

Lecture 12
Frequency Response of FIR
21-Feb-03

Info: Web-CT, Lab, HW

- Lab #6: FIR Filtering of Images
 - Edge Detection
 - Due next week (25-27 Feb) except for L12 & L14
- Prob Set #7 due next week
- Quiz #2 on 14-March (Friday)
 - Coverage: HW #4, #5, #6, #7 and #8

LECTURE

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

LECTURE OBJECTIVES

- SINUSOIDAL INPUT SIGNAL
 - DETERMINE the FIR FILTER OUTPUT

- FREQUENCY RESPONSE of FIR
 - PLOTTING vs. Frequency
 - MAGNITUDE vs. Freq
 - PHASE vs. Freq

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

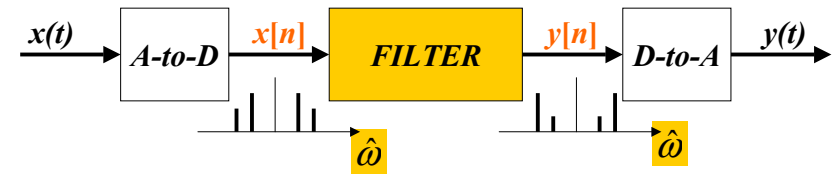
MAG

PHASE

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**

DIGITAL “FILTERING”



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

FILTERING EXAMPLE

- 7-point AVERAGER

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

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

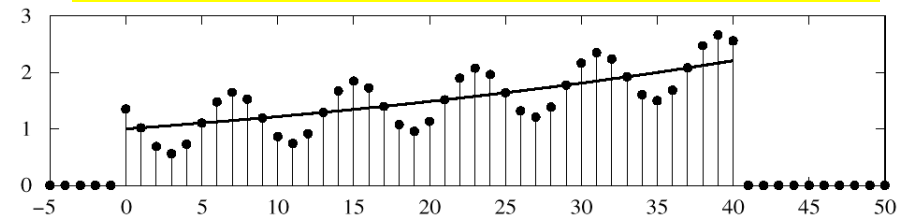
- 3-point AVERAGER

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

- Changes A slightly

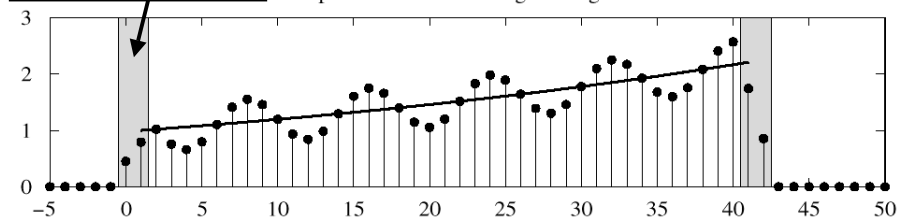
3-pt AVG EXAMPLE

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



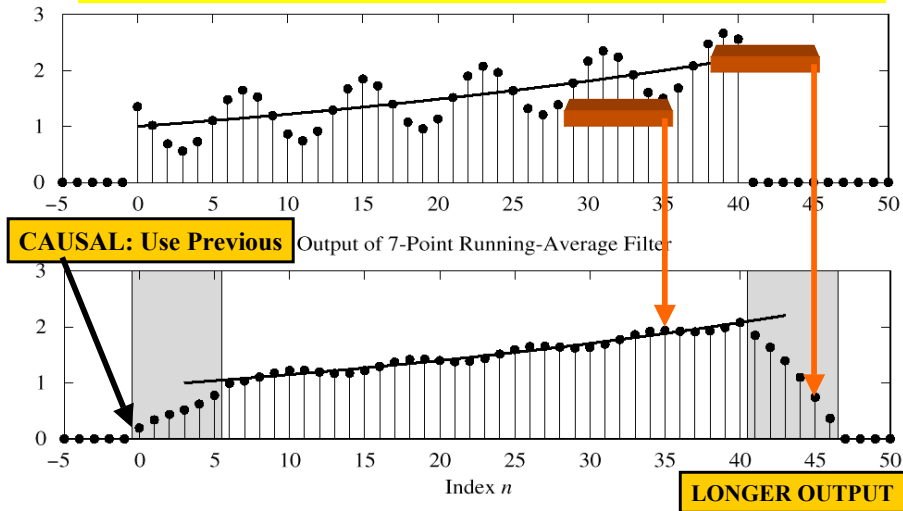
USE PAST VALUES

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 $0 \leq n \leq 40$



SINUSOIDAL RESPONSE

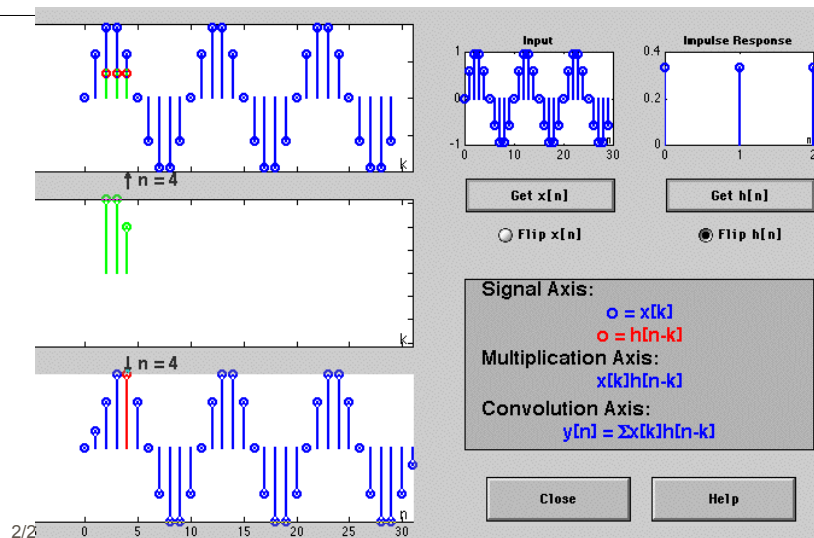
- INPUT: $x[n] = \text{SINUSOID}$
- OUTPUT: $y[n]$ will also be a SINUSOID
 - Different Amplitude and Phase
 - SAME** Frequency
- AMPLITUDE & PHASE CHANGE
 - Called the **FREQUENCY RESPONSE**

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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

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COMPLEX EXP OUTPUT

- Use the FIR “Difference Equation”

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

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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

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

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

EXPLOIT SYMMETRY

$$\text{Since } (2 + 2\cos\hat{\omega}) \geq 0$$

$$\text{Magnitude is } |H(e^{j\hat{\omega}})| = (2 + 2\cos\hat{\omega})$$

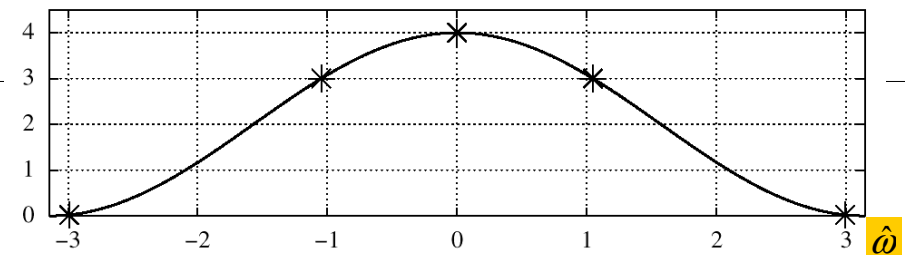
$$\text{and Phase is } \angle H(e^{j\hat{\omega}}) = -\hat{\omega}$$

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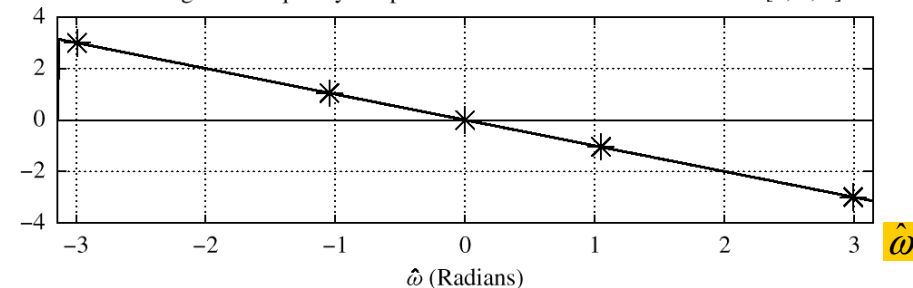
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Magnitude of Frequency Response of FIR Filter with Coefficients [1, 2, 1]



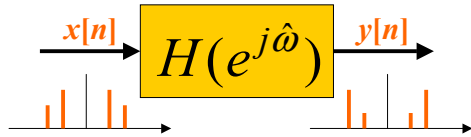
$$H(e^{j\hat{\omega}}) = (2 + 2\cos\hat{\omega})e^{-j\hat{\omega}}$$

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



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

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

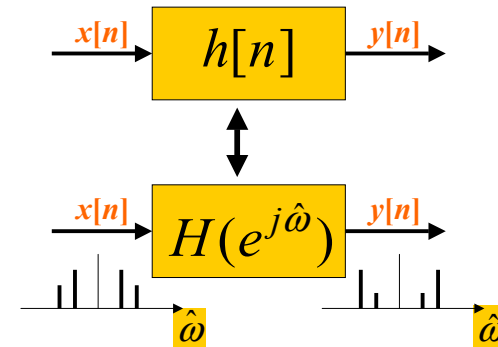
- Get Frequency Response from $h[n]$
 - Here is the FIR case:

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

IMPULSE RESPONSE

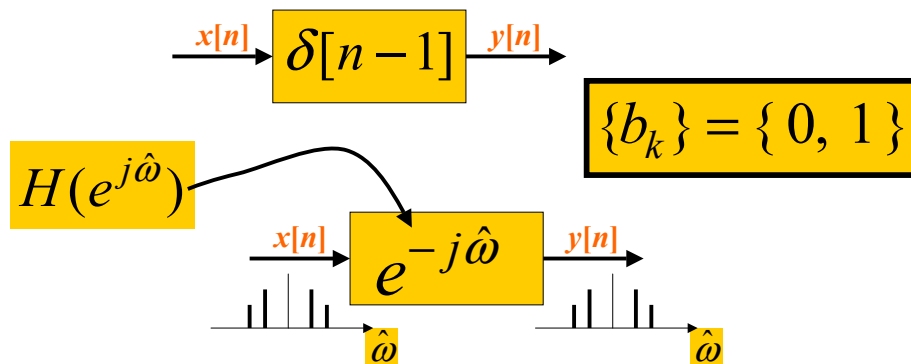
BLOCK DIAGRAMS

- Equivalent Representations



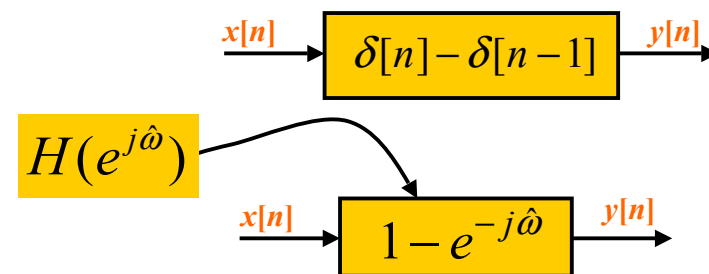
UNIT-DELAY SYSTEM

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

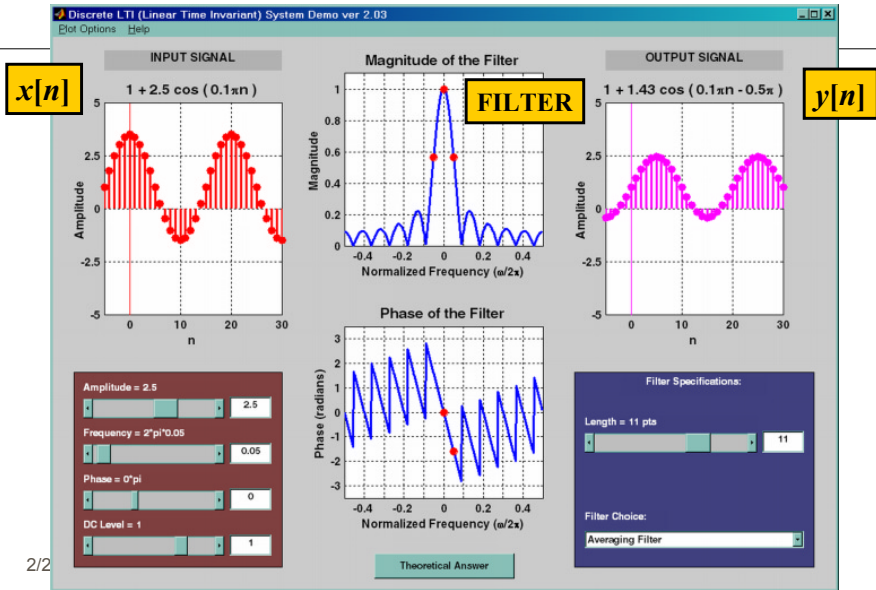


FIRST DIFFERENCE SYSTEM

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

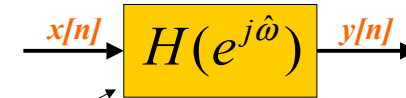
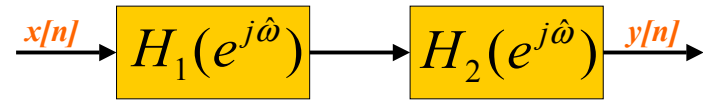


DLTI Demo with Sinusoids



CASCADE EQUIVALENT

- **MULTIPLY** the Frequency Responses



EQUIVALENT SYSTEM

$$H(e^{j\hat{\omega}}) = H_1(e^{j\hat{\omega}})H_2(e^{j\hat{\omega}})$$

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 ?

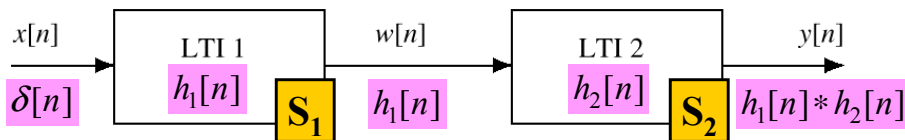


Figure 5.19 A Cascade of Two LTI Systems.