

ESE 531: Digital Signal Processing

Lec 13: February 23st, 2017
Frequency Response of LTI Systems

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Adapted from M. Lustig, EECS Berkeley



Lecture Outline

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

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2

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

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3

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

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

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4

Phase Response

- Limit the range of the phase response

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

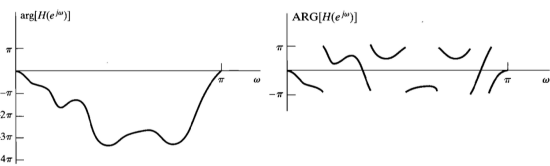
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6

Group Delay

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

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

- More later...

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7

Linear Difference Equations

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

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

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

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8

Magnitude Response

Magnitude of products is product of magnitudes

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

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9

Magnitude Response

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Consider one of the poles:

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

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10

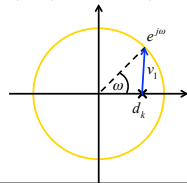
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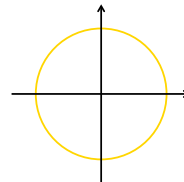
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11

Magnitude Response Example

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

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



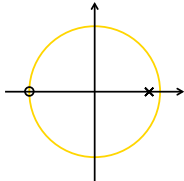
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12

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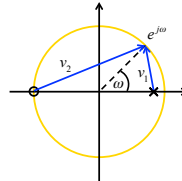
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13

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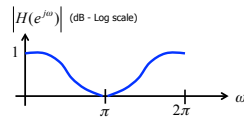
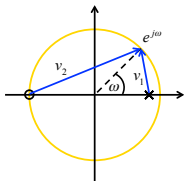
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14

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15

Simple Low Pass Filter

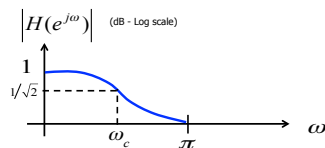
$$H_{LP}(z) = \frac{1 - \alpha}{2} \frac{1 + z^{-1}}{1 - \alpha z^{-1}} \quad |\alpha| < 1$$

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16

Simple Low Pass Filter

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



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

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17

Simple High Pass Filter

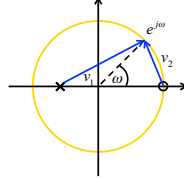
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18

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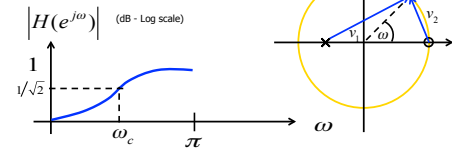


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19

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Simple Band-Stop (Notch) Filter

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

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

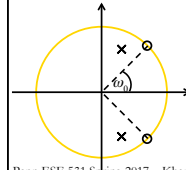
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21

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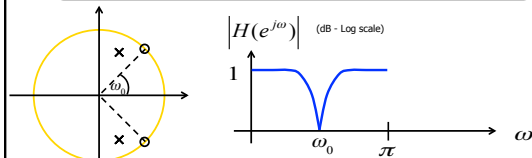
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22

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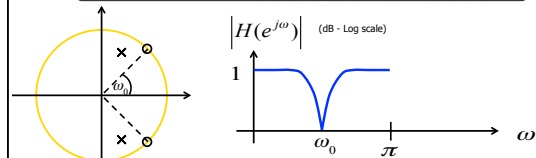
23

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Note:

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



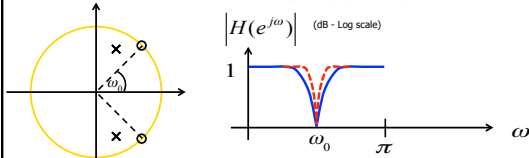
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24

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Note: As $\alpha \rightarrow 1$ poles approach zeros
 $H_{BS}(\mp 1) = \frac{1+\alpha}{2} \frac{2 \pm 2\beta}{(1+\alpha)(1 \pm \beta)} = 1$



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25

Simple Band-Pass Filter

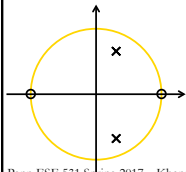
$$H_{BP}(z) = \frac{1-\alpha}{2} \frac{1-z^{-2}}{1-\beta(1+\alpha)z^{-1}+\alpha z^{-2}} \quad \begin{matrix} |\alpha| < 1 \\ |\beta| < 1 \end{matrix}$$

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26

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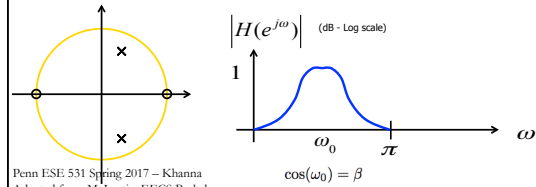


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27

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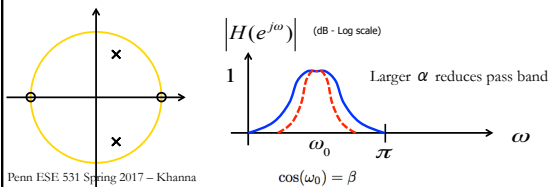


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28

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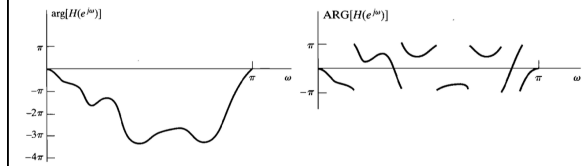
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29

Phase Response

Limit the range of the phase response

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



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30

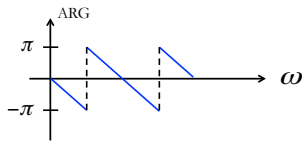
Phase Response Example

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

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

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

ARG is the wrapped phase
arg is the unwrapped phase



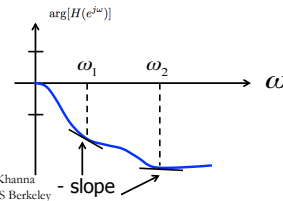
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31

Group Delay

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

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



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32

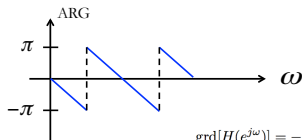
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For linear phase system, group delay is n_d

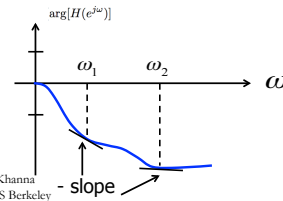
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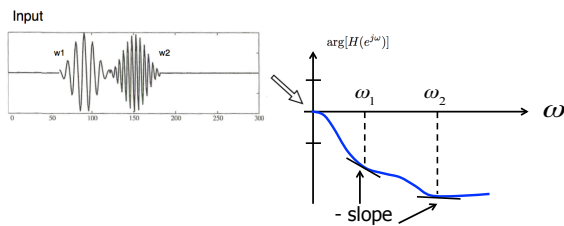


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34

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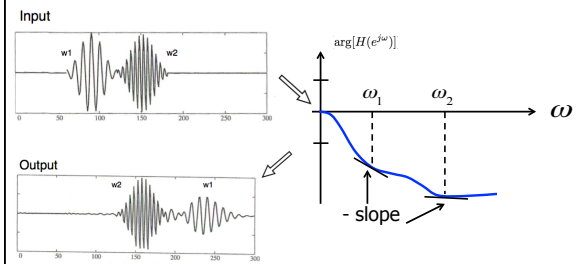


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35

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36

Group Delay Math

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

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37

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arg of products is sum of args

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

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

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38

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:

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

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

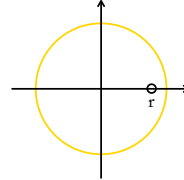
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39

Example: Zero on Real Axis

□ Geometric Interpretation for ($\theta = 0$)

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



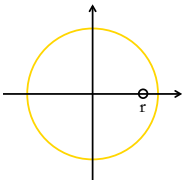
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40

Example: Zero on Real Axis

□ Geometric Interpretation for ($\theta = 0$)

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



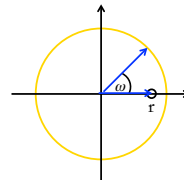
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41

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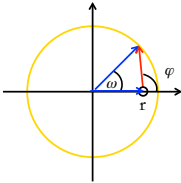
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42

Example: Zero on Real Axis

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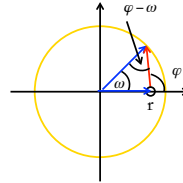
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43

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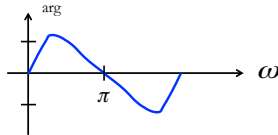
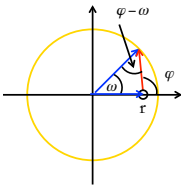
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44

Example: Zero on Real Axis

- Geometric Interpretation for ($\theta = 0$)

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



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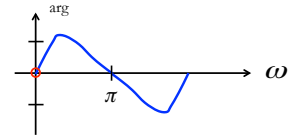
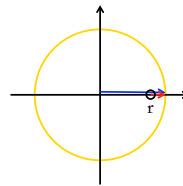
45

Example: Zero on Real Axis

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

$\omega = 0$



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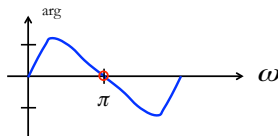
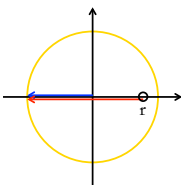
46

Example: Zero on Real Axis

- Geometric Interpretation for ($\theta = 0$)

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

$\omega = \pi$



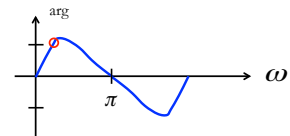
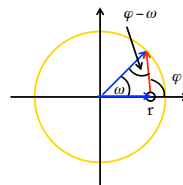
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47

Example: Zero on Real Axis

- Geometric Interpretation for ($\theta = 0$)

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



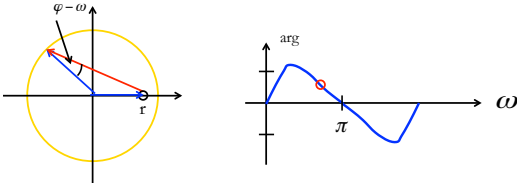
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48

Example: Zero on Real Axis

- Geometric Interpretation for ($\theta = 0$)

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



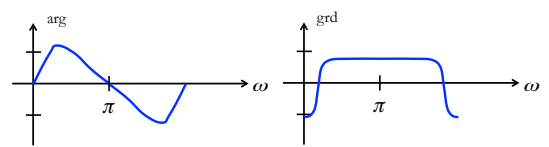
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49

Example: Zero on Real Axis

- Geometric Interpretation for ($\theta = 0$)

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



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50

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:

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

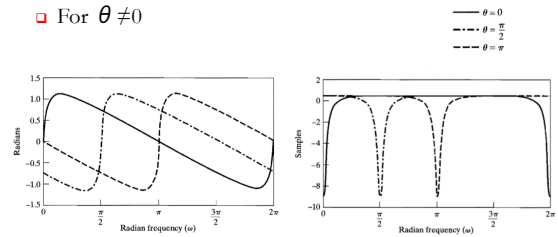
$$\text{grd}[1 - re^{j\theta} e^{-j\omega}] = \frac{r^2 - r \cos(\omega - \theta)}{|1 - re^{j\theta} e^{-j\omega}|^2}$$

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51

Example: Zero on Real Axis

- For $\theta \neq 0$

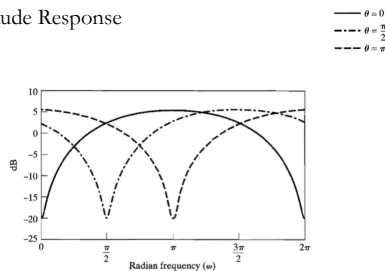


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52

Example: Zero on Real Axis

- Magnitude Response

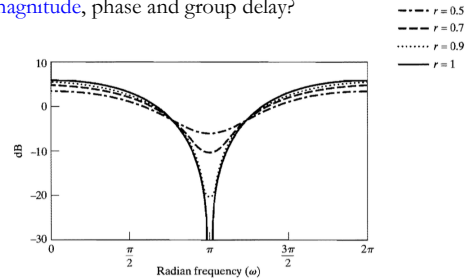


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53

Example: Zero on Real Axis

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

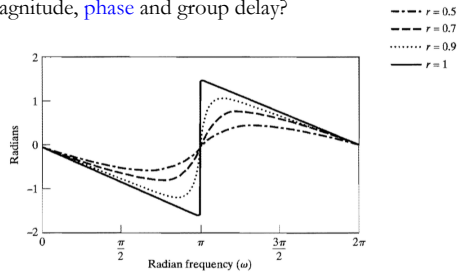


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54

Example: Zero on Real Axis

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

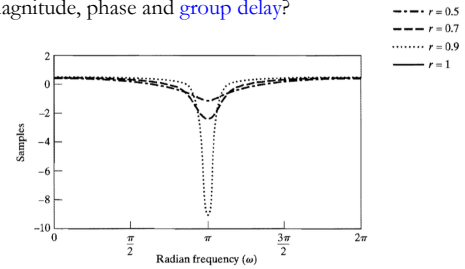


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55

Example: Zero on Real Axis

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

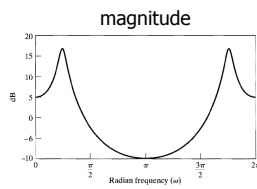


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56

2nd Order IIR with Complex Poles

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

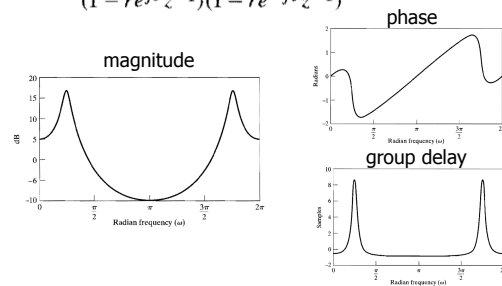


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57

2nd Order IIR with Complex Poles

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



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58

Big Ideas

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

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59

Admin

- HW 5
 - Due Friday 3/3
- Homework solutions to be posted soon

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60