the servo controls the recorder so that this signal is locked to a local crystal oscillator. Three major manufacturers currently employ such servos (Schultze [1962]).

The primary objective of such a tight servo lock is to minimize instantaneous time-displacement error. Whereas a typical gross time-displacement error specification for a recorder with a 60-cycle servo may be plus or minus a quarter millisecond, high-frequency servo machines offer ±5.0, ±0.5, or even ±0.2 microsecond instantaneous time-displacement error. The conceptual design of these servos is discussed under "Disturbances to Tape Motion;" the function of the electronic elements of the servo is usually merely to be reliable and rugged and to provide enough power to drive the controlled motor. Two manufacturers drive a printed-circuit or other low-inertia motor directly; another applies the controlled signal not to the motor but to a low-inertia drag disc operating as an eddy-current clutch.

A special form of speed servo is used in rotary-head recorders. In the most straightforward application of this to the four-head transverse recorder, the servo guarantees that the reproduce head tracks along the recorded track. In effect the recorded track could be considered a long thread, as on a long threaded rod, inscribed at a slight angle along the length of the tape. A separate reproduce head plays along the edge of the recorded tape and receives a timing signal which was derived from the rotation of the recording head drum. This timing signal drives the rotary drum of the playback recorder through a motor drive amplifier. The effect of the servo is to guarantee that the playback and record processes do not become "cross-threaded" and that the playback head passes over the same area as did the record head.

The emphasis in the preceding paragraphs has been on the very-high-performance servo with relatively simple environmental requirements for application to ground-based recorders. For both satellite and deep-space recorders, however, with emphasis on the latter, control of the playback rate of a flight recorder may be required. A phase-locked-loop servo has therefore been used with these devices and some of the specific problems associated therewith are discussed in chapter 13.

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CHAPTER 11

Tape Recorder Mechanical Components

A modern weapons system or hardware array for a major space program includes many mechanical and electrical components as well as electro-mechanical components which partake of the characteristics of both. In designing for reliability, very different approaches seem to be taken for the mechanical and electronic parts of such systems.

Modern electronic devices always contain a very large number of components and component arrays in small subsystems. A particular type of element may appear in the system in the form of many nominally identical copies. Such a massive array of components and subelements lends itself particularly well to statistical reliability analysis.

Statistical reliability analysis involves, first, the basic process of testing individual elements in large enough quantities to derive statistically valid failure information for the element. From this failure information and knowledge of how many of which kind of elements are involved in a complete system, failure rate figures for the entire system can be derived. The fundamental definition in reliability analysis on which this calculation is based is, "The overall probability of success of equipment is the product of the individual in-line component parts probability of success." The validity of the derivation has been extensively tested by true life testing of subsystems containing elements on which the same kind of failure data is known. By such a statistical reliability analysis one can determine an *MTBF* or Mean Time Before Failure for a complex array. If properly done, this prediction can be correlated with actual practical failure rates even of large systems.

Even though correlation with actual failure rates may not be perfect, the statistical approach is useful in placing emphasis on the way in which the individual component failure rate affects the whole system. It forces the equipment designer to evaluate the relative advantages of cutting down the number of components for simplicity versus increasing the number of components to provide redundancy.

The statistical method makes it possible to make a systematic decision between these two approaches in a particular case.

The individual elements of mechanical parts of hardware systems are never duplicated in as great a quantity as are the electronic elements. Obviously, however, mechanical failure can be as disastrous as electronic failure. Magnetic tape recorders are essentially electromechanical in nature and contain many special mechanisms for which no documented reliability statistics exist. It has therefore been difficult with too small a mechanical "population" for valid application of statistical techniques to obtain a probable mechanical failure rate with as much confidence as one can obtain an electronics failure rate. For example, many tables of failure statistics are available for resistors, capacitors, transistors, and other electronic components, but there are no such data on pressure roller assemblies, bearing modules, tape magazines, or capstan assemblies. In the absence of a true statistical population of mechanical elements, reliance must be placed on detailed life and performance testing of these key mechanical subassemblies.

It can be argued that there is no substitute for a genuine life test. If a device is to operate for one year it is desirable to be able to test a nominally identical component continuously for one year. Since such extended life tests are not practical, the mechanical engineer has developed truncated life tests or accelerated life tests. These tests give overall life predictions on the basis either of testing over an abbreviated period, with detailed attention to every aspect of partial failure of the component, or of stressing the component beyond the stress to be expected in practical use and thus increasing the significance of a short test. This latter operation sometimes is difficult, since space hardware may be stressed in normal application as much as it can be stressed in any testing means.

When life testing giving results of good confidence is difficult to come by, the mechanical engineer automatically turns to historical experience with similar equipment. Even though not formally life tested, a device can be used with considerable confidence of reliability if many hours of previous successful application have been obtained with it. This has led to strong emphasis on modular construction of mechanical assemblies of approximately the complexity of the magnetic recorder. In a modular assembly the major elements can be those which already have been tested and used in practice to such an extent that their reliability is well understood. The recorder for a particular application can be assembled from elements which are as identical as they can be manufactured to elements which have already proved themselves in use. Reliable operation can be predicted with a high degree of confidence for a completely new recorder designed in this way.

As a general principle, failure to utilize previous developments to the utmost of their applicability increases the cost of an individual project, extends its development time, and reduces its reliability. The most readily apparent of these effects is the increased cost of the individual program resulting from duplication of development engineering and qualification tests. For these reasons as well as to obtain the benefit of increased reliability, the modular use of previously developed elements is desirable.

In this section of the survey, the reliability and the important operating characteristics of certain key mechanical elements are discussed. The work in modular design that has already been accomplished under NASA's sponsorship will also be covered. Only in a few cases will detailed component technology be discussed since most advances in this direction have been made or sponsored outside the specific region covered by the survey. Where NASA has directly sponsored development on reliable mechanical components primarily for flight recorders the work will be discussed.

Little work has been done in the area of seeking reliable components specifically for ground recorder equipment. Admittedly failure of a ground recorder could have as disastrous an effect as the failure of a flight recorder on the results of any complex test. However, the lack of limitation on space, weight, and power leads to redundant use of ground based recorders and the presence of operators at all times makes maintenance of such recorders possible. Therefore, although this section is titled "Mechanical Components," it is limited to components for flight recorders.

MODULAR CONSTRUCTION OF FLIGHT RECORDERS

The technique of modularization appears particularly attractive for application to flight recorders. NASA has therefore taken the lead in developing this concept by undertaking in-house modularization studies and modular flight recorder developments as well as sponsoring additional contractor activity in these fields (Cole, Peake and Rice [1962]) (Lockheed [1962]). As this work has progressed, the advantages to be gained from modularization have become ever more apparent. The tremendous dollar savings alone have more than compensated for the costs of initiating the modular approach. A level of reliability appears to have been achieved which could hardly have been predicted for conventional development methods.

One of the results of this work has been the clarification and organization of the fundamental reasons for the utility of the modular approach, as outlined in the following quotation from one study (Lockheed [1962]):

> Different space programs tend to generate many similar performance requirements for spacecraft recorders. This fact results only partly from those characteristics resulting from the application to space use such as the operating environment, the reliability requirement, and the minimization of size, weight, and power. Other parameters such as recording time, data rates, capacity, and the like are often similar as a result of common functional needs such as telemetry of spacecraft performance, measurement of space environment, celestial scanning, and other more-or-less standard data collection operations.
>
> These similarities lead to the conclusion that a large percentage of applications can be handled by a few basic classes of recorders with selected modular subassemblies. The designer of a spacecraft recorder could then assemble, from a collection of tested and proven off-the-shelf components, a unit that would fit his requirements. Considerable savings in cost and time can be obtained from such an approach, along with the additional benefits of improved performance and reliability.
>
> This first phase in developing the concept for a modularized spacecraft recorder is the determination for each parameter, the total range of values that must be provided. Subsequently, the degree to which each of these ranges may be quantized must be determined; that is, how many discrete parameter values will the spacecraft designer be given from which he can select one that meets his requirement. These steps were undertaken for this report through a study and analysis of the available data on past and future space programs from which the corresponding spacecraft recorder requirements could be inferred. This resulted in segregating the requirements for spacecraft recorders into various classes based upon types of application. One such class, designated as Class I, calls for a low storage capacity instrument for telemetry, space environment measurement, and elementary scanning in orbits between 100 and 8,000 miles altitude. This class of recorder was selected for further study to establish detailed subassembly specifications compatible with modularization.
>
> Having the parameter values established, the next step in modularization is the breakdown of the unit into those components and subassemblies that provide the optimum set of modularized elements. In this effort, the tradeoffs between the flexibility of numerous elements and the expense of large inventories must be evaluated. The number of modular elements must be capable of providing a selection for all orbit-time conditions and yet not defeat the original purpose of modularization by resulting in an excessive number of components. For the Class I recorder, reduction of the requirements to a

reasonable set of modules was accomplished as shown in this report.

The result of this study thus provides a basis for future spacecraft recorder development projects, and in particular, the detailed design parameters for a Class I recorder design project. Following the approach outlined will result in a program that can replace a great number of individual development efforts now in existence or planned for the future.

In the study referred to, a classification of recorders on the basis of function and size was proposed and the following is an edited quotation from the same modularization study which describes the classes selected.

Class I. This class fulfills the requirements for the majority of scientific measurements necessary to define the immediate environment of the spacecraft and the factors affecting this environment. Functional telemetry measurements to provide detailed data on the operation of the spacecraft are included in this class also.

Long waits, sometimes approaching or exceeding the orbital period, occur between recording events for this class. Data examples include pressure, temperature, voltage, and go/no-go indications of operation. Certain elementary long-time-constant scanning applications can uitilize this class of recorder also.

Functional telemetry of "raw" R. F. and vibration information require bandwidths beyond the capabilities of Class I. Such raw data can be converted to level and frequency distribution and handled at lower data rates.

The Class I recorder is characterized by low record frequencies (not exceeding 1 kc) and short lengths of tape (not exceeding 300 feet).

Class I recorders also require time compression of the reproduce cycle. The determination of the time-compression ratios required is an important conclusion of the modularization study.

Class II. This classification includes recorders used for celestial and solar system scanning devices utilizing high-resolution sensors and slow-scan TV System. Also, it includes elementary communication relay recorders. Both time-compression and real-time reproduction are required.

Since the information content of the Class II recorder is in many cases limited by the transmitting power, storage requirements can be derived from this consideration. An important point in determining the limits of performance required of this class is the general tendency in spacecraft design to add diversity of experiments and redundancy of equipment rather than to extend the transmission and data-storage requirements of a single recorder. The determination of classification will therefore be heavily tempered by the type of equipment presently in use.

A summary of the tentative requirements to date indicates that a selection of FM and Digital recorders with a capacity of 400 to 1,500 feet of ½-inch tape and providing up to 8 or 9 tracks will provide good coverage.

Class III. Class III recorder systems include the ultimate in data-storage capabilities that can accommodate requirements of even our largest future spacecraft. The capabilities of this class parallel some of the most sophisticated ground station equipment. Major differences between comparable ground station equipment is in the relative importance of size, weight, power, and environmental factors. Limits cannot be established because exact applications for these recorders have not yet been determined and the programs are in the initial stage of development.

The way in which the modularization process has been carried out for the Class I recorder is given in the following listing of elements and parameters from the study:

Heads

(a) A full-track, quarter-inch analog record and reproduce head assembly for FM-multiplex recording. (b) A four-track, interlaced, record and reproduce head assembly for FM or digital recording. (c) A six-track, interlaced, record and reproduce head assembly for digital recording. (d) A full-track permanent magnet erase head.

Tape Cartridges

Tape length in feet:

75 to 125
125 to 175
175 to 225
225 to 300

Tape Drive System

A single differential-capstan tape drive system with five selections of interchangeable driven pulleys.

Pulley System

Four record motors, with four reproduce-motor pulleys and five low-speed pulley choices.

Record Tape Speeds

A total of eleven tape speeds in the record mode, ranging in 0.05 ips increments from 0.15 to 0.65 ips.

Reproduce Tape Speeds

A total of eleven tape speeds in the reproduce mode, ranging from 1 to 20 ips in steps of 2 ips. (The reproduce system may utilize 6 of the record speeds, from 0.40 to 0.65 ips, also.)

Record and Reproduce Drive Motors

A total of seven drive motors ranging from ¼ to 2 watts input power, all in a standard case.

Track Switching

Provisions to switch record/reproduce head tracks by means of either a conductive spot on the tape or by an internal timing mechanism (reference only, meaning not truly a subject of standardization).

Transport Base

Two sizes of transport base module to accommodate two different cartridge sizes.

Recorder Case

Two case sizes to contain the two transport base sizes.

At the present time the modularization concept has been applied only to the so-called Class I recorder. There seems little reason to believe, however, that it cannot be extended since this would seem to require only continuation of the quantized set of tape capacities and perhaps some additional complication of the type of head stack available. As motor capabilities change and are improved, the modular concept can undoubtedly be maintained in the drive area. It may therefore be anticipated that a large percentage of flight recorder requirements may, in the not too distant future, be soluble through the use of modular recorders.

MOTORS

Motors of all kinds are involved in the construction of magnetic recorders. The ac synchronous motor is usually called on to determine the absolute speed of movement of the tape past the recording heads. An ac synchronous motor rotates at a uniform average speed unless it is pulled out of synchronism by overload. However, a certain amount of torque variation during the revolution of the motor is inherent in its construction. Such torque variation, usually called "cogging," can be visualized as the effect of the motor having a specific number of separate magnetic poles. As the rotor and stator poles progress past each other, the torque varies during the passage with the degree of pole alignment. Although the hysteresis synchronous motor has no mechanically defined rotor poles, it still shows in practice a residual cogging. Reduction of this cogging is essential to low-flutter performance in the recorder.

In satellite recorders the performance requirements laid on the synchronous drive motor are quite severe. Very low power is available and it is often desirable to use only one motor. The low-power synchronous motor is thus asked not only to provide the accurately timed basic tape drive, but also to drive the takeup mechanism through some inefficient slippage device. Much refinement of such miniature low-power motors has taken place recently—primarily in the interest of satisfying the requirements of NASA and other users of motors for flight application.

Where the power consumed by the drive motor of a recorder must be minimized at any cost because there simply is no more power available as, say, in a deep space probe, the question of motor efficiency is extremely important. A large ac induction or synchronous motor in the horsepower range is a device of efficiency approaching perfection (85 to 95%). In the small single- or two-phase motor for a flight recorder, most of this efficiency has disappeared through design optimization for minimum size and weight. Ac motor efficiency may be 60 percent (rare for the small motor) (Bahm [1964]) but alternating current is usually not directly available on satellite or probe. Since a converter is necessary to provide ac power in flight the overall motor efficiency must be considered to be the product of converter efficiency and the efficiency of the motor proper. With the converter efficiency about 75 percent, the motor combination seldom has an efficiency above 45 percent. Extreme refinement of motor design may be required to raise this efficiency a few percent. Conventional motor design usually produces a motor of one half this efficiency in flight recorder sizes.

Extensive attempts have been made to apply the conventional dc motor, which can often be considered and used as a servo motor, to satellite recorder use. The almost analytical rectangular hyperbolic relationship between torque and speed of the series dc motor makes it particularly attractive for reeling applications. However, the problems of commutation involving switching-arcs and brush and commutator wear, have discouraged this use; commutation simply fails in the vacuum.

Perhaps a new era has begun for the dc motor with the current development of brushless motors. In the brushless dc motor transistors, or other solid state devices, including photodiodes, are used to switch current between successive sections of the rotor in the way in which communtator switching is used in the conventional dc motor. Although not as yet used extensively, the brushless dc motor appears very promising for some applications (Studer [1964]). Studer reports on the development of a brushless dc motor with an efficiency of 50 percent and acceleration as good as a typical brush-type dc servo motor.

The ac servo motor, which is essentially a two-phase ac motor which runs completely in synchronism with the applied electric wave form is necessarily a poor design compromise from the point of view of efficiency from a conventional synchronous motor designed to run at all times at the relatively high speed. The servo motor must, for example, be able to creep ahead slowly under direction of the applied signal without overheating its windings. It has therefore been little used for miniature recorder applications. However, for space probe applications it has been found necessary at times to "slave" the playback operation of a recorder to the local clock generated within the spacecraft. A servo motor action is necessary under these circumstances. This servo motor, however, does not have to be designed on the same basis as a servo motor for universal application. What is required here is not that the motor run at *any* chosen speed but that when it is running at its designed synchronous speed its instantaneous rotation be tightly coupled to the driving wave form rather than so loosely coupled. The efficiency of such a motor is not too different from a conventional synchronous motor and conventional synchronous motors have been used for this service.

In much ground-based recorder service as for many other applications, multispeed ac motors are used. The multispeed ac motor is one which has a large number of poles which can be rearranged in such ways as to give different synchronous speeds depending on the supply frequency and the number of poles used. For example a 60 cycle synchronous motor with two poles operates at 3,600 rpm, one with four poles at 1,800 rpm, and one with eight poles at 900 rpm. Motors with four synchronous speeds have been produced but two speeds seem to be about the limit for high efficiency. Although two operating speeds are almost invariably used in a flight recorder, the speed ratio is such (from 10 to 1 to as high as 1,000 to 1) that the rearrangement of poles is not a useful technique for providing different motor speeds.

The method usually adopted for providing multispeed synchronous operation of a single flight recorder motor is to vary the supply frequency. It appears from a collection of not too well organized practical experience data that a speed variation of about 8 to 1 can be accomplished by this method. Inherently, running a motor over as wide a frequency range as this requires much compromise in design. The iron losses in the motor vary widely and both the inductance of the stator windings and the impedance coupled into the stator from the rotor also vary almost proportional to frequency. However, the loss of efficiency inherent in this compromise speed design is purchased at the price of considerable simplification of the structure, since the motor always operates with the same number of poles.

The transistor motor is a term applied to an ac motor which runs from a dc source via generation of its ac driving power from a transistor oscillator. For many applications this combination is ideal and it essentially is described above in reference to the problems of generation of ac power for a synchronous motor in a flight recorder. Where the generation of the power can be optimized for motor service alone admittedly somewhat better efficiency can be obtained than where the ac power is generated for many different applications. Nevertheless the transistor motor at present cannot be considered to be a high-efficiency device although, for lack of anything better, it is extensively used in flight recorders.

Synchronous motors for flight recorder use may be designed to run either two-phase or single-phase. The two-phase motor places the requirement for the generation of the second phase on the internal ac power supply of the satellite. The single-phase motor generates the necessary second phase for motor operation from some internal or closely related phase shift device. The choice between the two approaches depends on a number of factors. For example, where a playback motor is to be servoed to a local clock, the two-phase approach is essential and the two-phase power supply is generated from the local clock. Particularly in a record motor where a single record speed is used, the internal phase-shift method of obtaining the second phase may be more efficient. However, the simple expedient of providing a capacitor for phase shift, effective with sinusoidal power sources, runs into difficulty when the power source is square wave, as it often is in a spacecraft.

In a detailed study by E. Bahm of Jet Propulsion Laboratory (Bahm [1963] [1964]), the first part of which has already been reported, certain other characteristics of small motors for flight recorder application are discussed. Bahm points out that the ac motor has certain fundamental disadvantages for flight recorder use. These include a very low efficiency-to-weight ratio and very poor acceleration characteristics. He also mentions that whereas cogging may not be too bad a problem with a properly designed motor under sine wave excitation, the power supply in a spacecraft may be far from sinusoidal. Particularly when slaved phase-locked-loop playback is required, the waveform tends to be rectangular and cogging is almost invariably encountered. In addition to producing cogging these waveforms may produce unstable operation of the motors, and damper windings, with the consequent loss in efficiency, may be necessary to stabilize them.

Bahm has produced a combination induction-synchronous motor which has the high starting torque and good damping of the induction motor as well as synchronous operation. This is arranged by providing both a permanent-magnet rotor structure for hysteresis action and a set of conducting cage bars for induction motor action. By varying the conductivity of the cage bars, using, for example, copper, brass and bronze, different values of starting and near-synchronous torque are obtained and the damping of hunting action of the motor is also affected. Bahm makes the interesting observation that because the high-conductivity copper cage bars develop enough synchronous torque at such low values of slip as may be developed by variations in angular velocity of the rotating field, if the source of power is square-wave, the copper-cage motor can be expected to have much more jitter than the others. He decides on a bronze rotor structure for the best balance of characteristics. Table 11-1 gives the mechanical characteristics of his developmental motors and shows the improvement of efficiency, start time and stall torque of the hysteresis induction over the hysteresis motor.

TABLE 11-1.—*Comparison of Hysteresis-Induction Motor with Conventional Hysteresis-Synchronous Motor*

Parameter	Hysteresis motor	Hysteresis induction motor (0.0045-in. air gap)
Maximum pull-out torque	5.27 g cm	5.2 g cm
Voltage resulting in maximum pull-out torque	30 v rms	32 v rms
Stall torque at same voltage	5.8 g cm	7.1 g cm
Input power at pull-out torque	2.33 w	1.79 w
Efficiency	28%	36%
Current per phase at maximum pull-out torque	70.5/77.5 mA	58/64.5 mA
Start time without load, using the same bearings	129 ms	117 ms

BEARINGS

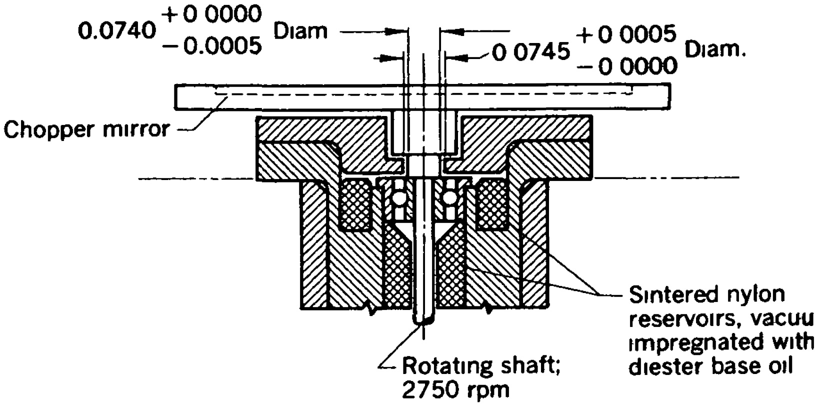
Both sleeve and ball bearings have been used in tape recorders. When properly constructed, a sleeve bearing, although relatively high in friction, can be extremely uniform in torque requirement. By "properly constructed" is meant that both the shaft and the bored hole in the bearing in which it turns must be perfectly round. Achieving adequate roundness, even with modern machine fabrication techniques, can be quite difficult. For very low speed, limited-rotation operation such as the anchor bearing for a tension arm which only moves 10°, an occasional sleeve bearing is used in the modern recorder. However, the only type of bearing about which significant performance information has any relevance for the current tape recorder is the ball bearing. Particularly in the flight recorder, where available power is at a minimum, the low friction of the ball bearing is essential.

A bearing for a major function in a tape recorder requires a torque as uniform with rotation and as low on the average as possible. The bearing must have as long a useful life as possible; the useful life usually is considered to end when the torque variation becomes unacceptable, the average torque becomes too high, or actual failure occurs. In many specialized recorder applications, and particularly for flight recorders used in severe environments, the techniques by which ball bearings have in the past been made to have high performance are unavailable to the designer. Conventional lubrication cannot be used in a vacuum; that some recorders must operate satisfactorily for one year after one year storage is also a very difficult requirement for most bearing lubricants to meet. Temperature extremes limit the classes of fits available for ball bearings and material choice is also limited by the requirement of satisfactory operation under the temperature and environment range.

Several studies have been made of bearing performance under specific flight recorder conditions (Weinreb [1961]) (Raymond [1962]) (Bisson [1964]). Although the picture certainly is not completely clear as yet, it appears that if the bearing is properly constructed and the lubricant properly chosen, preventable contamination is the major source of failure. Fabricating the bearings from the wrong material has turned out to be a cause of quite a few failures (wrong heat treating reported by Raymond, above). Contamination by materials not contained in either the lubricant or the ball or race material has caused failures which ought to be preventable by proper handling of the bearings.

The lubrication of bearings in space is, of course, a severe problem. One of the most successful techniques so far devised for providing a specified lubrication life for a bearing running in a vacuum environment is described by Weinreb and commented on by Bisson in the references cited (see also Bahm [1963]). The bearing is intended to run with a very small amount of a relatively nonvolatile lubricant. The lubricant initially installed in the bearing can be expected to evaporate. Additional lubricant is supplied to the bearing from a source consisting of a piece of Nylasint (nylon sponge) impregnated with the lubricant. As the lubricant gradually diffuses out of the Nylasint, it encounters the bearing surfaces. Eventually, the entire supply of lubricant will evaporate in the vacuum, but by so arranging the geometry of the Nylasint, the bearing, the bearing housing and the rotating members that the lubricant vapor escapes very slowly, it is possible to predict an extremely long lubrication life. The mean free path of the vapor of the lubricant in question can be determined and the passage between the rotating parts so designed as to minimize the diffusion of a vapor of this characteristic.

The Weinreb paper points out that, in addition to vacuum chamber testing, a radiometer in which this bearing technique was used has actually run in orbit for a period of 2360 hours without signs of deterioration. Figure 11–1 shows the construction of this unit, in which a shaft clearance of 0.00075 inch was maintained to control lubricant loss. The life data was taken at the time of the publication of the paper, 1961.



(drawing from Bisson and Anderson [1964]).

FIGURE 11–1.—Vapor-lubricated radiometer spindle bearing—see text (Weinreb [1961]).

The actual load life for a ball bearing is sometimes calculated from the following formula: $L_H=\frac{16667}{N}\left(\frac{C}{R_e}\right)^3$. This formula gives an evaluation of the effect on the load life of damage from cyclic fatigue of the materials of the bearing. In the formula, L_H is the load life in hours, N is the speed of rotation of the bearing in rpm, C is the manufacturer's dynamic load rating in pounds, and R_e is the equivalent radial load in pounds actually experienced by the bearing. Obviously the utility of the formula depends on what the manufacturer considers the dynamic load ratings of his bearings to be; the methods of calculating this differ from manufacturer to manufacturer. The formula therefore does not give absolute results but establishes the basic relationships for this particular bearing-failure cause. It can be used as the basis for discussion of some of the important factors in bearing design (Uber [1964]).

The dynamic load rating is usually based on optimum lubrication. Silicone lubricants are often used in severe environments because they survive better or have lower vapor pressure. It is usually a rule of thumb that the dynamic load rating must be reduced to one-third of its normal value when a silicone lubricant is used. Similarly, the equivalent radial load must be known accurately to determine the load life from the formula. This means that preload and external load from belts and pulleys must be known and evaluated accurately. Improving the frictional surface of a pulley so that a lower belt tension can be used can be expected to improve the load life of the bearing directly since it reduces the equivalent radial load.

The most severe environmental stress to which a ball bearing can be subjected is shock. A ball bearing almost seems designed not to survive shock because it operates successfully on the basis of using point contact, for which shock stresses will be a maximum. Shock may damage one or more of the balls or may cause the race to be dented or to harden locally (Brinelling of the race). A single severe shock may terminate the bearing life unless the design and loading are very carefully worked out.

The unloaded, axially-free, pure-radial-load ball bearing is a device with clearance around the individual balls, whence comes this poor resistance to vibration or shock. Preload is the technique which is universally applied to improving the shock performance of such a bearing. There are basically two methods of obtaining preload. One of these is by means of spring pressure in which a dished washer of spring material is used to force one race axially with respect to the other. This is a very simple method of preloading but must be used with considerable care. If the purpose of the preloading is to avoid the development of bearing clearance under severe shock of vibration, it is essential that the stiffness of the spring be designed so that even under the extreme environment, some preload will remain.

The alternate method of preloading is by means of rigid spacers which force the races axially relative to each other using essentially the internal elastic properties of the race involved as the restoring force. The stiffness of these elastic forces being so much greater than that of the spring washer, such bearings are less subject to removal of preload under the effect of external forces. Nevertheless the preload must be carefully designed.

A preloaded bearing requires, of course, considerably more torque to rotate it than does an unloaded bearing. This is unfortunately the price of shock resistance. For spacecraft recorders the preload usually ranges between one-quarter and one pound of axial force and in bearings used in this service these values of preload result in bearing torque of 5 to 20 thousandths of an ounce inch.

The duplex-pair ball bearing is a pair of axially preloaded bearings placed as close together as possible. The inner race of these bearings may be deliberately made a 1 or 2 thousandths of an inch higher than the outer race so that a preload is generated when the bearings are simply placed in contact. The pair in contact forms an excellent single-point bearing but provides little opposition to motion in which the ends of the shaft rotate around an axis normal to the axis of the shaft. The vibration and shock forces to which flight recorders may be subjected tend to induce this motion in any shaft and some sort of support must therefore be provided for the "outboard" end of the shaft. Unless this too is a duplex-pair, the advantages of preload and freedom from problems of vibrations are lost.

Since there are already two bearings in the duplex pair it seems logical to attempt to perform both functions, that is, to provide the freedom from axial movement inherent in the duplex-pair as well as the freedom from normal-axis rotational movement with the same bearings. A spaced, preloaded bearing capsule is therefore generally preferred for spacecraft service. In this arrangement, the bearings are separated by a distance adequate to prevent normal-axis rotation and are preloaded by axial spacers just as in the duplex-pair. This effectively provides a duplex-pair bearing but one which has somewhat more complicated load calculation than one where the bearings are close together.

NASA has recently completed a detailed study on new bearing technology much of which is directly applicable to some of the problems raised in flight recorder bearings (Bisson and Anderson [1964]). Part of this bearing technology is also directly applicable to the bearings of ground-based recorders. With low-mass servos producing extremely low time displacement error and a general improvement of flutter originating in the mechanical elements of the recorder, the bearings of the ground-based recorder must be very close to perfect. Only the finest bearing technology will provide bearings of this quality.

In addition to a calculated load life, which apparently correlates fairly well with measured load life of bearings when used carefully, there are many other causes of bearing failure, some of which have been mentioned above. The technique of measuring the actual torque with rotation of a bearing is the kind of preliminary precaution which can prevent early bearing failures from actual defects. Improper materials, improper lubrication, and even contamination at an early stage of assembly may be turned up as improper performance in such a test. Whatever means are available to pretest the actual bearing operation must be used if real reliability prediction is to be made for bearings.

CLUTCHES

Clutches have been widely used in tape recorders to provide the slip necessary in the reeling process. If a constant-speed drive is applied to the reeling and unreeling mechanism, some slippage must take place to provide for the change in diameter of the supply and takeup reels. A characteristic of clutches very important for tape recorder use is uniformity of drag with rotation. The average value of drag should not change over the clutch life. The clutch must have the right shape of speed-torque characteristic to provide controlled tension during the reeling and unreeling process. Unfortunately these characteristics are primarily dependent on the characteristics of the slipping materials. To expect these materials to maintain their characteristics over a long period is to invite problems. For this reason, slipping clutches are disappearing from flight and other scientific recorders.

Most flight recorders require different recording and reproducing speeds. Sometimes the two speeds are produced by two different motors or they may be produced by a single motor operating through a step-down mechanism to provide the two speeds. Often one speed may be produced by the motor running in one direction and the other speed by the motor running in the other direction using a differential drive mechanism to achieve the desired results. In any of these applications, it is necessary at some point or other to provide means for disconnecting one or both motors from the drive mechanism. An overrunning clutch provides the most straightforward method of accomplishing this. (The details of some of these drive methods are discussed in chapter 13. In this section the various kinds of clutches used for this service will be mentioned briefly.) This type of clutch functions as a go/no-go device and does not perform any slipping function. Since in the interest of minimizing power consumption, losses in the clutch should be minimized, considerable ingenuity has been brought to bear on the design of these clutches. In many cases a spring wire clutch, one form of which is shown in figure 11–2, has been used. With this clutch, for one direction of rotation of one shaft relative to the other, the spring tends to be wound up and hence to grip both shafts so that they are coupled together. For the opposite direction of rotation, the spring tends to unwind and the shafts are neither gripped or coupled. Although this is an effective clutch, there is a certain amount of drag in the disengaged direction. In order to remove this drag another clutch mechanism has been proposed by Stark (Stark [1963]). In this clutch, shown in figure 11–3, centrifugal force throws the dogs out so that they engage in the slots in the clutch housing when the inner portion rotates in one direction. For rotation in the other direction, the dogs are folded within the inner case as the outer element rotates in the other direction. Because the driving shaft is not rotating in the second case, there is no centrifugal force to engage the clutch. Properly constructed, this type of clutch should give no drag whatsoever in the nonengaged condition.

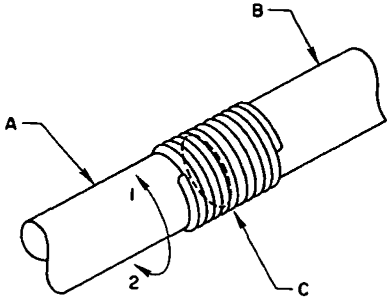


FIGURE 11–2.—Overrunning spring clutch

The shafts A and B are joined by a spring wire sleeve coupling C. If the shaft A is driven in the direction marked 1, small local friction will tend to move the coils of the spring in such a direction as to wind the spring up and hence to tighten it on both shafts. This will provide a very positive driving force to shaft B. When shaft A is driven in direction 2, no windup or gripping action is produced, and the driving shaft will rotate essentially free.

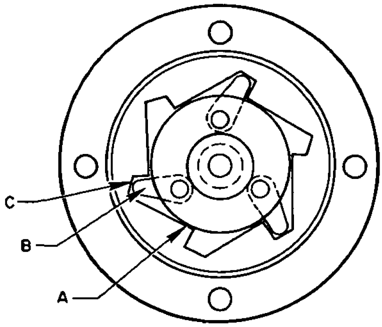


FIGURE 11–3 —A positive-acting zero-drag overrunning clutch.

This clutch, designed by Stark (see Stark [1963]) is designed for speed change application in a spacecraft recorder. The central assembly A is mounted on a shaft and carries the pivoting dogs B. When A rotates in a clockwise direction, even if the dogs are initially folded within the body of A, centrifugal force will cause them to be caught by the notches C in the outer circular member, thus providing positive drive to the outer member. If the outer member is, however, driven clockwise relative to a fixed A, the dogs will be folded within the body of A and there will be no forces causing them to engage the notches; the clutch will, in this mode of operation, have zero drag.

BRAKES

As with clutches, the uniformity and control of the torque of a brake used in a tape recorder is important. Tape recorder brakes are mainly used to control the starting and stopping of tape movement and their characteristics are of particular importance in fast start and stop modes. During fast start and stop it is very easy for the tape recorder to "throw a loop" and thus to damage either the tape or recorder. To prevent this brakes must have controlled uniform torque during transient conditions, and this torque must be maintained over a long useful life. The torque applied by almost any brake or clutch depends to some extent on the coefficient of friction of some material. Although sophisticated brake and clutch designs can be used, which depend on well-known and controlled values of friction, it is possible to depend on a brake or clutch over a long useful life only if the actual braking force is independent of the coefficient of friction. Mechanical networks are now available for providing a braking force almost independent of the coefficient of friction (Selsted and Dinsmore [1961]).

GUIDES

In almost any recorder guides are needed to direct the tape from the supply reel over the heads, past the metering device and on to the takeup reel. Guides are needed to insure that the tape passes in the correct line over the heads and the accuracy of these guides must be higher, the greater the density with which the tracks are displaced laterally across the tape. Guides are also needed to assure that the tape does not scrape against reel sides and that it winds up and unwinds smoothly to form a uniform tape pack.

The accuracy of guiding is dependent to a great extent on the tolerance with which the tape has been slit. Tapes can probably be slit with considerably greater accuracy than the formal tolerances currently allowed, and tape guiding can then be improved by using this greater slitting accuracy.

Guides may be either fixed or movable. "Fixed" or "movable" means, in one sense, that the guide is either a sliding post past which the tape slides or a roller around which the tape is wrapped and which moves with the tape. A guide may also be fixed in that it is a post or roller over which the tape, in passing, is guided against a fixed flange at one side by a spring-loaded flange pressing against the other tape edge. A primary factor in the choice of sliding or rotary guides is that the tape tends to be more self-locating with a fixed than with a rotary guide. In any fast start/stop mechanism fixed guides are almost essential because a rotary guide couples its inertia to that of the tape and disturbs the start and stop action.

Guides also become elements which enter into the mechanical network of any tape moving servo and the degree to which they couple to the tape is important in determining the servo performance. The application of fixed and movable guides is a complex subject.

In situations where time accuracy from track to track is of importance guiding must be accurate enough to prevent skew, that is, nonalignment of the normal to the head gap line and the axis of the tape. Skew may be both static and dynamic, meaning a permanent angular error or one which changes during tape movement.

While discussing the subject of tape guiding one important consideration in tape paths should be mentioned. When the tape is twisted around an axis along its length and at the same time stressed longitudinally, there is greater stress in the outside sections of the tape than in the center. This happens because the axis of the tape is the shortest distance between its two ends and the path of the twisted edges is necessarily longer. In some applications this difference in length and stress may be unimportant. However, in severe environments and in requirements where every possible unwanted stress on the tape should be avoided, the effect of this unequal stretching must be considered. It is always possible to design a tape geometry to avoid this stretching, assuming there is enough space.

If the tape is to pass between two rollers or other guides one may always construct planes tangent to these guides and extend them until the planes meet. These planes will necessarily meet in a straight line. Where the planes meet, a cylinder can be placed into the "corner" between them, tangent to both planes. If the tape is led from one of the guides along the plane tangent to that guide, around the cylinder just described and along the plane tangent to the other guide it can be transported between the two guides without twist. Because an infinite number of pairs of planes can satisfy these conditions, the pair used can be so chosen as to provide that the tape does not have to move laterally, between the two guides. In practice, a fixed guide replacing the cylinder will perform the necessary transition between the two end points. This transition function cannot properly be performed with any but a fixed guide, however, since only in this case is the tape self-locating.

DRIVE BELTS

In many of the miniature tape recorders described in chapter 13 reference is made to polyester film belts. They are used in the so-called Iso-elastic drive to drive the tape itself, in the so-called Cobelt drive to drive the tape and maintain head contact, and in other applications to provide the function of the pressure roller at the capstan. For almost every recorder, they are used as the means of power transmission between the motor and the rest of the mechanism. These polyester belts were originally developed within the NASA organization and its predecessors (Licht and White [1961]). These belts are constructed by calling on some of the unusual mechanical properties of the polyesters to provide a seamless high-strength flexible belt of good mechanical uniformity.

The primary technique of fabricating these belts is begun by cutting a ring out of a flat sheet of polyester. The exact size of the ring and the relationship between the dimensions of the ring and the desired dimensions of the final belt are complex and based on extensive practical experience. This ring of polyester is then progressively stretched and cold- and hot-worked to convert it from a flat washer to a belt. This is done by several different methods but one of the most straightforward is to allow the ring to operate as a belt on tapered rollers which gradually force it to stretch and to change into the belt form. When properly done, such belts can be made with dimensional accuracies almost as high as wanted. There are limits to the width-to-length ratio, since this ratio determines the amount that one side of the belt has to be stretched compared to the other side. The belt invariably has a small amount of thickness taper across its width because one side of the belt has been stretched more than the other. However, properly made, these belts have little tendency to revert to the original disc form except under the most severe environmental requirements. Because the polyesters may have limitations for high temperature use, DuPont H-film or Kapton, which is a polyimide, has also been successfully used for this service (Raymond [1964]).

VIBRATION ISOLATION

The flight recorder is usually mounted along with other pieces of apparatus within a carefully designed skeleton framework of a space vehicle. As the capacity of rocket boosters has increased over the last few years permitting an increase in weight of the vehicle from the grapefruit-sized initial experiments of 1959 to the many-hundred-pound devices of the present, the structure and other mechanical characteristics of the spacecraft have changed as well. The demands for space and weight for experiments and recorders has always, however, exceeded the booster capacity available. The structure of the spacecraft and of the technical apparatus mounted in it have therefore changed quite a bit; invariably this structure has had the minimum mass and the minimum stiffness to produce satisfactory stability.

As the booster capacity, spacecraft mass, and experiment complexity have increased, the demands on on-board recorders have increased.

The more sophisticated recorder of today cannot be allowed to vibrate internally as much as the simpler ones of a few years ago. However, the interrelated factors that affect the internal vibration of the recorder have not given any clear cut specifications, over the period of development for such recorders, as to how the recorders are best handled from the point of view of minimizing such vibration.

Minimum-weight flexible spacecraft structures transmit vibration in a rather complex way to a recorder mounted in such a structure. In the early stages of spacecraft and recorder development, some structures were so flexible that it appeared that the structure itself was an effective vibration mount. As with most statements about vibration, this is an oversimplification and is based on the fact that the actual structures used seemed to demonstrate this characteristic.

As spacecraft structures as well as recorders became stiffer and more massive, it was discovered that a recorder was often subject to too much vibration when it was hard mounted directly to the structure. The increase of local vibration because of vibration resonance within the recorder structure also began to be a problem. Resonances in the spacecraft structure, in the recorder mount, or in the internal structure of the recorder itself resulted in local "amplification" of the vibration of from 5 to 10 times.

This is the familiar problem of the "Q" of the vibrating structure. For small, relatively stiff structures the stiffness is adequate to assure that no important internal vibration induced relative motion takes place within the spectrum of the vibration to be encountered. As the structure increases in size, its stiffness by definition must go down for any practical mass; at some point resonances within the structure take place inside the vibration spectrum concerned. When this happens the internal vibration amplitude is amplified by resonance so that the recorder or other device simply does not act properly under vibration. The only ways of avoiding this situation are by shifting the frequency of the internal vibration resonance or by damping it. Techniques of resonance shifting by changing local distribution of masses and by local stiffening are sometimes effective. However, the only overall solution to resonance amplification is vibration damping. This may be done by internal damping of the structure by laying absorptive blankets in intimate contact with vibrating surfaces. A more general solution is achieved by placing damping vibration mounts between the recorder and the structure. Such vibration mounts can also be designed as high-pass filters to attempt to keep most of the low frequency vibration from passing into the recorder structure itself. A most important function, however, under the severe vibration requirements of a flight recorder sustaining vibration during boost, is by damping the amplitude of the vibration transmitted to the recorder.

Several studies of the technique and effectiveness of such damping vibration isolation have been performed within NASA laboratories and their substance is summarized above (Conn [1964]). This is, of course, a specialized application of the continuously developing understanding of vibration damping techniques. Significant technological progress has been made by some manufacturers of damping isolators within the last few years; the introduction of new materials and new construction techniques may increase the effective use of isolation in the near future.

TORQUING SPRINGS

"Neg'-ator" is the trade name of the Hunter Spring Division of Ametek, Inc. for their zero-gradient spring. Although a trade name, Negator is used, at least in the flight recorder field, as if it were a common noun and the application of these springs is widespread. Although these zero-gradient springs are available in many forms, the particular type used in the flight recorder is what is known as a "type B" spring motor. The flat coil spring is normally wound into a fairly tight spiral around one shaft or drum, labeled the "storage drum." It is led off this drum and wound up in the opposite direction on the so-called "power drum." The shape of the spring at this point is that of the letter S. The backward bent spring, in attempting to straighten itself out, unwinds itself from the power drum with essentially uniform torque over the whole winding range.

Such a source of uniform torque providing a continuous power flow is obviously useful for takeup and holdback in a flight recorder, as evidenced by its wide use. Certain characteristics of these springs require that care be used in mounting and guiding them. The way in which a spring is tempered to provide uniform torque gives it a certain tendency to move laterally; it sometimes seems to want to act like a flexible steel rule. Much ingenuity has therefore been brought to bear on guiding the spring in its passage from one drum to the other to overcome this twisting property while not applying any drag to the edges. In the OGO and Nimbus recorders, four large Negator springs are used to provide sufficient torque, winding from four storage drums onto a single central power drum. Tapered flanges are provided on both types of drum to guide the springs and to keep them from getting so far out of alignment under shock as to twist free. Under normal operation, however, the springs do not rub against the flanges.

CHAPTER 12

Methods of Testing and Evaluating Tape and Recorders

In many applications the tape recorder appears externally to the user to be a simple device, in the sense that it presents a relatively simple interface and offers little possibility of parameter change through adjustment. The internal mode of operation of the tape recorder is nevertheless very complex. Testing of tape recorder characteristics *per se*, therefore, requires care to insure that the tests are significant and controlled. This chapter is not intended to provide a working handbook for the recorder tester, but rather to justify and describe the controls appropriate to recorder testing.

DISTORTION TESTING

As with any electronic signal transmission equipment, a tape recorder can be tested in a fairly conventional way for harmonic distortion. Such a test is usually made by applying to the recorder a sinusoidal test signal at a level chosen to reproduce at some standard output value. The signal is recorded and reproduced; with a harmonic analyzer or similar device, the harmonic distortion components or total harmonic distortion are measured. Unless there is something grossly wrong with the electronics of the tape recorder this test will show the presence of essentially no even harmonic distortion.

It is difficult to decide what test frequency should be used for this distortion test. Typically one will find that the average recorder is specified, at least by its manufacturer, to be tested at some suitable mean frequency like 250 cps or 1,000 cps or, for a wideband recorder, perhaps 10 kcps. Unlike many other elements of signal transmission circuits, if the tester wishes to confirm the distortion results given in the manufacturer's specification for an audio tape recorder he had better believe precisely what the manufacturer says about the test frequencies used. A tape recorder with standard audio equalization is not capable of delivering a wide range of test signals with the same distortion as can be achieved for a mid-frequency test signal. This limitation results from the rather strange basic frequency response of the recorder when a constant recording current is applied to the recording head; as discussed elsewhere in this survey, this response is a rather badly humped curve (chapter 5). To provide uniform frequency response, severe equalization is required, and for audio recorders, pre-equalization as well as post-equalization is used. The results of this equalization, for distortion, are that every part of the frequency range is treated differently by the recorder from every other part of the range.

Ten to fifteen db of preemphasis may be used in an audio recorder at the upper end of its transmission range. This means that a signal which would produce only nominal distortion at the middle of the frequency range would drive the recorder into 10 to 15 db of overload at the upper range. For this reason the audio recorder manufacturer's specifications may contain a note that the frequency response is to be measured either 10 or 20 db below the nominal maximum output level.

This distortion situation precludes the possibility of using pre-equalization for scientific recorders. The only pre-equalization that is now used is a small amount of high-frequency boost to compensate directly for losses in the metal of the recording head, with the intent of producing a "flat" input flux on the tape. A more exact distortion specification than a single-frequency one is often used with the scientific recorder. This consists of plotting the output signal level as a function of frequency for a test signal of a level which produces 1 percent distortion at the mid-frequency reference. With no pre-equalization, the distortion at this output level is usually very close to 1 percent. In addition to this plot, a plot of the output at saturation of the tape recorder is placed next to it. The saturation level plot usually is almost a constant distance (in db) above the 1 percent response level. Typically this saturation response is 13 to 14 db higher than the 1 percent distortion response.

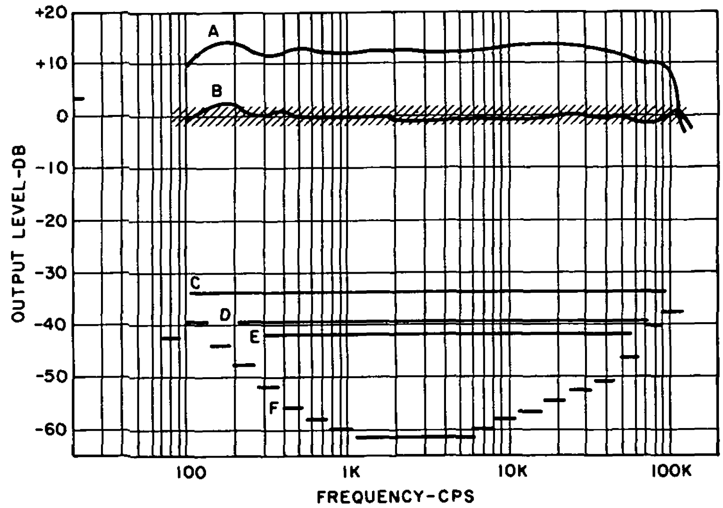
Although the phenomenon has been mentioned in chapter 5, it is well to point out again here a fallacy contained in this 13-db specification. When a tape recorder is badly overdriven, its output tends to have flattened or clipped peaks, and, in the limit, an applied sine wave is reproduced as a square wave. If the typical full-wave linear rectifier electronic voltmeter is used to read the value of such a clipped wave, a deceptive result can be obtained. The full-wave linear rectifier meter measures the average value of the rectified wave and is calibrated to read in rms value of an applied sine wave which has the average value measured. For example, a sine wave of 1 volt peak value, that is, one varying instantaneously from plus 1 volt to minus 1 volt, has an average value of 0.636 volt and an rms value of 0.707 volt. All the rectifier meter "knows" is that a signal with an average of 0.636 volt has been applied to it, and it cannot distinguish well between a square wave or a sine wave having the same average value. If a square wave which varies from plus 0.636 volt to minus 0.636 volt, with perfectly sharp transitions, is applied to such a meter, it will produce the same deflection as a sine wave of 1 volt peak value. If calibrated to read the rms or effective value of an applied sine wave, this meter will indicate 0.707 volt whether the 1-volt-peak sine wave or the 0.636-volt square wave is applied.

If one were to measure the output of an overdriven tape recorder with a peak-reading meter, it would be discovered that the peak value of the square wave produced by the overloading of the tape would be about 9.5 db higher than the peak value of a sine wave which was reproduced with 1 percent harmonic distortion. The typical full-wave linear rectifier meter would, however, interpret this level difference about 4 db higher ($20 \log_{10} 1.0/0.636$). Care must therefore be used in interpreting the manufacturer's saturation specification for the use of a recorder in applications requiring waveforms other than sinusoidal.

Intermodulation is seldom specified for tape recorders despite its importance. It can be tested in any of the conventional methods, subject to the limitations mentioned above which originate in the equalization.

SIGNAL-TO-NOISE RATIO TESTING

The peculiar equalization necessary to produce uniform response in a tape recorder is not only responsible for peculiarities in distortion response but in more important peculiarities in noise response. Because of the large amount of post-equalization required, the noise spectrum out of the tape recorder tends to have the same shape as that of equalization. This is the result of an approximately uniform noise output from the tape being equalized along with the signal by the equalizers (chapter 10). With scientific recorders it is a typical practice to specify several different noise levels in order to guide the user toward proper application of the recorder. One method of presenting the noise level of the tape recorder is shown in figure 12–1. The frequency response of the recorder for some reference input level, such as that for 1 percent output distortion for the distortion reference frequency, is plotted, centered around "0 db." The noise over the entire recorder bandwidth is measured with an averaging meter and this noise level is indicated by drawing a horizontal line, the ends of which are located at the upper and lower transmission limits of the filter with



(after an Ampex Corp. drawing)

FIGURE 12–1.—Tape recorder frequency response and noise display.

In this method of presenting the recorder performance, A represents the saturation output signal available from the tape (related to pulse or FM signal levels), B represents a plot of the 1% distortion frequency response, over which is laid a cross hatch indicating the specification limits, C represents the noise level observed in a band at the output of the recorder which has filtered limits represented by the ends of the line C. Similarly for D and E and F the vertical position of the line and the horizontal location of its end indicates the noise level and band limits for the particular measurement, respectively.

which this noise was measured. The vertical position of the line indicates the level of the noise signal relative to the reference signal level. Other lines are drawn for narrower noise-filter bands and typically these include a whole series of half-octave or third-octave filters. (The half-octave and third-octave filter values roughly plot out the shape of the post-equalization of the recorder.) This detailed noise specification is essential to the user of the recorder who wishes to "dig" a particular kind of signal out of the normal recorder noise. If he is shown the way in which the signal-to-noise ratio for a particular narrow band of frequencies varies over the recorder pass band, he is better able to decide how to apply the recorder than if simply given a single broadband noise value.

It should be emphasized that the exact way in which the noise band, of any width, is filtered is most important in determining the actual signal-to-noise figure that can be quoted, particularly for the very-wide-band recorder (Ratner [1965]).

As of the moment of writing this survey, it is difficult to say whether tape or equipment is the major limitation of recorder noise. It is standard practice to attempt to make high-performance recorder electronics provide a noise level somewhat better than that determined by the tape itself. As tapes have been improved, the manufacturer has been forced to improve his input system. The state of the art is currently such that it is becoming increasingly more difficult to achieve this electronic design goal. Signal-to-noise ratio has been discussed in considerable detail in chapter 10. It is appropriate to add here only that it is often a practice to indicate a system noise and an equipment noise. The system noise is that measured with erased tape running through the entire system and the equipment noise is that measured with the equipment operating as close to normal as possible but without tape contacting the reproduce head. Typically, the equipment noise is measured with tape moving but isolated from the head by a spacer so that such noises as hum from takeup and supply or capstan motors are included in the overall noise measurement.

Many ingenious schemes have been proposed for improving the relative signal-to-noise ratio of the tape recorder by such techniques as automatic switching between channels as a function of applied level. Although for specific applications such techniques may be useful, they are not considered to lie within the scope of this survey.

FLUTTER TESTING

In the simplest terms one may say that flutter is measured with a flutter bridge. The simplest flutter bridges are derived from the devices designed for disk- and film-recording measurements in theatrical and other audio systems. These often consist of a Wien bridge selective circuit tuned to discriminate against the particular test frequency used and calibrated to indicate the amount of average deviation from this frequency as the test signal is fed through the bridge. A simpler form of the flutter meter used with scientific recorders is now preferred as a more sophisticated audio flutter meter.

Such a flutter meter is basically an FM detector. A test signal is recorded on the tape and is then reproduced through this FM detector. If no flutter were present, there would be no signal output from the detector. Flutter appears as the output signal from the detector and may be measured in many ways. Flutter is sometimes recorded on a graphic recorder particularly when detailed analysis of the flutter performance is being made in the process of recorder development. Flutter may also be averaged and calibrated to indicate as a rms figure. The more critical flutter meters present single- or two-sided peak-to-flutter data.

As has been discussed in chapter 7, flutter occurs at a wide range of frequencies. In the specification of flutter it is essential that the bandwidth of the flutter components included in the measurement be noted.

An audio flutter-measuring device of good quality may use a test frequency of 3,000 cycles per second and include all flutter frequencies up to 250 cycles per second. According to commonly accepted practice, in this band up to 250 cycles per second, all those flutter frequencies are included which are perceptible to the ear. For a scientific recorder, however, such a narrow band of flutter frequencies does not describe recorder performance adequately. The recorder that is to be used for FM recording, particularly for wide band FM recording, is limited in its FM signal-to-noise ratio by its flutter performance. If, for example, an FM band 10 kilocycles wide is to be recorded in actual use of the recorder, no flutter measurement of this recorder would be adequate unless it included flutter frequencies up to the same 10 kilocycles per second. It is, therefore, necessary to make a much wider band flutter measurement on such a recorder than on an audio recorder.

The test frequency obviously must be much higher than 3 kilocycles to measure a 10 kc bandwidth and typically this test frequency is 10, 50, or 100 kilocycles per second. It is also a practice to present the results of the flutter measurement by passing the output of the FM detector through a variable bandwidth filter and to plot a level of output from this filter as a function of the filter bandwidth. The data are then labeled "cumulative flutter components up to a frequency of—," where that frequency is the horizontal axis (fig. 12–2). As a more conservative means of presenting flutter, peak-to-peak values

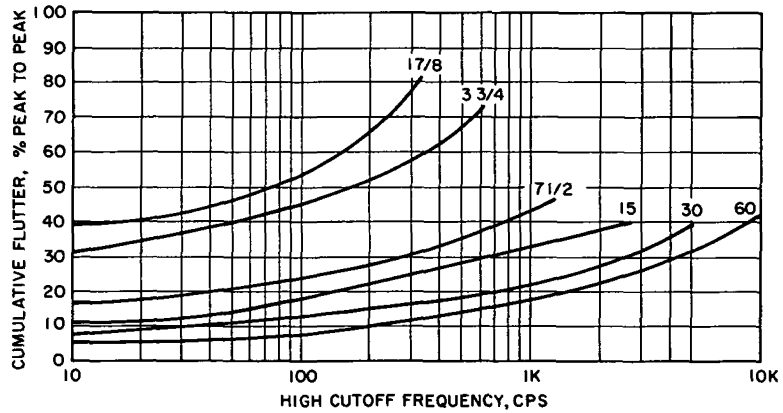


FIGURE 12–2.—Cumulative flutter presentation, with a fixed lower band limit and a variable high cutoff frequency

are usually given. (Current flutter performance of a high class instrumentation ground-based recorder may be 0.3% peak-to-peak with a bandwidth of 10 kilocycles per second.)

Although the plot of the measured peak-to-peak flutter of a particular high performance recorder may display a few irregularities at the lower filter bandwidths, it is usual for a smooth, slight rising curve of flutter versus filter bandwidth to be presented for high-frequency filter cutoffs. The flutter produced above about 1 kilocycle per second is almost all "hash" produced by shock exertation of the tape from scraping and friction. The smoothness of the flutter curve so presented often masks flutter problems which may be important for certain applications, particularly in FM recording.

The most exacting flutter performance measurement is made by searching the output of an FM detector with a narrow-band filter. Typically a fixed-bandwidth filter is traversed through the frequency region from zero to approximately 10 kcps or higher. Often this traverse is done by an automatic graphic recorder. An automatic traverse with a one-third octave bandwidth filter is not possible with any commercially available filter since it would require continuous filter adjustment. However, different parts of the spectrum can be examined with different fixed bandwidths to approximate the same results (fig. 12–3).

It is the usual practice to reduce such a detailed flutter spectrum measurement to the flutter per cycle basis. This means that the results are presented as if a 1-cycle-wide filter had been traversed through the flutter spectrum. Traversing with such a narrow filter would be a tedious and inaccurate process. With a 10-cycle filter, however, the search can be done quite easily—even more so for a 50- or 100-cycle filter. The total flutter energy intercepted in a 10-cycle band can usually be assumed to be 10 times as great as that intercepted in a 1 cycle band and in the same proportion for other bandwidths. If the scale of the flutter spectrum is thus modified to take care of the ratio of bandwidths, 10-, 50-, or 100-cycle data can be presented as 1 cycle data.

Such a detailed flutter spectrum is most useful for FM recording of complex signals, the spectrum of which must be searched in later analysis. As noted above, the typical flutter spectrum is fairly smooth with pronounced spikes or local irregularities at particular frequencies. These spikes often appear at the vibration frequency when a recorder is tested under vibration. Otherwise, they occur at frequencies related to once-around reels, capstans, capstan idlers, guide rollers, etc. Although the broadband flutter, and hence FM noise performance, of a recorder may be quite adequate for some applications, the

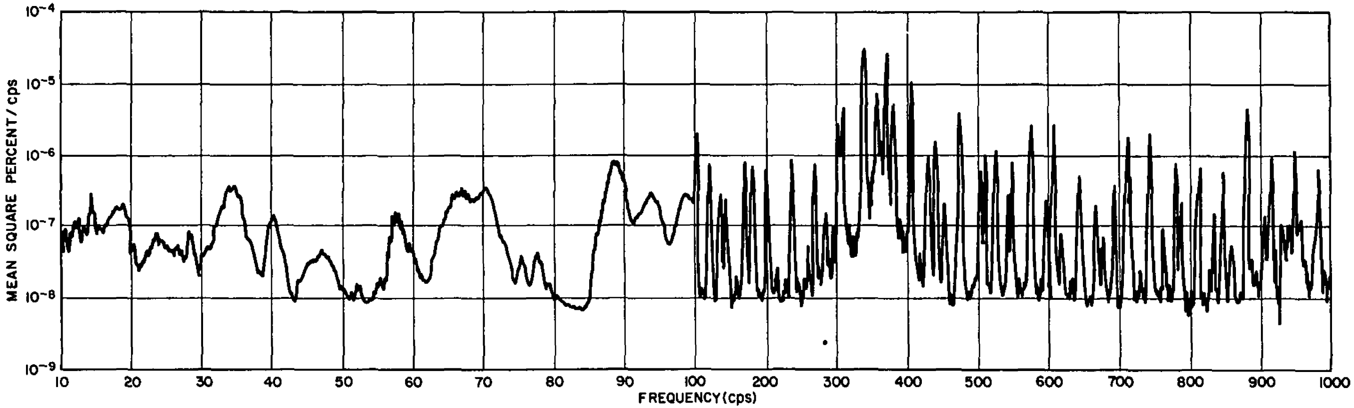


FIGURE 12-3.—Typical instrumentation recorder/reproducer flutter spectrum. The figure is traced from an original plotted by a graphic recorder—the calibration was adjusted for the different bandwidths used above and below 100 cps to give results in flutter per cycle.

use of such a recorder for detailed subsequent spectrum analysis may be severely limited if large flutter spikes are present. It is therefore sometimes a practice to specify the 1-cycle flutter spectrum for an application in which detailed analysis will later be required.

As a practical matter the usual high-performance flutter measurement is made with a telemetry discriminator and the crystal oscillator source. The IRIG specification, for example, calls out the discriminator made by a particular manufacturer, without comment, as being the proper instrument to use for routine flutter measurements.

Ratner (Ratner [1965]) points out that the practice of specifying broadband flutter in a 10-kcps band is not very useful with 400-kcps FM systems now in use.

TIME-DISPLACEMENT ERROR TESTING

Time-displacement error is now being routinely tested as an important recorder characteristic. Time-displacement error is closely related to flutter since in the simplest sense it is proportional to the time integral of flutter (chapter 7). In the information-theoretical sense, time-displacement error may be the measurement more fundamentally related to the ability of the tape recorder to transmit information. The time-displacement error is a direct measure of a contribution to the total uncertainty of the value of the recorded variable at a particular time. With a given signal-to-noise ratio the value of a particular variable at a particular time is known to a certain level of accuracy, as limited by the noise. At the same time, the total time displacement error is a measure of the uncertainty with which it can be stated at what time the variable had the specified value.

Two kinds of time displacement error testing are normally used. The most common is the so-called pulse-to-pulse test which is related not only to the more fundamental considerations noted above, but to the utility of the recorder for certain classes of pulse recording. Performance for PDM, PFM, and PCM recording is evaluated with this kind of pulse-to-pulse measurement.

The pulse-to-pulse measurement is made by synchronizing a good oscilloscope with each pulse reproduced by a recorder. A crystal-controlled pulse signal is then fed into the recorder and the oscilloscope set to trigger the start of its sweep as each pulse arrives. The actual pulse itself next in line is seen at the far end of the oscilloscope trace. Jitter along the base line of the pulse at the end of the line is a measure of the stability of the pulse-to-pulse spacing or relative time displacement error. No specific method for recording this is usually available although a time exposure of the oscilloscope display gives a better measure of the total pulse-to-pulse error than visual observation.

Visual methods are also used for absolute time-displacement error measurement. A standard method of making this measurement consists of recording a crystal-controlled square wave directly on the tape and reproducing this square wave to be displayed on an oscilloscope. The oscilloscope horizontal sweep is triggered from the same crystal oscillator as was used for recording. In the oscilloscope display, the jitter along the base line of the transitions of the square wave is a direct measure of the time-displacement error between the local crystal and the reproduced square wave. Depending on the performance of the recorder, a wide range of display techniques may need to be used; time-displacement error of this class in instrumentation recorders varies from ±0.2 microsecond to ±0.25 millisecond.

DROPOUT TESTING

Dropout testing is essential in the production of digital magnetic tape and its pre-evaluation for use. No tape can be sold today for digital use unless it has been 100 percent tested for some particular dropout performance. The cost of (digital) computer tape is often related directly to the packing density for which it has passed 100 percent dropout free test. For many applications in instrumentation recording such dropout testing is also important.

A dropout test consists of recording a pulse or other signal on a tape and reproducing this signal while observing the continuity of the reproduced level. Automatic dropout testing involves signal level detectors which indicate a dropout when the signal drops below a particular value. An extremely elaborate dropout tester has been built by one firm in which several different decreases of signal level are separately measured, if the signal drops 3 db at one point, this is noted as a "3 db-dropout"; if it drops as low as 6 db below normal this is noted as a "6 db-dropout," and so on for several different decreases in signal level. Although this device has been proposed as a useful and sophisticated tool for placing instrumentation and digital tapes in order of quality for dropouts, its primary utility is to the manufacturer of tape who is interested in observing the level of performance of his tape-manufacturing process. For the tape user, a dropout is usually an error, and he is interested in specifying one particular level of dropout which he can barely tolerate and is interested only in whether the tape achieves no dropouts as deep as that level or not.

The user is also concerned with the presence or absence of dropouts as a function of recording density. The computer tape manufacturer, therefore, tests his tape first for dropouts at a high recording density. For example, he may test first at 800 pulse bits per inch. If the tape passes this test, it is put into the "800-bit-per-inch" bin and sold at the highest possible price. Tape which fails this test may then be tested at 556 bits per inch and, if it passes, placed in the "556-bit" bin. This may progress on down through one or two intermediate stages until the tape either passes or fails a 200 bit per inch test. If it fails this test it is no longer considered useful for computer tape and is often sold to the unfortunate instrumentation tape buyer.

So little tape passes the more sophisticated of these tests and even some of the less sophisticated ones that the inspection process involved in computer tape manufacture also involves means for repairing dropouts. It is a typical practice when a dropout is found by the automatic tester to have an operator attempt to polish out the nodule or tape defect which caused the dropout. From observing the level of activity of such inspectors in a tape manufacturing plant, one concludes they are responsible for the salability of many reels of otherwise unusable computer tape.

TAPE TESTING

The testing of tape is now a fairly standardized operation and there are military specifications for tape of various kinds. Such tests include the measurement of the physical and mechanical properties of the tape, a simple measure of its output level, short-wavelength performance, and signal-to-noise ratio including both dc and ac noise. These tests have the value of being standardized and of having commercial validity because they are agreed to as a formal specification. The substance of these tests is best obtained from the appropriate military or NASA procurement specification.

For many applications these standardized tests do not go far enough. For example, lubrication of the tape is all-important for endless-loop service. No standardized tests are available for tape lubrication but it is certain that the user of an endless-loop recorder requires some kind of test to establish whether the tape can be used in his recorder at all or not. In the same way, for many applications, the actual life of the tape must be tested, particularly under extreme environments. No standardized tests have been worked out for these special cases.

ENVIRONMENTAL TESTS

Tape recorders and tape for satellite and space probe use must pass severe environmental tests. Typical vibration, shock, temperature, humidity, and the rest of the space environment tests can be applied to the recorder. These need differ in no fundamental way from any other environmental tests. Exceptions may, however, need to be taken because the tape itself cannot pass a really severe heat test. Specialized ways of applying heat tests and of attempting to assure recorder reliability without the full application of the tests is often, therefore, necessary.

Other tests which recorders can pass if carefully designed but which require careful design are those of shock and vibration. Recorder vibration testing and isolation is discussed in chapter 11.

CHAPTER 13

Miniature High-Environment Recorders

As a valuable means of documentation, the tape recorder has accompanied every step of development of space technology. The large, ground-based instrumentation recorder has participated in the process of developing space technology from the beginning and will continue to do so with steady refinement from its "pre-space" form. Tape recorders small and rugged enough to accompany experimental vehicles did not, however, exist when the space program started. Such recorders had to be developed from the crudest of beginnings to meet the increasing requirements of progressively more sophisticated programs.

The first rugged miniature recorders were intended to ride right along with test rockets, the resulting recordings being recovered after the test and reproduced on ground equipment. The recorder was required only to withstand the test environment and then simply to allow the record to survive the abrupt return to earth. In later stages, rocket sled recorders had to continue to record during shocks comparable to those encountered in a crash landing. As the technology progressed, recorders which could survive insertion into orbit and then play back data to the ground on command were needed. Ruggedness, survival and performance were no longer enough; the recorder also had to use very little power and to be small and light in order to be included in the payload of the tiny booster capacities initially available.

The technology was inadequate to the tasks of the initial attempts. The flight recorder acquired at one time a very bad reputation in the space program because recorder failure at a crucial moment could cause the loss of most of the time and energy that went into a large experimental project. This temporary reputation, combined with all the other problems of developing a new device, resulted in the subsequent flight recorder development program being best described as conservative. If one considers the situation where a large part of the utility of a single satellite launching, which may cost many million dollars, may depend on data which is recorded on relatively fragile, normally heat-sensitive magnetic tape, the conservatism seems more than justified.

NASA has purchased many types of recorders as have other government agencies. NASA has also sponsored, directly or through subcontractors, the development of recorders to meet requirements where no commercially available unit met the need. This development has been concentrated in the field of flight recorders for severe environments. As a major customer for ground-based recorders and the various other equipments involved in data acquisition and reduction, NASA has naturally influenced the development of this equipment class as well, as would any major customer. Direct NASA sponsorship of *new* recorder technology, however, has been concentrated on the flight recorder.

The historian of the art of high-environment recording encounters certain difficulties because of the nature of the space program. Relatively small quantities have been needed of each specific recorder developed for a particular application. There may have been a couple of engineering models, a prototype or two, and a certain number of flight models, some of which were actually flown and others of which were employed entirely in preflight testing. Detailed instruction books and the usual amount of documentary material generated in the process of producing a production device is often lacking because of the small quantities involved. More documentation could very well have been done for some of these units, but the speed with which the space program has moved forward has militated against it. The result is that there is very little formal documentation of many specific recorders, some of which included features which were genuine innovations. In the following sections, an attempt is made to include those recorders for which the best documentation is available, emphasizing the innovative features. To assure as complete a review of the art as possible, many recorders developed for other services of the government are included, as are recorders which are proprietary developments of manufacturers.

Despite the impressive performance capability demonstrated by flight recorders currently being applied to the most advanced space programs, some of the older and less sophisticated "workhorses" are still in use. They should therefore be included in any general review of the development of the present state of the art of high-environment recorders. To provide this historical function and at the same time to describe the current state of the art, the next sections of this chapter will consider in order:

(1) the reel-to-reel recorder used with ground-based playback from physically-recovered tape,
(2) the reel-to-reel recorder commanded in flight to play back its recorded data, and
(3) the endless-loop recorder.

The unusual recorder formats required for special tape drives will then be discussed, as will transverse-scan flight recorders. Finally, certain mechanical design problems peculiar to miniature recorders will be considered.

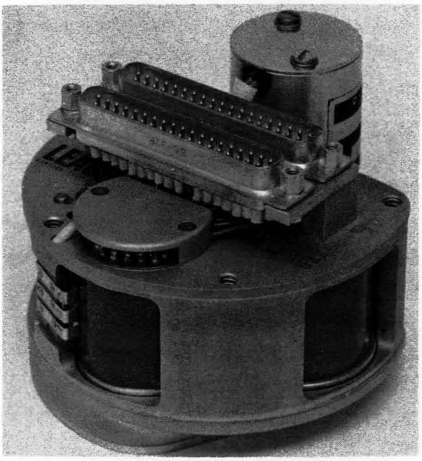
REEL-TO-REEL, RECORD-ONLY RECORDERS

One of the earliest forms of miniature high-environment recorder to be developed and used is shown in figures 13–1, 2, 3 and 4. Recorders of this type were developed and supplied by several companies including Leach Corporation, Borg-Warner Controls, Astro-Science, and Cook Electric. This recorder usually held 50 to 100 feet of half-inch or 1-inch tape in a reel-to-reel configuration. It is no criticism of the device to say that it was "brute force;" the entire objective was to get a mechanically rugged device into as small a space as possible. In some of the early sounding rockets in which it was used, not more than a 3- or 4-inch diameter tube was available for all the instrumentation and the recorder had to share this space with other devices. The flutter was often high and the carrier-erase technique of recording (chapter 4) was widely used since this permitted dc response and required minimum record electronics complication without the flutter-sensitivity of FM.

The initial tape metering and tensioning mechanism was extremely elementary. Some recorders used capstans with rubber pinch rollers in a conventional manner with mechanical drag on the supply reel and a slipping clutch on the takeup reel. The design concentrated entirely on getting some kind of a record under extremely high impact; the actual amount of power used was often not too important. Particularly with the short record time required, the design could be somewhat inefficient and still be satisfactory. When longer record times were demanded and the recorders were used in more sophisticated systems the efficiency and hence the method of tape drive had to be reexamined.

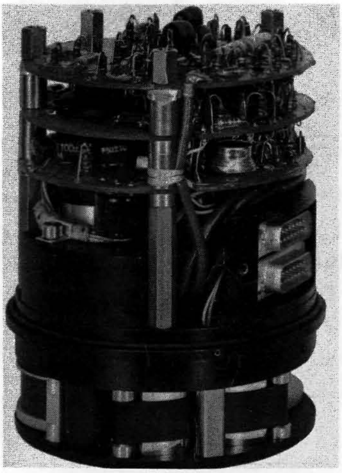
The following slightly edited statement by the chief engineer of one of the pioneer manufacturers of this class of recorder is self-explanatory in its coverage of the development of current capability:

"The original machine was puck-driven by a dc motor and was used for carrier-erase recording only. Since the original development, a gear drive has been substituted for the puck drive and an ac motor



(*photo courtesy Leach Corp.*)

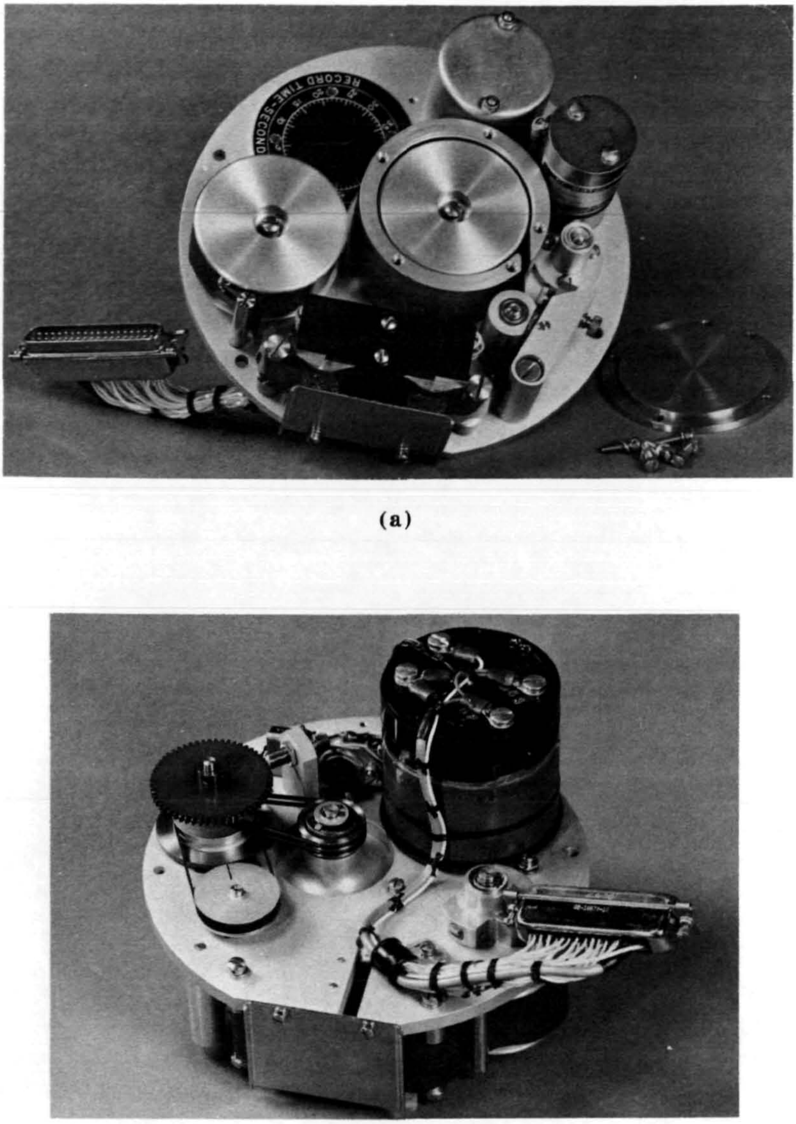
FIGURE 13–1.—The Leach Model MTR–362 miniature high-environment recorder.



(*photo courtesy Astro-Science Corp.*)

FIGURE 13–2.—The Astro-Science Model TR–1875 miniature high-environment recorder.

The tape path can be deduced from the parts of the tape visible as well as positions of the two reels on the extreme lower left and right with the pinch roller visible in the center left. This view shows early-1960's electronic construction in the rear of the mechanism.



(a)

(b)

(photos courtesy Cook Electric Co.)

FIGURE 13-3.—Front (a) and rear (b) views of the Cook Model MR-51 high-environment tape transport.

Note in (a) that the takeup reel is surrounded by a rugged housing to protect the recorded data. Note also, in (b) the gear-tooth-tonewheel speed-sensing mechanism. The tape path is clear in this unit as are the pressure pads for maintaining head/tape contact.

(photo courtesy Borg-Warner Controls)

FIGURE 13–4.—The Borg-Warner Model R–101 miniature high-environment recorder (the photograph is of an early version of this recorder which has been renumbered).

The small space for electronics shown in this photograph probably indicates that this particular unit took advantage of the simplicity of carrier-erase recording technique to limit the amount of electronics necessary.

has been employed to improve the speed regulation and environmental immunity of the machine. The simplicity of the machine is what makes its high-environment characteristics possible. Basically, it has a single capstan with a permanently engaged rubber pinch roller. The supply reel is held by means of a friction brake and the take-up reel is driven by means of a rubber-covered roller driving the perimeter of the reel. Slippage occurs in the center drive for the rubber-covered roller. The tape path is simply across the head and through the pinch roller onto the take-up reel.

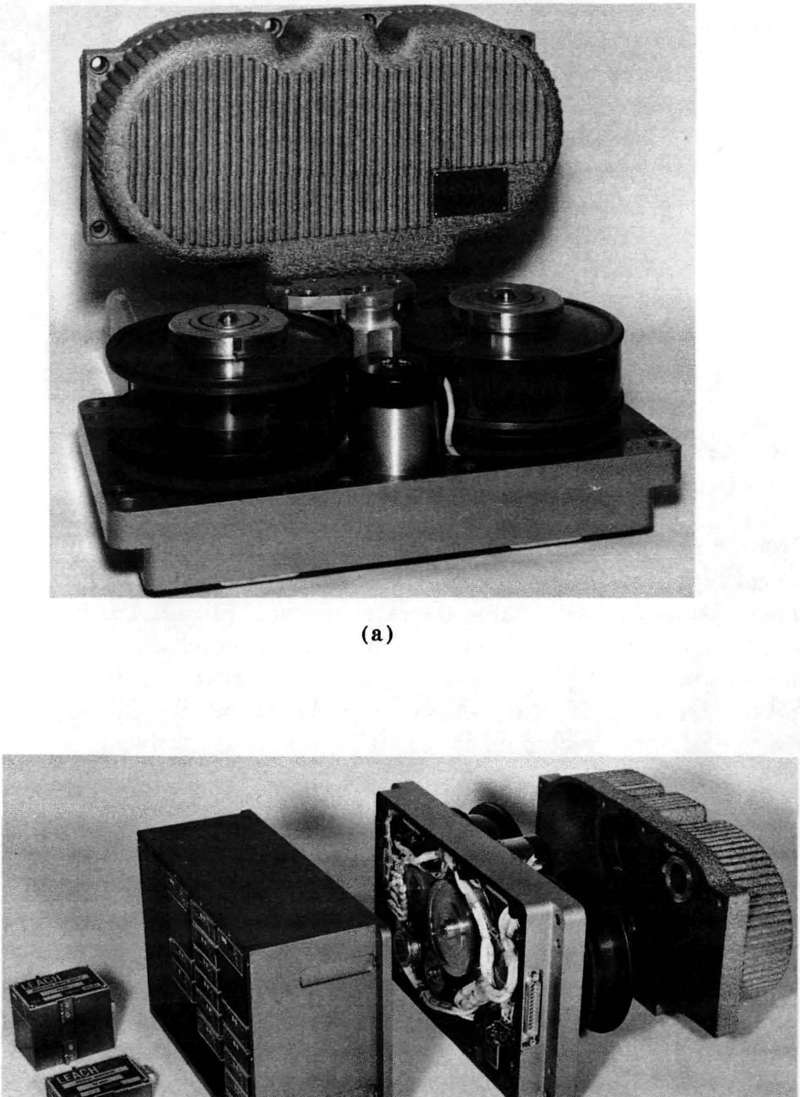
"Environmental test data have proved that it can start and run at 400 G's sustained acceleration with less than 3 percent peak-to-peak flutter. The machine will run at 600 G's sustained acceleration if started at a lower level with the same flutter characteristics. Shock tests have been performed up to 610 G's for 3 milliseconds. In this case, the peak-to-peak flutter does not exceed 2 percent. Higher shock levels up to 1,200 G's for shorter durations have been performed. In these tests, a stutter is observed with a recovery time approximately 50 milliseconds. The machine operates through extremely high vibration environment with a random input to the shaker of 0.8 G^2 per cps."

The development of this basic type of recorder was carried much further. Larger reels, more sophisticated tape moving mechanism, and more conventional electronics were added to its capabilities. Units of this general class, using about one-inch-wide tape moving from reel-to-reel in a very straightforward array, eventually acquired differential capstans and quite satisfactory tape motion. Such recorders were available essentially as commercial items fairly early in the high-environment testing business and were supplied by several organizations. An example of a typical recorder of somewhat larger capacity than the original cylindrical units developed before the move to differential capstans is shown in figure 13–5. It is essentially a small IRIG–standard instrumentation recorder for severe environment.

Quite a few straightforward tape recorders were developed for such record-only service as rocket sled data collecting and ejection seat testing, where size was relatively less important. These recorders differed radically in format and appearance from the miniature cylindrical type just discussed. A typical example is shown in figure 13–6. They use 1-inch-wide tape, operate between 10 and 120 inches per second, and usually record on from 8 to 15 data tracks, with rms flutter below 1 percent. They are driven by shunt-wound dc motors, often governor-controlled, and usually weigh between 9 and 20 pounds. A feature of these recorders is that the tape, as it is recorded, passes into a cassette (shown on the right in the figure) of very rugged construction. The idea is that, even though the recorder mechanism itself may not survive the impact, the tape in the cassette will do so.

Recorders were also designed to allow the record to survive reentry tests by being ejected just before impact of the reentry vehicle itself so that the recorder could be recovered after not quite as rugged an impact as that suffered by the test vehicle proper. Such recorders often actually recorded under relatively mild environments. One version of such a device is shown in figure 13–7. It is 5½ inches in diameter by about 7 inches long when encased, and weighs 5.3 pounds. It holds 900 feet of quarter-inch tape, operating at 45 inches a second for 3.6 minutes. In one particular application for this unit, IRIG FM subcarriers are recorded and flutter compensation can be applied to improve the overall flutter performance.

Clearly an offspring of the original reel-to-reel rugged recorder, but very specialized and subjected only to about the same environment as an astronaut is a recorder recently developed for bio-medical use in the Gemini spacecraft. It is shown in figure 13–8. The overall dimensions are 9 x 6.5 x 1.7 inches and the weight 4 pounds plus a half pound for tape. It records seven channels in direct mode for



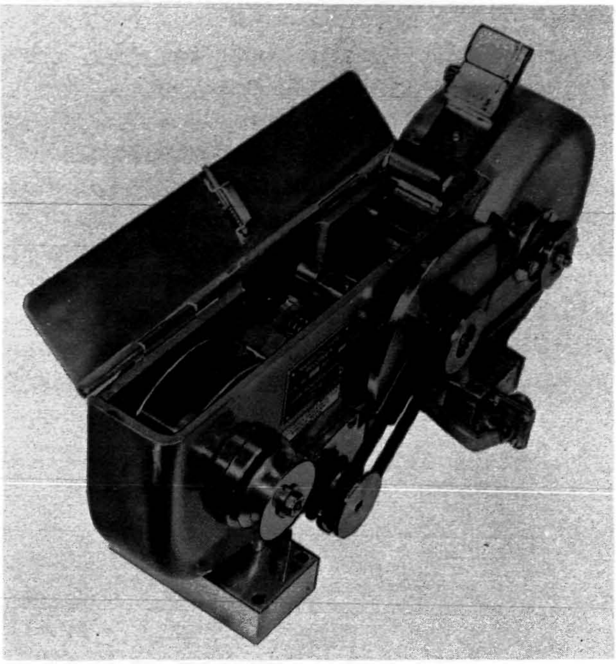
(a)

(b)

(*photos courtesy Leach Corp.*)

Figure 13–5.—The Leach Model MTR–1200 high-environment recorder.

(a) A closeup view of the reel and head structure, (b) an exploded view of the entire recorder showing another version of modular electronic elements.



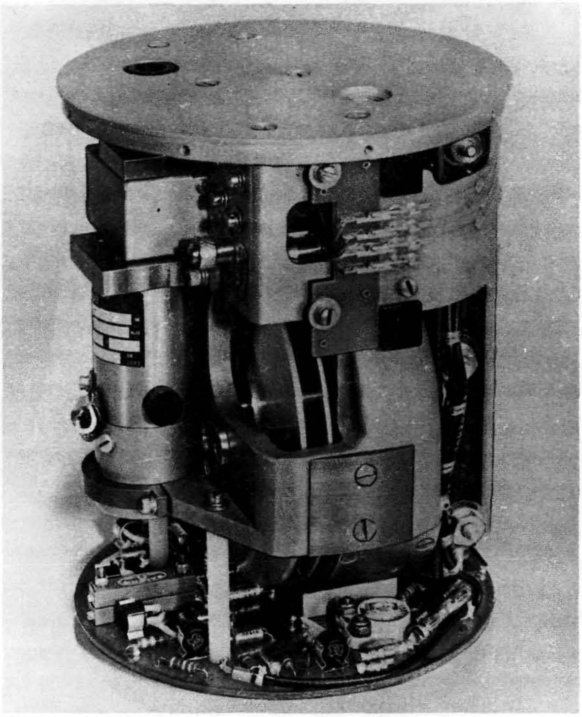
(photo courtesy Cook Electric Co.)

FIGURE 13–6.—The Cook Electric MR–31E high-environment tape transport.

Note the rugged construction of the cassette, upper right, designed to protect the recorded tape no matter what happens to the recorder.

100 hours using a tape capacity of 880 feet, operating at 0.0293 inch per second. Such data as electrocardiogram and electroencephalogram signals, blood pressure, temperature, respiration, and galvanic skin response are recorded by this device. The use of a direct record mode at this very low speed is relatively unusual.

The playback of the data from this recorder is done through a special preamplifier designed to deal with the phase problems existing at the very low frequencies involved in bio-medical recording. The tape is played back after recovery from the capsule (along with the astronauts) at 16 times its record speed or at 0.4688 inch per second. It is copied onto another tape, also operating at 0.4688 ips in an FM mode to preserve low frequencies and dc response. The first copy is then played back at 16 times its record speed or at 7½ inches per second through a conventional FM-mode playback amplifier for final data reduction. Thus a 256-to-1 speed increase is achieved.



(*photo courtesy Cook Electric Co.*)

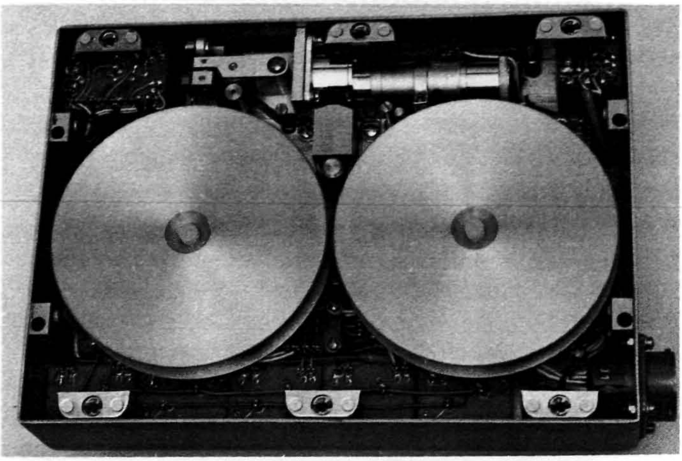
FIGURE 13–7.—The Cook Model DR–25–2 recording system designed for recoverable-capsule service (see text).

The recorded-tape cassette of rugged construction is visible to the right of the center line.

REEL-TO-REEL RECORDERS, RESPONSIVE TO PLAYBACK COMMANDS

The recorder shown in figure 13–9, designed for use on the Mariner A program, is at the same time one of the last stages in the development of the recorder type discussed above and an early example of the recorder group of the current heading. This recorder was developed to replace one similar to that shown in figure 13–5, but with capacity to accept playback command. It records and plays back at the same speed.

The recorder carries 80 to 90 feet of 1-inch tape which passes a 14-channel record and playback head driven by a differential-capstan scheme at 15 ips. The two capstans each have rubber pinch rollers and the downstream capstan (the one on the takeup side) is driven at 2 percent faster surface speed than the upstream capstan. The pinch roller pressures are so adjusted that the upstream capstan is



(*photo courtesy Cook Electric Co.*)

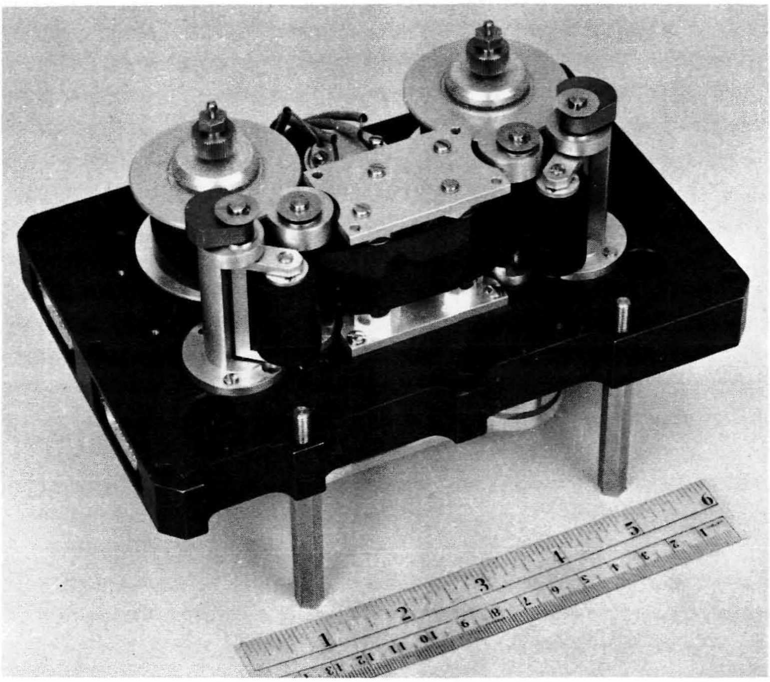
FIGURE 13–8.—The Cook Model DR–30C–7 biomedical recording system.

This is the Gemini biomedical recorder. Note the single head with its thick pressure pad (right of upper center) and the extremely long thin motor (above and to right of head).

the metering element and the tape moves essentially at the speed of the surface of this capstan. The downstream capstan is designed to slip but in so doing to maintain a controlled tension in the tape.

The drive motor for this unit is a 6,000 rpm, 400-cycle hysteresis synchronous one requiring 3½ watts and operating at an efficiency of approximately 40 percent. In the development of these transports it was discovered that conventional motor design could not approach this efficiency by as much as 2 to 1 and a specialized design was required.

The capstan is driven at 600 rpm through a two-stage reduction using Mylar belts. The capstan pulls the tape off the supply reel and the supply reel drive is supplied by a Mylar belt to the takeup reel through a clutch differential. The belting and pulleys are so arranged that the takeup reel is always slightly overdriven. This, of course, requires that a maximum amount of slippage be dealt with. That is, the full difference in speed between the supply and takeup reel is consumed in the clutch. Driving in this fashion avoids the use of two separate clutches, one acting as a brake on the supply reel and the other acting as a clutch on the takeup reel, with the consequent potential unreliability. One of the interesting aspects of this recorder is that, with indirect drive of the takeup, a complex belting system, and a motor with an efficiency of 40 percent, it still can be accelerated or reversed in 1 second.



(*photo from a NASA report*)

FIGURE 13–9.—A reel-to-reel tape transport designed for the Mariner A program.

This recorder, although never flown, was given at least preliminary vibration tests and survived them. It is interesting to note that there was no means of relieving the pressure between the pressure roller and the capstan and it was therefore possible for a flat to develop on the pressure roller. The probability of the elastomer surviving a temperature cycle and a long storage period with a continuously applied pressure seems not very great.

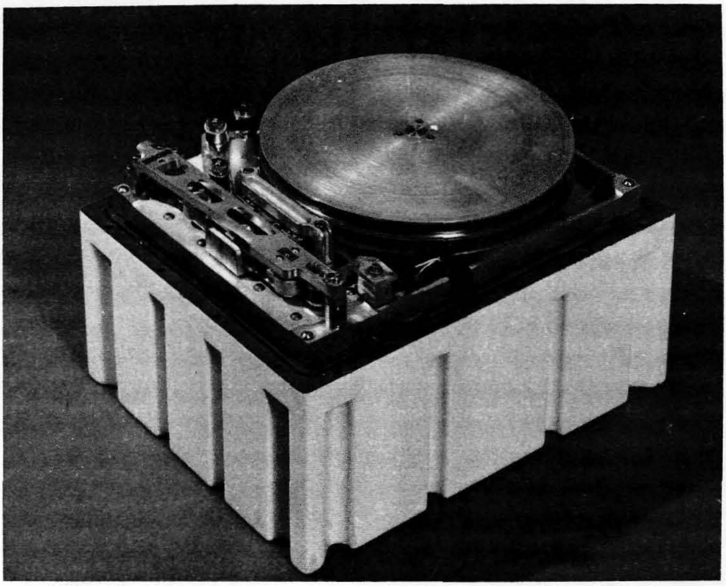
A basic problem of a reel-to-reel recorder that must record and playback on command is that it must not only be able to reverse itself, but must be provided with various safety mechanisms to be sure that the tape is, in fact, stopped or reversed before the end is pulled off the reel. On many occasions the author of a paper who is busy apologizing for some shortcomings of an endless-loop recorder justifies the use of such a recorder on the basis of its avoidance of the complications of control of a reel-to-reel device. Given the control complications, the recorder engineer immediately attempts to put as much storage capacity into the recorder as possible to justify them. The Mariner A recorder described above was therefore probably the only reel-to-reel recorder subject to ground command which held as little tape as 75 feet.

It does not seem possible or profitable to attempt to follow in detail the development of the current reel-to-reel ground commandable recorder. There are many such recorders currently available in a relatively fixed format, plus a few somewhat unusual ones for special applications. The discussion of this section will be limited to a description of representative recorders of this class.

The most widely-used reel-to-reel flight recorder has the reels mounted co-axially, uses differential capstans, substitutes tape wrap for the pressure roller at the capstan and maintains reel tension by means of Negator springs. Examples of such recorders are shown in figures 13–10, 11, and 12. The Negator spring-tensioning system is implemented differently by each manufacturer and sometimes varied by the individual manufacturer for different applications. A representative tensioning system is shown in the photograph figure 13–13 and in the diagram figure 13–14.

(*photo courtesy Leach Corp.*)

FIGURE 13–10.—The Leach Model MTR–2100 coaxial-reel flight recorder.

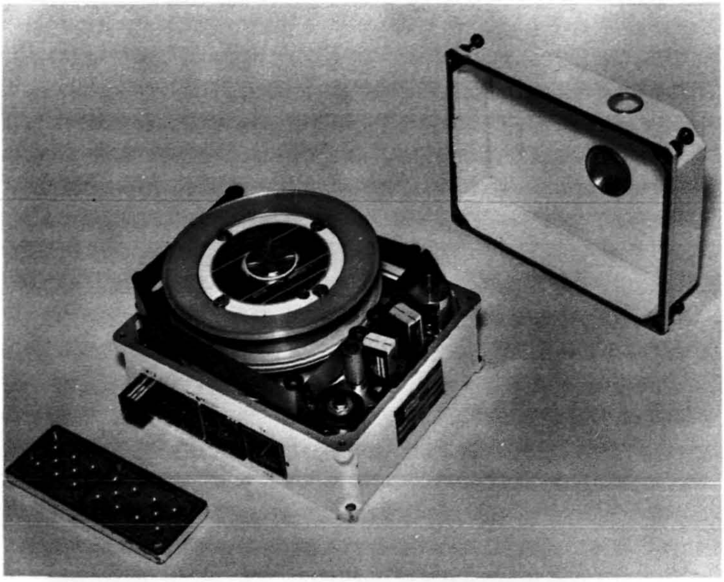


(*photo courtesy Precision Instrument Co.*)

FIGURE 13–11.—The PI type PS–303T coaxial-reel flight recorder.

Many of these recorders operate at one speed for record and another for playback. Some of the more subtle aspects of achieving this dual-speed operation are discussed in a later section. Two rather straightforward ways of achieving dual-speed operation are shown in figures 13–15, 16, and 17.

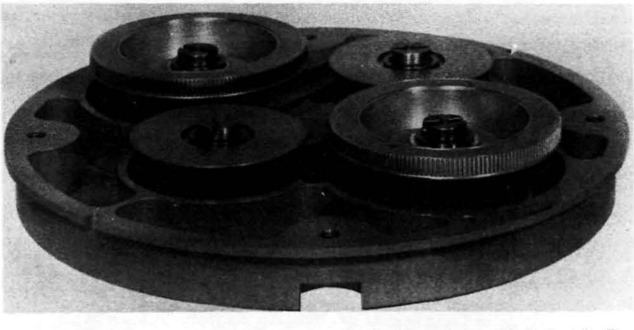
Figure 13–15 shows a capstan-drive system operated at two speeds by a single motor operating always at the same speed. It involves the use of a magnetic clutch to perform the speed shift. (It may be assumed that this is for a unit which records relatively slowly and then plays back rapidly.) In the slow-record mode, the motor drives the shaft pulley and clutch element combination labeled "High Speed Input" through a plastic belt speed reduction. This jackshaft is belted to another intermediate shaft which carries the flywheel and which, in turn, is belted to another jackshaft which is so labeled in the drawing. The second jackshaft turns somewhat slower than the flywheel and, in turn, the pulley labeled "Low Speed Input" is driven at a still lower speed by an additional plastic belt. When the magnetic clutch is not activated (this is the condition shown in the drawing), the low speed input drives by clutch friction the shaft labeled "Clutch Output." This shaft is belted in turn to one of the two capstans which is connected by still another belt to the second capstan for differential action. When the clutch is activated, the cross-hatched



(photo courtesy Ralph M. Parsons Co.)

FIGURE 13–12.—The Parsons Model AIR–940 coaxial-reel flight recorder.

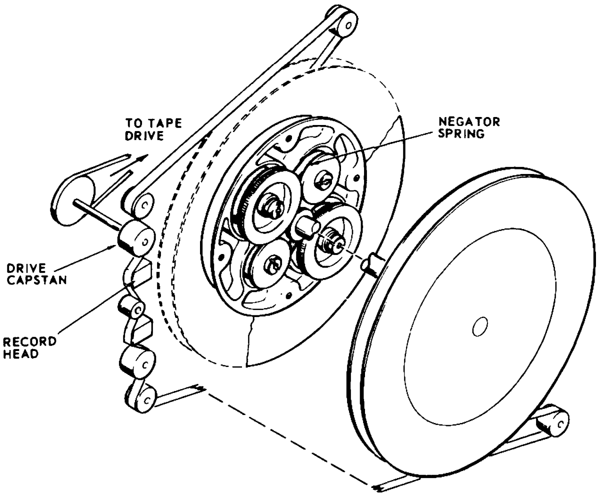
This particular version of this recorder is currently being supplied to the NASA Flight Research Center at Edwards Air Force Base and is representative of the large number of variations on this basic format manufactured by the Parsons Company.



(photo courtesy Ralph M. Parsons Co.)

FIGURE 13–13.—Negator springs as employed to provide holdback and takeup torque in a coaxial-reel recorder.

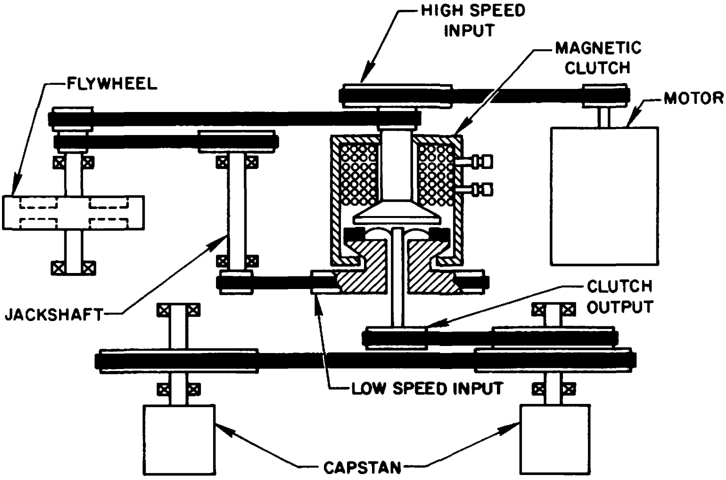
The "S" configuration of the springs can be seen, as can the gears needed to transmit the spring torque to an output shaft.



(*drawing courtesy Ralph M. Parsons Co.*)

FIGURE 13-14.—Exploded mechanical schematic of the Negator tension system shown in figure 13-13.

This configuration of springs forces the two reels to rotate in opposite directions.



(*from a Leach Corp. drawing*)

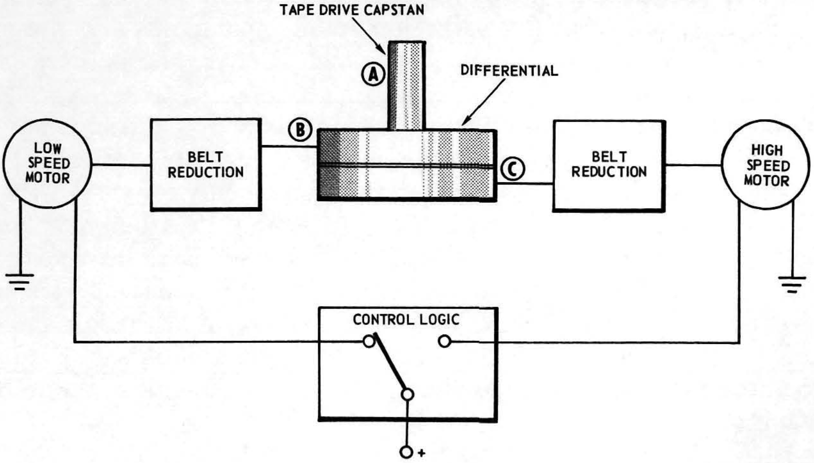
FIGURE 13-15.—A solenoid-clutch-operated speed-change mechanism for a differential-capstan flight recorder driven by a single motor (see text).

member, which is mounted by a bellows to the output shaft of the clutch, is drawn away from the low-speed input point and presses against the high-speed input. The clutch output then is driven at the higher speed.

The mode chosen when the clutch is activated is the high-speed mode because the high-speed mode obviously lasts for shorter length of time. The clutch current is therefore needed only for a short time. The particular form of clutch shown desirably does not have any moving magnetic elements. The flywheel is used as an intermediate element in the low-speed drive where its filtering action will be more effective because the filter action is more important at the low speed. This explanation and drawing is somewhat over-simplified and diagrammatic but is intended to illustrate here the principle of the active clutch for speed change.

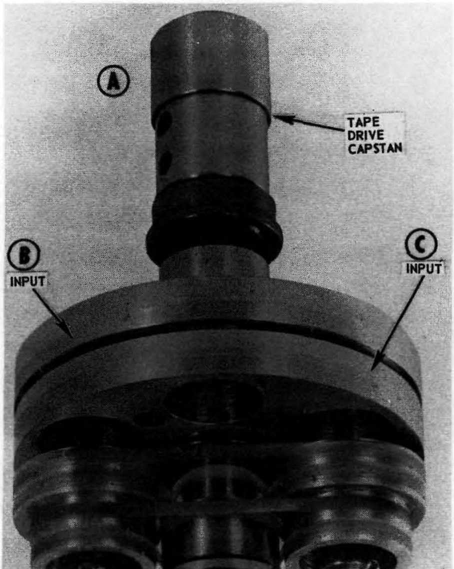
An alternate method of obtaining two-speed operation which involves two motors but no mechanical clutches is illustrated in figures 13–16 and 17, which were provided by the manufacturer. In this operation, the speed of the capstan A is dependent on the algebraic sum of the speeds of the two possible drive pulleys B and C. For low-speed operation the starting friction of the high-speed motor multiplied by the belt reduction from that motor to pulley C essentially locks C in a fixed position. The low speed motor then drives B and B in turn drives the capstan A. With the control logic switch in the other position, pulley B is essentially locked and the speed of A is dependent on the speed of pulley C. In this particular device, as shown in the photograph of figure 13–17, there is also a reduction ratio within the differential proper. The nearer large pulley carries the pivots for the small pulleys and the entire structure rotates as one. The far pulley is locked to the smaller diameter of the two pulleys on the center shaft. If B, the far pulley, is locked in position and C is caused to rotate, the small idler pulleys on the outside of C rotate around their own pivots as well as the whole assembly rotating. The motion of the small pulleys is transmitted to the larger center shaft pulley according to the reduction ratio between the two pulley-pairs involved. This larger center pulley drives the capstan. The assembly then provides, if B is allowed to rotate, an output speed which is the alegbraic sum of B and C but modified by the small pulley diameters involved.

Many versions of the co-axial reel-to-reel recorder are available commercially and they have been applied for many different services. The general physical arrangement of these recorders is apparent from the photographs. Although the developers of these units emphasize individual novel features in recommending their use there is a certain



(*drawing courtesy Ralph M. Parsons Co.*)

FIGURE 13-16.—A two-motor two-speed flight recorder drive system using a differential to connect the separate drives to the capstan without clutches (see text).



(*photo courtesy Ralph M. Parsons Co.*)

FIGURE 13-17.—A plastic-belt-driven differential capstan drive for a flight recorder, such as used in the system of figure 13-16 and as described in the text.

similarity between the various designs which will be described by reference to figure 13–12. (This figure is chosen not to recommend or criticize its particular design but because the photograph shows the tape path more clearly.) It will be noted that the tape is led around two sides of the case from its exit from the reel to its engagement with the capstan. This is done to minimize the twist imparted to the tape in transferring from between the reels located at two different levels. Although the twist cannot be avoided, the unequal stress it places on the tape is minimized by spreading it out over a long distance. Another common feature visible in this recorder is that the path of the tape around the capstan is so arranged as to provide almost a 270° wrap. (The capstan is the lighter-colored roller nearer the camera, just to the left of the head.) The same kind of wrap is provided at the far capstan but it appears from the photograph that the actual wrap is accomplished with an unflanged roller, while the side guiding of the tape is being handled by a flanged roller some distance from the capstan. It will be further observed that the case of this recorder is quite ruggedly constructed and has provision for gasket sealing against the environment.

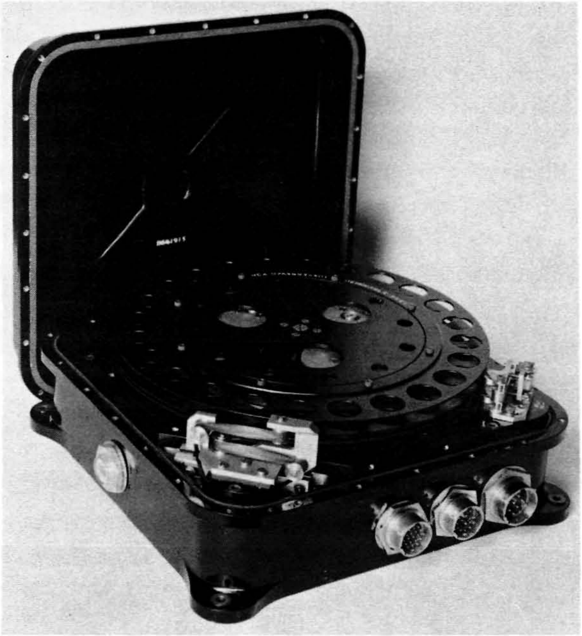
The electronics is also of modular construction which is typical of such devices. In figure 13–10 a somewhat lighter construction of recorder is shown where a somewhat different technique is employed to minimize the amount of tape twist.

It must be realized that there are many forms of these recorders and that every manufacturer individually modifies his principal design for different applications. However, the general functional and structural concept appears to be quite sound, which explains the wide use of this general format.

In addition to the co-axial recorders just discussed, which have been very widely applied, it seems appropriate to describe in some detail some specific NASA-sponsored recorders which have been developed for particular programs. Three such recorders will therefore be described in the following paragraphs.

A coaxial-reel recorder of fairly standard format but exhibiting some unusual features was recently developed for the Gemini program. This recorder is designed to receive two channels of PCM data from on-board systems of the Gemini capsule, to record this data for 4 hours at 1⅞ inches per second and to play it back on command at 22 times that speed or 41.25 inches per second. The playback occupies 10.9 minutes.

The general arrangement of the recorder can be seen from figure 13–18. This recorder uses quarter-inch tape wound on reels of relatively low inside/outside diameter ratio but adaptable to direct play-



(photo courtesy Radio Corp. of America)

FIGURE 13–18.—The Gemini PCM recorder.

The two 90° tape twists are arranged to provide edge-guiding forces (see text).

back on standard NAB reel recorders. The tape tension is maintained by a series of four Negator springs operating between two reels which rotate in opposite directions. With the low inside/outside diameter ratio of the reels and opposite directions of rotation, the addition of a single flywheel brought the residual rotational inertia of this unit to a very low value.

The tape path contains two rather sharp 90° twists as can be seen in the front of the picture. Although this produces the nonuniform stresses in the tape which have been discussed elsewhere, this recorder is so designed that the lateral aligning forces, by which the tape in being twisted attempts to regain its original form, are used to provide a positive edge guiding influence and are claimed to reduce the skew to an extremely low value.

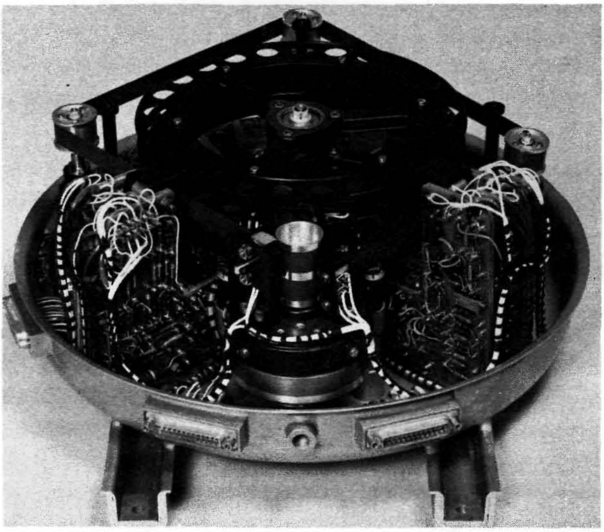
Another interesting feature of this recorder, about which no detailed data is available, is the use of the speed-change mechanism. The two speeds are achieved through two different plastic belt mechanisms connecting the motor to the capstan at different reduction ratios. The shift between the two belts at the capstan is achieved by what is described by the manufacturer as a "hysteresis speed changer." This device, which appears to operate somewhat like a hysteresis synchronous motor, energizes one of two stationary coils to transmit the motor power to a selected belt transmission system.

This recorder employs a modified diphase recording technique to achieve a high packing density and self-clocking action. The packing density is 2,730 bits per inch and the modulation scheme guarantees one flux change per bit cell. A one is represented by a change of flux in the center of the cell and a zero by the absence of such change. The reproduce scheme involves having a precision one shot multivibrator time an interrogation of the flux value three-quarters of a bit cell after the start of the cell. If the flux value is the same as at the last inquiry the bit under examination is a one; if it differs, the bit is a zero (Katz [1964]).

This particular self-clocking mode appears to have certain advantages for relative high packing density. The self-clocking feature is used to derive a control signal for operating a phase-locked-loop playback scheme. In this system the data is essentially read out by a multivibrator oscillator in a phase-locked-loop which is locked to the clocking impulses in a somewhat loose manner. The particular playback scheme provides an output which is smooth in time jitter or short-term jitter but follows long-term speed variations so as to guarantee accurate data, although leaving some irregularities in output bit rate.

Perhaps the most sophisticated reel-to-reel commandable recorder flown so far is that employed to record the output of the AVCS (Advanced Video Camera System) and HRIR (High Resolution Infrared) systems aboad the Nimbus satellite. Two different forms of this particular recorder are used for these two applications but the two are almost identical physically in the two cases. The basic unit is shown in figure 13–19 (Burt, Clurman and Wu [1963]).

The following description, adapted from that of the designers of this recorder, is a general review of its design techniques. The tape is stored on and exchanged between two parallel co-axial reels approximately ¾ of an inch apart. As the tape leaves one reel, it passes around a series of four rollers and enters the second reel. The axes of two of the rollers are inclined at slight angles to the reel axis in order to lead the tape out of the plane of one reel and into the plane of the second. These angles are computed so that if all components are perfect the tape will track perfectly. To correct for any unavoidable small errors, however, two of the rollers are slightly crowned to provide a restoring action for any small lateral displacements of the tape.



(*photo courtesy Radio Corp. of America*)

FIGURE 13–19.—The Nimbus AVCS and HRIR tape transport.

The tape passes around one of the rollers twice—once upon leaving one reel and again upon leaving the second reel. This roller is belt driven by the motor and serves as the tape drive capstan. The capstan has an effective tape wrap of nearly 360°. The double contact of the tape with the capstan constitutes in effect a closed-loop system; this tends to cancel out at the capstan disturbing torques due to some low-level transients in the tape tension. The tension from the tape outside of the closed loop is provided by Negator springs which torque the two reels in opposite directions. The presence of the steady torque from the springs permits the large wrap around the capstan to develop enough friction to avoid the use of pressure rollers. It is interesting to note that whereas for 1,200 feet of tape one of the reels turns about 750 times, the relative number of turns between the reels in this case which is the number of turns the Negators have to deal with is only 50, or $1/15$ of that value.

Since two speeds are required in this recorder, although different speeds for the two applications, a planetary belt reduction scheme is used similar in principle if not in execution to the one discussed above. For the AVCS system this recorder runs at the same speed on record and playback. For the HRIR system the record speed is $1/16$ of the playback speed. The record speed is 30 ips, as is the playback speed for the AVCS, and the HRIR record speed is $1\frac{7}{8}$ ips.

This recorder is quite good in flutter performance, delivering about 0.02 percent rms between 0.5 and 30 cycles per second and 0.10 percent rms between dc and 5,000 cycles per second. Despite these rather impressive flutter figures, as noted in chapter 14, it is necessary to compensate for picture displacement in the high-resolution vidicon pictures handled by this recorder.

In AVCS service, a 60 kcps-bandwidth signal is recorded in FM mode. The actual subcarrier deviation is from 73 to 120 kcps, indicating that the modulation scheme resembles that used for rotary-head video recorders. The HRIR data has a bandwidth of 5 kcps and is also recorded in FM mode. Erasure for the AVCS is accomplished with no power consumption through the use of a 3-permanent-magnet dc erase scheme. This method is not usable for the HRIR because the latter carries two tracks, recorded in opposite directions, and the unused track would be ruined by permanent magnet erase.

The recorder used for OGO for orbital data storage had to be of reel-to-reel format because of the long storage time required (12 hours). This recorder, which actually is the predecessor of the Nimbus unit described above, uses the same general physical layout (Weintraub, D'Amanda and Resek [1964]).

Two forms of the same recorder are used in OGO. The first for EGO (the Eccentric Orbiting Observatory) is the one which requires the long storage time. The highly eccentric orbit of this satellite has an apogee of 60,000 miles and a perigee of 400 miles. The second OGO, known as POGO (for "Polar Orbiting Geophysical Observatory"), is scheduled for later launch with an apogee of 570 miles and a perigee of 160 miles. In EGO the data may be collected for a continuous 12-hour interval and played back in 11½ minutes. In the POGO mission, data is collected for 3 hours and played back in 5½ minutes. In either case, a total storage capacity of 4.3×10^7 bits is provided.

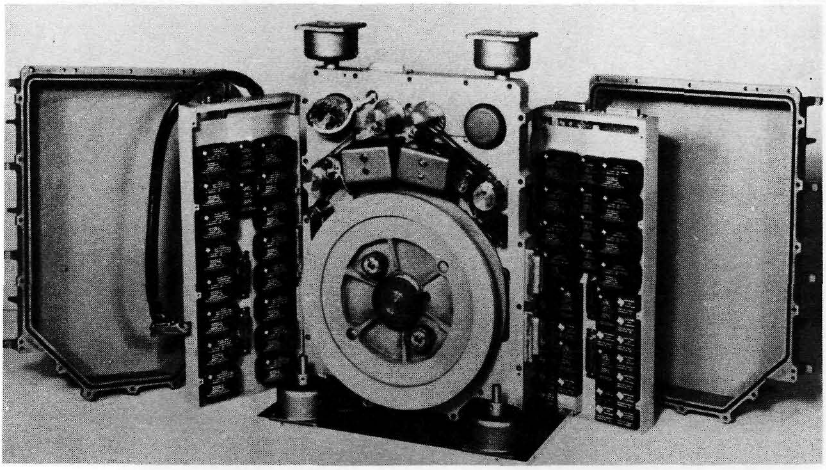
The OGO recorder has an effective tape packing density of 3,375 bits per linear inch but it achieves this by providing 9 tracks with an individual track density of only 375 bits per inch. It is designed for a very good error rate, between 1×10^5 to 5×10^6 bits per error.

For EGO the record speed is 0.296 ips for 12.2 hours and the playback speed is 18.96 ips for 11.4 minutes. For POGO the record speed is 1.18 ips for 3.05 hours and the playback speed is 37.9 ips for 5.7 minutes. In each case the recorder is responsible for conversion from serial input to parallel recording and from parallel recording back to serial output.

An interesting difference between this and the Nimbus recorder is that the two reels travel in the same direction and the residual angular momentum is reduced by a necessarily larger flywheel than needed for Nimbus.

One extreme was perhaps reached in the coaxial-reel commandable flight recorder with the 10^8-bit unit developed for the Mariner program. This unit carries 1,800 feet of 1-inch tape and records on seven data tracks and one sync track at 24 ips. The gross data input rate is 83,333 bits per second, and this can be played back at 84, 168, 336, or 672 bits per second. The record-playback speed ratio reaches a maximum of 1,000-to-1, and the slowest playback speed is 0.024 ips. The particular recorder developed for this program uses many of the techniques discussed later under the Mariner 10^6-bit and 10^7-bit endless-loop recorders. The 10^8-bit unit also had to provide a phase-locked-loop playback scheme to operate at four different speeds. In this recorder, serious consideration had to be given to the effects of sterilization temperatures as high as 145° C for the first time.

Figure 13–20 is a photograph of the prototype 10^8-bit recorder.



(photo from a NASA report)

FIGURE 13–20.—The recorder designed to store 10^8 bits of information, developed by Raymond Engineering Laboratory Inc. for the Jet Propulsion Laboratory Mariner program. One reel is visible; the other is located in a symmetrical position on the other side of the mounting plate.

THE ENDLESS-LOOP RECORDER

Mechanisms for supplying strips of material from a reel-like pack and returning it to the same pack have existed for many years. Endless-loop motion picture projectors have long been available, using a storage geometry which resembles closely that of the current endless-loop flight recorder. For some time, endless-loop tape recorder cartridges have been commercially available from several manufacturers. These commercial cartridges are used primarily for "point of sale" message repeater devices in retail stores or for storing commercial announcements for radio stations. Although most such commercial tape packs hold only a few feet of tape, some have a capacity that reaches or even exceeds that of current endless-loop flight recorders.

The existence of these commercial endless-loop tape cartridges and their successful use for many years did not produce a cartridge technology that could be relied on to provide reliable endless-loop flight recorders. This is simply because the commercial tape cartridge does not have to have the level of reliability of the flight recorder cartridge and because it is not subjected to any kind of severe environment. The commercial and flight recorder cartridges are identical in principle. The tape is wound in each case on a one-sided reel of the sort that would be called in the motion picture industry a "flange." The tape is supplied from the center of the pack by being pulled out between the inner layer of the pack and the hub of the flange or reel. After passage through the recording mechanism it is wound-up on the outside of the pack. With a simple flat flange as described, the hub of the flange follows the tape as it is pulled off and hence rotates at a speed which is the linear velocity of the tape divided by the circumference of the hub. The hub-flange combination is therefore over-driven as far as the rest of the tape pack is concerned since every other part of the pack is larger in diameter than the center. This overdriving force is that which winds the tape up on the outside of the pack.

The same geometry guarantees that every layer of the tape pack is moving at a different speed from its inside or outside neighbors. Since the tape is pulled out at a certain linear speed at the inside and wound up at the same linear speed at the outside, the linear tape speed is the same at all points. However, as the diameter of the individual layers increases gradually from the innermost to the outermost layer, the rotational velocity of each layer must correspondingly decrease. This relationship is responsible for the continuous slip.

With the geometry just described there is a holdback force opposing the pulling of the tape from the inside of the capstan, made up of whatever holdback force in the external mechanism opposes the winding up of the tape on the outside transmitted through the interlayer friction of the pack to the inside layer. If the friction between layers is high, these forces will be transmitted freely through the pack. However, if the interlayer friction, which is certain to be nonuniform from layer to layer and probably to be of the stick-slip type, is too high, the pack will probably jam. Any practical application of such a pack thus requires that there be interlayer lubrication. (No one has ever been able to reduce the interlayer friction to the point where it is too low for tape windup.) The supply and takeup forces produced by and working on the pack are thus created by a complex relationship between the rotating friction of the supporting flange and hub and the tape interlayer friction, which in turn is based on the coefficient of friction between the layers and the interlayer forces which depend on the tightness of the pack.

For the commercial application of this principle, development was largely by frustration. Endless-loop tape packs always have had a reputation for jamming more easily than any other kind of tape recording equipment. Gradually a body of practical know-how on tape lubrication and pack geometry has grown up. The same process had to take place in the development of the endless-loop flight recorder, but had to proceed by a somewhat more systematic route.

If the ratio of the inside to the outside diameters of an endless-loop tape pack is low, that is if the ratio approximates unity, the relative velocity between layers is also low. Put simply, if n is the ratio of the outside diameter to the inside diameter and there are m layers, the interlayer velocity is the mth root of n multiplied by the velocity of the outside of the pack. Early recorders (Project Vanguard, for example) used only 75 feet of tape in a very slim pack. The interlayer problems were relatively small for this recorder. As the tape length requirements grew, to 200, 300, 600 and now 1,200 feet, in as compact a recorder as possible, the interlayer problems have grown as well. In the earliest endless-loop flight recorders, the tape pack performed the normal supply and takeup functions in much the same way that these must be performed for an open-loop recorder. A single capstan was used which pulled the tape forward over the heads against the holdback force of the tape being pulled off the center of the pack. There is invariably a holdback force at the center, no matter what the bulk of the pack does, because of the friction involved in extracting the inner layer from the space between the next layer of tape and the hub. This holdback force, however, is relatively irregular, and as the pack size grows, the irregularity grows. Thus, as larger tape packs and better tape moving performance were demanded, a basic change from the original open-loop tape-metering configuration was required. The change was to the differential capstan, a configuration which placed the burden of maintaining tension across the heads entirely on two capstans, the up-stream one rotating slightly faster than the down-stream one. The pressure of the roller holding the tape against the up-stream or supply capstan is adjusted to a force great enough to assure that this capstan does the actual metering of the tape and overcomes as far as possible irregular holdback forces in the pack. The down-stream capstan, being slightly over-driven, slips continuously, with somewhat less roller pressure, to maintain the tension across the heads.

With a solid hub-flange combination, there is continuous overdrive of the flange relative to each layer of the tape in the pack, since the hub rotational rate is dependent on the minimum or inner diameter. Friction between the edges of the tape and the flange provides a force tending continuously to wind the tape up. This force is one of those involved in providing take-up of the entering section of tape on the outside of the pack. As packs increased in size the friction between the flange and the rest of the pack increased to the point where ball-bearing rollers were substituted for the flange in the interest of reducing the total motor load. When rollers were substituted, much of the wind up force, present with the solid flange, disappeared, since there is no positive drive from the hub to actuate the rollers. Although not a problem in medium-sized cartridges, for larger cartridge packs it was found necessary to put steps in the diameter of the rollers so as to guarantee that there would be a certain amount of overdrive to the outer layers of the tape (Stark [1964]).

Obviously, the interlayer friction problem requires that the tape have good lubricating properties and the difficulty of obtaining these properties has been one of the leading forces slowing down the development of the endless-loop recorder. The mechanical interrelationships in such a device are discouragingly complex. For example, unless the interlayer friction is low enough the pack will jam up and the recorder will simply not work; the major tape takeup force, however, is generated by the interpack friction and the two influences must somehow be reconciled.

Inherent in any such recorder is a twisting and warping of the tape as it leaves the center of the pack. The effect of this distortion on the tape path must be prevented from causing flutter at the head. Endless-loop recorders developed recently for the Aeronomy Group at Goddard Space Flight Center have therefore provided a shallow groove, as wide as the tape, in the capstan pressure roller to improve the guiding of the tape at this point. Work is currently under way in the Aeronomy Group to study the "peel off" geometry in detail and to provide positive guiding of the tape during this entire operation.

In addition to "jamming up" of the pack, a basic tape handling problem with endless-loop recorders is that under certain conditions a "loose loop" may be formed. This means that with marginal takeup forces severe mechanical environment stresses may cause a loose loop of tape to appear between the end of the useful tape path and the takeup function in the pack. The tape used in such recorders tends to shrink on heating; the amount of tape which is placed in the pack must therefore be so adjusted that the pack will neither jam from over-shortening of the tape nor throw a loose loop. The pack must be somewhat loose to control intrapack friction and yet means must be provided for taking up possible excess tape. For example, adjustment of the diameters of the tapered pack-support rollers can control the takeup relationship.

An endless-loop recorder may be required to operate during the launch phases of a space operation and this means it will be required to continue to operate under shock and vibration, as well as perhaps at severe temperature extremes. Under some circumstances this may be an advantage; some endless-loop machines throw a loop *unless* they are operated during launch. Recently an endless-loop recorder with a particularly large tape pack could not be flight-qualified until snubbers were designed to maintain the pack in position in the non-operating mode during launch. Without the snubbers, a loose loop appeared as the pack "shook down" during the launch vibration.

A general treatment of the static and dynamic characteristics of the endless-loop tape pack presents extraordinary analytic problems. Certain rather simple relationships have been established between the parameters of the pack but any attempt to construct a mathematical model has resulted in conclusions largely inapplicable to the practical tape pack (General Kinetics [1963]).

Quite a few modifications of the basic circular pack in the endless-loop recorder have been tried to minimize the intrapack friction. One particular concept which has been thoroughly investigated on paper but does not seem to have found its way into much flight equipment is that of the so-called "square-loop" tape pack. Figure 13–21 shows the basic difference between a square-loop and a circular-loop array. The idea behind the square loop is simply that the only friction between the layers of a square loop configuration occurs at the corners. If the size of the square can be increased and the radius of the corners left the same, the length of tape may be increased almost without limit without increasing the amount of friction. No friction occurs between layers during the straight travel between the corners because the linear speed of the tape in all parallel paths is the same. Therefore, for example, if one has a 3-inch diameter circular tape pack one can, as it were, cut the pack apart into four quadrants and insert lengths of straight tape between those quadrants. In theory this decreases the amount of friction for the amount of tape stored. In practice the large addition to size resulting from this configuration

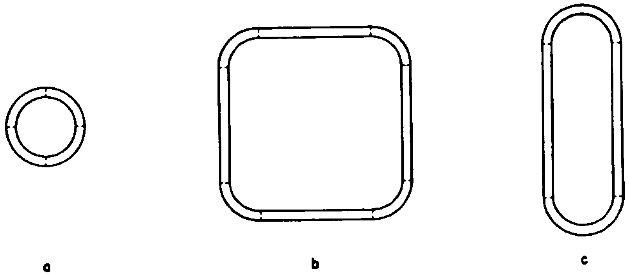


FIGURE 13-21.—Endless-loop tape configurations.

The compact circular tape pack of (a) can be "cut apart" and straight segments of tape added thereto to produce the larger storage arrays of (b) and (c) without adding interlayer friction (see text).

and the greater difficulties of controlling the tape over the straight portion compared to the geometric simplicity of dealing with it in a circular pack have prevented extensive use of this concept. The inertia-compensated recorder and one other reentry recorder discussed elsewhere use modified versions of this particular configuration. In these two recorders the loop is not square but oval and there are simply two straight portions between semicircular ends (fig. 13-21c). In the application for which these recorders are designed other characteristics necessarily reduce the effectiveness of the reduction in friction and in most cases the internal friction for the guiding necessary to produce the oval loop configuration loses much of the advantage of the reduced friction.

The many problems discussed above may make it appear that the endless-loop recorder could not successfully meet the challenging requirements of flight application. It is a tribute to the skill, resourcefulness and persistence of the engineers who have undertaken the development of such recorders that the low-to-medium-capacity endless-loop recorder can now be described as a very reliable device. One has only to note the long and useful lives of many such units in unattended space application, as described in the following pages, to be convinced of this accomplishment. With the current level of technical effort directed toward increasing the tape capacity of the endless-loop recorder, it can be anticipated that it soon will be possible to remove the modifier "low-to-medium-capacity" from the sentence above.

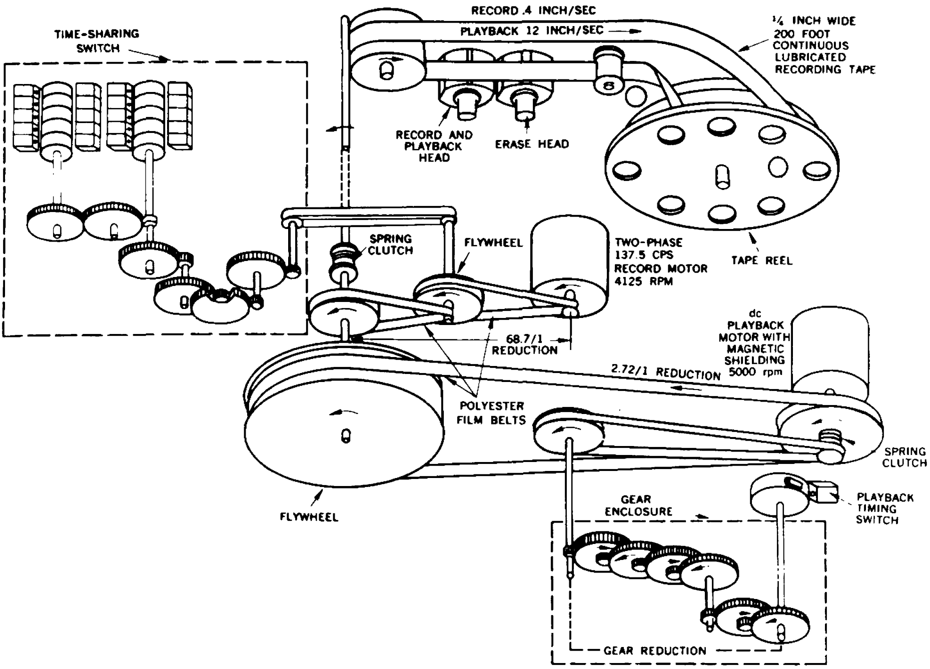
The endless-loop recorder has specific application to the satellite and space probe field because it permits operating continuously without having to provide the complex control modes involved in reversing a reel-to-reel recorder. One of the first of these units to fly was that on Score I which carried 35 feet of tape in an endless-loop and recorded at 3¾ inches per second for 4 minutes. Its major purpose was to repeat voice and teletype messages on ground command. The Vanguard II recorder carried a 75-foot continuous loop of tape and operated on interrogation from the ground station to repeat data on cloud brightness.

The tape capacity, number of tracks, and general performance level of the endless-loop recorder have gradually increased. The Tiros satellite contained a recorder employing a 200-foot endless tape loop for storing the data for the low-resolution radiometer. This was in addition to the reel-to-reel recorders used for the weather pictures themselves. The Orbiting Solar Observatory which has appeared in two forms, OSO–1 and OSO–2, has in each case employed a somewhat larger endless-loop recorder. A 285-foot loop was used in OSO–1 to store analog FM data and the same length of tape was used in OSO–2 to store PCM data. A somewhat smaller recorder, following the modular scheme of construction discussed in chapter 11, was developed for the UK–2 international satellite. Other recorders of this class are used to store spacecraft situation and grid data aboard Nimbus. Recorders of 10^6- and 10^7-bit capacity have also been built for the Mariner program.

The Tiros endless-loop radiometer recorder has successfully operated for more than 2 years in orbit. The design of this unit is interesting in being an intermediate between the simple recorders of the Vanguard series and the sophisticated units currently being produced. The overall mechanical drive scheme of the recorder is shown in figure 13–22. It has several interesting features.

In this recorder the holdback force was provided entirely by the opposition of the tape to being pulled out from the center of the endless-loop cartridge, that is, it was an open-loop transport. Two motors were used, a dc motor for the high-speed playback mode, and a two-phase, 137.5 cps ac record motor operating at 4,125 rpm. It was felt that the dc motor could be used despite the brush problems in the vacuum because being the high-speed unit it operated for a relatively short time (Falwell, Stark and White [1963]).

An interesting feature of the two-speed drive is that the record motor operates during the playback operation. The overrunning spring clutch shown in the drawing allows the playback motor to drive the capstan while essentially ignoring the relatively slow rotation produced by the record motor. One of the gear-driven switches, labelled the "Time-Sharing Switch," is driven at 256 rpm by a plastic belt and through gear reduction provides a switching function between various input signals, sampling each of the signals for approximately 6 seconds. The other gear-driven switch is that for playback timing.



(*from a NASA report*)

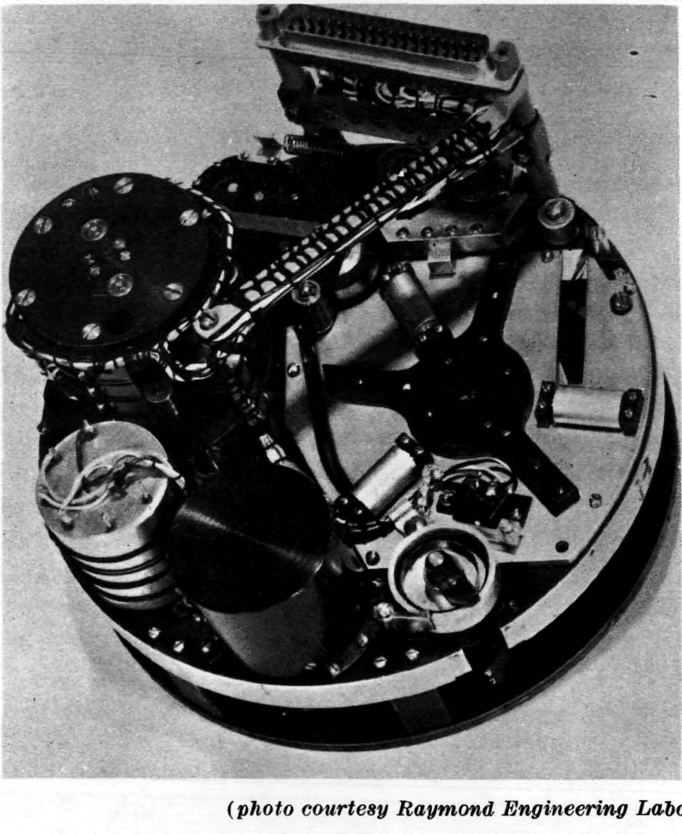
FIGURE 13–22.—Mechanical schematic of the drive mechanism of the Tiros infrared data recorder.

The function of this switch is to ensure that the playback cycle only continues for the length of the endless loop and that the recorder is switched back into the record mode when the entire tape has been played back. The function of the switch is rather simple since it counts the number of revolutions of the playback motor and then operates the mode reversing switch.

An interesting method has been used to remove playback jitter in this recorder. Since one of the required recorder functions is to convert the input serial information to parallel for recording and then to convert it back from parallel to serial, a storage buffer is needed for playback. In the jitter-removal system, the reproduced word is placed in parallel in a storage register in a conventional manner. If the storage register is not full at the point when the next serial word should be read out of it, a series of zeros is automatically transmitted until a signal is received indicating that the register is full. The word is then read out of the register while another word is being fed into the second layer of the register. The series of zeros and the output word are both timed by a local crystal clock and the data rate is therefore perfectly uniform. The cost of this method of compensating for recorder jitter is that the transmitted data word varies in length from 9 to 15 bits rather than simply having the same length as the input data word (Townsend, Feinberg, and Lesko [1963]).

The dc motor used for playback is servo-controlled through the signal generated by a tachometer ac generator placed on its output shaft. This somewhat unusual arrangement was felt to give a better weight-efficiency ratio than was obtainable with the synchronous motors then available. A photograph of this recorder is shown in figure 13–23. A rather similar recorder, although mounted on a square rather than a round structure and differing in details, is also used aboard the Nimbus weather satellite, primarily to store PCM orbital data on spacecraft sensors and grid data.

An endless-loop recorder which represents rather clearly the state of the art at the time of its development is that used on the UK–2 satellite. This was the first recorder in which the concept of modu-

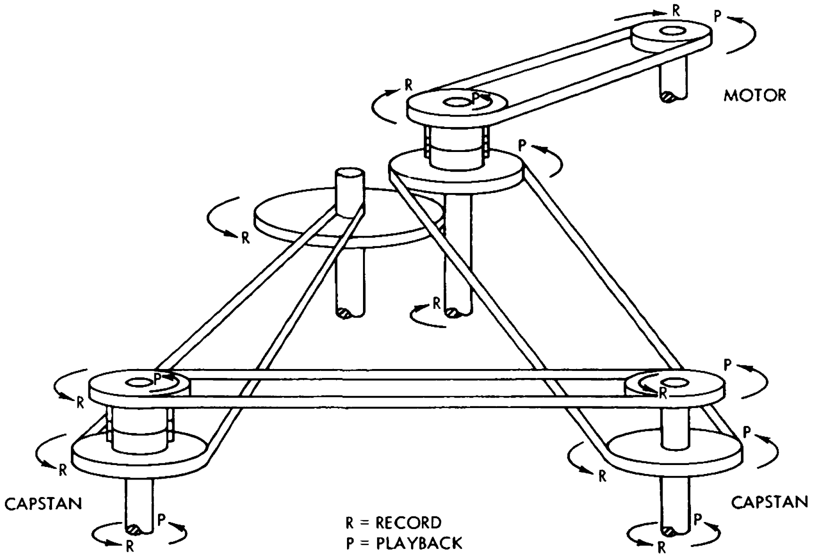


(photo courtesy Raymond Engineering Laboratory)

FIGURE 13–23.—The Tiros I infrared recorder.

larization was formally used. The development of this recorder through breadboard, engineering test model and prototype was undertaken in-house at the Goddard Space Flight Center.

The recorder is an endless-loop unit holding about 300 feet of quarter-inch-wide tape. In record mode it operates at 0.15 ips and in playback at 12 ips. The two-speed operation is achieved by means of a single motor which rotates in one direction for record and in the other direction for playback. The speed reduction for the two modes is accomplished by a technique shown in figure 13–24. Two overrunning clutches are involved in the speed change technique. In record mode, the motor drives the intermediate shaft but the overrunning clutch on that shaft is disengaged and the belt between that shaft and one of the capstans therefore does not transmit any power.



(*from a NASA report*)

FIGURE 13–24.—Mechanical schematic of method of obtaining two speed drive in the UK–2 recorder by reversing the direction of a single motor (see text).

The intermediate shaft drives the rim of a Mylar-covered wheel mounted on the auxiliary shaft next to it at a reduced speed. The belt from this shaft then drives the second capstan through an overrunning clutch. The direction of operation of that clutch is such that in the record mode this belt drives the capstan positively. The two capstans are belted together. When the motor is reversed, the overrunning clutch on the intermediate shaft engages and the belt from that shaft to the capstan then supplies power to it and, through the interconnecting belt, to the other capstan. The direction of rotation of the overrunning clutch on the second capstan shaft is such that it is then disengaged from the record auxiliary shaft.

The hysteresis synchronous motor is driven by a 100 cycle per second square wave which is generated by countdown from a 400 cps tuning-fork-controlled oscillator. The frequency and hence the speed provided is claimed to be accurate within 0.1 percent.

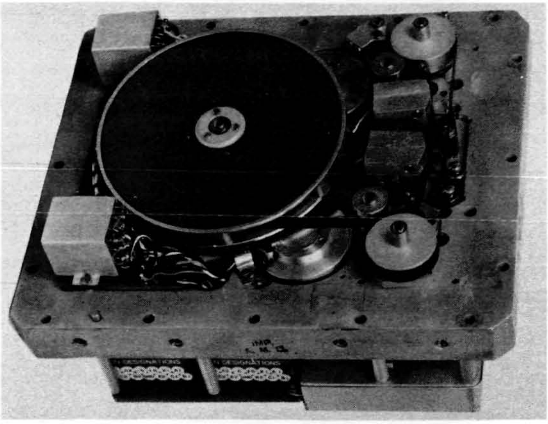
A remote-controlled endless-loop recorder requires a timing device to deliver a message that all that has been recorded has been played back so that the recorder can be restored to record mode. In this unit the timing mechanism is a solid-state oscillator operating at approximately 7 cycles per second. When playback is desired, the command receiver, triggered from the ground, supplies a pulse to the playback timer relay which switches the record-playback circuit into playback and turns on the 7-cycle oscillator which then feeds a 1,000-pulse divider. At the end of a thousand pulses, or approximately 140 seconds, an output pulse is sent by the pulse divider to the record-playback mode relay, returning the recorder to the record mode.

Endless-loop recorders for use in deep-space probes have very low power consumption and slow playback speeds. For example, a breadboard 10^6-bit PCM storage recorder for use in the Mariner programs has a total power input of 0.425 watts with a record speed of 3.6 inches per second and a playback speed of 0.03 inch per second. To play back the entire loop of tape at this low speed requires 33 hours.

The rigid timing required for successful data transmission over interplanetary distances requires that space-probe recorders be locked in playback bit rate to an internal spacecraft clock. This recorder therefore employs a phase-locked-loop servo to drive the playback motor. Typically, the output of the phase-locked-loop oscillator in such a servo is a square wave and a hysteresis-synchronous motor of maximum efficiency (low damping) may jitter with this input waveform. Any ripple in the output of the phase-locked-loop driving amplifier will cause further motor jitter. A special gated-integrator technique was developed for this recorder to minimize the ripple. To insure a satisfactorily-uniform output bit rate, an additional locked-oscillator clocking system had to be used. In this scheme the output bits are put into a one-bit-deep register out of which they are clocked by a local VCO. This VCO is locked to the somewhat jittery bit rate coming off the tape through a filter which assures that the oscillator rate will not jitter fast but may change at a relatively slow rate. This matching between high-speed input jitter and low output data rate change is accomplished with storage only one bit deep. A photograph of this recorder is shown in figure 13–25.

Figure 13–26 shows a 10^7-bit version of the 10^6-bit Mariner recorder made by the same contractor. It differed from the 10^6-bit unit in holding 700 instead of 300 feet of tape and in using four rather than two data tracks. Mylar "pinch belts" are used to maintain contact between tape and capstan.

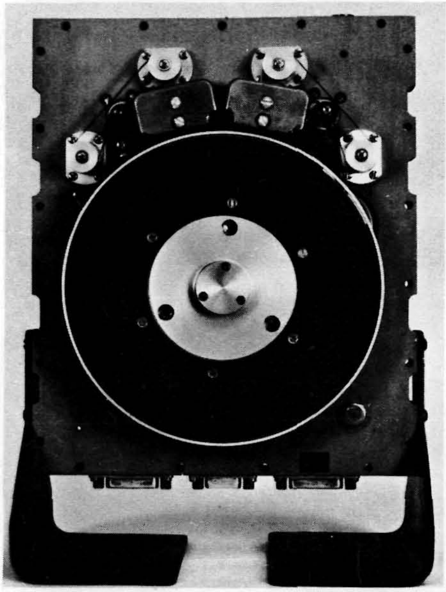
The flight recorder used in the successful Mariner IV mission which, in July, 1965, sent to earth the first closeup pictures of Mars, combined features of the 10^6-bit and 10^7-bit breadboards. This unit had a record speed of 12.84 ips and a playback speed of 0.01 ips, giving a playback data rate of 8.33 bits per second with a recording density of 833 bits per inch. Two tracks were used on a 330-foot loop of ½″ tape, giving a usable storage capacity of 5.2×10^6 bits. A two-capstan drive system with polyester pinch belts was used. This recorder lay dormant in space for the more than seven months of the flight to Mars and was then successfully turned on to record 21 digitally-encoded 240,000-bit pictures. It then operated in playback mode for eighteen days to transmit the entire picture series to earth twice.



(photo courtesy Raymond Engineering Laboratory)

FIGURE 13–25.—The 10^6-bit storage-capacity recorder built by Raymond Engineering Laboratory for the Mariner program.

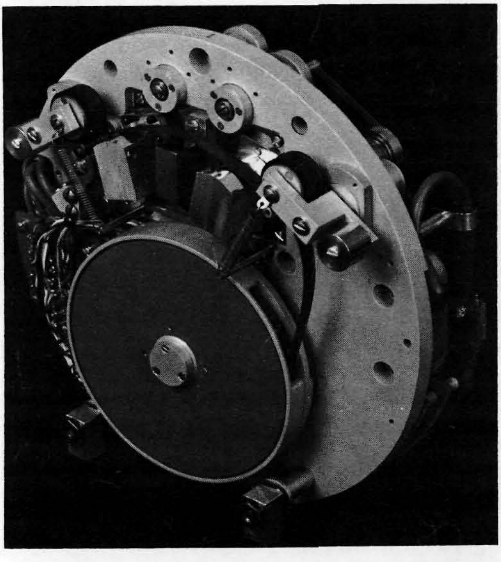
The Orbiting Solar Observatory (OSO) program has used continuous loop recorders for orbital data storage. The first of these operated successfully for 11 weeks for a total of 1,000 hours of information recording during 1,380 orbits on OSO–1 (fig. 13–27). This first OSO recorder handled analog FM data recording at 0.60 ips for 95 minutes on 285 feet of quarter-inch tape. Playback was accomplished in 5.2



(*from a NASA report*)

FIGURE 13–26.—The Mariner program 10^7-bit endless-loop recorder, built by Raymond Engineering Laboratory Inc.

The paths of the elastic "pinch-belts" which substitute for the pressure roller in providing tape-capstan friction are clearly apparent in this picture.



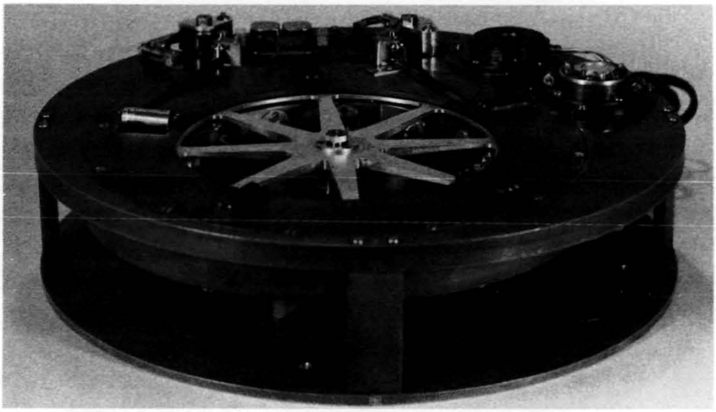
(*photo courtesy Raymond Engineering Laboratory*)

FIGURE 13–27.—The OSO–1 (S–16) Orbiting Solar Observatory endless-loop analog recorder.

minutes at a tape speed of 11.0 ips. This recorder was 7 inches in diameter and 3 inches high, weighing 5 pounds.

A second version of this recorder similar in mechanical characteristics but manufactured by another organization was used to record PCM data for OSO–2.

Stark has described an endless-loop recorder with very large tape capacity (1,200 feet), which was recently developed by the Aeronomy Group at Goddard Space Flight Center (Stark [1964]) (fig. 13–28).

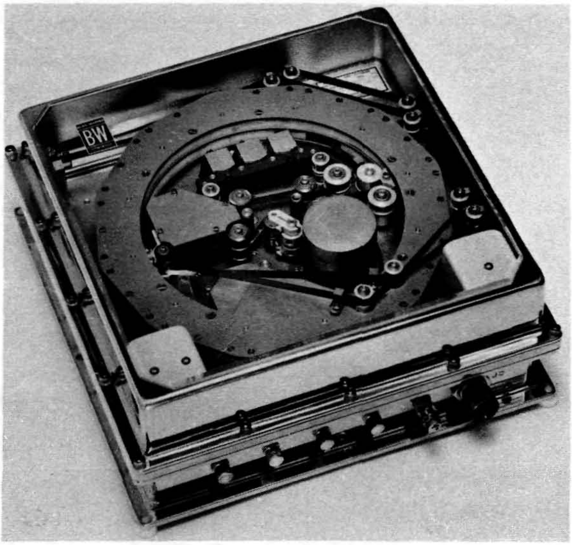


(*NASA photograph*)

FIGURE 13–28.—An experimental 1,200-foot capacity endless-loop flight recorder developed by the Aeronomy Group at Goddard Space Flight Center.

The endless-loop recorders described immediately above are all of the so-called classic type. The tape is in the form of a flat circular pack and the supply is from the inside of the pack, which causes the pack as a whole to rotate, and the takeup is on the outside of the pack. NASA has carried out and sponsored a considerable amount of work on this particular class of endless-loop structure. There are, however, other means of storing an endless-loop of tape in compact form. One of these, shown in figure 13–29, stores the tape in two levels in the standard format to conserve space. The tape is wound onto the outside of one pack and is pulled from the center of that pack to be wound on the outside of the other pack. It then is drawn from the center of the second pack.

A very unusual endless-loop construction is that shown in figure 13–30. The tape is strung back and forth in a series of loops and the entire array of loops is wound around a drum. The tape is carried out of the pack by a belt similar to the Cobelt (see below), and the entire

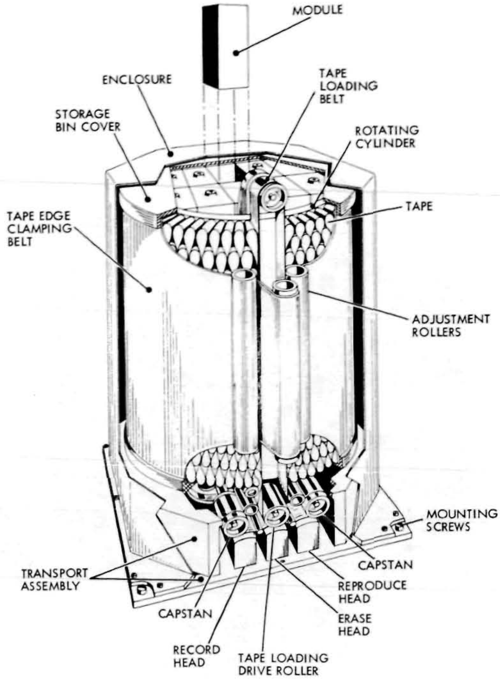


(*photo courtesy Borg-Warner Controls*)

Figure 13–29.—The Borg-Warner R302 endless-loop recorder which stores the tape loop at two levels to provide improved tape handling.

structure is rotated by an enveloping wide belt. Short endless-loop recorders have also been built with the tape simply random-stored, that is, left loose in a bin, as shown in figure 13–31. This is not, of course, a compact construction but is a very simple one. In this recorder a belt is also used to carry the tape in and out of the bin.

A somewhat unusual endless-loop recorder developed for reentry studies is shown in figure 13–32. This top view emphasizes the extremely rugged construction and the unusual loose tape pack which is essentially the conventional endless-loop configuration expanded from a circle to an oval. An elaborate procedure is followed in getting the tape from the inside to the outside of the storage loop to avoid the twist stretching of the edges of the tape discussed elsewhere. The tape travels counterclockwise around the outside of the pack and on the lower side of the pack, that is, toward the bottom of the picture, passes just below the center of the picture around a roller. This roller guides it around a very similar roller somewhat above it and to the left and the tape is then carried around an unusually-shaped fixed guide. This guide is clearly of a form which translates the tape from one plane to another in such a way that no part of it is stressed more than any other. The price of the very heavy friction encountered at this guide



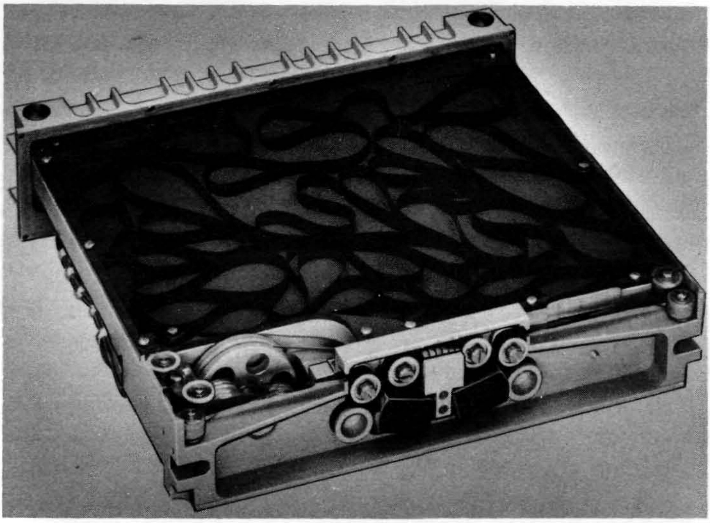
(drawing courtesy Ralph M. Parsons Company)

FIGURE 13–30.—The Parsons Model CRB–80 continuous rotary-bin recorder/reproducer (see text).

is apparently willingly paid for the smooth transition this technique provides. The first roller referred to above is mounted on a pivoted arm and is apparently spring-loaded to take care of stretch of the pack. The arm rotation is also damped by a plastic belt pressed against its outer surface.

The manufacturer of this device stresses the advantages of this particular tape configuration and guiding technique for avoiding bindup between the layers of the tape under severe acceleration. This unit is understood to survive 100 G's acceleration without binding and to be operable with somewhat reduced performance at 80 G's acceleration continuously. A particular version of this unit operates at 30 inches a second and reaches a maximum delay time of 40 seconds, which means a storage of 100 feet of tape.

An interesting point is made by the manufacturer in discussing the use of this recorder for short-term time delay for bridging the reentry flame attenuation period. The life of the recorder in active service is dependent on the tape life and this tape life depends on the number of cycles rather than any actual number of hours. For example, a 40-second-delay loop is circulated 900 times during a 10-hour period while a 20-second loop circulates 1,800 times in the same period. The manu-



(*photo courtesy Ralph M. Parsons Co.*)

FIGURE 13-31.—The Parsons CLR-225 "bin" recorder.

This technique of storing a relatively short loop of tape in random coils in a flat bin has been widely used.

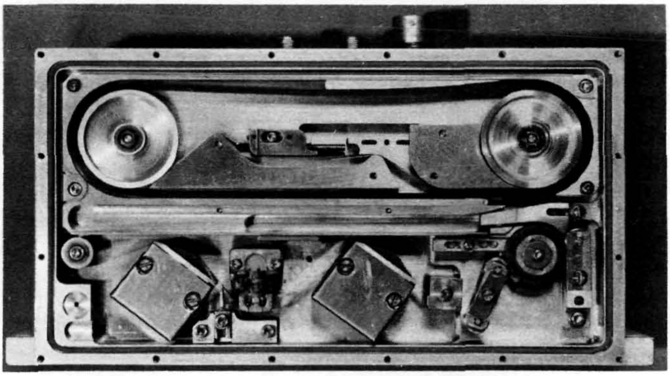
(*photo courtesy Litton Ind.*)

FIGURE 13-32.—The Westrex Model RA-1683-B reentry recorder/reproducer.

facturer points out that a 30-second tape loop operating continuously for a period of 30 hours exhibits serious loss of high frequency response. No tape apparently now available will exceed this performance. The statement is made that 1,500 to 1,800 cycles per operation may be considered the tape life limit for acceptable high frequency response. A 30-second tape loop therefore has a life of approximately 12 to 15 hours within specifications.

An orbital tape recorder operating in a 90-minute orbit and interrogated on each pass goes through 16 double cycles, that is, one of record and one of playback, every day. There are orbital recorders which have operated for a year or more under these circumstances, representing a total number of tape passes of 6,000 or more. It is not intended as a criticism of the reentry unit discussed above to comment that the additional tape strain and friction which is introduced in the interest of making this machine survive an extremely severe shock and vibration environment increases the tape friction and hence shortens the tape life.

The basic technique used to provide the compensation of the so-called inertia-compensated recorder shown in figure 13–33, is to fill the recorder operating volume with a fluid of approximately the same specific gravity as the tape. This recorder also has other interesting features. The tape is in an oval loop endless-loop configuration, some



(photo courtesy College Hill Ind. Division)

FIGURE 13–33.—The College Hill Industries inertia-compensated recorder/reproducer Model 005.

The mechanism by which the tape travels from the inside to the outside of the oval loop is not easily followed in this photograph but careful examination will show the corrugations on the outside of the capstan (lower right) resulting from the slitting technique and also the sharp radius on each head preceding the active gap as described in the text.

of the difficulties of which are discussed elsewhere. The presence of the inertia compensating fluid surrounding the tape can, to a certain extent, improve the lubrication of the tape layers but the hydrodynamics of the situation are far from simple and it appears that some of the tape bind complications that have occasionally arisen result from the presence of this liquid.

In order to operate a tape recorder, as it were, under a liquid, it is necessary to take certain precautions to insure that the recorder operates in a normal manner. The typical pinch roller and capstan construction is somewhat reduced in effectiveness by the tendency of the inertia-compensating liquid to lubricate the contact between these elements. A specialized technique is used in this particular recorder to overcome this difficulty. The actual capstan driving the tape is of rubber and the tape is pressed against it by a metal roller. To insure friction between the capstan and the tape even in the presence of the fluid, slits are placed in the surface of the capstan at an angle to the center line of the tape. These slits apparently act as squeegee pumps to clean out the fluid so that good adhesion takes place between the capstan and the tape.

Another somewhat unusual aspect of this recorder is that the tape is operated in a Moebius strip. The tape is coated on both sides and the center of the tape passes through the mechanism twice before the same point on the recording surface is reached for the second time. This extends the recording time at the cost of the possibility of print-through from tape layer to tape layer. However, the presence of the compensating fluid probably minimizes the importance of this print-through since the separation between the layers is maintained by the fluid.

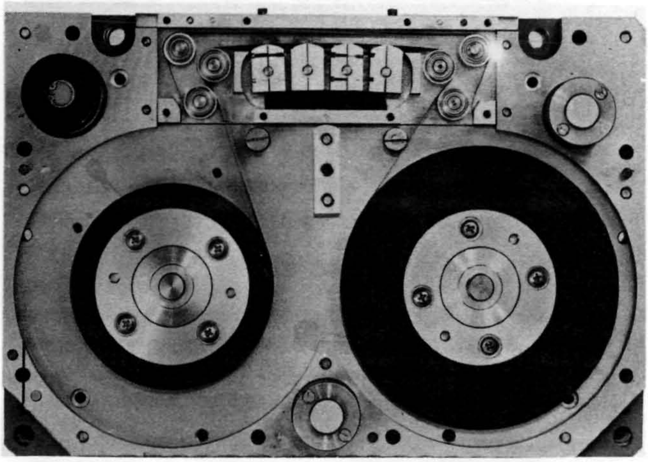
The same fluid film which tends to reduce interlayer friction and print-through in the pack also tends to keep the tape away from the heads. In order to reduce the thickness of the layer at the record and reproduce point the tape is passed around a sharp radius (0.004 inch) under a pressure of 10 to 15 grams just before it encounters the head gap. This reduces the thickness of the residual fluid film to 1 micron, which provides satisfactory high-frequency response for the applications considered (Monopoli [1962]).

UNUSUAL RECORDER FORMATS

Several unusual drive mechanisms have been developed for and applied to flight recorders to overcome some of the fundamental problems of such recorders. Although the general scheme of the recorders using these novel drives resembles closely the schemes of recorders discussed under the three classifications covered above, the drive mechanisms change the design philosophy of these recorders enough to make it advisable to consider them separately. This section is therefore devoted to the "Cobelt" and "Iso-elastic" drive schemes.

The Cobelt drive scheme was first applied to a recorder designed for use on a rocket sled. This recorder had several features designed to permit it to operate satisfactorily under heavy vibration and accelerations up to several hundred G's. In this recorder, shown in figure 13–34, no conventional reels are used. Instead the recorder is constructed very solidly of a "sandwich" of heavy metal plates which are assembled rigidly on both sides of precision spacers only 0.001 inch thicker than the tape width. The tape, instead of being supported between reel sides, is handled by the blocks of metal which form the body of the recorder. When the recorder is assembled, the entire tape guide function is carried out by these side plates. For withstanding shock, this construction is much superior to one using a reel of any kind since a reel side must necessarily be relatively flimsy.

In order to maintain contact of the tape with the head, the Cobelt drive is used here. This, as can be seen in the photograph, consists of an auxiliary plastic belt which presses the tape toward the heads. This belt also provides the drive normally supplied by the capstan and pinch roller. The tape is thus both pulled along by friction with the



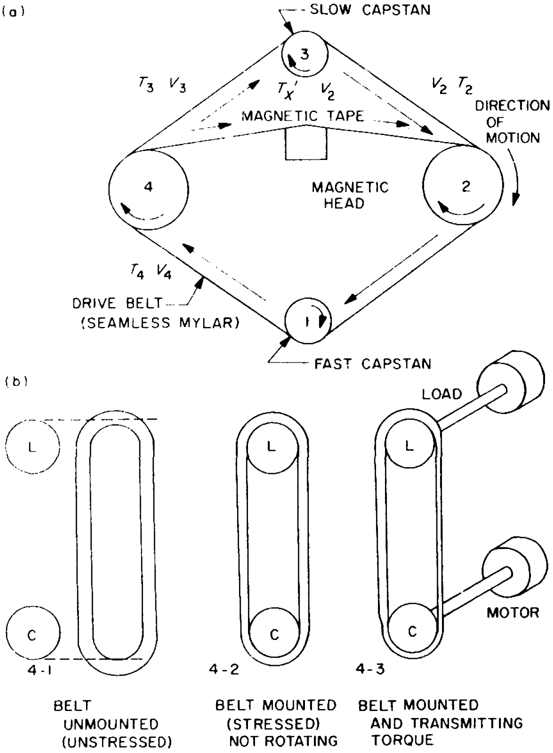
(*photo courtesy Genisco Data*)

FIGURE 13–34.—The Genisco Data Model 10–110 tape transport.

The Cobelt return path can be seen directly above the four heads, as can the way in which the massive base plate is hollowed out to support the rolls of tape. The depressed portion of the structure is actually as deep as the full tape width and the housing is completed by laying a flat plate over the structure seen here.

Cobelt and pressed by it against the heads. The only disadvantage of use of the Cobelt drive outside of this particular equipment is that the lateral guidance of the tape, unless it is severely constrained as it is in this recorder, is affected by the straightness of the driving belt. There is a tendency for the tape to wander to follow the belt and the technique therefore seems limited at the moment to use where it is as precisely guided as in this particular recorder.

The "Iso-elastic" drive technique, which is illustrated in figure 13–35, was introduced to improve the tape drive and reeling functions by combining them in a unique way.



(*from a NASA report*)

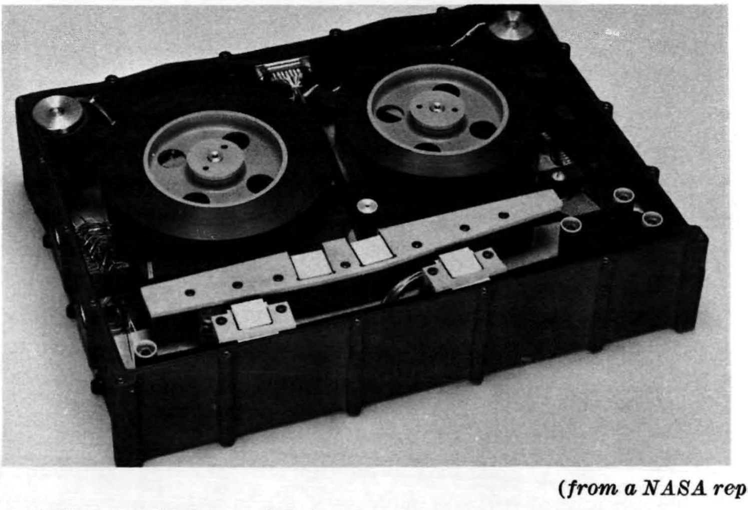
FIGURE 13–35.—Schematic representation of the principle of the Iso-elastic tape drive.

The principle on which this drive operates is clearly described in this drawing.

The reel packs are driven at a constant velocity at their periphery by a polyester belt. Tape tension is determined by the difference in the surface speeds of the two driven capstans which transfer motion to a so-called Iso-belt under a nonslip condition. The tension in the tape results from the physical properties of the Iso-belt and is not dependent on the transfer of forces through dynamic friction as in more conventional systems. A brief description of some recorders developed around this principle follows, adapted from JPL–SPS 37–25 Vol IV p. 217–227.

A series of tape recorders, primarily designed for space probes, was developed to prototype form using this drive system. At the time of initiating this development program, a series of specific requirements existed at the Jet Propulsion Laboratory for space probe recorders. These are shown in table 13–1. The tape transport mechanism which was developed to meet the general requirements of the 10^8 bit recorder/reproducer of table 13–1 is shown in figure 13–36. The major elements defining the specific features of its operation are (1) the Iso-elastic belt system, (2) a specialized differential drive, (3) tape guides and heads, (4) the supporting structure, and (5) reliability considerations.

The Iso-elastic belt is a seamless polyester belt which rides directly on the outer layer of the tape on each reel pack. The belt is driven by two capstans, a fast capstan and a slow capstan. Sufficient pretension is applied to the belt by the tension idlers that a nonslip condition is maintained between the capstan surface and the belt. A schematic representation of the mechanics of the Iso-elastic principle is shown in figure 13–35. The effective operating tension Tx′ results from the fact that the magnetic tape is inelastic when compared to the elastic properties of the drive belt. Therefore the peripheral speeds of the tape pack are, in effect, synchronized by the inelastic coupling of the tape itself between them regardless of the relative diameter of either.



(from a NASA report)

FIGURE 13–36.—A 10^8 bit-capacity developmental spaceprobe recorder employing the Iso-elastic drive principle.

TABLE 13-1.—*Tape Recorder-Reproducer General Requirements*

10^8 Bit recorder-reproducer	
Storage capacity, information bits	$>10^8$ bits (NRZ)
Total volume, including electronics	10 x 14 x 3 in.
Weight, exclusive of electronics	<10 lb
Power consumption, 400 cycles	<4 w
Sterilization	125° C
Two-speed operation	50:1 ratio
Bit error probability	10^{-5}
10^7 Bit recorder-reproducer, two-motor drive	
Storage capacity, information bits	10^7 bits (NRZ)
Total volume, including volume for electronics	6 x 6 x 2⅜ in.
Tape width	¼ in.
Bit packing density for 10^5 bit error probability	1,000 bits/in.
Number of channels	4
High speed	12 in./sec
Low speed	0.5 in./sec
Speed change mechanism	Mylar-belt differential
Weight, exclusive of electronics	<3 lb
Flutter, high-speed	$<10\%$
Stop-start distance, low-speed	<0.15 in.
Power consumption, motors only	<6w
Hermetic sealing	0.1 atm residual, 2 yr
10^7 Bit recorder-reproducer, single-motor drive	
Storage capacity, information bits	10^7 bits (NRZ)
Package size, including volume for electronics	6 x 6 x 2⅜ in.
Tape width	¼ in.
Bit packing density for 10^5 bit error probability	1,000 bits/in.
Number of channels	4–8
High speed	15 in./sec
Low speed	1.5 in./sec
Speed change mechanism	Drive frequency change to motor
Weight, exclusive of electronics	<3 lb
Flutter, high-speed	$<2\%$
Stop-start distance, low-speed	<0.1 in.
Power consumption	<2 w
Hermetic sealing	0.1 atm residual, 2 yr

In the practical case of the recorder, initial tension is supplied by the tension idler. This is required to account for the change in length of the Iso-elastic belt because of the change in geometry resulting from the variable amount of tape on each pack as a consequence of operation. This assembly and those described later were designed on the basis of a resultant zero spring rate of the assembly so that the initial tension would be held constant.

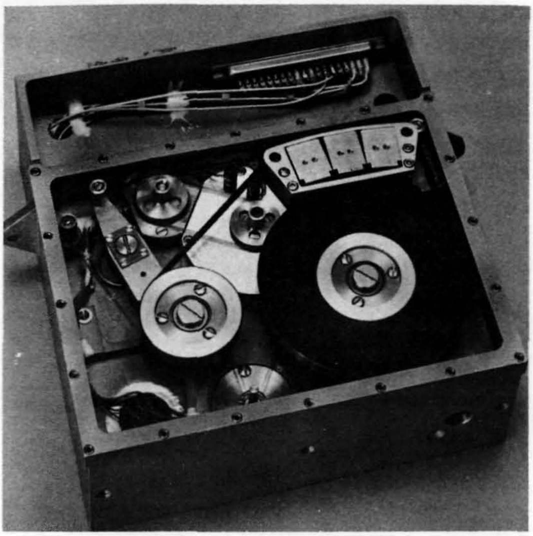
The special differential mechanism referred to above is one in which two motors drive two elements of a differential at slightly differing speeds. The differential so operates that when the motors are driving the differential pulleys in the same direction the output speed is the average of the sum of the two pulley speeds. When the motors are driving in opposite directions the output velocity is the average of the difference of the two speeds.

The Iso-elastic belt structure displaces the tape transversely relatively little, but in order to guarantee extremely good guidance so that low amplitude modulation from lateral motion of the tape will occur, a long trough guiding system is used in this recorder. The overall guide length is approximately 9 inches.

It was discovered in analyzing the vibration sensitivity of tape packs of the size required for this machine in a system of reasonable stiffness that the resonant frequency of the tape-mass-supporting-structure combination was well within the range of vibration frequencies to which the overall mechanism would be subjected. The concept was therefore introduced of providing support for the entire recorder assembly not only at its borders but also at the reel hub shafts to increase the effective rigidity of the overall system.

A 10^7-bit recorder meeting another set of requirements in the table was developed with the view to providing a much smaller package. The general arrangement of this recorder is shown in figure 13–37. The same type of differential was used in this mechanism as in the 10^8-bit recorder, but because of size problems, the differential itself had to be reduced considerably in diameter. This meant that the spider belt within the differential might exceed its life cycle. Although several attempts were made to substitute other materials for the Mylar when it was discovered that a very short failure-free life was predictable, it was necessary to estimate that this recorder could not successfully operate with the differential concepts originally proposed over the necessary active life cycle.

Another 10^7-bit recorder was therefore developed in an attempt to simplify construction on the basis of what had been learned in the first 10^7-bit unit. In this recorder, a single motor driving the capstan peelley through a single polyester belt was substituted for the differential. The two speeds were achieved by running the motor at 12,000 rpm with a 400 cycle per second power supply and at 1,200 rpm with a 40 cycle per second power supply. This recorder (fig. 13–38) appears, as a prototype, to meet most of the requirements indicated in Table 13–1 and promises a useful set of flight hardware in the future.



(*from a NASA report*)

FIGURE 13-37.—A 10^7 bit-capacity spaceprobe recorder employing two motors and a plastic-belt differential drive (see text).

(*from a NASA report*)

FIGURE 13-38.—The improved 10^7 bit-capacity spaceprobe recorder employing a single motor drive.

MINIATURE TRANSVERSE-SCAN RECORDERS

For dealing with megacycle bandwidths and massive data storage, the rotary-head video-type recorder has been proposed for flight service. The mechanical complexity and short head and tape life of this class of recorder did not originally hold out much hope of adapting it to an application requiring such high reliability and ruggedness. However, in 1961 a ¾-cubic-foot, 40-pound rotary-head recorder was designed specifically for flight service. This unit had a bandwidth of over 4 megacycles and recorded for 20 minutes. Although this recorder has not flown it was an interesting demonstration of the feasibility of this technique. More recently, two separate programs have been undertaken by NASA to investigate the potentiality of the rotary-head recorder for two-speed operation. A group at the Flight Research Center is investigating the high-speed record, low-speed playback capabilities of the helical scan industrial television recorder to see if two-speed operation can be achieved for this unit. Recently an extensive investigation of many aspects of rotary-head recorder application was completed by Ampex Corporation for Goddard Space Flight Center.

The Ampex study covered a wide range of experiments and can only be summarized in the briefest outline here. The broadly stated objectives were:

1. To evaluate existing or proposed magnetic tapes usable for this class of recorder and to determine whether tape life could be adequately defined or predicted,
2. To evaluate the factors which influence head life and to attempt to define head life quantitatively,
3. To evaluate and propose methods for achieving various time base-expansions (up to 50/1 expansion), and
4. To evaluate generally methods of applying rotary-head recorders to space.

Many results of the investigation were encouraging. It was found that tape usually showed initial dropouts which disappeared after a few passes, then settled down to a uniform number of fixed dropouts over a given life and then suddenly developed a sharply increasing number of dropouts as the oxide binder apparently failed mechanically and the end of tape life was indicated by clogging of the head. "Good" tape apparently can be selected by automatic dropout testing, which divides tape samples into groups which differ by an order of magnitude in error or dropout rate, the lower rates shown in this test being well correlated with long life. The study indicates that current tape should survive 600 passes under reel-to-reel conditions and 3,000 passes for loop service. The lower reel-to-reel figure apparently results from damage in end-of-reel handling.

Head life factors are extremely complex, and the study showed that several suspected influences had no actual effect, such as damage from a "shock wave" phenomenon propagated ahead of the head tip as it indented the tape. The conclusions included confirmation that bidirectional operation, which seems almost unavoidable in space application of such recorders, is not an optimum operating condition. This results from another conclusion, which is that the tip shape of the head wears to a true circular arc inclined toward the direction of travel, and the head therefore operates peculiarly when the direction is reversed. Head wear goes down very rapidly with speed, as could be expected, with, for example, an expected number of feet of tape traversed before wearout eight times as great at 30 ips as at 1,500 ips.

A test bed recorder operated so well at high-time-expansion ratios in these tests that the following prediction is made of achievable expansion performance: Signal-to-noise ratio, 36 db (video S/N) total time displacement error, 15 microseconds, potential time expansion ratio with usable S/N ratio, 150/1, and shortest wavelength recoverable, 85 microinches (12,000 cycles per inch).

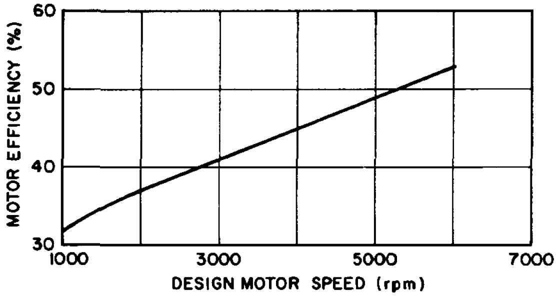
Although the breadboard recorder delivered at the conclusion of this study is designed only for further investigation of influences and design factors for this class of recorder and not as a first step for rotary recorders into space, the conclusion can probably be drawn that the step is inevitable in due time.

DRIVE SYSTEMS FOR MINIATURE RECORDERS

Although there are situations in which a high-environment recorder has few limitations on its size, weight, and power consumption, advanced technology needs to be brought to bear on the recorder drive problem when these limitations are present. This discussion is directed to the situation where maximum efficiency, minimum weight and maximum reliability must be achieved.

Many of the characteristics of motors used for miniature recorders and the considerations involved in motor choice are discussed in chapter 11. The discussion in this section is limited to specialized matters such as the choice as to whether one motor or two should be used and how fast the motor should be designed to rotate. In the Lockheed report referred to above, the point is made that the hysteresis-synchronous motor has great advantages of speed, accuracy, reliability and low noise generation, although the low efficiency of these motors is a strong disadvantage. They are particularly susceptible to the fact that when attempts are made to increase their efficiency, the damping against jitter oscillation becomes very poor. As the report points out, a deliberate choice to accept some jitter is often made in the interest of efficiency.

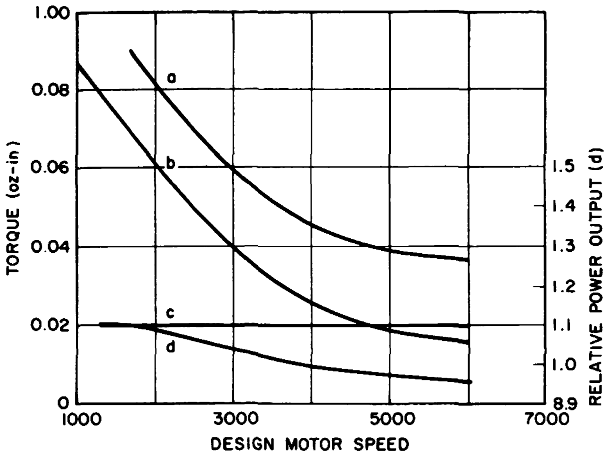
In applying the hysteresis synchronous motor, the operating speed and hence the number of poles and the supply frequency must be established. Although the motor is usually expected to be more efficient in every way the faster it runs, there is a limit to usable motor speed because the higher the speed the greater the burden on the speed reduction unit. In figure 13–39, motor efficiency is plotted versus rotational speed for a typical hysteresis-synchronous motor, where the frictional losses are assumed to lie largely outside the motor. In figure 13–40, the output torque of the motor as well as the torque of a typical duplex-pair bearing, which represents the frictional losses within the motor, is plotted against motor speed. The difference between these curves, which is the relative net power, is also plotted; it is interesting to note that it is *higher* for *lower* speeds. A significant comment is made in the report apropros of this unusual result, that, although optimum efficiencies can be obtained at speeds less than 2,000 rpm, peak efficiency shifts toward higher speeds as the power is increased. Two thousand rpm therefore appears an optimum motor speed. Having chosen a speed one must somehow standardize the supply frequency.



(*after Lockheed* [*1962*])

Figure 13–39.—Motor efficiency versus design motor speed for a typical 0.3-watt synchronous motor (typical spacecraft record power level).

Many such motors have been designed for 400 cps because of their history of use in aircraft systems. Under normal circumstances, 400 cps produces much too fast a motor for spacecraft service but it is desirable to use a frequency which is derived from 400 cycles. One hundred cps is about as low a frequency as can be used without requiring oversized inductive components in the power supply, and also



(*after Lockheed* [*1962*])

Figure 13–40.—Torque and power relationships in the motor of figure 13–39.

(a) Output torque of equivalent frictionless motor, (b) available output torque with typical bearings, (c) torque requirement of a typical duplex-pair bearing set, (d) relative net power output.

permits using a relatively small number of poles for a 2,000-rpm motor.

A primary decision which must be made in the spacecraft recorder is how it shall be operated at two different speeds. There are several ways in which two-speed operation can be achieved. These include running a single motor at two different speeds with a fixed reduction, using a single motor and selecting different reduction ratios with solenoid-operated clutches, running the motor in one direction for one speed and in the other direction for the other speed with a differential to change speeds, and providing two independent motor-speed-reduction systems. A table comparing the single and double motor approach is reproduced here from the report (table 13–2). In the report from which this data came, the two-motor drive system is recommended for the particular class of recorders emphasized in the report but it is not necessarily the universal best choice. The schematic perspective drawings of figures 13–41 and 13–42 show the differences between typical single- or two-motor spacecraft recorder drive. Other systems for providing two-motor operation are discussed under specific recorders in previous sections of this chapter.

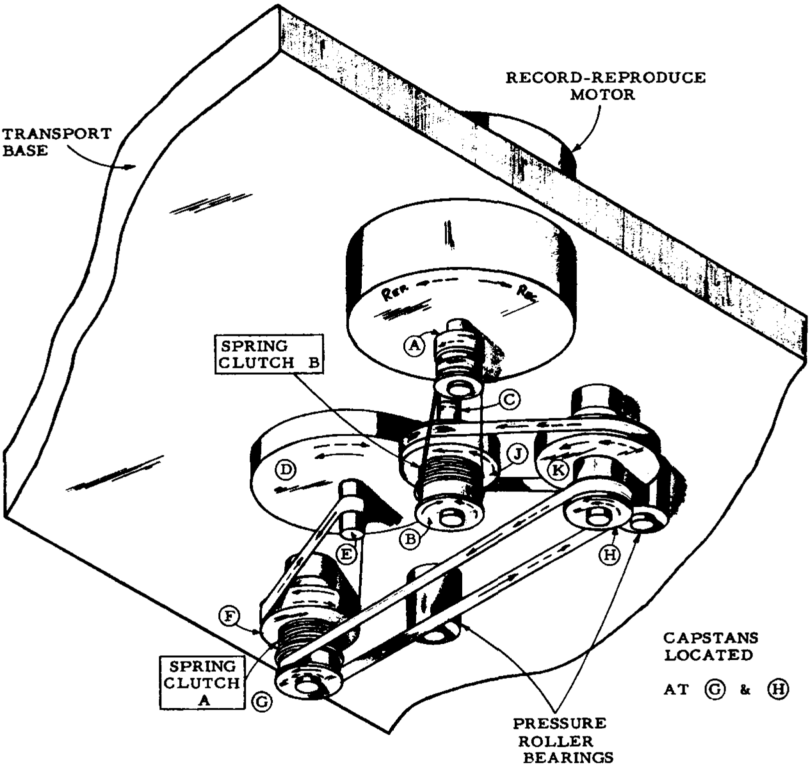
A preliminary feasibility and breadboard study of an intermittent-motion digital tape recorder/reproducer was sponsored by the Jet

TABLE 13–2.—*Comparison of Single- and Double-Motor Drives for Class I Spacecraft Recorders*

Type	Advantages	Disadvantages
Single-motor	Less weight. Smaller plan size. Lower cost.	Greater depth required. Compromise motor design increases power required at low speed. More complicated. Transmission requiring pressure-run drive for reversal. Harder to modularize because of interdependence of record and reproduce drives.
Double-motor	Low-speed motor designed for purpose allows greater efficiency. Smaller depth. Easily modularized because of split drive. All-belt drive. Fewer parts, less complicated.	Additional weight of motor. Larger size. Higher cost (additional motor).

Propulsion Laboratory during 1963. The interest in this program originated in a requirement in typical interplanetary space probes for recording the output of such devices as ion chambers and Geiger-Muller tubes which have extremely large dynamic ranges (from 1 count per hour to 100,000 counts per second), operate asynchronously and, despite the wide dynamic range, have a low average data rate when the output is converted to digital form (maximum of 20 bits per second). These requirements suggested the desirability of a device capable of recording, uniquely, one bit at a time, placing such recorded bits on a magnetic tape in a regular fashion and having the capability of synchronous read out. To achieve these ends, the following basic systems considerations were established:

1. The recorder-reproducer is to record and playback only upon receipt of a command pulse.
2. The maximum stepping rate is to be 200 steps per second or greater.
3. Size and physical configuration shall be such as to store 10^5 bits.
4. No standby power shall be supplied to the recorder-reproducer.



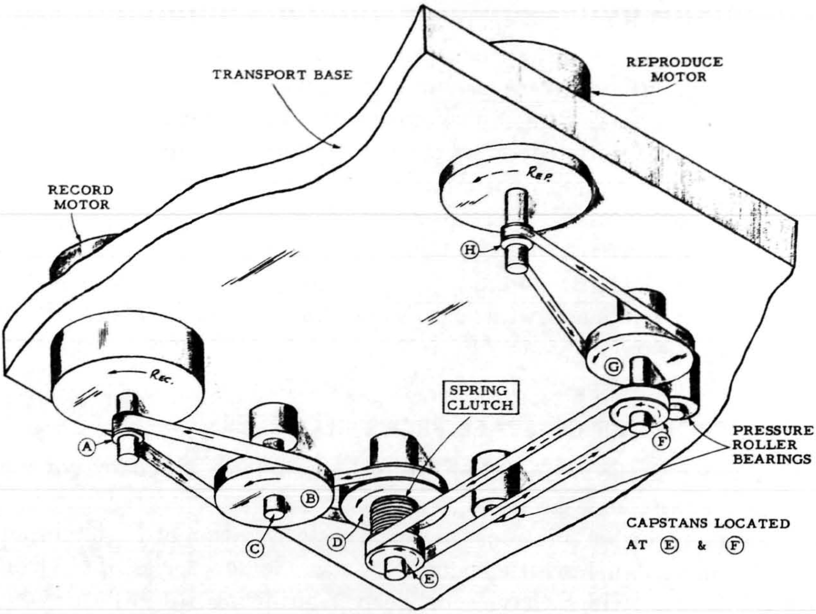
(from a NASA report)

FIGURE 13–41.—Mechanical arrangement of a typical single-motor spacecraft recorder.

This is a perspective representation of essentially the same elements shown in figure 13–24. The reference letters are appropriate to the report in which this drawing first appeared.

5. Ultimate life expectancy of the recorder-reproducer is to be about 10^8 steps. (Storer [1963]).

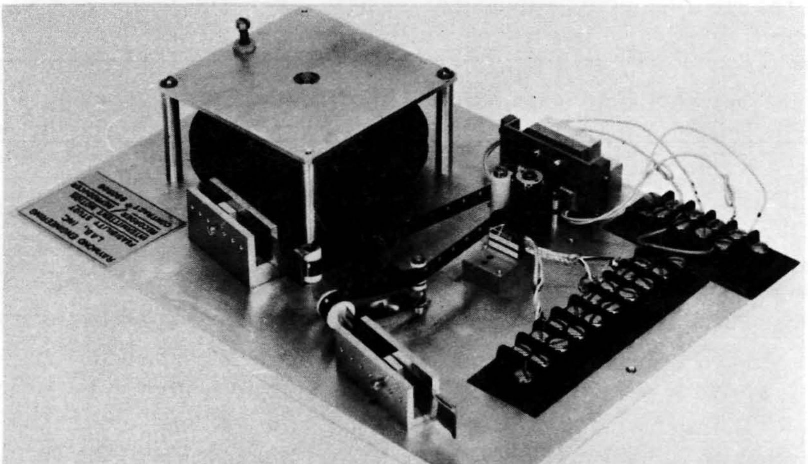
A successful breadboard model of this unit was completed. A general view is shown in figure 13–43. A special quarter-inch tape, perforated with standard 8-mm motion picture film sprocket holes and silicon-lubricated on the oxide side, was used. The reels, in this case, were torqued by a Negator spring in a stacked-reel configuration. The magnetic actuator visible in the photograph required refined and careful design. It consists basically of an armature which swings back and forth through a 6° arc between two pole pieces of high-permeability metal. A permanent magnet is inserted in the magnetic circuit so that the armature will be held against whichever pole piece



(from a NASA report)

FIGURE 13-42.—Mechanical arrangement of a typical two-motor spacecraft recorder.

This drive method limits the number of overrunning clutches required to one.



(from a NASA report)

FIGURE 13-43.—Breadboard intermittent-motion spacecraft recording mechanism (see text).

it has contacted last. The motion is transmitted to the tape from the actuator through a small sprocket engaging the tape perforations.

This study, although very preliminary, does establish the feasibility of the use of such an intermittent recording mechanism. The breadboard was tested with a loop of tape at a rate of 200 steps per second for a continuous period of 5 days before failure. This amounted to over 90 million accumulated steps and failure was due simply to wear-out of the armature pivot shaft.

This mechanism gives hope of making proper recordings of many intermittent phenomena which, up to now, have been left unrecorded because of the continuous drain that normal recording techniques would place on the spacecraft power supply.

SPECIAL PROBLEMS OF SPACE PROBE RECORDERS

In addition to the normal flight recorder problems which are covered above, there are some peculiar to space probes.

Any tape recorder that must undergo a sterilization at high temperature for interplanetary use encounters a whole new series of environmental stresses which have not been significant in any previous development. Just how to make recorders survive this process is not, as yet, well known. Tape, naturally, is the weakest link in the recording process as far as withstanding heat is concerned and tape temperature problems are discussed in chapter 9. The same temperature problems occur with plastic drive belts, and many other parts of the recorder may be damaged by heat. For example, the head is almost always constructed partially of plastic and few plastics will withstand sterilization temperatures. The result is distortion of the head and resulting poor head performance. At the moment, this entire subject is under intensive study, but as of the time of the survey, there are no "guaranteed methods" for assuring that a flight recorder will survive the temperature cycle.

Because the space probe must transmit its data over such long distances, data rates reproduced from the onboard recorder are always very low. A problem which must always be solved in any tape recorder which plays back at such low speed is that of dealing with the extremely small playback voltages obtained from a conventional $d\phi/dt$ playback head. Typically, at 0.03 ips, playback voltages do not exceed 100 microvolts. However, although the voltages are tiny, the bandwidth needed is correspondingly low, and surprisingly, without any very spectacular development, most contractors have had little difficulty in providing conventional playback amplifiers for these signals. Flux sensitive heads have therefore not been promoted for space-probe service as yet.

CHAPTER 14

Complete Recording Systems

It probably would be fairly realistic to say that the magnetic recorder is currently a necessary evil in any complex electronic data gathering system. The recorder has been gathering technical data for us for 15 years or more, and the technical personnel involved in the gathering process are now completely accustomed to the peculiarities of the recorder. Although an occasional complaint expresses the discontent which the typical user feels from time to time about the shortcomings of his recorder (Ratner [1965]), and one occasionally hears of proposals to replace magnetic recording with a photographic or similar technique, by and large the technical community suffers in silence with the recorder problems of the current state of the art. Like a benevolent tryant, the magnetic recorder impressed men originally by being so much better than anything else available that it was accepted gladly. Disenchantment with the new regime soon set in, however, with the realization that the recorder was not quite as good as it was originally expected to be. The gradual step-by-step improvement from year to year of recorder capabilities has, however, kept the using public from extensive overt expressions of unhappiness with recorder limitations. Nevertheless, the tape recorder *does* have many shortcomings, and great ingenuity is employed in its application today to minimize the effects of those shortcomings.

Typically, a tape recorder is used in a complex system. A great deal of the system design must now be based on satisfying the recorder limitations, that is, on so designing the balance of the system as to minimize the effect of the imperfections in the recorder. Until something better comes along, this necessarily must be the way in which data acquisition operates. One of the purposes of this chapter is to discuss the way in which this compensating process takes place and the overall results so achieved.

The approach here will be simply to describe several typical data-gathering systems in which tape recorders are used. These will include two rather simple and one rather complex satellite recorder applications. In another application, a ground-based recorder is used directly with a satellite, where the experimenters responsible for the satellite have specifically rejected the use of an on-board recorder. The final example will be one of the use of magnetic recorders in a ground installation for research and development data gathering and analysis in some of its more complex forms. This latter system is representative of many of the data reduction systems which are associated with the complex gathering systems.

The Interplanetary Monitoring Platform (IMP) is an example of a research satellite employing no on-board recorder and making the necessary compromises inherent in the decision not to carry a recorder. The information presented is intended to show the complexity of data and coding involved in the basic satellite decisions and some aspects of the data reduction problem inherent in the lack of the on-board recorder.

The next Operational Plan presented is that for the Orbiting Geophysical Observatory, OGO–A also known as EGO for its extremely eccentric orbit. The recorder developed by RCA for use in this program is described in chapter 13 which includes a discussion of the provision in the recorder design for its use both in EGO and POGO. The data reduction and ground recording requirements of this satellite are covered here.

The third Operations Plan discussed is that of Nimbus. Nimbus is the most complex of the satellites involved and requires overall system performance of the recording channel greater than any previous satellite. It involves two separate on-board recording functions, the recorders for which are discussed in chapter 13. It also employs the particular flutter compensation technique discussed in the section immediately preceding the description of the Nimbus operational plan below.

THE INTERPLANETARY MONITORING PLATFORM (IMP)

The mission of the Interplanetary Monitoring Platform project (IMP) is described as follows in NASA–GSFC Operations Plan 10–64, paragraphs 1.0, 1.1 and 1.1.1 through 1.1.5:

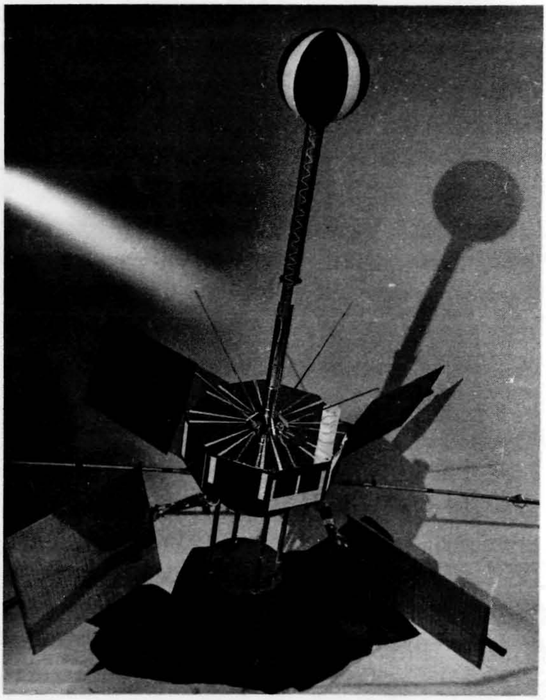
> *Mission*
>
> The Interplanetary Monitoring Platform (IMP) Project consists of a series of spacecraft which will contain scientific experiments to provide comprehensive data from the intensity and charge spectra of cosmic rays, information on the solar wind and the interplanetary magnetic field.

Objectives

There are five objectives of the IMP project. The objectives may be detailed as indicated below:

1. To make a detailed study of the radiation and environment of cislunar space and to monitor this region over a significant portion of a solar cycle. (This information necessary for support of Project Apollo requires that an operational IMP be in orbit at all times during this project.)
2. To study the quiescent properties of the interplanetary magnetic field and its dynamical relationship with particle fluxes from the sun.
3. To develop a solar-flare prediction capability for Apollo.
4. To extend our knowledge of solar-terrestrial relationships.
5. To further the development of relatively inexpensive spin-stabilized spacecraft for interplanetary investigations.

Figure 14–1 is a photograph of IMP.



(from a NASA photograph)

FIGURE 14–1.—The Interplanetary Monitoring Platform (IMP) flight unit.

The orbit of IMP is extremely eccentric with an apogee of 110,000 nautical miles and a perigee of 105 nautical miles. The period is 98.5 hours. In this respect IMP is similar to the Orbiting Geophysical Observatory (OGO) but almost every other aspect of its plan differs. Despite the extreme distance over which data must often be transmitted in such an eccentric orbit, the information from IMP will be transmitted direct to the ground recording installation *without* on-board tape recorder delay. Because the total amount of information to be transmitted in any unit time is relatively low, a certain amount of digital on-board storage has been provided for part of the experiment. Otherwise the data is transmitted directly. That is, the output of a particular sensor modulates the telemetry transmitter directly through an encoder and the data is recorded in real time on the ground.

Some nine experiments carried on this spacecraft are divided according to the type of output obtained from each. The output signals from four of these experiments are in analog form and those from the other five are in digital form. The output of these multiple signal sources must, of course, be sampled. This sampling is not in the simple iterative form used for the conventional PCM commutator-decommutator system, since the input signals are not in identical format. For example, to quote from the Operations Plan:

"Rb-vapor magnetometer: the Rb-vapor magnetometer output will directly modulate the transmitter for 81.92 seconds once every 5.46 minutes."

Similar statements are made concerning each of the other three analog experiments. A certain period of time during which the analog signal is telemetered directly is assigned to each experiment. The digital experiments are sampled on a more conventional basis in which instantaneous sampling of the output is done at regular intervals and the samples are stored in a small on-board digital memory. The digital data in the memory is then extracted on an irregular time schedule compatible with the analog sampling. The basic digital encoding technique is via PFM with which a modified burst FM analog coding has been integrated. The coding technique and experiment array may be understood from the following quotation from the Operations Plan (paragraphs 4.3.6.1, 4.3.6.1.1, 4.3.6.1.2):

> Experiment Outputs
>
> Following is the list of experiments grouped according to the output of each (analog or digital):
>
> *Analog*
>
> Low-energy proton analyzer (Ames)

Plasma probe (MIT)
Thermal-ion and electron spectrometer (GSFC)
Fluxgate magnetometers (GSFC)

Digital

Range vs. energy loss (University of Chicago)
Total energy vs. energy loss (GSFC)
Neher-type ion chamber (University of California)
Othogonal Geiger counter telescope array (GSFC)
Optical aspect sensor (GSFC)

Analog

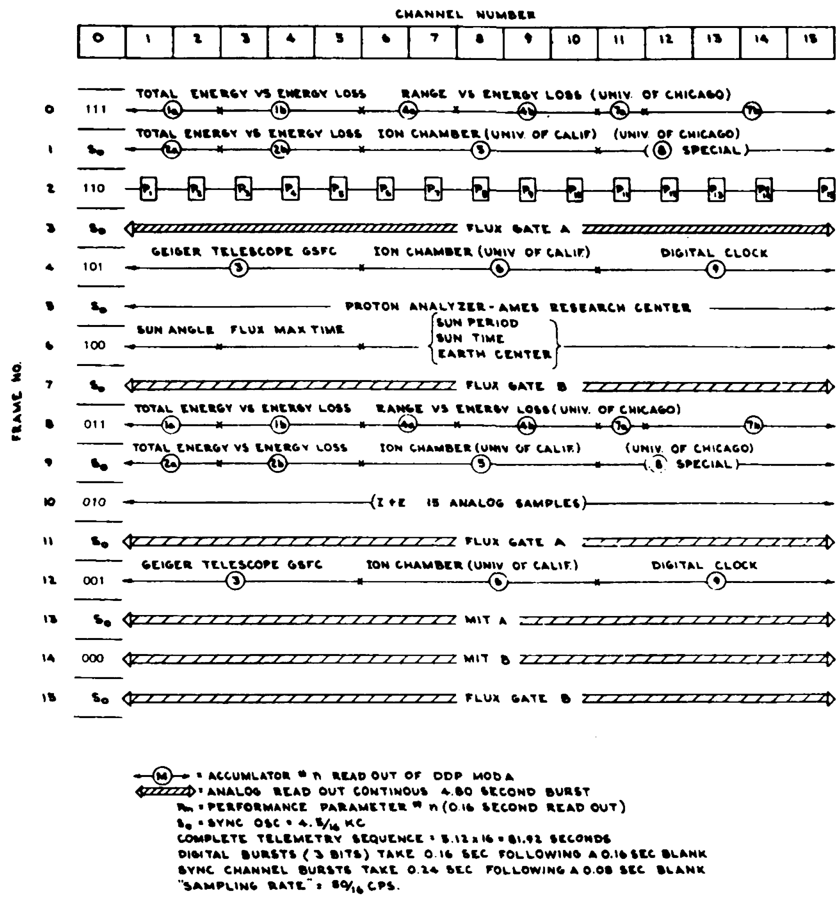
The outputs (between 0 and plus 5 volts dc) of the analog experiments are converted into frequency outputs from 15 to 5 kc by analog oscillators. Zero volts corresponds to approximately 15 kc while plus 5 volts corresponds to approximately 5 kc. Several inputs may be gated into a single oscillator. The oscillator outputs are later divided by 16, so that the modulating frequency is in the range of 5/16 to 15/16 kc.

Digital

The outputs of the digital experiments (except the optical aspect sensor) are fed into the DDP (Digital Data Processor) which does much of the accumulation and digital subcommutation. The output of the DDP goes to a series of pulsed digital oscillators which accept three bits of information and encode this as one of eight discrete frequencies in the band from 5 to 15 kc. These oscillator outputs are also later divided by 16. The eight possible frequency levels correspond to the eight possible combinations of 3 bits. Thus digital information, which is already in a digital form, may be easily encoded.

Figure 14–2 shows the IMP telemetry format for "normal" sequences.

The ground receiving station instructions for acquiring the telemetry data from IMP are somewhat unusual in that, for example, the satellite has no command channel, cannot be commanded to operate in any particular way and therefore transmits all the time. This means that no command data must be transmitted or recorded and several modes of recording operation are necessary to guarantee that all the data is obtained from the compromise transmission design required by continuous operation of the satellite. There are two different recording modes provided for. In one, the tape recorder operates at 1⅞ inches per second and all data is recorded on one set of duplicated recorders. In the second mode, the data is recorded simultaneously at 1⅞ and 30 inches per second, again with individual recorders duplicated. The following note about additional safety



(*from a NASA report*)

FIGURE 14-2.—The IMP telemetry format for "normal" sequences.

The terminology is typically somewhat obscure. The format designates what information is transmitted in what channel for each frame. The entire process is sequential here, that is, a frame in which samples from each channel are transmitted in time order is followed also in time order by another frame in which a new set of samples is transmitted in each of the various channel times. For some experiments (note "flux gate A" in frame 3), the entire frame is occupied with a data transmission. A frame identification symbol is transmitted in the zero channel and there are other circumstances under which all or part of this sequence are preempted for steady transmission of certain data.

factors in obtaining a complete record quoted from the Operations Plan is of interest (paragraph 6.1.3.2):

"There will be at least 30 minutes of recorded telemetry overlap between stations, 15 minutes of recorded overlap between tapes of 1⅞ inches per second and 10 minutes of recorded overlap between tapes of 15 ips and 30 ips."

The reference to speeds of 15 to 30 ips undoubtedly means that, since either Ampex FR–100 or FR–600 recorders may be used, the FR–600 with its somewhat more modern heads and electronics is capable of adequate bandwidth at the lower speed.

The track assignments for the two recorder speeds describe pretty clearly the recording technique. Track 1 for the low speed (1⅞ ips) mode direct (analog) records the AGC levels of the receivers in the form of IRIG Channel 1 and 3 VCO outputs. Track 2 carries the control track in the form of 60 cps modulated on 1 kcps in order to permit synchronization of the recorder on playback. Track 3 records the phase-detected data signal derived from the diversity combiner in direct mode. Track 4 carries the Minitrack time standard in the form of 1 kc modulated with binary-coded-decimal time, recorded in direct mode. Track 5 carries the phase-detected data signal in an FM recording mode. Track 6 carries the Minitrack time standard in the form of serial decimal time code recorded in FM, and Track 7 carries a voice commentary and WWV time, recorded direct.

By using both FM and direct mode recording, data signal response down to direct current with a relatively wide overall channel bandwidth can be obtained.

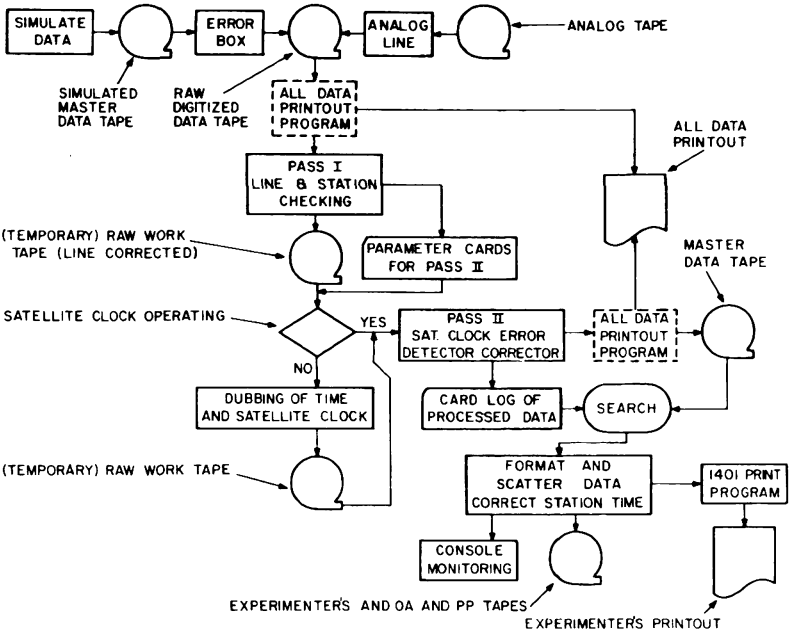
The track assignments for the high speed (15/30 ips) record scheme are similar. Track 1 again carries the receiver AGC signals, direct recorded in the form of VCO outputs. Track 2 carries a direct recording of Minitrack time in the form of 1 kcps modulated with binary-coded-decimal time, mixed with the standard speed control track (60 cps) modulated, in this case, on 18.24 kcps (for playback synchronization). Track 3 records directly the phase-detected signal from the diversity combiner and Track 4, also direct recorded, carries a 10 kcps reference frequency derived from the Minitrack format generator. Track 5 carries a direct recording of WWV time from the WWV receiver. Track 6 carries an FM recording of the Minitrack time standard in the form of a serial decimal time code and Track 7 carries a direct-recorded voice commentary.

Not only in the eccentricity of its orbit but also in much of its data handling is IMP an unusual satellite. Because data must be recorded when the satellite is quite far from the earth, the data rates have been held down as low as possible. Pulse frequency modulation is chosen as the first step in the encoding scheme as it appears to maximize the signal-to-noise ratio with relatively simple encoding and decoding equipment. The use of comb filters permits the decoding of PFM data at an optimum signal-to-noise ratio by picking up noise only in the total bandwidth of all the comb filters combined rather than in the bandwidth from the bottom of the first filter passband to the top of the last filter passband (chapter 4). With these very low recording rates, the tapes are reproduced for data reduction at 16 times the recorded rate. (Data recorded at 1⅞ ips is reproduced at 30 ips.) The mixture of digital and analog data on one channel is somewhat unusual, as is the method of transmitting an 8-bit digital sample. In this technique, mentioned above, 8 different pulse repetition frequencies appear at the output of the PFM encoder. A burst of the selected frequency is transmitted, chosen on the basis of the number between 0 and 7 that is to be transmitted at a particular time. In other words, 3 bits of digital data are converted to octal form and transmitted as the pulse frequency corresponding to that number. This technique was undoubtedly chosen because the system has the relatively good signal-to-noise ratio required to transmit the analog information effectively. This signal-to-noise ratio makes octal coding possible with the corresponding improvement in transmission efficiency over straight digital coding.

Because the reduction of the data from IMP is, although not standard, relatively simple, it provides a good sample of the basic techniques involved in any satellite data reduction. The actual reduction process is described in the following (edited) quotation from the Operations Plan (paragraphs 9.2 through 9.6).

A block diagram of the functions involved is given in figure 14–3.

> 9.2 Analog-Telemetry Tape to Digital-Computer Tape
>
> Telemetry data is designed to be recorded at 1⅞ ips, on tape compatible with Ampex FR600 playback equipment operating at 30 ips, allowing a theoretical reduction of processing time approaching 16/1. This feature of the IMP telemetry system yields a substantial improvement in the rate of processing data. Information recorded on tape at the acquisition stations must be of uniformly high quality; a major problem in formulating a processing philosophy can develop if station operations are other than satisfactory. Systems operation will be set up on the assumption that the data-acquisition stations will perform adequately. The problem of correctly recording coded time on tape simultaneously with telemetry information will be checked by an on-board satellite clock.
>
> Necessary to the PFM encoding technique is the utilization in the data-processing operation of comb filters, the function of which is to improve the S/N ratio by reducing the noise bandwidth. The conditioned signal is sampled at a particular rate and in a particular mode determined by the output of the frame, channel, and sequence sync detector under the control of the programmer. The time code is recovered in a separate operation which depends upon an initial automatic or manual read-in of time, and subsequent updating using the reference fre-



(*from a NASA report*)

Figure 14–3.—Block diagram IMP data reduction system (see text).

quency recorded on the telemetry tape. The sampled signal is converted to a digital form and stored sequentially in the magnetic-core memory of the output buffer which produces the digital tape. Each time a frame sync pulse is detected, the updated time, frame, and sequence identification are also stored in the memory. A flag bit indicates the correspondence of updated time and recorded time. At the appropriate time, the entire sequence of stored characters is dumped on an output digital magnetic tape.

Since the analog-to-digital tape-conversion process operates at 16/1 ratio relative to acquisition time, there is no need for preprocess editing of tape. During the initial processing of step I (fig. 14–3), both visual and recorded displays will monitor the quality of tape recording and playback of satellite information. For those samples of data during which there is insufficient S/N ratio to accurately recover the data, a flag will be recorded, indicating a signal-dropout condition. Special purpose processing equipment will be employed for the Rb-magnetometer signal when the spacecraft is within 5 earth radii (2% of orbital period). In summary, the equipment consists of:

(1) FR600 playback tape deck.
(2) Comb filters.
(3) Synchronizer detector and identifier.

(4) Analog-digital conversion (discriminator providing a precision of 1/1000, and filter-tooth detector providing a precision of 1/100).
(5) Time decoder.
(6) Programmer-control.
(7) Core memory buffer and tape drive.
(8) Digital tape deck.

9.3 Master Data-Tape Production

The output tape from step I consists of a string of BCD characters with tape identification, time, and data recorded in a single block corresponding to an individual sequence. A prime function of step II is to check the time-code data for accuracy with reference to the satellite clock and to perform the necessary corrections. In addition, the information content will be checked and corrected for character-count consistency. The information is put into format logically with correct time and identification, and a master data tape is generated and printed simultaneously. In addition, a punched-card log of the telemetry tapes recorded on the digital master data tapes will be maintained for summary and searching functions in step III. The medium-scale computer of the Data Processing Branch, Data Systems Division, will also be used for this phase of IMP information processing. These master data tapes will form the library from which the experimental data tapes will be prepared.

9.4 Experimental Data-Tape Production

The experimenter's data tapes will be prepared using the master data tapes produced in step II as input. The accompanying telemetry-tape log on punched cards will provide a means for automatically reading a master data tape at random, so that a chronological data sequence can be readily generated. In addition, it will provide documentation for both steps II and III. The prime function of step III is to decommutate the individual experimenter's data to separate tapes in different formats and provide an accompanying printout.

9.5 Master Trajectory-Data Production

This operation is principally a merging of data and an extensive computational effort which produces the final master trajectory information. It is best accomplished on a large-scale computer system such as the IBM 7090, which is planned to be employed for this purpose. Approximately 2 hours of 7090 time will be required per week of trajectory. Duplication of the trajectory tapes and the printouts for each of the experimenters will be accomplished on the 7094 computer in the Data Processing Branch.

9.6 Data Evaluation

The station telemetry tapes will be received by the Data Processing Branch for evaluation and reduction. A representative cross sample from each station will be reviewed for quality and quantity of usable data and checked against expected station performance. A summary of tapes by station will be maintained as a control input for station operation and as a guide for processing. Tapes will then be arranged in chronological order to enable processing in a time-history sequence. It is anticipated that there will be three categories of tapes. They are (1) unusable tapes resulting from inadequate signal-to-noise ratio, interference, or operator error; (2) questionable tape requiring extra handling to recover the data; and (3) good tapes of sufficient quality to warrant immediate machine processing. The first class of tapes will be retained for archival purposes and possible exploitation as the state of the art is advanced. The remaining two categories will be processed through the system described in the preceding paragraphs of this section.

OGO–A

As described in the Operations Plan (Paragraphs 1.1 and 1.2, Plan 11–64):

> The primary objective of the Orbiting Geophysical Observatory program is to conduct large numbers of significant, diversified geophysical experiments for obtaining a better understanding of the earth-sun relationships and the earth as a planet. The secondary objective of the program is the development and operation of a standardized observatory-type oriented spacecraft consisting of a basic structure and a subsystems design which can be used repeatedly to carry large numbers of easily integrated scientific experiments in a wide variety of orbits.

OGO–A is the first mission in the OGO program and is also referred to as EGO for Eccentric Orbiting Geophysical Observatory. For data handling, *eccentric* is the key word because it refers to the very wide range of distances this satellite will have from the earth. Actually the apogee is 149,000 kilometers (80,400 nautical miles) and the perigee is 275 kilometers (148 nautical miles). The rotational period of the satellite is 63.85 hours, a figure many times that usually considered to be a reasonable satellite period.

In the OGO–A mission, magnetic tape recorders have the following tasks to perform:

1. Ground-station recording of FM/FM telemetry data on conditions aboard the Atlas and Agena launch phase.
2. On-board recording of the data from a large number of experiments in the form of wideband PCM. This on-board data is stored during the orbit period and "dumped" at a high rate of speed while the satellite is in view of a ground station.
3. Recording at ground stations of PCM data telemetered via playback from the on-board recorder.
4. Recording at ground stations on a semi-continuous basis of

special purpose telemetry which produces data on the spacecraft incompatible with the PCM telemetry and which hence is transmitted FM/PM. This data consists primarily of noise and electrical phenomenon measurement related to a study of of very low frequency (VLF) radio transmission.

Another function is required of magnetic recording in the launching of the vehicle and its injection into orbit. This function has now become so routine as hardly to require mentioning. The Minitrack function is performed in that a transponder aboard the spacecraft is interrogated from various of the ground stations and returns a signal to the ground station which is received by a complex extended antenna array on the ground. This antenna array is so instrumented as to give precision phase and amplitude information from the received signal, from which information the spacecraft's relative slant range and track can be determined. Typically the raw Minitrack phase and amplitude data are recorded, as well as computed phase data reduced to digital numerical form and slant range calculations in digital form. This recorded information is used later to determine the spacecraft's track and orbit with precision.

There is some overlap between the functions of the various recording subsystems. For example, data from the sensors on board the spacecraft which determine operating conditions during launch and orbit injection are telemetered to the ground by a system having quite different ground station recording requirements from that used with spacecraft sensors for determining orbital conditions. The orbital satellite sensors are carefully integrated with the PCM system used for transmitting the data from the orbital experiments, and use the same telemetry transmitters and receivers. The Atlas and Agena launch vehicle sensors are independently instrumented for the individual parts of the vehicle and are telemetered with still another system with its own ground recording requirements.

The extremely eccentric orbit and correspondingly long orbit time of OGO is unusual. During much of the orbit, little information can be obtained for the satellite whether it is in "view" of the ground station or not. Data is collected relatively slowly in distant parts of the orbit and then "dumped" relatively fast while the satellite is near the earth. For satellites with a more nearly circular orbit the data is collected slowly and dumped fast, not because of change in distance between satellite and earth but because only in a limited part of the orbit is the satellite in "view" of the relatively few tracking stations available. (Compare these two modes of operation with that of IMP, discussed earlier.)

However, OGO has three different basic bit rates in its PCM system.

These are 1,000, 8,000, and 64,000 bits per second. All data which is recorded is taken at 1,000 bits per second but data which can be transmitted in real time direct from the spacecraft to the ground station can be obtained at any of the three bit rates. Depending on receiving conditions and the signal-to-noise ratio of the telemetry link, the ground station can command real time data at a rate appropriate to the transmission conditions obtaining. Recorded data is always played back at a 64 to 1 increase in speed in order to take full advantage of the short time during which the satellite is in good "viewing" distance.

To make the playback of data completely independent of the timing within the orbit, two tape recorders are provided. One of them records at any particular time and the other is ready to take over when for any reason the operation of the first is interrupted. A simple operation interrupt would occur when the first recorder came to the end of its tape. Under these circumstances, the second recorder would then proceed to record. Another interruption might be the demand from the ground that the tape recorder play back its recorded data. The following quotation from the operations plan document will indicate clearly the format used for the recorders (part of paragraph 4.3.1–4.2):

> The OGO–A Observatory will carry two on-board magnetic tape recorders for storage of PCM data. The data will be stored at the rate of 1,000 bits per second and played back on command at 64,000 bits per second. The data is played back in reverse order from which it was recorded. Each of the two spacecraft recorders is capable of recording for a maximum of 12 hours. When one recorder has been filled, recording is automatically switched to the second recorder. When the spacecraft accepts a command to play back stored data, one of the following two sequences takes place depending on which recorder is in operation at that time:
>
> 1. If data is being recorded by the first recorder when the command is given to play back, recording will be switched to the second recorder while the first recorder is playing back. Upon completion of first recorder playback, recording will revert back to the first recorder and that data stored by the second recorder (during playback of the first recorder) will then be played back.
> 2. If data is being recorded by the second recorder when the command is given to play back, data will continue to be recorded by the second recorder while the entire first recorder is played back. Upon completion of first-

> recorder playback recording will be switched to the first recorder and all data stored by the second recorder will be played back.
>
> The time required to complete a playback sequence depends on the amount of data stored. Playback of one completely filled recorder requires 11.25 minutes.

Because the total period of this satellite is 63.85 hours, the 24-hour recording capability does not, of course, cover the entire orbit. It does not even cover the entire relatively distant part of the orbit. For example, 20 hours into the first orbit, which is about 12 hours before apogee, the spacecraft is 132,000 kilometers from the earth. At apogee it is 150,000 kilometers away at some time after 32 hours, and at 54 hours it appears from extrapolation on the subsatellite plot that it would be about 100,000 kilometers from the earth. It appears, therefore, that the recording scheme is not used necessarily to assure that the data will be dumped when the satellite is near the earth but rather to assure that the data will be received when the satellite, even though distant from the earth, is in clear view of any specific receiving station.

The ground recorders for this satellite are used in a fairly typical manner during each of the several phases of the flight. The Goddard Space Flight Center Space Tracking and Data Acquisition Network (STADAN) records the data from the normal tracking part of the operation, that is, during the stable established orbit, on seven-channel Ampex FR-600 recorders. The tape recorder speeds will be 30 inches per second for a 64,000 bits per second bit rate, 3¾ inches per second for 8,000 bits per second and 3¾ inches per second for 1,000 bits per second. All seven channels of the recorder and its monitor voice track are used. The track assignments are quite typical of such an application.

For example, in the case of the wideband PCM telemetry, track 1 and track 7 are considered to be relatively poor tracks because of the possibility of edge damage to the tape and the most important data are placed on tracks 3, 4, and 5. Track 1 records the receiver AGC's and a 10-kcps reference frequency. These signals are multiplexed by using the 10 kcps reference frequency direct and mixing it with FM telemetry subcarrier signals placed in IRIG channels 1, 3, 5, and 7, to cover the AGC's of the four receivers used in the double-diversity system. Track 2 takes the raw unconditional PCM data from the receiver outputs after it has been passed through one of the receiver-pair diversity combiners. It is recorded as a direct signal. Channel 3 is also recorded direct and consists primarily of conditioned PCM data which has passed through a signal conditioner. Track 4 carries the direct recording of the time standard system which involves decimal time of day derived from the time standard generating system. Track 5 is also recorded direct and records the bit-rate clock which has been derived from the PCM synchronizer and signal conditioner. The purpose of recording the bit-rate clock is to permit quick reduction of the PCM data in the acquisition station if the local PCM synchronization is operating correctly. Since the raw, unconditioned PCM data is available in the record, a better synchronizing job may be done later on playback if the ground-station job is inadequate. Track 6 is an FM-recorded time-standard system which gives a serial decimal time code, a key input to any such tracking operation. Track 7, which is also recorded direct carries the command signals that have been sent from the command transmitter to the satellite. Track 8, which is really the voice monitor track, carries a direct audio recording of the voice commentary and also contains the WWV reference time.

The special-purpose telemetry transmitted in FM/PM form is recorded on an identical recorder somewhat differently implemented. On track 1, as before the receiver AGC's are modulated onto IRIG subcarriers and recorded directly. On track 2 there is a mixture of the binary time code from the time-standard system and the control track signal which is used to synchronize the playback of the recorder to the power system of the playback point. The control track signal is a 60 cps signal amplitude-modulated on an 18.24-kcps carrier. On track 3, the FM data output, direct from the diversity combiner, is direct recorded. On tracks 4 and 5 there are two separate 10 kcps reference signals recorded from the time-standard system. On track 6 the serial decimal time code is recorded via FM from the time-standard system. On track 7 the satellite commands are recorded direct, and on track 8, the monitor track again, the voice commentary and WWV time are recorded.

A significant difference between the implementation of the two recorders is the absence of the control track signal from the PCM recorder. Since any time error can always be removed from a PCM signal by storing it in a buffer at an irregular rate containing time errors and clocking it out under an accurate time reference, the absolute speed of the playback recorder is not important. For the special-purpose telemetry, where the signal is in FM/FM form it is important that the playback be synchronous with the original recording if the data is to be transmitted accurately and hence the control track is needed. It is also significant that it appears that the accuracy of the playback from a conventional recorder is good enough here that no flutter or wow compensation is considered to be necessary. It is further interesting to note that the tape speed, as of the time of producing the document from which this data is taken, for the special purpose telemetry had not been decided, although it was assumed at that time that it would be 30 inches per second near perigee and 15 inches per second at all other times.

An interesting compatibility problem is shown by the handling of the vehicle sensors from the Atlas and Agena vehicles. This data is to be recorded primarily by the Manned Space Flight network stations and is therefore recorded on their standard tape units which use not half-inch but one-inch tape. The one-inch machines are not used intensively in this application since many of the tracks are empty. The compatibility problem arises in that the data for both these vehicles will be reduced by the Lockheed Missiles and Space Company which has responsibility for the Agena data. Since Lockheed uses a half-inch standard data format, all data taken by the Manned Space Flight network on one-inch machines must be transferred to half-inch tape before Lockheed can deal with it.

The track assignments for the one-inch machines are as follows: On track 1 the direct video output from the 244.3 megacycle telemetry receiver is recorded. (This seems somewhat strange because an edge track is easily damaged.) On track 2 a voice monitor is recorded and on track 3 a 100 kcps reference signal which will be used later for FM flutter compensation. Tracks 4, 6, 8, 10, 12, and 14 are not used. Track 5 contains WWVH timing, and track 7 records the 244-mcps signal strength frequency modulated on a 10.5 kcps VCO, and the 244-mcps video signal strength modulated on a 5.4 kcps VCO. Track 9 carries the direct video, described as a backup, but probably the primary track, since it is more protected from edge damage than track 1. Track 11 carries serial decimal time and track 13 carries a 50 kcps reference. When these data are transferred to a half-inch machine the track assignments are: Track 1 244.3-mcps video, track 2 voice, track 3 WWVH timing, track 4 the signal strength (AGC), track 5 the video backup, track 6 serial decimal time, and track 7, the 50 kcps reference.

In specifications for the on-board recorder forming part of a complete data transmission system the problems, discussed in chapter 13, of providing a reliable enough unit within the space, weight and power limitations of satellite use must be considered. The performance of the on-board recorder must, in the interest of system efficiency, be limited as far as possible. Therefore a study of the tradeoff between limitation of the performance level required of the on-board recorder and the possible complexity this limitation adds to ground recording and data reduction must be performed.

The state of the flight recorder art can be expected to be inadequate to provide completely the performance required from the on-board recorder if the precision of that unit were to determine the overall system precision. It is naturally not possible to abandon an entire line of research because at first glance the on-board recorder appears to require techniques beyond the state of the art. It is, however, possible so to design the complete data transmission system that the limitations of the on-board recorder are formally integrated into the system and the data reduction technique provides automatically for correction of initial recorder deficiencies. A complete recording and data recovery system can then be devised which permits an overall accuracy higher than that delivered by the original recorder itself.

Before deciding that the state of the art is inadequate to provide satisfactory on-board recorder performance it is necessary to examine the state of that art very carefully. Many ingenious recording modes and permutations of standard coding systems have been used to avoid the on-board recorder limitations directly. The simple compensation techniques used, for example, in FM flutter compensation in the ground-based recorder can be extended to the flight unit. The reference tone can be transmitted to the flight unit at the same time that the data is transmitted and reproduced from the flight unit at the same time that the data is reproduced. Without the system being concerned with where the flutter originates, a conventional flutter-compensation operation performed on the data reproduced from the ground recorder will remove most of the flight-recorder flutter at the same time.

The decision in the case cited to use FM recording might, of course, involve initially a careful consideration of whether the increased bandwidth of the FM system was worth the overall data improvement that the complex double-FM transmission system involved. In the same way, the decision to use PCM recording for on-board data always involves an acceptance of the greatly increased bandwidth that PCM requires over direct recording. As accuracies required have increased, the decision to accept the bandwidth problems of PCM is apparently being accepted more freely by system designers.

After selecting the flight recorder recording mode with care, the quality of the data played back using routine compensation techniques or using redundant coding to increase accuracy may still be too low to provide adequate overall system performance. Complex compensation can then be considered. By complex compensation is meant an approach in which the entire data transmission system is designed specifically to provide compensation for a fully expected and engineered-in limitation of the on-board recorder.

A classic example of this sort of compensation is used in recording the data from the Nimbus AVCS (Advanced Video Camera System). Whereas for the earlier Tiros weather picture satellite with its relatively low 300-line-per-picture video resolution, adequate pictures could be reproduced from the on-board recorder without compensation for its flutter, this is no longer possible with the 800-line-per-picture images produced by Nimbus. In order to deal with such high-resolution pictures when the satellite recorder has typical on-board recorder flutter, a compensating system peculiar to the signal involved has been devised.

When the satellite is interrogated and the signal is telemetered to the ground station, a reference tone is transmitted along with the video signal. This reference tone is recorded at the same time as the video signal and is played back by the satellite recorder simultaneously with it. It therefore has the same time irreglarities as the video signal. Either at the time of reception by the ground station or after reproduction from a high-performance ground recorder system, the reference tone is passed through a discriminator. The instantaneous amplitude of the signal recovered from the discriminator is proportional (in a conventional discriminator) to the instantaneous flutter in the satellite recorder. That is, its instantaneous value is proportional to the instantaneous fractional speed error in the recorder. The signal is then integrated, producing now a signal proportional to the instantaneous displacement of the point on the tape being reproduced from the position it would have if the tape motion were perfectly regular.

Since this is a scanning system which produces television pictures by "painting" them onto a monitor screen, the disturbance produced by the existence of flutter will be the displacement of picture elements from their proper positions when they are laid down at a uniform rate by the scanning beam. The reference signal, which is now proportional to time displacement along the tape, is also proportional to time displacement along the scanned picture line. The derived reference signal is therefore used to add a corrective displacement to the uniform sweep of the cathode ray tube beam which is "painting" the television picture in such a way as to restore the picture elements to their proper positions. The brightness of the scanning beam is dependent both on its current/voltage product and its velocity; the disturbance of the uniform movement of the scanning beam should normally produce irregularities in brightness. However, in this case, the brightness variation, which is proportional to the rate of change in the displacement and hence to the flutter, appears to be unimportant. Displacement of the picture element is apparently a severe enough fault that, when it is corrected by the means described, the residual brightness errors appear invisible.

NIMBUS

The Nimbus weather satellite data handling system is one of the most complex applications of magnetic recording to satellite data. Essentially all data from the satellite is returned to the ground from on-board recorders and the precision required of the data is such that compensation for on-board recorder irregularities must be provided. One of the Nimbus recorders is also unusual in that the record and playback speed are the same, although the recorder is actually used to "dump" the data in a fraction of the orbit time.

The television cameras in Nimbus have a large angular coverage toward the earth. If Nimbus has taken a picture of one part of the earth, about two minutes elapse before it has reached such a position that the desired overlap between the current picture and one just taken occurs. The angle of coverage and overlap are such that Nimbus need only take about 33 pictures per orbit. Eight seconds are required to scan a single Nimbus picture off the sensitive surface of the vidicon. Actual recording during an entire orbit therefore lasts only a little over 4 minutes. This 4 minutes of recording is then played back for a ground station at exactly the same rate at which it was recorded, in effect a dumping operation, although carried out at the recording speed.

There are many similarities between the video systems of the Nimbus and the earlier Tiros. Tiros produced pictures with an equivalent horizontal and vertical resolution of about 300 television lines whereas Nimbus has a resolution capability of 800 lines in both directions. It was permissible to playback the Tiros television signal from the on-board recorder and place it directly on the cathode ray tube monitor on the ground for photographic recording without compensating for deficiencies in the on-board recorder. However, the higher resolution of Nimbus showed up the flutter and wow of the on-board recorder as unacceptable errors in geometry of the reproduced picture. Compensation for the on-board spacecraft irregularities was therefore provided, as discussed in the preceding section.

The Nimbus system includes not only the so-called AVCS or Advanced Vidicon Camera System for daytime pictures of the earth but also the so-called HRIR or High Resolution Infrared monitoring system. The HRIR system is in effect a crude mechanically scanned television system operating in the infrared and thus permitting pictures to be obtained at night when starlight would not be adequate to produce pictures in visible light. Along with this double imaging system the satellite transmits data from several other on-board sensors besides the image forming ones and must send extremely accurate attitude and position determining data.

The attitude and position data is necessary so that the precise relationship between the pictures taken and the position of the satellite over the earth can be established so that properly-integrated continuous picture coverage can be obtained. In order to use the pictures most effectively, a grid system indicating latitude and longitude lines, is generated in a computer on the ground and applied to the final images produced so that the weather pictures are accurately referenced to the earth. The satellite therefore has a recorder for the video system, a recorder for the HRIR system and a recorder for the PCM, attitude and other satellite on-board data. The operation of these systems is best understood by the following quotation from the Nimbus Data Handling System (NDHS) Manual (X650–64–189, paragraph 3.2):

> ### *Typical Data Handling Sequence*
>
> A typical sequence of data handling operations at the NDHS during and immediately following a normal 8-minute station pass is described below.
>
> Since a high degree of flexibility is inherent in the NDHS data processing system, the sequence of operations indicated are representative rather than absolute.
>
> After spacecraft acquisition, ground and spacecraft time correlation is performed by the Command Console Operator. Then, the spacecraft is commanded to transmit "A" stored data, a direct AVCS picture, and stored HRIR data. The following PCM data sequence occurs:
>
> > "A" stored raw data are received and recorded at the station over approximately a 4-minute interval; during this interval the Computer Subsystem calibrates and records attitude data and selected parameters required for meteorological data processing (metro parameters).
> >
> > Following the 4-minute playback, the Computer Subsystem provides a synopsis listing of computer-recommended command instructions and mode status, based on an analysis of "A" stored data.
> >
> > During the time remaining to the end of the station pass, selected "A" real time parameters are received, calibrated,

> and printed out. This provides data for a near real time evaluation of the effect on the spacecraft of commands transmitted during the current pass.
>
> The "B" telemeter is considered a backup data source and "B" real time data would be received when it is not possible to receive "A" data.

Concurrent with PCM data sequence described above, the following meteorological data sequence occurs:

> The direct AVCS picture is received during the first 3 minutes of a station pass which occurs during earth day, thereby providing picture data for assessment of AVCS performance in real time.
>
> Following the direct picture period, the spacecraft is commanded to transmit stored AVCS data, which are then received and recorded over approximately a 4-minute interval. During this period, time points are stripped off and stored in the Computer Subsystem approximately every 8 seconds. Meanwhile, the computer uses part of each 8-second interval to calculate time/position points.
>
> The remaining free time of the Computer Subsystem is used to smooth the attitude data and write a tape containing calibrated metro data and smoothed attitude information.
>
> The smoothed attitude and metro data tape is rewound. At the GILMOR NDHS the attitude and metro data tape is then transmitted to the Goddard NDHS via the wideband data link.
>
> The smoothed attitude data are also retained in the computer core storage for calculation of time/attitude points at the end of the AVCS reception period.

Continuing with a consideration of the meteorological data sequence, reception of HRIR data also starts at the time of spacecraft acquisition and continues for about 7 minutes. When reception is complete, the following events occur:

> The AVCS–HRIR Mincom recorders A and B are rewound and HRIR gridding begins using Mincom A for data playback. At the GILMOR NDHS the gridded HRIR data are transmitted to the Goddard NDHS via the wideband data link. The transmission of the data is simultaneous with the gridding process and is completed approximately 17 minutes after the start of spacecraft interrogation.
>
> During HRIR gridding, Mincom B is played back for the computation of AVCS horizontal and vertical sync offsets.
>
> As soon as the HRIR gridding and offset synchronization activities are completed, AVCS gridding is started. It requires approximately 32 minutes. Transmission of the gridded triplets from the GILMOR NDHS to the Goddard NDHS is automatic and simultaneous with gridding. At the GILMOR NDHS, the transmission of the gridded AVCS data begins immediately after transmission of the PCM Engineering Units Tape described below.

The off-line processing sequence is less fixed and will depend upon the requirements established by the NTCC for the particular station pass. Typical off-line processing would be performed as follows:

> Off-line processing of PCM "A" stored data can begin at the end of the acquisition period, starting with the reduction of the entire "A" stored record to engineering units. Simultaneously, a sync summary is printed out to provide a complete history of interrupt words, mode changes and bad frames, subframes or words.
>
> The Engineering Units tape produced at the GILMOR NDHS is transmitted to the Goddard NDHS for further analysis.
>
> The spacecraft status (electrical energy balance and nitrogen status) is completed and the results printed out. These data are also punched on paper tape for transmission to the NTCC when this processing is performed at the GILMOR NDHS.
>
> Selected items are limit-checked (Limit Summary Module), function listed (Data Listing Module) and subjected to the averages and extremes routine (Average and Extreme Module). These results are printed out and made available to the NTCC.

The seqüence of operations described for this typical case requires a station pass of 8 or more minutes.

It should be noted, however, that a pass time of little more than 6 minutes would suffice for all but the 3 minutes of the HRIR data. A pass time of little more than 4 minutes would allow the reception of the "A" stored record and most of the stored AVCS data (assuming no direct picture). Pass time in excess of 8 minutes, of course, would allow reception of additional real time data.

A common variation of the above sequence will be the interrogation of "A" real time data prior to the receipt of "A" stored data. The alteration of the sequence in which PCM data are acquired from the spacecraft poses no data handling problems since the telemetry computer program can automatically recognize the type of data ("A" stored, "A" real time or "B" real time) being input and will automatically initiate the appropriate data processing subroutines.

CENTRAL DATA PROCESSING FACILITY

NASA Technical Note D–1320 describes in detail "A Central Facility for Recording and Processing Transient Type Data." This facility was constructed at Lewis Research Center to accomplish the objectives which are set forth in this edited quotation from the introduction to the technical note referred to:

> In 1954 a central automatic data processing system was placed in operation at the Lewis Research Center. This system met

> all design objectives and is still in operation; however, it is only useful for processing steady-state-type data. Since that time, advances in the state of the electronic art have made it possible to build a data system capable of recording and automatically processing transient-type data. Increasing quantities of such data are recorded at this center as a result of experiments such as vibration testing, heat-transfer experiments, and rocket testing. The data system described in this report came as a natural outgrowth of the need for an improved means of processing transient-type data and the proven usefulness of a central automatic data processing system. This system makes possible the analysis of data by mathematical techniques that would be too time-consuming if done manually, and gives results of much greater accuracy than could be attained by older methods of processing.
>
> Recording is done by two types of equipment, which may be classified as analog and digital. These two recording systems are independent and complement each other. The analog system has the advantage of high-frequency response, while the digital system gives greater accuracy but with lower frequency response characteristics.

This facility was installed, of course, to fulfill the data processing requirements of the Lewis Center as a research operation. The particular choice of equipment and data reduction techniques was related directly to this function of the Lewis Center. However, almost every function that is performed in this facility is directly related to a function which is now performed in data reduction from essentially every NASA or military flight or research program. Certain aspects of the techniques involved are specialized to the Lewis Center needs of transmitting data over long distances within the Center and concern the problems of long telephone cables. Other parts of the operation are essentially identical with those that would be performed for flight data originating from a boost vehicle, a satellite, or some reentry test vehicle.

In a typical flight program there is a certain amount of local use at the data acquisition station of raw, unreduced data. This function is very similar to the quick-look facility which is described in the Lewis operation. Whereas at Lewis the data is recorded at the time of the test and the tape is immediately available, for most flight operations the data is recorded fairly remotely from the central management of the flight. Either tapes must be transmitted to a data reduction facility, or the data itself may be transmitted by land lines. In some cases, immediately after acquisition, crucial data is played back at reduced speed to fit the transmission bandwidth of the land lines available and thus transmitted to interested parties hundreds of miles away.

The following description of the Lewis installation is derived directly from the material of the technical note, and is not intended to be an exhaustive review since the best source of that is the technical note itself.

Digital System

The digital recording system has 128 input channels. The voltage resolution is 0.1 percent of full scale which results in an overall system accuracy of 0.25 percent of full scale. It operates at a sampling rate of 4,000 samples per second. This sampling rate is limited by the analog-to-digital converter available and may be distributed among channels as desired. For example, if there are 12 channels of data being sampled, the sampling rate for the individual channel would be 333 times per second.

The operation of this digital system is carefully designed around minimizing the amount of complex and expensive equipment needed. This system, therefore, has as few analog-to-digital converters as possible, in this case, only one. By multiplexing, it is possible to use this single converter with great efficiency. In more complex systems several converters may be used with even more complex multiplexing systems.

The multiplexing performed for this data recording system consists in switching in a systematic way between the selected ones of the 128 input channels to connect these to from 1 to 8 output channels. For example, the multiplexing scheme might be for channels 1 through 16 to be sampled in rotation and the samples connected to output channel 1, at the same time input channels 17 through 32 would be likewise treated and the output sent to output channel 2, and so forth. In this way 128 input signals are made available 8 at a time to the recording system. In this particular unit, the switching is accomplished with oil-damped sealed reed switches which are switched by magnets which rotate past the array of switches arranged in drum form.

The eight output channels of this multiplexer are fed to "analog storage units." These storage units, in effect, open a switch for a short period of time and arrange for an internal capacitor to store charge to produce a voltage equal to the instantaneous value of the input signal at the time of switch opening and then to close the switch and hold the charge on the capacitor. This is in effect a "sample and hold" circuit. In order, then, these eight samples are interrogated by the analog-to-digital converter. The converter used in this particular system employs successive approximation to provide a complete conversion in 22 microseconds with an 11-binary-bit output. The unit is operated at two different speeds, either 1,000 or 4,000 conversions per second depending on the recording mode.

The output of the analog-to-digital converter is recorded on tape and is sent at the same time to various "quick look" facilities. In the quick-look facility provision is made for examining the data after it has passed through all stages of the reduction process except recording and reproduction. The digital information is presented on numerical displays and is also reconverted to analog form for this purpose by plotting on an x–y recorder or put into other visual presentation form (storage oscilloscope, etc.) for examination by the operator.

The recording operation is performed on 8 parallel tracks in a digital "tape handler." The data word consists of the 10 data digits plus the polarity digit produced by the 11-bit converter plus 7 other bits which identify the individual data word. In other words, each successive data number as converted by the analog-to-digital converter is identified serially in recording. The 8th track serves to keep a complete running record of the data on a larger scale. In addition to the individual data reading identification provided by the 7 word bits, the so-called "ancillary coding" on track 8 further indexes the data as to block number, test number and facility (of origin) number. For the complete index identification, the ancillary code requires some 96 frames.

The terms "word," "frame," and "block" will be identified as they are used here to avoid confusion. A data "frame" is the series of 8 bits or pulses which are laid across the 8 tracks in the digital recorder and a word is made up of 3 such frames. On tracks 1 through 7 there are word number identification bits 1 through 6 and a parity bit. The 8th track for this frame carries an ancillary coding bit. Frame 2 contains the 7th word bit and the polarity bit and bits 1 through 4 of the binary number which constitutes the date, followed by an additional parity bit and ancillary coding on track 8. In this case bit 1 is the most significant and bit 10 the least significant of the data bits. Data frame 3 contains data bits 5 through 10 and an additional parity bit as well as the ancillary coding data. The parity bits here are, as usual, placed in the 7th position to guarantee that the 7 bits in a row always contain an odd number of ones. If the data information has an even number of ones, the parity bit is made unity and if the data bits have an odd number of ones the parity bit is made zero. The ancillary coding actually does not fit frame by frame but is transmitted at every other frame and really does not enter into the frame proper.

A "block" is a group of 32, 64, or 128 data words. The blocks of data are numbered in sequence, starting with 1 from the beginning of the reel of magnetic tape; the block number essentially indicates reel data time and is useful for editing the data later. A "reading" which is a special term used in this particular data reduction system, consists of any number of blocks of data needed to record a data event from one facility. Thus a reading is bounded at the beginning by the start of the recording from a facility and at the end by the stopping of the record equipment after the data event.

The ancillary coding track contains the following information in order: (Every other frame is used, that is, there is no recording in odd-numbered but only in even-numbered frames and up to 96 frames are needed to contain the complete unit of ancillary data.) First, a block start indication, the one piece of data that is recorded in both even and odd frames (1 and 2). It is followed by the block number in binary number form, the reading number in the same form, an identification of the facility number in the same form, and finally, an identification of the computer program which is to be used in later reduction of the data. The ancillary code concludes with a single index bit in frame 94 (always a one) which notes the end of the code.

This kind of ancillary coding is universal in data acquisition because it is always essential to identify each piece of information with its exact time of occurrence and the corresponding physical event. Reference is made in describing the satellite data acquisition techniques to such items as "WWV reference time" and "binary-coded-decimal real time"; these data perform essentially the same task as does the ancillary coding described here.

Data editing takes place, once the recordings have been made, in order to identify important or erroneous parts of the data. Various display systems are designed for displaying in numerical or graphical form the various pieces of data and their location for an operator who scans through the recorded data. The ancillary coding is essential to locating this data within the mass recorded on a single tape. In the editing process, data of interest is selected and all errors are identified either by the operator or automatically by the equipment. Such errors might be incorrect frame identification, a loss of consecutive order in blocks or the like. When the data is to be transferred to a computer for reduction, the same error identification is automatically performed, and information on the errors is transmitted simultaneously to the computer along with the data from the tape.

The individual interested in the results of this recording and data reduction can, in the editing process, select the items of particular interest to him and can decide exactly what is to be done with the data and so indicate by establishing a specialized computer program. When he has completed his selection, the data reduction process is then automatic and the tape may either be played over telephone lines to the computer or may be physically transported to a digital tape playback unit at the computer.

Analog System

In the analog data reduction and acquisition process in this facility the methods of data identification are quite similar to those of the digital facility. A 14-track analog tape recorder is used, 12 tracks being assigned to parallel recording of 12 sets of data and 2 tracks being used for identification and playback system control. Every 50 milliseconds a marker signal is placed on one of the control tracks; a binary block number, identifying serially each individual 50-millisecond interval from the start of the recording, is placed on the same track between these markers (a "block" has now become a 50-millisecond interval).

FM recording with a bandwidth of 0 to 10 kcps is used for the analog system. With this wide frequency response, analog data recording is used for high-frequency analysis; it may be accompanied by simultaneous digital data-taking if several aspects of a single experiment are to be analyzed. Because the analog system is subject to drift of gain and zero, careful calibration procedures are followed.

Seven "zones" occur in sequence on the tape after the start of the record. Zone one carries the record number on one of the control channels (this is a 4-digit binary-coded-decimal number, the first two digits of which identify the facility of origin and the last two the reading number); this zone lasts for 2 seconds. Zone two is the zero-calibrate zone; for 3 seconds the transducers from which data are to be recorded are set to zero and the corresponding FM frequency recorded on the tape. Zone three carries a 3-second full-scale calibrating signal corresponding to the zero-calibration of zone two. Zone four is called the "pre-data" or "non-usable-data" zone and lasts from 150 milliseconds to 2 seconds, during which, automatically or manually, the normal operation of the transducers is reestablished. After this pre-data zone has passed, zone five or the "usable data" zone then occurs to the end of the test.

The end of the test data zone is established by the sending of a "stop" command from the test facility. A 1½-second zero-calibrate signal followed by another 1½-second full-scale-calibrate signal is automatically recorded on the tape. The zones are identified by signals on the control channels as well as by block and reading numbers.

The output of the analog tracks can be analyzed either by an analog or a digital computer. For the analog computer, the functions of compensating for drift of gain and zero during the experiment as well as for wow and flutter may be required. The same search functions as in the digital system are necessary for editing and for informing the computers as to their data reduction duties. Facilities are provided for looking at the results of the records either in graphical or numerical form, and automatic search is provided.

> The analog data may be played back at the speed at which it was recorded or at one-half, one-quarter, one-sixteenth, or one-thirty-second of normal recording speed. These slower playback speeds are required because the analog computer is seldom able to handle the full bandwidth of the actual experimental data. Slow speeds are also required because for precision data analysis, the data may be digitized and analyzed by the digital computer. The digitizing process is, of course, limited in speed to the capability of the analog-to-digital converter.

This brief description of the particular facility installed at the Lewis Research Center parallels closely what might be said for the somewhat more elaborate data reduction facility at Langley Research Center and in many other government and industrial installations. Likewise the data reduction processes involved in handling data from satellite and space probe experiments is parallel to, although obviously not identical with, the techniques used at Lewis. Multiplexing, for example, is performed onboard the vehicle for most flight experiments. Elaborate identification is not possible on the vehicle; identification is usually supplied in the ground data acquisition system. Timing data and signals derived on the ground for synchronizing the later demultiplexing operation are usually provided at the time of ground acquisition. Quick-look facilities are also provided at the data acquisition point to indicate whether, in fact, the experiment from the flight vehicle is proceeding properly and to decide if it is not, what if anything can be done about this.

For example, in the special-purpose telemetry on board the IMP satellite, certain data about low-frequency radio transmission are transmitted continuously to the ground. The experimenter in this case happens to have access to a large (150-foot diameter) receiving antenna and installation and can listen directly to his data as it is received from the satellite. Without requiring transmission of data to him from an acquisition facility within the NASA complex, the experimenter can determine that certain commands should be sent to the satellite to modify its operation to extend the utility of the experiment. This is a rather special kind of "quick-look" ability!

Typically, the data output from almost all data acquisition plants in the NASA complex except the self-sufficient ones such as those at Lewis and Langley is eventually copied and transmitted to experimenters in various parts of the United States who will use the data in different ways. The functions indicated from this brief description of the Lewis Center are, however, essentially those which will be used by the various experimenters. For example, vibration data from the launch vehicle of the Agena is transmitted to Lockheed, the contractor for the vehicle. (This is referred to above in connection with the OGO–A satellite.) Lockheed engineers will look at the actual vibration data on oscilloscopes or on oscillograph charts and may then perform either analog or digital spectrum analysis of this vibration. Whatever the nature of the data from a satellite or space experiment, it receives the same general sort of handling for each user. The Lewis data handling facility is therefore a representative "microcosm" of the world of data reduction.

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CHAPTER 15

Utilization Factors in Magnetic Recording

Ten chapters of this survey, following the introduction, were concerned with the nature and performance of elements of magnetic recorders. Chapter 13 discussed methods of testing and evaluating recorders. Chapter 13 surveyed the special requirements of miniature high-environment recorders and some of the ways in which these requirements are met. In chapter 14 attention was shifted to the use of the recorder in a complete system and to an almost philosophical discussion of what the task of the recorder is within such a system. What now are the utilization factors with which we should be concerned?

The external performance specifications of the magnetic recorder have been continuously improved since its first use for technical data recording. The bandwidth of the recorder has been widened, the signal-to-noise ratio has been improved and the flutter and distortion have been reduced. At the same time, the effectiveness with which the magnetic recording medium is utilized has increased. The longitudinal density of recording, for example, has increased from 500 cycles per inch for the original hi-fidelity broadcast audio recorders operating at 30 inches per second to 8 kilocycles per inch for home audio use, and 12,500 cycles per inch routinely for data recorders—now 17,000 cycles per inch is in the offing. Some increase in lateral packing density has also been made but not all in the same order of magnitude. These individual increases have resulted in an overall increase in the amount of data recorded per square inch of medium.

For this recording density to increase, both the medium and the methods of using it had to be improved. Controlled very narrow gaps, improved head finishes, and, most important, increases in uniformity and surface smoothness of magnetic tape, have all contributed to the improved density.

It is tempting to try to establish a criterion for individual recorder performance on the basis of achieved recording density. With care, this can be done, but the value of the criterion is limited. It has been suggested that one might set a criterion for recorder packing densities on the basis of the classic Shannon information theoretical measurement of channel capacities (Shannon [1948]). The Shannon channel capacity statement is so beautifully simple that it is often misinterpreted; the misinterpretation is particularly easy in the case of magnetic recording. Recording density will be briefly analyzed here using a "conservative" approach to the Shannon criterion:

$$C = W \log_2\left(\frac{S + N}{N}\right)$$

This classic Shannon formulas states only that, for a communication channel with a bandwidth in cycles per second of W, with an average signal power of S, and a "white" noise power of N, the capacity in bits per second is W times the logarithm to the base 2 of signal plus noise power over noise power (and this is the important part) *for an optimum coding method.* The Shannon channel capacity is the capacity for optimum coding but not necessary for any less than optimum coding. The optimum method of coding is definitely not implied or included in the formula.

If we take the full width of a strip of magnetic tape and consider that this is a communication channel, the coding process for this channel will include the decision as to how many tracks the tape shall be divided into, what the spacing between tracks shall, be and the particular mode of recording to be used on the individual track. One might try to evaluate the performance of a particular code choice by comparing the total information per linear inch of tape with that for optimum coding or for ultimate channel capacity. Unfortunately, this cannot be done because, although the calculation can be performed for the individual tracks, no such calculation can be performed for the tape as a whole. There is no meaning to the term signal-to-noise ratio or bandwidth for a one inch strip of tape until the decision has been made, for example, to use a one-inch wide record/reproduce head combination with it or to divide it into 20 separate tracks of a given width. The Shannon criterion, therefore, cannot directly be used with magnetic tape to compare any recording mode choice with the ultimate capacity of the tape.

The Shannon criterion is useful, however, in another sense. Slightly restated, the Shannon channel capacity formula gives the capacity in digital terms, i.e., in binary bits per second, of an analog channel of a given bandwidth and signal-to-noise ration. The Shannon criterion, therefore, can be used, not as a statement of the ultimate but as a statement of analog capacity in digital terms. Having stated capacity in this way for an individual track as a specific channel, one can then obtain overall performance figures for a given width of tape containing several tracks. This overall performance figure is a measure of the effective storage density on the tape. This conversion to digital form permits comparing analog and digital coding choices on the basis of total information capacity.

An indirect method is also available for deriving a figure of merit for the effectiveness with which a given coding choice, particularly an analog one, is used in a given recorder. If, following Eldridge (Eldridge [1963a]), one determines for a given tape and head combination the width of the track which will give unity signal-to-noise ration, this track width can be used as a criterion of recorder performance. One can, for example, measure with care the signal-to-noise ratio and bandwidth capabilities of a practical narrow track on a piece of tape. In performing this measurement, the tape and the rest of the parameters of the record/reproduce unit can be specified. Then, using the theoretical relationship that for a given longitudinal recording density, the power signal-to-noise ratio is proportional to track width, the figure which Eldridge experimentally verified, one can derive the track width for unity signal-to-noise ratio. This W_0 as Eldridge calls it, is the smaller the more effectively the tape is used. If, for example W_0 is smaller in one case than in another, the track width necessary *for a given higher than unity signal-to-noise ratio* will also be less for the first than for the second case. It, therefore, will be possible to pack more information on a given width of the tape in the first case than in the second.

One could postulate a situation requiring no mechanical guardbands between tracks and placing as many tracks of width W_0 across the tape as possible. One could then derive the individual track channel capacity for zero signal-to-noise ratio in this case and multiply by the number of tracks, thereby obtaining a figure for total information recorded on the width of the tape. Although not a true statement of Shannon's criterion for an ideal channel, this is a useful figure for comparing recorder performance. This ultimate capacity is not a practical number, since guardbands are necessary and a zero signal-to-noise ratio system is not useful for most applications. However, the calculation provides a means for comparing recorder performance where two recorders may be coded and operated in completely different ways. It would otherwise be difficult to calculate, under these circumstances, whether one was really doing a better job than the other. Such a determination is useful in deciding which way to direct the development of a high performance recorder system when several means of coding are available and a choice between them is difficult.

The preceding discussion referred to the problem of specifying analog system capability in digital terms. The discussion implied that so specifying analog capability is useful because it gives a coherent basis for a performance comparison between digital and analog systems for accomplishing the same thing. This comparison can be made, however, only for the recorder itself and not for the overall system. Given an analog signal which must be recorded, the user's criterion is "How much tape must be used to record the desired signals with the desired characteristics?" If the signal is to be recorded directly in analog form, the calculation of tape utilization is very straightforward. To record the same signal in digital form, all the criteria and design parameters involved in analog-to-digital conversion as well as the accompanying limitations of sampled data systems must be considered. The Nyquist criterion that slightly more than two samples per cycle can transmit completely the information contained in an analog signal is sometimes used in calculating the conversion efficiency. Users of sampled data systems, most of them admittedly working at very slow data rates (in the order of a few cycles per second), find this too optimistic a calculation by far (Edwards [1964]). Ten, twenty, and even thirty samples per cycle are often used when attempting to collect data in this form (chapter 4). The primary difficulty arises here because the bandwidth of the system is seldom under complete control.

In other words, in much data collection, certain useful slowly varying data must be extracted from a very noisy band containing disturbances of frequencies much higher than the highest in the data of interest. If one samples at just slightly more than two samples per cycle of the useful data, one also samples the unwanted data at the same time and the phenomenon of "aliasing" or "frequency folding" results in the desired data being distorted by the presence of undesired data of higher frequency (Susskind [1957]). The data can be filtered before sampling to eliminate these higher disturbing frequencies. In so doing, one must be careful not to change the amplitude of the desired data, i.e., the filter must have extremely uniform amplitude and phase response in the useful pass band. A filter designed to have this conservative inband characteristic will not attenuate out-of-band disturbances very rapidly.

To obtain a particular accuracy of the sampled data in the most conservative way, the filter must attenuate signals at any frequency where aliasing or frequency folding can take place. The potentially disturbing signal at this frequency must be attenuated to below the accuracy percentage desired. In practice, this means that the two samples per second criterion must be applied, not to the upper useful frequency, but *to the highest frequency of possible disturbing signal which is not attenuated below the desired accuracy percentage.* A simple example may illustrate this: To obtain data samples with an accuracy of one percent, undesired signals must be attenuated by 100 to 1 or 40 db. With an 18 db per octave presampling filter of essentially flat response up to the upper useful frequency, 40 db attenuation would be reached at a frequency 6 to 8 times that of the upper useful one. This means that the two samples per cycle criterion must be based on, say, 8 times the upper useful frequency or 16 samples per cycle of the useful frequency. For higher accuracies the situation is correspondingly more severe.

The problem in the tape recorder may actually not be this bad because external physical influences may reduce the amplitude of undesired signals of frequency higher than the upper useful band. How much this amplitude is reduced, however, is not usually known, and it is therefore almost impossible to make a general specification of what the sampling characteristics should be for an analog-to-digital conversion system. Since these conditions cannot be specified, it is essentially impossible to compare an analog-to-digital conversion followed by digital recording with direct analog recording as a method of coding for magnetic recording.

Although, as Eldridge shows, narrow track digital recording is by far the most effective way to use magnetic tape, this advantage may have little significance in the practical case. There are, however, circumstances under which this process of conversion to digital and recording on narrow tracks may be extremely useful. The use of digital recording as the ultimate standard of efficiency is, however, an oversimplification. The factors derived from the discussion above should be brought into any analysis of tape recorder utilization.

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APPENDIX

Review of General References

Since this survey was not designed to be a definitive text on magnetic recording, it is appropriate to include here capsule reviews of the major textbooks to which reference has been made. These capsule reviews are intended to direct the inquiring worker toward the source most useful to him for solution of particular problems. By characterizing the emphasis and point of view of each of the works as a whole, these reviews may help a newcomer to the field decide which ones might well become part of his technical library. The reviews represent the personal opinions of the author.

The most recent work is "Magnetic Tape Recording" by H. G. M. Spratt (Spratt [1964]) now in its second edition. Mr. Spratt is an Englishman and almost all the illustrations and equipment references in his book are to English or Continental equipment. The Spratt book stresses both the characteristics and the manufacture of magnetic tape and concentrates on magnetic recorders used for sound. The emphasis on sound and audio phenomena is somewhat disconcerting, but does not disguise the excellence of the fundamental approach to magnetic recording problems. For example, Spratt paraphrases four different explanations of the action of high-frequency bias in linearizing analog recording. Spratt has extracted from the applicable current literature most of the recent descriptions and analyses of the fundamental processes of magnetic recording.

The sections on tape manufacturing, tape materials, and tape testing are relatively complete and contain information not found elsewhere. The sections on the principles of sound reproduction and electroacoustics fall beyond the scope of this survey as do the descriptions of audio tape recorders. Spratt does not refer directly to pulse recording or to the use of recording in connection with computers, but he does include excellent references to dropout problems.

The Spratt book, although specialized, can be recommended to a newcomer on the basis that its author is very careful to include as many aspects of magnetic recording as possible and to take no controversial position on issues which have not been resolved. Although its emphasis misses the area of interest in this survey, it is actually as broad as any text in English which attempts to deal in detail with the major parts of magnetic recording.

For a detailed discussion of the magnetics and the relationship between head and tape in pulse recording, "Digital Magnetic Recording," a recent book by A. S. Hoagland of IBM, can be recommended (Hoagland [1963]). This book summarizes the current understanding of the relationships most important in magnetic pulse recording and is remarkably free of any commercial biases. It, however, does not consider any of the mechanism of drum, disk or tape recording and has little to say about dropouts. It is particularly useful in giving numerical approximations to field distributions around the magnetic heads in terms that can be used to analyze head-tape system performance.

The title, "Physics of Magnetic Recording," of a new text by C. D. Mee (Mee [1964]), also now of IBM, although accurate, is somewhat misleading. Mee considers every aspect of the head, the tape and the interaction between the two in considerable detail. There probably are more accurate references here to the important work currently going on in increasing the understanding of the fundamentals of magnetic recording than in any other text. The bibliography is particularly useful, being relatively brief but clearly critical, in that the author appears to have read and analyzed each reference and to have decided on specific criteria to include it. I will confess to a prejudice against the "bubble" mechanism which is promulgated by Mr. Mee as an aid to the understanding of the action of ac bias, but other workers in the field may not suffer from this prejudice. The bubble theory, it should be pointed out, is not advanced as an explanation but simply as a study or calculation aid by Mr. Mee.

This text is the second in a series of monographs on selected topics in solid state physics edited by E. P. Wohlfarth. It is easily missed in a technical library or book store because it seems to be classified under Solid State Physics and to be alphabetized under W for Wohlfarth. This isolation is not appropriate to the really basic utility of this text.

An earlier book which covers most of the areas of magnetic recording of interest to NASA is "Magnetic Tape Instrumentation" by Gomer L. Davies (Davies [1961]). This text covers the state of the entire field of magnetic tape instrumentation in approximately 1960. It includes more discussion of magnetic recording mechanisms of the instrumentation type than any other reference in English. However, because it covers a very wide range and is a relatively short book, the coverage is not very deep for any one subject. It is to be recommended for a rather complete study of data irregularities resulting from flutter and of criteria for flutter performance in instrumentation recorders.

"Magnetic Recording Techniques" by W. Earl Stewart (Stewart [1958]) appeared in 1958 and is another relatively short book on magnetic recording with an emphasis on audio recording. Three-eighths of the book is devoted to appendices on magnetic recording standards of audio, some definitions of magnetic quantities, a magnetic and sound recording glossary, and the text of four papers written by others. These appendices are of mixed utility at the present time because the standards are obsolete as is some of the technical work quoted in the light of current understanding of the magnetic recording process. Most of the material dates from 1953 but it does represent the best work that was available at that time.

In addition to these five English texts, each of which covers all of magnetic recording to some extent, there are a number of more specific works directed to the user of specific devices such as, for example, the video tape recorder for broadcast use. I do not believe these texts are useful for an introduction to any subject except that for which each is specifically written. The five general works are therefore recommended to the newcomer.

There is a sixth work on magnetic recording on which some comment should be made. It is "Technik Der Magnetspeicher" edited by Fritz Winckel (Winckel [1960]), a collection of the work of 14 German engineers and scientists in a rather massive (612 pages) German review of the field of magnetic recording as of 1960. I am familiar in detail only with certain portions of this book. It appears to be extremely complete in its coverage of some of the important parts of magnetic recording technology but it is also padded with rather specific material on equipment and on special problem solution, most of which is now obsolete. I also believe, on the basis of rather solid evidence, that some of the theoretical analyses contained in this text are simply incorrect. This is necessarily a controversial subject, but the book can be used with profit by an experienced worker in magnetic recording since many of the analyses, controversial or not, are extremely complete. The newcomer to the field, even if well equipped with a reading knowledge of German, should approach this book with care.

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