

Signal Processing First

Lecture 12 Frequency Response of FIR Filters

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READING ASSIGNMENTS

- This Lecture:
 - Chapter 6, Sections 6-1, 6-2, 6-3, 6-4, & 6-5
- Other Reading:
 - Recitation: Chapter 6
 - FREQUENCY RESPONSE EXAMPLES
 - Next Lecture: Chap. 6, Sects. 6-6, 6-7 & 6-8

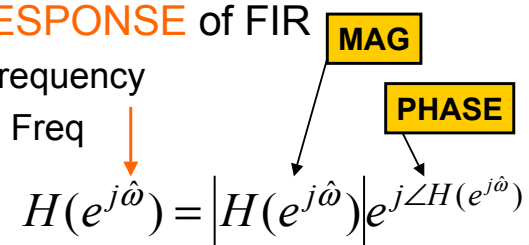
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LECTURE OBJECTIVES

- **SINUSOIDAL** INPUT SIGNAL
 - DETERMINE the FIR FILTER OUTPUT

- **FREQUENCY RESPONSE** of FIR
 - PLOTTING vs. Frequency
 - MAGNITUDE vs. Freq
 - PHASE vs. Freq
- $H(e^{j\hat{\omega}}) = |H(e^{j\hat{\omega}})| e^{j\angle H(e^{j\hat{\omega}})}$
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DOMAINS: Time & Frequency

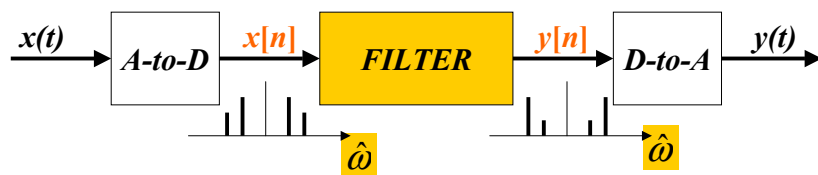
- **Time-Domain: “n” = time**
 - $x[n]$ discrete-time signal
 - $x(t)$ continuous-time signal
- **Frequency Domain (sum of sinusoids)**
 - Spectrum vs. f (Hz)
 - ANALOG vs. DIGITAL
 - Spectrum vs. ω -hat
- Move back and forth **QUICKLY**

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DIGITAL “FILTERING”



- CONCENTRATE on the **SPECTRUM**
- SINUSOIDAL INPUT
 - INPUT $x[n] = \text{SUM of SINUSOIDS}$
 - Then, OUTPUT $y[n] = \text{SUM of SINUSOIDS}$

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FILTERING EXAMPLE

- 7-point AVERAGER

- Removes cosine
- By making its amplitude (A) smaller

$$y_7[n] = \sum_{k=0}^6 \left(\frac{1}{7}\right) x[n-k]$$

- 3-point AVERAGER

- Changes A slightly

$$y_3[n] = \sum_{k=0}^2 \left(\frac{1}{3}\right) x[n-k]$$

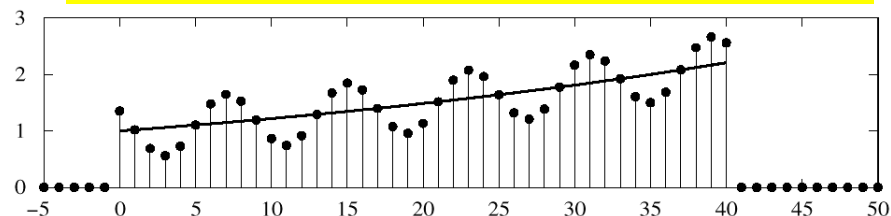
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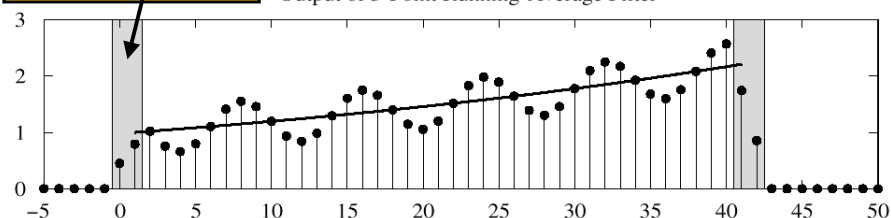
3-pt AVG EXAMPLE

Input : $x[n] = (1.02)^n + \cos(2\pi n/8 + \pi/4)$ for $0 \leq n \leq 40$



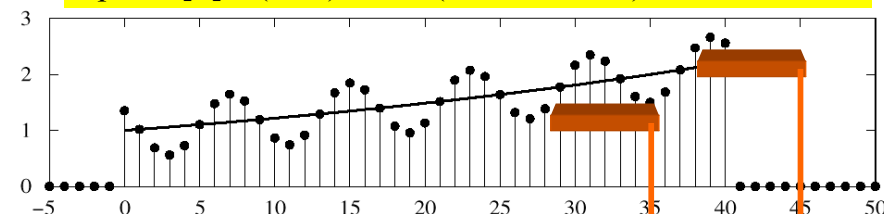
USE PAST VALUES

Output of 3-Point Running-Average Filter



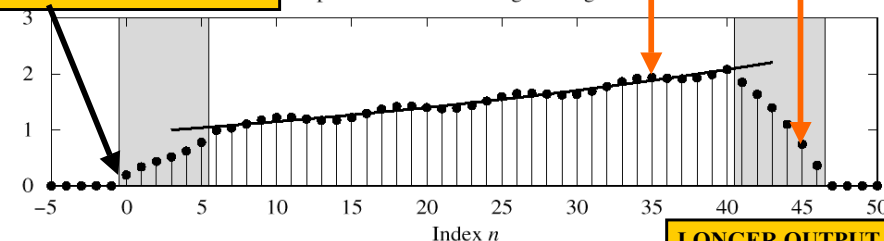
7-pt FIR EXAMPLE (AVG)

Input : $x[n] = (1.02)^n + \cos(2\pi n/8 + \pi/4)$ for $0 \leq n \leq 40$



CAUSAL: Use Previous

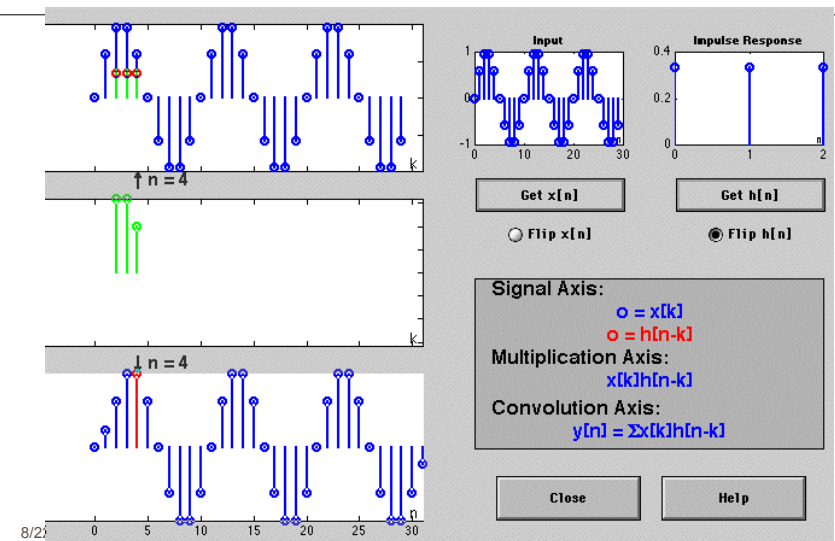
Output of 7-Point Running-Average Filter



SINUSOIDAL RESPONSE

- INPUT: $x[n] = \text{SINUSOID}$
- OUTPUT: $y[n]$ will also be a SINUSOID
 - Different Amplitude and Phase
 - SAME** Frequency
- AMPLITUDE & PHASE CHANGE
 - Called the **FREQUENCY RESPONSE**

DCONVDEMO: MATLAB GUI



COMPLEX EXPONENTIAL

$$x[n] = Ae^{j\varphi} e^{j\hat{\omega}n} \quad -\infty < n < \infty$$

$x[n]$ is the input signal—a complex exponential

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

FIR DIFFERENCE EQUATION

COMPLEX EXP OUTPUT

- Use the FIR “Difference Equation”

$$\begin{aligned} y[n] &= \sum_{k=0}^M b_k x[n-k] = \sum_{k=0}^M b_k Ae^{j\varphi} e^{j\hat{\omega}(n-k)} \\ &= \left(\sum_{k=0}^M b_k e^{j\hat{\omega}(-k)} \right) Ae^{j\varphi} e^{j\hat{\omega}n} \end{aligned}$$

$$= H(\hat{\omega}) Ae^{j\varphi} e^{j\hat{\omega}n}$$

FREQUENCY RESPONSE

- At each frequency, we can **DEFINE**

$$H(e^{j\hat{\omega}}) = \sum_{k=0}^M b_k e^{-j\hat{\omega}k} \quad \leftarrow \text{FREQUENCY RESPONSE}$$

- Complex-valued formula
 - Has **MAGNITUDE** vs. frequency
 - And **PHASE** vs. frequency
- Notation: $H(e^{j\hat{\omega}})$ in place of $H(\hat{\omega})$

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EXAMPLE 6.1

$$\{b_k\} = \{1, 2, 1\}$$

$$\begin{aligned} H(e^{j\hat{\omega}}) &= 1 + 2e^{-j\hat{\omega}} + e^{-j2\hat{\omega}} \\ &= e^{-j\hat{\omega}}(e^{j\hat{\omega}} + 2 + e^{-j\hat{\omega}}) \\ &= e^{-j\hat{\omega}}(2 + 2\cos\hat{\omega}) \end{aligned} \quad \leftarrow \text{EXPLOIT SYMMETRY}$$

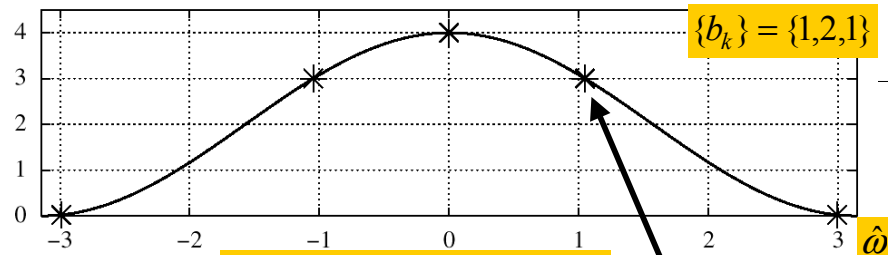
Since $(2 + 2\cos\hat{\omega}) \geq 0$
 Magnitude is $|H(e^{j\hat{\omega}})| = (2 + 2\cos\hat{\omega})$
 and Phase is $\angle H(e^{j\hat{\omega}}) = -\hat{\omega}$

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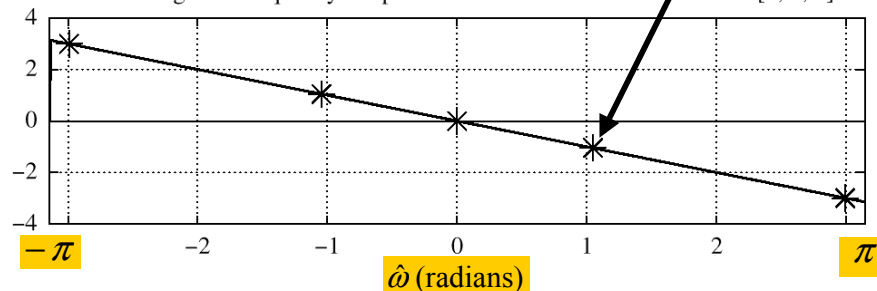
Magnitude of Frequency Response of FIR Filter with Coefficients [1, 2, 1]



$$H(e^{j\hat{\omega}}) = (2 + 2\cos\hat{\omega})e^{-j\hat{\omega}}$$

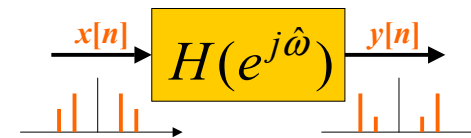
RESPONSE at $\pi/3$

Phase Angle of Frequency Response of FIR Filter with Coefficients [1, 2, 1]



EXAMPLE 6.2

Find $y[n]$ when $H(e^{j\hat{\omega}})$ is known
 and $x[n] = 2e^{j\pi/4}e^{j(\pi/3)n}$



$$H(e^{j\hat{\omega}}) = (2 + 2\cos\hat{\omega})e^{-j\hat{\omega}}$$

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EXAMPLE 6.2 (answer)

Find $y[n]$ when $x[n] = 2e^{j\pi/4} e^{j(\pi/3)n}$

One Step - evaluate $H(e^{j\hat{\omega}})$ at $\hat{\omega} = \pi/3$

$$H(e^{j\hat{\omega}}) = (2 + 2\cos \hat{\omega})e^{-j\hat{\omega}}$$

$$H(e^{j\hat{\omega}}) = 3e^{-j\pi/3} \quad @ \hat{\omega} = \pi/3$$

$$y[n] = (3e^{-j\pi/3}) \times 2e^{j\pi/4} e^{j(\pi/3)n} = 6e^{-j\pi/12} e^{j(\pi/3)n}$$

MATLAB: FREQUENCY RESPONSE

■ **HH = freqz(bb,1,ww)**

■ VECTOR **bb** contains Filter Coefficients

■ DSP-First: **HH = freekz(bb,1,ww)**

■ FILTER COEFFICIENTS $\{b_k\}$

$$H(e^{j\hat{\omega}}) = \sum_{k=0}^M b_k e^{-j\hat{\omega}k}$$

LTI SYSTEMS

- LTI: Linear & Time-Invariant
- COMPLETELY CHARACTERIZED by:
 - **FREQUENCY RESPONSE**, or
 - IMPULSE RESPONSE $h[n]$
- **Sinusoid IN -----> Sinusoid OUT**
 - **At the SAME Frequency**

Time & Frequency Relation

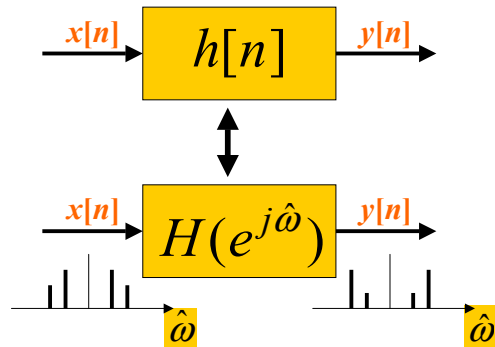
- Get Frequency Response from $h[n]$
 - Here is the FIR case:

$$H(e^{j\hat{\omega}}) = \sum_{k=0}^M b_k e^{-j\hat{\omega}k} = \sum_{k=0}^M h[k] e^{-j\hat{\omega}k}$$

IMPULSE RESPONSE

BLOCK DIAGRAMS

Equivalent Representations



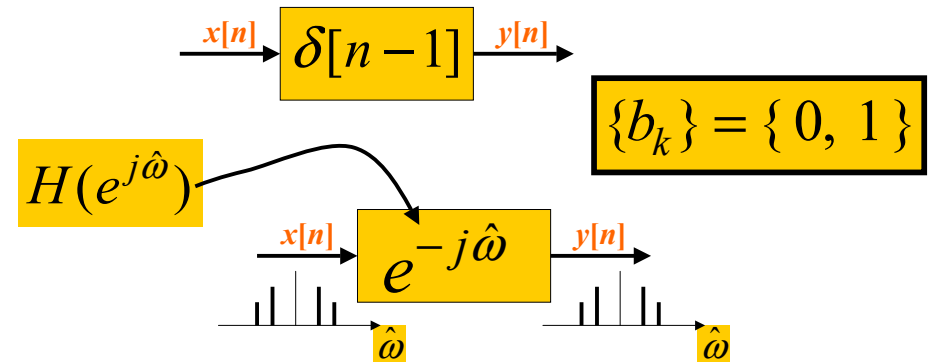
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UNIT-DELAY SYSTEM

Find $h[n]$ and $H(e^{j\hat{\omega}})$ for $y[n] = x[n-1]$



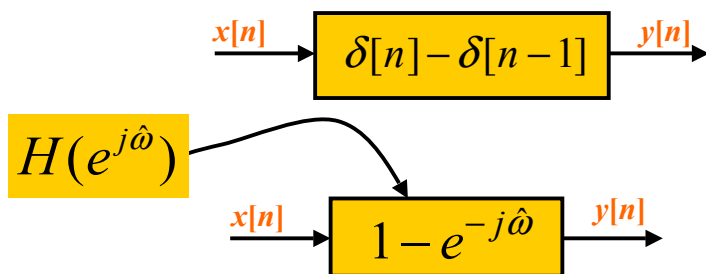
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FIRST DIFFERENCE SYSTEM

Find $h[n]$ and $H(e^{j\hat{\omega}})$ for the Difference Equation: $y[n] = x[n] - x[n-1]$

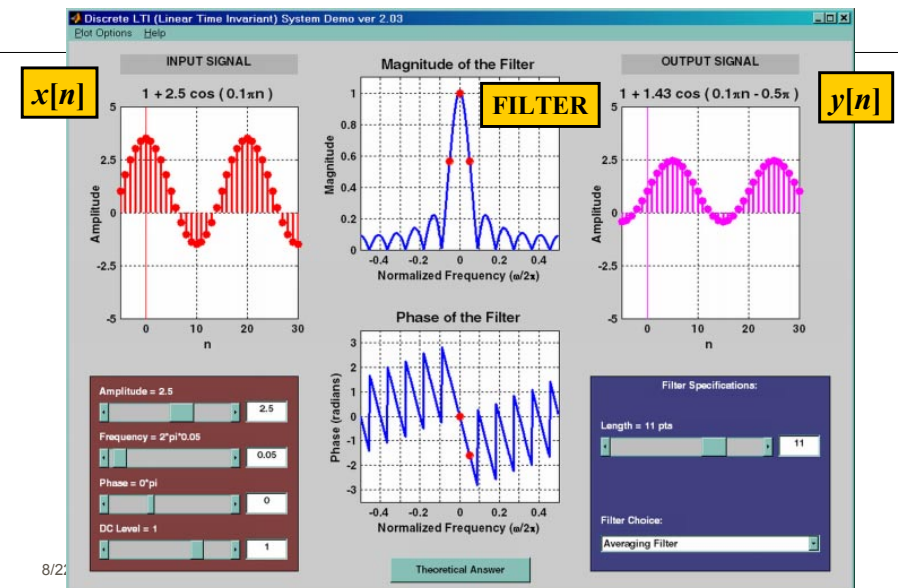


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DLTI Demo with Sinusoids



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CASCADE SYSTEMS

- Does the order of S_1 & S_2 matter?
 - NO, **LTI SYSTEMS can be rearranged !!!**
 - WHAT ARE THE FILTER COEFFS? $\{b_k\}$
 - WHAT is the overall FREQUENCY RESPONSE ?

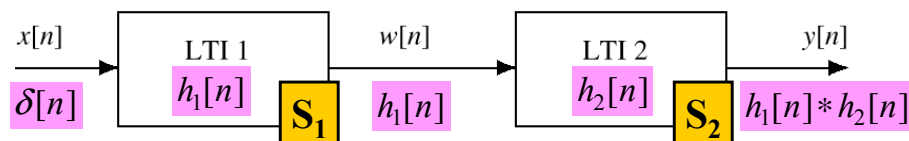


Figure 5.19 A Cascade of Two LTI Systems.

CASCADE EQUIVALENT

- MULTIPLY** the Frequency Responses

