Minimum Phase (2A)

Please send corrections (or suggestions) to youngwlim@hotmail.com.

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Properties of a Minimum Phase System

Lowest Time Delay

Group Delay

Energy Compaction

Invertible

Min Phase Filter — { flat response, correct phase response }

Equalizer — { flat response, incorrect phase response }

Minimum Phase System

Stable Causal System

All its poles are in the left half of the s plane

Minimum Phase System

Left half	Right half
All poles All zeros	

Maximum Phase System

Left half	Right half
All poles	All zeros

Mixed Phase System

Left half	Right half
All poles some zeros	some zeros

Minimum Phase System Properties (1)

Minimum Phase System

If an amplitude response is known

$$A(\omega) = |H(j\omega)| \qquad 0 \le \omega < \infty$$

⬇

the minimum phase response can be determined uniquely

$$\Phi_{min}(\omega) = arg\{H(j\omega)\}$$

Non-Minimum Phase System

some / all zeros in the right half s plane

With the same amplitude response

$$A(\omega) = |H(j\omega)| \qquad 0 \le \omega < \infty$$

The non-minimum phase response is always greater

$$\Phi(\omega) \ge \Phi_{min}(\omega)$$

Minimum Phase System Properties (2)

Minimum Phase System

Phase Response $\Phi(\omega)$ can be unambiguously determined from the amplitude response $A(\omega)$

Non-Minimum Phase System

Not valid

Verification of a Minimum Phase System

Check the progression of $\Phi(\omega)$ and $A(\omega)$ at high frequency

$$H(\omega) = \frac{N(s)}{D(s)}$$

$N(s)$: order m

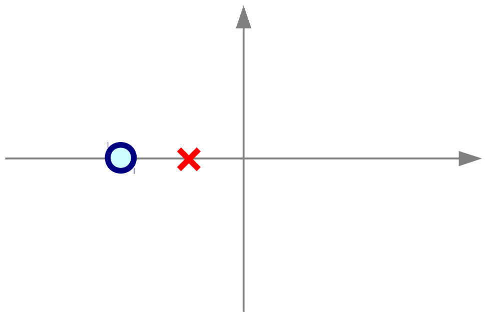
$D(s)$: order n

	Minimum Phase System	Non-Minimum Phase System
Phase	$\Phi_{min}(\infty) = -90^\circ (n - m)$	$\lvert\Phi(\infty)\rvert \geq \lvert\Phi_{min}(\infty)\rvert$
Slope	$-20(n - m)\, dB / decade$	$-20(n - m)\, dB / decade$

Example

Minimum Phase System

$$H(s) = \frac{1+2s}{1+4s} \quad \begin{matrix} \rightarrow -0.5 \\ \rightarrow -0.25 \end{matrix}$$



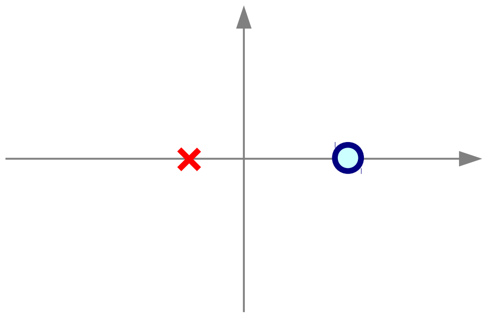
$$\frac{1+j2\omega}{1+j4\omega} = \frac{1+j2\omega}{1+j4\omega} \cdot \frac{1-j4\omega}{1-j4\omega}$$

$$= \frac{(1+8\omega^2) - j2\omega}{1+16\omega^2}$$

$$\Phi(\omega) = -\tan^{-1}\left(\frac{2\omega}{1+8\omega^2}\right)$$

Non-Minimum Phase System

$$H(s) = \frac{1-2s}{1+4s} \quad \begin{matrix} \rightarrow +0.5 \\ \rightarrow -0.25 \end{matrix}$$



$$\frac{1-j2\omega}{1+j4\omega} = \frac{1-j2\omega}{1+j4\omega} \cdot \frac{1-j4\omega}{1-j4\omega}$$

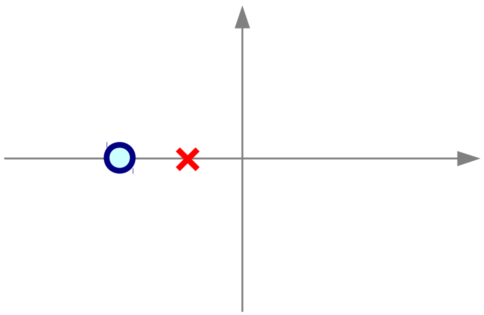
$$= \frac{(1-8\omega^2) - j6\omega}{1+16\omega^2}$$

$$\Phi(\omega) = -\tan^{-1}\left(\frac{6\omega}{1+8\omega^2}\right)$$

Example - Decomposition

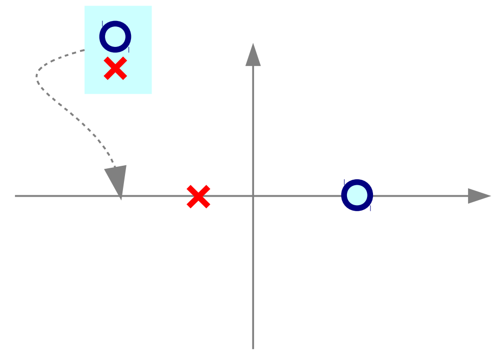
Minimum Phase System

$$H(s) = \frac{1+2s}{1+4s}$$



Non-Minimum Phase System

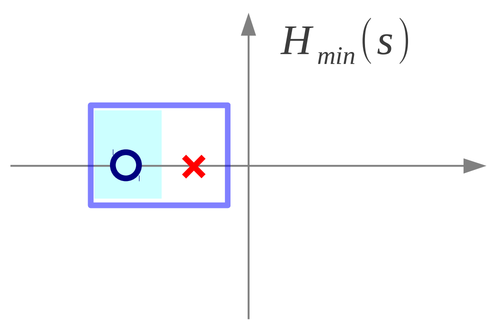
$$H(s) = \frac{1-2s}{1+4s} = \frac{1-2s}{1+4s} \cdot \frac{1+2s}{1+2s}$$

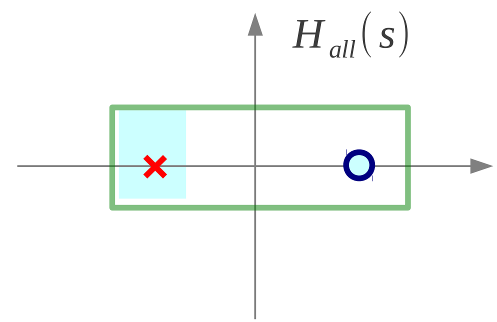


$$H(s) = \frac{1-2s}{1+4s} \cdot \frac{1+2s}{1+2s}$$

$$= \frac{1+2s}{1+4s} \cdot \frac{1-2s}{1+2s}$$

$$= H_{min}(s) \cdot H_{all}(s)$$





A non-minimum phase system can always be decomposed into $H_{min}(s) \cdot H_{all}(s)$

Example - All Pass Filter (1)

$$H_{all}(s) = \frac{1-2s}{1+2s}$$

Flat Magnitude

$$\left|\frac{1-j2\omega}{1+j2\omega}\right| = \frac{|1-j2\omega|}{|1+j2\omega|}$$

$$= \frac{\sqrt{1+4\omega^2}}{\sqrt{1+4\omega^2}} = 1$$

$$|H_{all}(j\omega)| = \frac{\sqrt{1+4\omega^2}}{\sqrt{1+4\omega^2}} = 1$$

A Pure Phase Shifter

$$\frac{1-j2\omega}{1+j2\omega} = \frac{1-j2\omega}{1+j2\omega} \cdot \frac{1-j2\omega}{1-j2\omega}$$

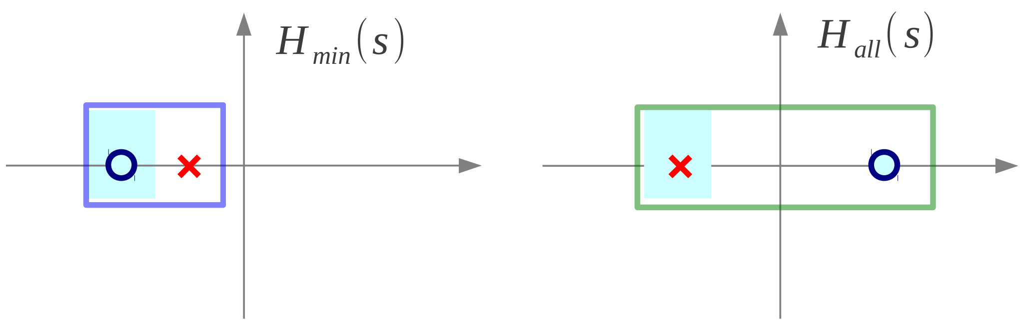
$$= \frac{(1-4\omega^2) - j4\omega}{1+4\omega^2}$$

$$arg\{H_{all}(j\omega)\} = -\tan^{-1}\left(\frac{4\omega}{1-4\omega^2}\right)$$

$$H(s) = \frac{1-2s}{1+4s} \cdot \frac{1+2s}{1+2s}$$

$$= \frac{1+2s}{1+4s} \cdot \frac{1-2s}{1+2s}$$

$$= H_{min}(s) \cdot H_{all}(s)$$



A non-minimum phase system can always be decomposed into $H_{min}(s) \cdot H_{all}(s)$

Example - All Pass Filter (2)

$$H_{all}(s) = \frac{s - 0.5}{s + 0.5}$$

$$= \frac{s + 0.5 - 1}{s + 0.5}$$

$$H(s) = 1 - \frac{2}{(s + 0.5)}$$

Inverse Laplace Transform

$$h(t) = \delta(t) - e^{-0.5t}$$

$$H_{all}(j\omega) = \frac{j\omega - 0.5}{j\omega + 0.5}$$

Flat Magnitude

$$|H_{all}(j\omega)| = \frac{\sqrt{\omega^2 + 0.25}}{\sqrt{\omega^2 + 0.25}} = 1$$

Phase Shifter

$$arg\{H_{all}(j\omega)\} = -2\tan^{-1}\left(\frac{\omega}{0.5}\right)$$

Group Delay

$$-\frac{d}{d\omega}\left(arg\{H_{all}(j\omega)\}\right)$$

$$= -\frac{d}{d\omega}\left(-2\tan^{-1}\left(\frac{\omega}{0.5}\right)\right)$$

$$= \frac{4}{(1 + \omega^2/0.25)} > 0$$

All Pass Filter

$$G_{all}(s) = \pm \frac{(s-\bar{s}_1)(s-\bar{s}_2)\ \cdots\ (s-\bar{s}_n)}{(s-s_1)(s-s_2)\ \cdots\ (s-s_n)}$$

Flat Magnitude

A Pure Phase Shifter

zero $\bar{s}_i$

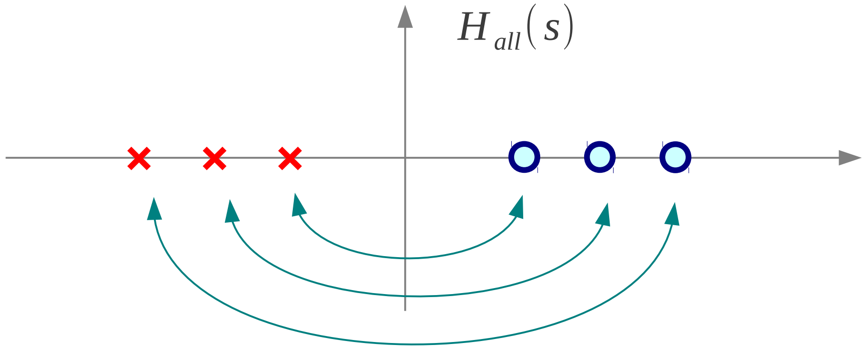
pole s_i

not complex conjugate

$s_i = +a + jb$

$\bar{s}_i = -a + jb$

only differ in the signs of their real parts



All Pass Filter

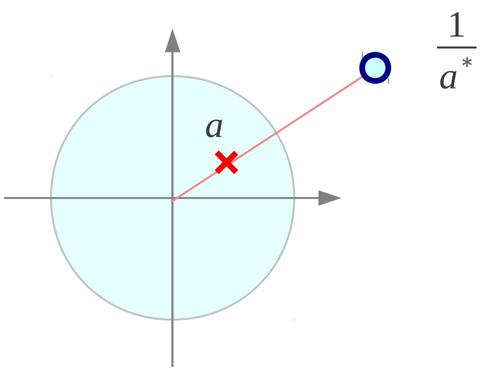
$$H(z) = \frac{z^{-1} - a^*}{1 - a z^{-1}}$$

$z^{-1} = a^* \rightarrow z = \frac{1}{a^*}$

$a z^{-1} = 1 \rightarrow z = a$

Flat Magnitude

A Pure Phase Shifter



$$H(e^{j\omega}) = \frac{e^{-j\omega} - a^*}{1 - a e^{-j\omega}} = e^{-j\omega} \frac{1 - a^* e^{+j\omega}}{1 - a e^{-j\omega}}$$

$$(1 - a^* e^{+j\omega})^* = (1 - a e^{-j\omega})$$

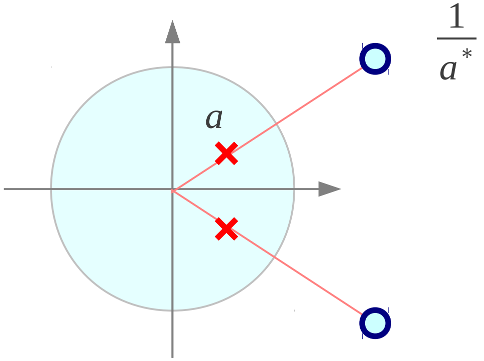
$$|H(e^{j\omega})| = |e^{-j\omega}| \left| \frac{1 - a^* e^{+j\omega}}{1 - a e^{-j\omega}} \right| = 1$$

All Pass Filter

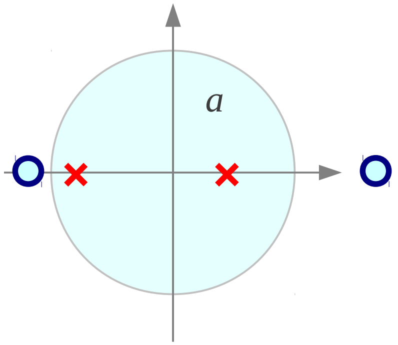
Flat Magnitude

A Pure Phase Shifter

$$H_{all}(z) \;=\; A \prod_{k=1}^{M_r} \frac{z^{-1}-d_k}{1-d_k z^{-1}} \prod_{k=1}^{M_c} \frac{(z^{-1}-e_k^*)(z^{-1}-e_k)}{(1-e_k z^{-1})(1-e_k^* z^{-1})}$$

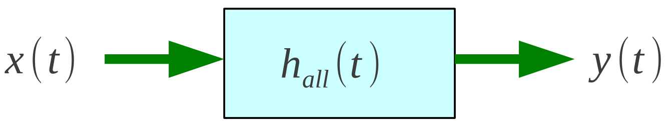


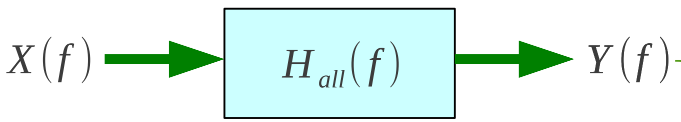
Cascade form of all pass system for real-valued impulse response system



Conjugate symmetric $H(e^{j\omega})$

All Pass Filter (4)



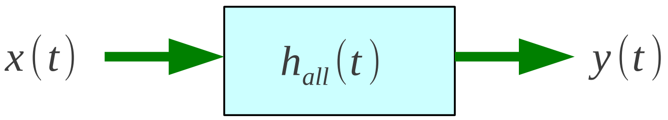


Parseval's Theorem

$$\int_{-\infty}^{+\infty} |x(t)|^2\, dt = \int_{-\infty}^{+\infty} |y(t)|^2\, dt$$

Energy Compaction

$$\int_{-\infty}^{t_0} |x(t)|^2\, dt \geq \int_{-\infty}^{t_0} |y(t)|^2\, dt$$



The energy build-up in the input is more **rapid** than in the output

Parseval's Theorem

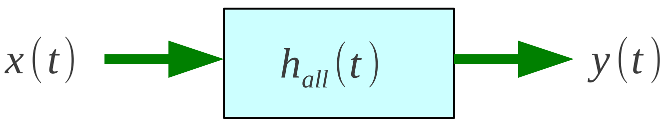
$$\int_{-\infty}^{+\infty} |x(t)|^2\, dt = \int_{-\infty}^{+\infty} |X(f)|^2\, dt$$

$$\int_{-\infty}^{+\infty} |y(t)|^2\, dt = \int_{-\infty}^{+\infty} |Y(f)|^2\, dt$$

$$Y(f) = H_{all}(f)\,X(f) \quad \Rightarrow \quad = \int_{-\infty}^{+\infty} |H_{all}(f)|^2 |X(f)|^2\, dt$$

$$|H_{all}(f)| = 1 \quad \Rightarrow \quad = \int_{-\infty}^{+\infty} |X(f)|^2\, dt$$

Allpass Filter $\int_{-\infty}^{+\infty} |x(t)|^2\, dt = \int_{-\infty}^{+\infty} |y(t)|^2\, dt$



Parseval's Theorem

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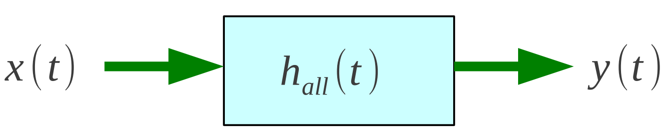
Energy Compaction

$$\int_{-\infty}^{t_0} |x(t)|^2\, dt \geq \int_{-\infty}^{t_0} |y(t)|^2\, dt$$



The <u>energy build-up</u> in the input is more **rapid** than in the output

Truncated input

$$x_1(t) = \begin{cases} x(t) & (t \leq t_0) \\ 0 & (t > t_0) \end{cases}$$

For $t \leq t_0$ ➡ $x_1(t) = x(t)$ ➡

$$y_1(t) = \int_{-\infty}^{t_0} h(t-\tau) x_1(\tau)\, d\tau = \int_{-\infty}^{t} h(t-\tau) x(\tau)\, d\tau = y(t)$$

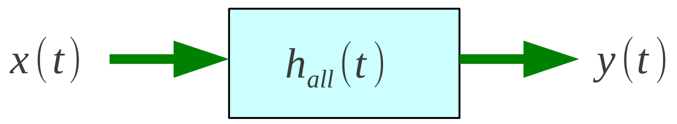
$$\int_{-\infty}^{+\infty} |x_1(t)|^2\, dt = \int_{-\infty}^{+\infty} |y_1(t)|^2\, dt$$

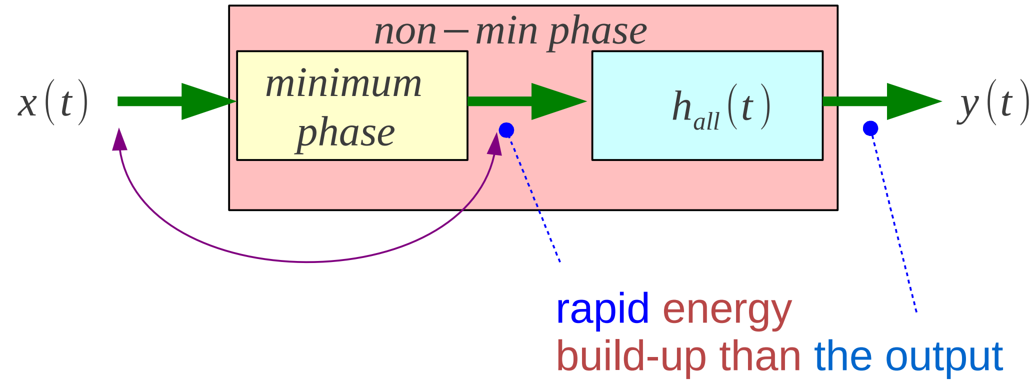
For $t > t_0$ ➡ $x_1(t) = 0$ ➡

$$\underline{\int_{-\infty}^{t_0} |x_1(t)|^2\, dt} = \int_{-\infty}^{+\infty} |y_1(t)|^2\, dt = \underline{\int_{-\infty}^{t_0} |y_1(t)|^2\, dt} + \int_{t_0}^{+\infty} |y_1(t)|^2\, dt$$

$$\int_{-\infty}^{t_0} |x(t)|^2\, dt \geq \int_{-\infty}^{t_0} |y(t)|^2\, dt \quad \textit{For} \quad t \leq t_0$$

All Pass Filter (6)



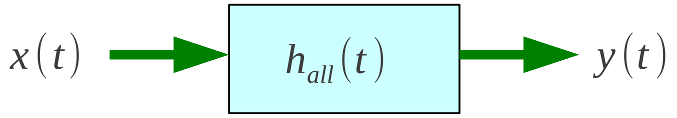


Parseval's Theorem

$$\int_{-\infty}^{+\infty} |x(t)|^2\, dt = \int_{-\infty}^{+\infty} |y(t)|^2\, dt$$

Energy Compaction

$$\int_{-\infty}^{t_0} |x(t)|^2\, dt \geq \int_{-\infty}^{t_0} |y(t)|^2\, dt$$



The energy build-up in the input is more **rapid** than in the output

The signal energy until t_0 of the minimum phase
≥ any other causal signal with the same magnitude response

Thus minimum phase signals
➡ maximally concentrated toward time 0 when compared against all causal signals having the same magnitude response

minimum phase signals
➡ minimum delay signals

Properties of a Minimum Phase System

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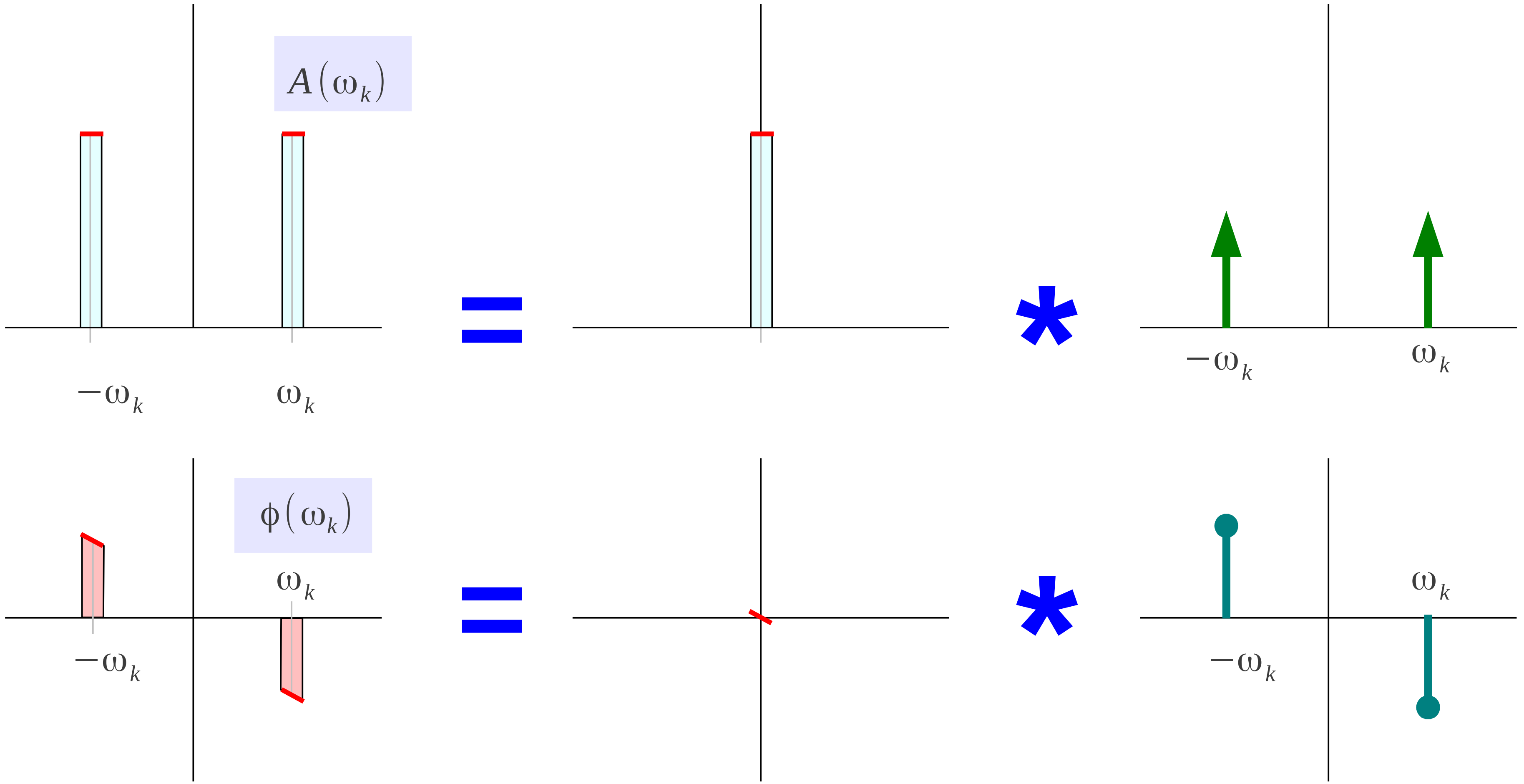
Properties of a Minimum Phase System

Simple LPF – Approximation (2)

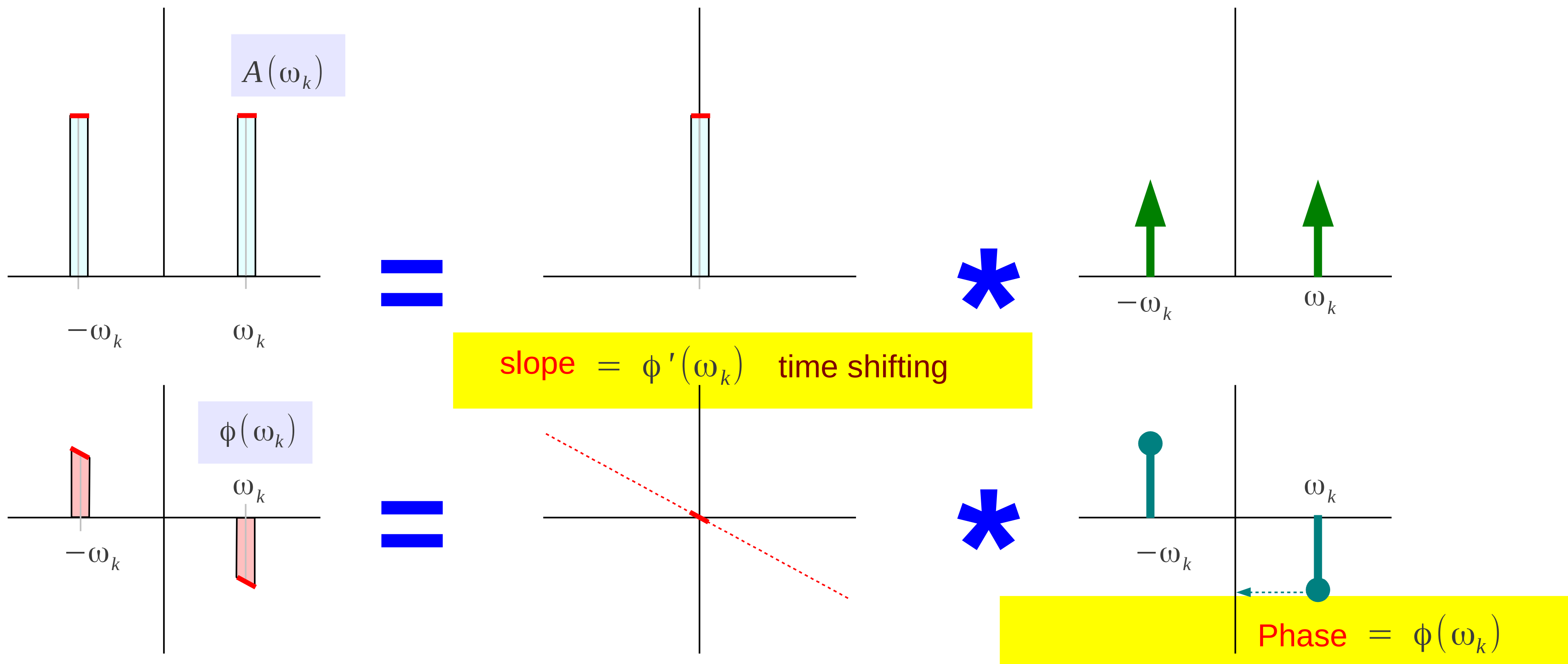


$$2A(\omega_k)B\,\frac{\sin[B(t+\phi'(\omega_k))]}{\pi B(t+\phi'(\omega_k))}$$

$$\begin{cases} A(\omega_k) & (-B \le \omega \le +B) \\ 0 & else \end{cases}$$

$$\pi[e^{+j\phi(\omega_k)}\delta(\omega-\omega_k) + e^{-j\phi(\omega_k)}\delta(\omega+\omega_k)]$$

Simple LPF – Approximation (3)



Frequency Domain

$$\begin{cases} A(\omega_k) & (-B \le \omega \le +B) \\ 0 & else \end{cases} \quad * \quad \pi[e^{+j\phi(\omega_k)}\delta(\omega-\omega_k) + e^{-j\phi(\omega_k)}\delta(\omega+\omega_k)]$$

Group Delay

Phase Delay

Time Domain

$$2A(\omega_k)B\frac{\sin[B(t+\phi'(\omega_k))]}{\pi B(t+\phi'(\omega_k))} \quad \times \quad \cos(\omega_k t+\phi(\omega_k))$$

References

[1] http://en.wikipedia.org/
[2] J.H. McClellan, et al., Signal Processing First, Pearson Prentice Hall, 2003
[3] http://www.libinst.com/tpfd.htm
[4] K.Shin, J.K. Hammond, "Fundamentals of Signal Processing for Sound and Vibration Engineers"
[5] www.radiolab.com.au/DesignFile/DN004.pdf