ESE 531: Digital Signal Processing

Lec 13: February 23st, 2017

Frequency Response of LTI Systems

Lecture Outline

- Frequency Response of LTI Systems
  - Magnitude Response
    - Simple Filters
  - Phase Response
    - Group Delay
  - Example: Zero on Real Axis

Frequency Response of LTI System

- LTI Systems are uniquely determined by their impulse response

$$y[n] = \sum_{k=-\infty}^{\infty} x[k]\, h[n-k] = x[k] * h[k]$$

- We can write the input-output relation also in the z-domain

$$Y(z) = H(z)X(z)$$

- Or we can define an LTI system with its frequency response

$$Y(e^{j\omega}) = H(e^{j\omega})X(e^{j\omega})$$

- $H(e^{j\omega})$ defines magnitude and phase change at each frequency

Frequency Response of LTI System

$$Y(e^{j\omega}) = H(e^{j\omega})X(e^{j\omega})$$

- We can define a magnitude response

$$|Y(e^{j\omega})| = |H(e^{j\omega})||X(e^{j\omega})|$$

- And a phase response

$$\angle Y(e^{j\omega}) = \angle H(e^{j\omega}) + \angle X(e^{j\omega})$$

Phase Response

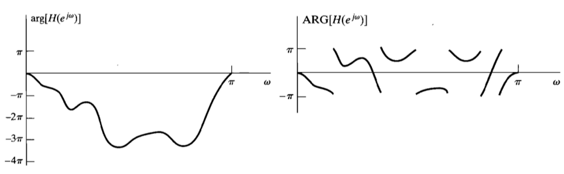
- Limit the range of the phase response

$$-\pi < \mathrm{ARG}[H(e^{j\omega})] \le \pi.$$

Phase Response

- Limit the range of the phase response

$$-\pi < \mathrm{ARG}[H(e^{j\omega})] \le \pi.$$



Group Delay

- General phase response at a given frequency can be characterized with group delay, which is related to phase

$$\mathrm{grd}[H(e^{j\omega})] = -\frac{d}{d\omega}\{\arg[H(e^{j\omega})]\}$$

- More later…

Linear Difference Equations

$$\sum_{k=0}^{N} a_k y[n-k] = \sum_{k=0}^{M} b_k x[n-k]$$

Example: $y[n] = x[n] + 0.1y[n-1]$

$$H(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_M z^{-M}}{a_0 + a_1 z^{-1} + \ldots + a_N z^{-N}} = \frac{b_0}{a_0}\frac{\prod_{k=1}^{M}(1 - c_k z^{-1})}{\prod_{k=1}^{N}(1 - d_k z^{-1})}$$

Magnitude Response

Magnitude of products is product of magnitudes

$$|H(e^{j\omega})| = |\frac{b_0}{a_0}| \cdot \frac{\prod_{k=0}^{M}|1 - c_k e^{-j\omega}|}{\prod_{k=0}^{N}|1 - d_k e^{-j\omega}|}$$

Magnitude Response

Magnitude of products is product of magnitudes

$$|H(e^{j\omega})| = |\frac{b_0}{a_0}| \cdot \frac{\prod_{k=0}^{M}|1 - c_k e^{-j\omega}|}{\prod_{k=0}^{N}|1 - d_k e^{-j\omega}|}$$

Consider one of the poles:

$$|1 - d_k e^{-j\omega}| = |e^{+j\omega} - d_k| \quad = |v_1|$$

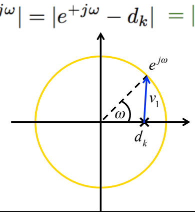
Magnitude Response

Magnitude of products is product of magnitudes

$$|H(e^{j\omega})| = |\frac{b_0}{a_0}| \cdot \frac{\prod_{k=0}^{M}|1 - c_k e^{-j\omega}|}{\prod_{k=0}^{N}|1 - d_k e^{-j\omega}|}$$

Consider one of the poles:

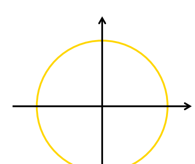
$$|1 - d_k e^{-j\omega}| = |e^{+j\omega} - d_k| \quad = |v_1|$$



Magnitude Response Example

$$H(z) = 0.05\frac{1 + z^{-1}}{1 - 0.9z^{-1}}$$

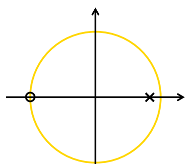
$$|H(z)| = 0.05\frac{|v_2|}{|v_1|}$$



Magnitude Response Example

$$H(z) = 0.05 \frac{1 + z^{-1}}{1 - 0.9z^{-1}}$$

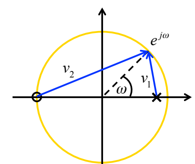
$$|H(z)| = 0.05 \frac{|v_2|}{|v_1|}$$



Magnitude Response Example

$$H(z) = 0.05 \frac{1 + z^{-1}}{1 - 0.9z^{-1}}$$

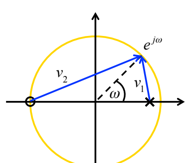
$$|H(z)| = 0.05 \frac{|v_2|}{|v_1|}$$

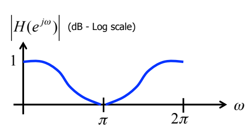


Magnitude Response Example

$$H(z) = 0.05 \frac{1 + z^{-1}}{1 - 0.9z^{-1}}$$

$$|H(z)| = 0.05 \frac{|v_2|}{|v_1|}$$



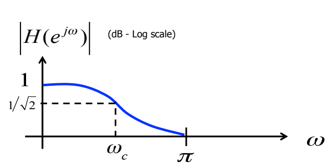


Simple Low Pass Filter

$$H_{LP}(z) = \frac{1-\alpha}{2} \frac{1 + z^{-1}}{1 - \alpha z^{-1}} \qquad |\alpha| < 1$$

Simple Low Pass Filter

$$H_{LP}(z) = \frac{1-\alpha}{2} \frac{1 + z^{-1}}{1 - \alpha z^{-1}} \qquad |\alpha| < 1$$



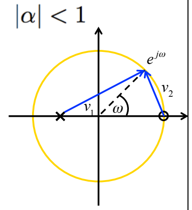
w_c is the 3dB cutoff frequency $\quad \alpha = \frac{1 - \sin(\omega_c)}{\cos(\omega_c)}$

Simple High Pass Filter

$$H_{HP}(z) = \frac{1+\alpha}{2} \frac{1 - z^{-1}}{1 + \alpha z^{-1}} \qquad |\alpha| < 1$$

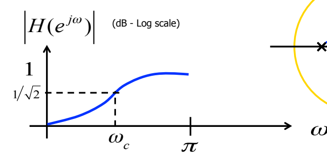
Simple High Pass Filter

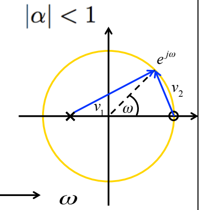
$$H_{HP}(z) = \frac{1+\alpha}{2}\frac{1-z^{-1}}{1+\alpha z^{-1}} \qquad |\alpha| < 1$$



Simple High Pass Filter

$$H_{HP}(z) = \frac{1+\alpha}{2}\frac{1-z^{-1}}{1+\alpha z^{-1}} \qquad |\alpha| < 1$$





w_c is the 3dB cutoff frequency $\qquad \alpha = \frac{1-\sin(\omega_c)}{\cos(\omega_c)}$

Simple Band-Stop (Notch) Filter

$$H_{BS}(z) = \frac{1+\alpha}{2}\frac{1-2\beta z^{-1}+z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad \begin{matrix}|\alpha| < 1\\ |\beta| < 1\end{matrix}$$

Note: $1-2\beta z^{-1}+z^{-2} = (1-e^{j\omega_0}z^{-1})(1-e^{-j\omega_0}z^{-1})$

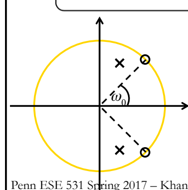
$\cos(\omega_0) = \beta$

Simple Band-Stop (Notch) Filter

$$H_{BS}(z) = \frac{1+\alpha}{2}\frac{1-2\beta z^{-1}+z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad \begin{matrix}|\alpha| < 1\\ |\beta| < 1\end{matrix}$$

Note: $1-2\beta z^{-1}+z^{-2} = (1-e^{j\omega_0}z^{-1})(1-e^{-j\omega_0}z^{-1})$

$\cos(\omega_0) = \beta$

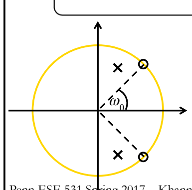


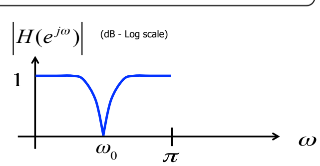
Simple Band-Stop (Notch) Filter

$$H_{BS}(z) = \frac{1+\alpha}{2}\frac{1-2\beta z^{-1}+z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad \begin{matrix}|\alpha| < 1\\ |\beta| < 1\end{matrix}$$

Note: $1-2\beta z^{-1}+z^{-2} = (1-e^{j\omega_0}z^{-1})(1-e^{-j\omega_0}z^{-1})$

$\cos(\omega_0) = \beta$



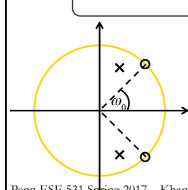


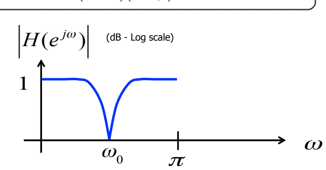
Simple Band-Stop (Notch) Filter

$$H_{BS}(z) = \frac{1+\alpha}{2}\frac{1-2\beta z^{-1}+z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad \begin{matrix}|\alpha| < 1\\ |\beta| < 1\end{matrix}$$

Note:

$$H_{BS}(\mp 1) = \frac{1+\alpha}{2}\frac{2\pm 2\beta}{(1+\alpha)(1\pm\beta)} = 1$$



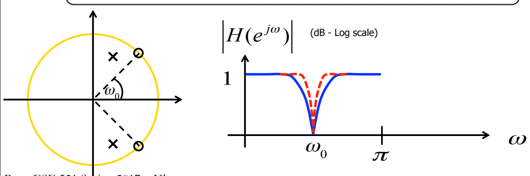


Simple Band-Stop (Notch) Filter

$$H_{BS}(z) = \frac{1+\alpha}{2}\frac{1-2\beta z^{-1}+z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad |\alpha|<1,\ |\beta|<1$$

Note: As $\alpha \to 1$ poles approach zeros

$$H_{BS}(\mp 1) = \frac{1+\alpha}{2}\frac{2\pm 2\beta}{(1+\alpha)(1\pm\beta)} = 1$$

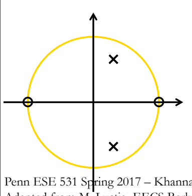


Simple Band-Pass Filter

$$H_{BP}(z) = \frac{1-\alpha}{2}\frac{1-z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad |\alpha|<1,\ |\beta|<1$$

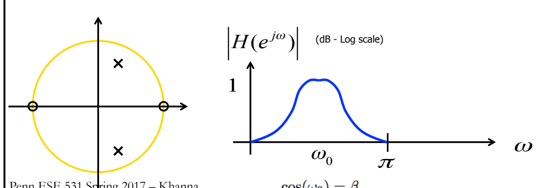
Simple Band-Pass Filter

$$H_{BP}(z) = \frac{1-\alpha}{2}\frac{1-z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad |\alpha|<1,\ |\beta|<1$$



Simple Band-Pass Filter

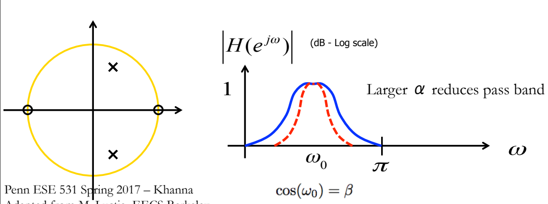
$$H_{BP}(z) = \frac{1-\alpha}{2}\frac{1-z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad |\alpha|<1,\ |\beta|<1$$



$\cos(\omega_0) = \beta$

Simple Band-Pass Filter

$$H_{BP}(z) = \frac{1-\alpha}{2}\frac{1-z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \qquad |\alpha|<1,\ |\beta|<1$$

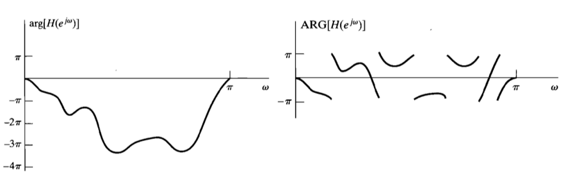


$\cos(\omega_0) = \beta$

Phase Response

- Limit the range of the phase response

$$-\pi < \text{ARG}[H(e^{j\omega})] \leq \pi.$$



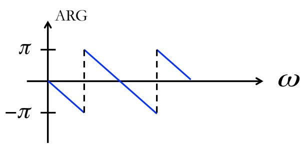
Phase Response Example

$$H(e^{j\omega}) = e^{j\omega n_d} \quad \leftrightarrow \quad h[n] = \delta[n - n_d]$$

$$|H(e^{j\omega})| = 1$$

$$\arg[H(e^{j\omega})] = -\omega n_d$$

ARG is the wrapped phase
arg is the unwrapped phase

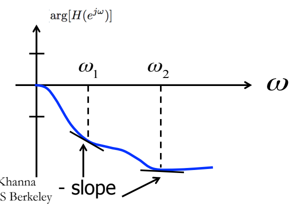


Penn ESE 531 Spring 2017 – Khanna
Adapted from M. Lustig, EECS Berkeley

Group Delay

- General phase response at a given frequency can be characterized with group delay, which is related to phase

$$\text{grd}[H(e^{j\omega})] = -\frac{d}{d\omega}\{\arg[H(e^{j\omega})]\}$$



Penn ESE 531 Spring 2017 – Khanna
Adapted from M. Lustig, EECS Berkeley

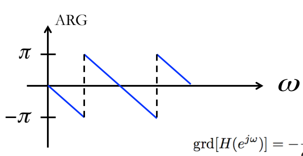
Phase Response Example

$$H(e^{j\omega}) = e^{j\omega n_d} \quad \leftrightarrow \quad h[n] = \delta[n - n_d]$$

$$|H(e^{j\omega})| = 1$$

$$\arg[H(e^{j\omega})] = -\omega n_d$$

ARG is the wrapped phase
arg is the unwrapped phase



$$\text{grd}[H(e^{j\omega})] = -\frac{d}{d\omega}\{\arg[H(e^{j\omega})]\}$$

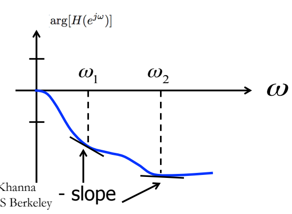
For linear phase system, group delay is n_d

Penn ESE 531 Spring 2017 – Khanna
Adapted from M. Lustig, EECS Berkeley

Group Delay

- General phase response at a given frequency can be characterized with group delay, which is related to phase

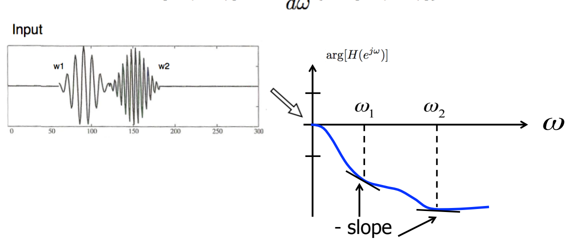
$$\text{grd}[H(e^{j\omega})] = -\frac{d}{d\omega}\{\arg[H(e^{j\omega})]\}$$



Penn ESE 531 Spring 2017 – Khanna
Adapted from M. Lustig, EECS Berkeley

Group Delay

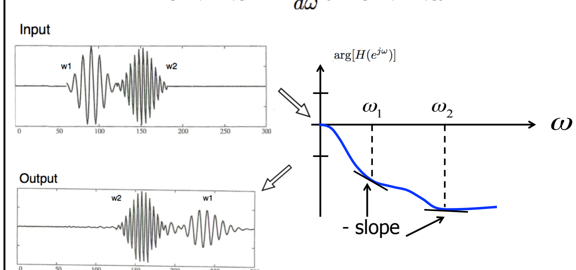
$$\text{grd}[H(e^{j\omega})] = -\frac{d}{d\omega}\{\arg[H(e^{j\omega})]\}$$



Penn ESE 531 Spring 2017 – Khanna
Adapted from M. Lustig, EECS Berkeley

Group Delay

$$\text{grd}[H(e^{j\omega})] = -\frac{d}{d\omega}\{\arg[H(e^{j\omega})]\}$$



Penn ESE 531 Spring 2017 – Khanna
Adapted from M. Lustig, EECS Berkeley

Group Delay Math

$$H(z)=\frac{b_0}{a_0}\frac{\prod_{k=1}^{M}(1-c_k z^{-1})}{\prod_{k=1}^{N}(1-d_k z^{-1})} \qquad H(e^{j\omega})=\frac{b_0}{a_0}\frac{\prod_{k=1}^{M}(1-c_k e^{-j\omega})}{\prod_{k=1}^{N}(1-d_k e^{-j\omega})}$$

Group Delay Math

$$H(z)=\frac{b_0}{a_0}\frac{\prod_{k=1}^{M}(1-c_k z^{-1})}{\prod_{k=1}^{N}(1-d_k z^{-1})} \qquad H(e^{j\omega})=\frac{b_0}{a_0}\frac{\prod_{k=1}^{M}(1-c_k e^{-j\omega})}{\prod_{k=1}^{N}(1-d_k e^{-j\omega})}$$

arg of products is sum of args

$$\arg[H(e^{j\omega})]=\sum_{k=1}^{M}\arg[1-c_k e^{-j\omega}]-\sum_{k=1}^{N}\arg[1-d_k e^{-j\omega}]$$

$$\operatorname{grd}[H(e^{j\omega})]=\sum_{k=1}^{M}\operatorname{grd}[1-c_k e^{-j\omega}]-\sum_{k=1}^{N}\operatorname{grd}[1-d_k e^{-j\omega}]$$

Group Delay Math

$$\operatorname{grd}[H(e^{j\omega})]=\sum_{k=1}^{M}\operatorname{grd}[1-c_k e^{-j\omega}]-\sum_{k=1}^{N}\operatorname{grd}[1-d_k e^{-j\omega}]$$

- Look at each factor:

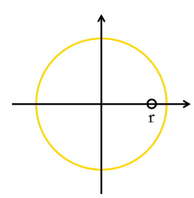
$$\arg[1-re^{j\theta}e^{-j\omega}]=\tan^{-1}\left(\frac{r\sin(\omega-\theta)}{1-r\cos(\omega-\theta)}\right)$$

$$\operatorname{grd}[1-re^{j\theta}e^{-j\omega}]=\frac{r^2-r\cos(\omega-\theta)}{\left|1-re^{j\theta}e^{-j\omega}\right|^2}$$

Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

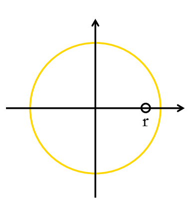
$$\arg[1-re^{-j\omega}]$$



Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

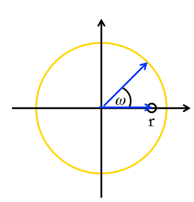
$$\arg[1-re^{-j\omega}]=\arg[(e^{j\omega}-r)e^{-j\omega}]=\underbrace{\arg[e^{j\omega}-r]}_{\varphi}-\underbrace{\arg[e^{j\omega}]}_{\omega}$$



Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

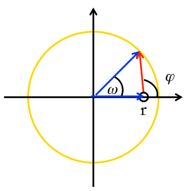
$$\arg[1-re^{-j\omega}]=\arg[(e^{j\omega}-r)e^{-j\omega}]=\underbrace{\arg[e^{j\omega}-r]}_{\varphi}-\underbrace{\arg[e^{j\omega}]}_{\omega}$$



Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

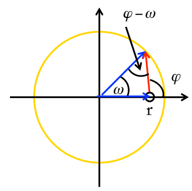
$$\arg[1-re^{-j\omega}] = \arg[(e^{j\omega}-r)e^{-j\omega}] = \underbrace{\arg[e^{j\omega}-r]}_{\varphi} - \underbrace{\arg[e^{j\omega}]}_{\omega}$$



Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

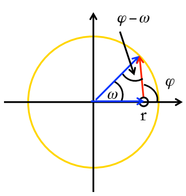
$$\arg[1-re^{-j\omega}] = \arg[(e^{j\omega}-r)e^{-j\omega}] = \underbrace{\arg[e^{j\omega}-r]}_{\varphi} - \underbrace{\arg[e^{j\omega}]}_{\omega}$$

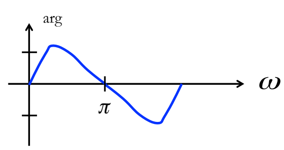


Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

$$\arg[1-re^{-j\omega}] = \arg[(e^{j\omega}-r)e^{-j\omega}] = \underbrace{\arg[e^{j\omega}-r]}_{\varphi} - \underbrace{\arg[e^{j\omega}]}_{\omega}$$



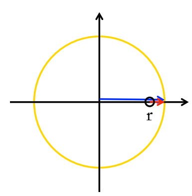


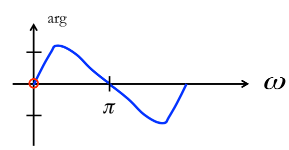
Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

$$\arg[1-re^{-j\omega}] = \arg[(e^{j\omega}-r)e^{-j\omega}] = \underbrace{\arg[e^{j\omega}-r]}_{\varphi} - \underbrace{\arg[e^{j\omega}]}_{\omega}$$

$\omega = 0$



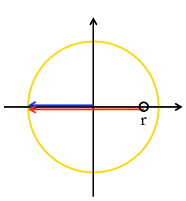


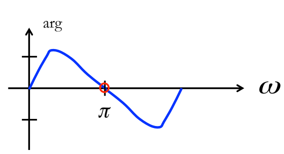
Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

$$\arg[1-re^{-j\omega}] = \arg[(e^{j\omega}-r)e^{-j\omega}] = \underbrace{\arg[e^{j\omega}-r]}_{\varphi} - \underbrace{\arg[e^{j\omega}]}_{\omega}$$

$\omega = \pi$

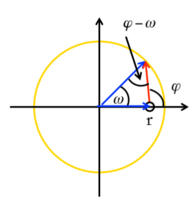


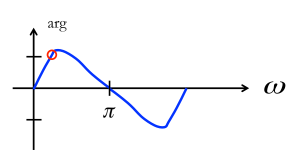


Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

$$\arg[1-re^{-j\omega}] = \arg[(e^{j\omega}-r)e^{-j\omega}] = \underbrace{\arg[e^{j\omega}-r]}_{\varphi} - \underbrace{\arg[e^{j\omega}]}_{\omega}$$

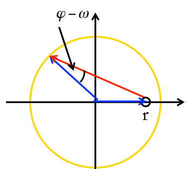


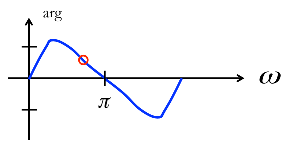


Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

$$\arg[1-re^{-j\omega}]=\arg[(e^{j\omega}-r)e^{-j\omega}]=\underbrace{\arg[e^{j\omega}-r]}_{\varphi}-\underbrace{\arg[e^{j\omega}]}_{\omega}$$

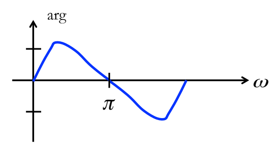


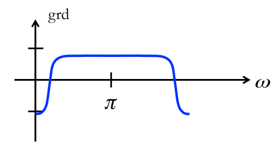


Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

$$\arg[1-re^{-j\omega}]=\arg[(e^{j\omega}-r)e^{-j\omega}]=\underbrace{\arg[e^{j\omega}-r]}_{\varphi}-\underbrace{\arg[e^{j\omega}]}_{\omega}$$





Group Delay Math

$$\text{grd}[H(e^{j\omega})]=\sum_{k=1}^{M}\text{grd}[1-c_k e^{-j\omega}]-\sum_{k=1}^{N}\text{grd}[1-d_k e^{-j\omega}]$$

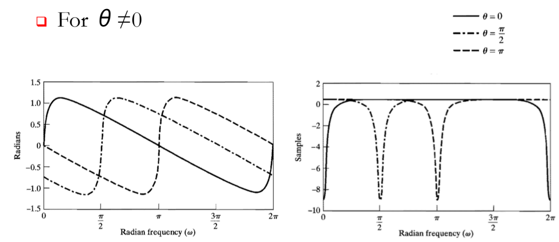
- Look at each factor:

$$\arg[1-re^{j\theta}e^{-j\omega}]=\tan^{-1}\left(\frac{r\sin(\omega-\theta)}{1-r\cos(\omega-\theta)}\right)$$

$$\text{grd}[1-re^{j\theta}e^{-j\omega}]=\frac{r^2-r\cos(\omega-\theta)}{\left|1-re^{j\theta}e^{-j\omega}\right|^2}$$

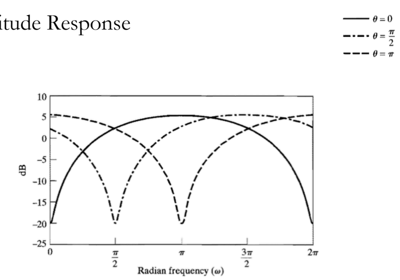
Example: Zero on Real Axis

- For $\theta \neq 0$



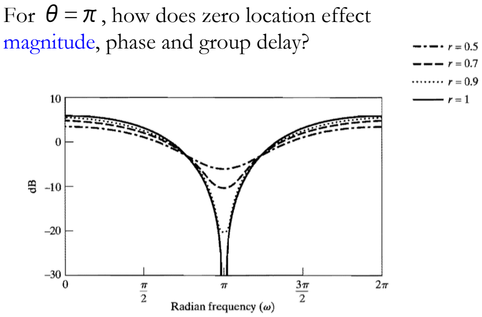
Example: Zero on Real Axis

- Magnitude Response



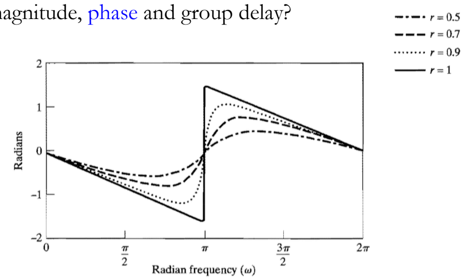
Example: Zero on Real Axis

- For $\theta = \pi$, how does zero location effect magnitude, phase and group delay?



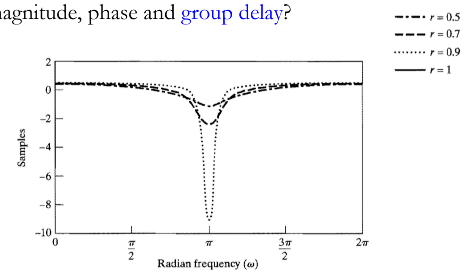
Example: Zero on Real Axis

- For $\theta = \pi$, how does zero location effect magnitude, phase and group delay?



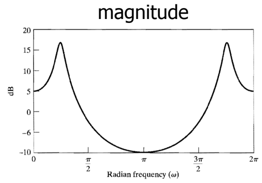
Example: Zero on Real Axis

- For $\theta = \pi$, how does zero location effect magnitude, phase and group delay?



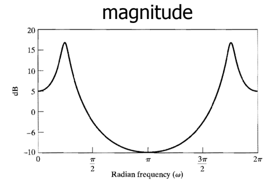
2nd Order IIR with Complex Poles

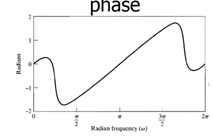
$$H(z) = \frac{1}{(1 - re^{j\theta}z^{-1})(1 - re^{-j\theta}z^{-1})}$$

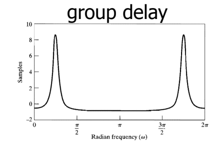


2nd Order IIR with Complex Poles

$$H(z) = \frac{1}{(1 - re^{j\theta}z^{-1})(1 - re^{-j\theta}z^{-1})}$$







Big Ideas

- Frequency Response of LTI Systems
  - Magnitude Response
    - Simple Filters
  - Phase Response
    - Group Delay
  - Example: Zero on Real Axis

Admin

- HW 5
  - Due Friday 3/3

- Homework solutions to be posted soon