EE-2200 Fall-98

Lecture 11

Frequency Response of FIR

2-Nov-98

Info: Web-CT, Lab, HW

- Calendar:
  - Quiz #2 on 13-Nov (Friday)
- Prob Set #4 due TODAY
  - Solutions for #3 are posted (complete)
- Lab #5 on Filtering
  - Frequency Response

READING ASSIGNMENTS

- This Lecture:
  - Chapter 5, pp. 157-165, 169-176
- Other Reading:
  - Recitation: Ch. 6, pp. 176-188
    - FREQUENCY RESPONSE EXAMPLES
  - Next Lecture: Chapter 6, pp. 188-194

LECTURE OBJECTIVES

- SINUSOIDAL INPUT SIGNAL
  - DETERMINE FIR OUTPUT
- FREQUENCY RESPONSE of FIR
  - MAGNITUDE vs. Frequency
  - PHASE vs. Freq
  - PLOTTING:

MAG

PHASE

$$H(\hat{\omega}) = \left|H(\hat{\omega})\right| e^{j\varphi(\hat{\omega})}$$

DIGITAL "FILTERING"

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

GENERAL FIR FILTER

- FILTER COEFFICIENTS $\{b_k\}$
  - DEFINE THE FILTER

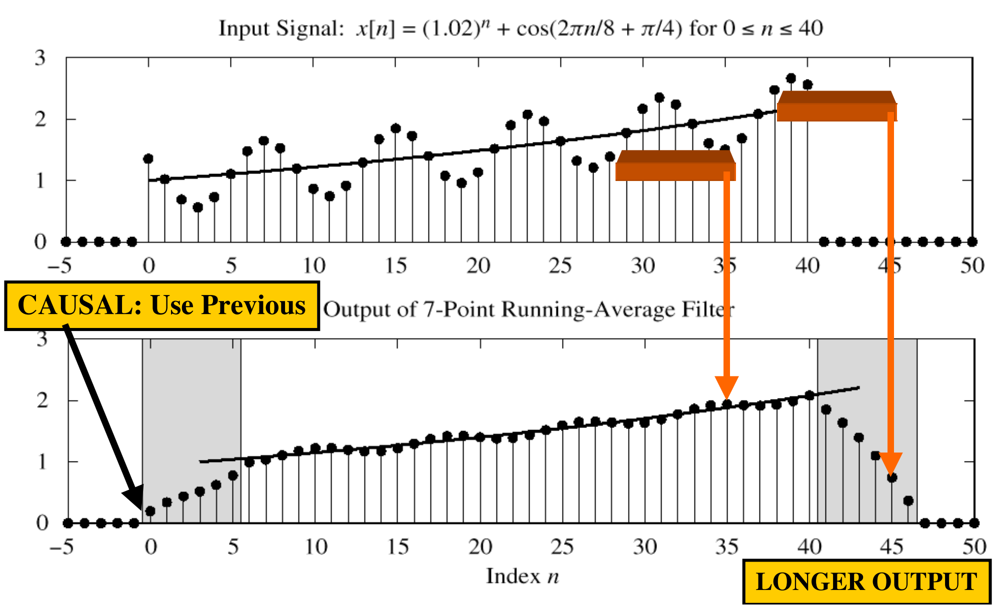
$$y[n] = \sum_{k=0}^{M} b_k\, x[n-k]$$

  - For example, $\{b_k\} = \{3, -1, 2, 1\}$

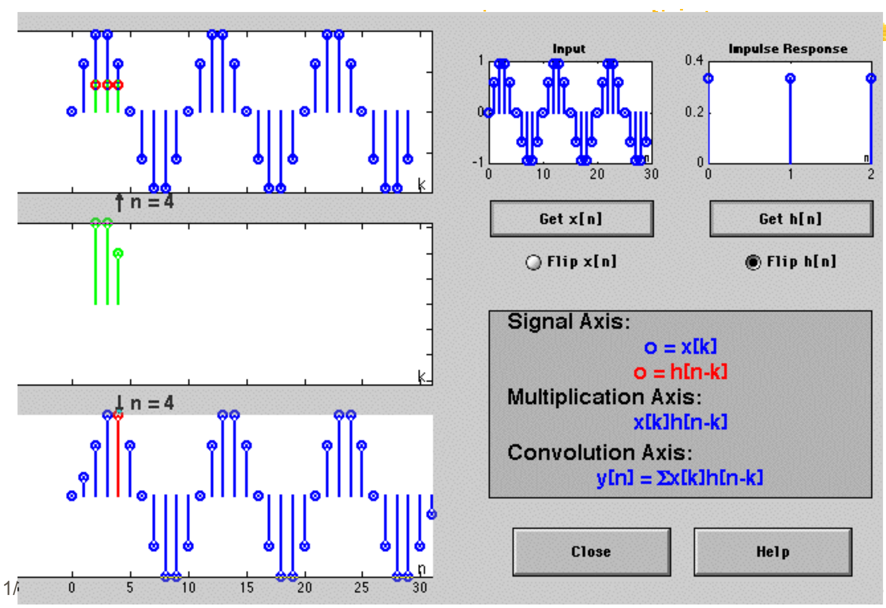
$$y[n] = \sum_{k=0}^{3} b_k x[n-k]$$

$$= 3x[n] - x[n-1] + 2x[n-2] + x[n-3]$$

ANIMATION of FIR FILTER



CONVDEMO: MATLAB GUI



SPECIAL INPUT SIGNALS

- x[n] = SINUSOID
- y[n] will also be a SINUSOID
  - Different Amplitude and Phase
  - SAME Frequency
- AMPLITUDE & PHASE CHANGE
  - Called the **FREQUENCY RESPONSE**

COMPLEX EXPONENTIAL

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

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

FIR DIFFERENCE EQUATION

COMPLEX EXP OUTPUT

- Use the FIR “Difference Equation”

$$y[n] = \sum_{k=0}^{M} b_k \, Ae^{j\phi}e^{j\hat{\omega}(n-k)}$$

$$= \left(\sum_{k=0}^{M} b_k e^{-j\hat{\omega}k}\right) Ae^{j\phi}e^{j\hat{\omega}n}$$

$$= \mathcal{H}(\hat{\omega})Ae^{j\phi}e^{j\hat{\omega}n} \qquad -\infty < n < \infty$$

FREQUENCY REPONSE

- At each frequency, we can define

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

- Complex-valued formula
  - Has MAGNITUDE vs. frequency
  - And PHASE vs. frequency

EXAMPLE 6.1

Example 6.1

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

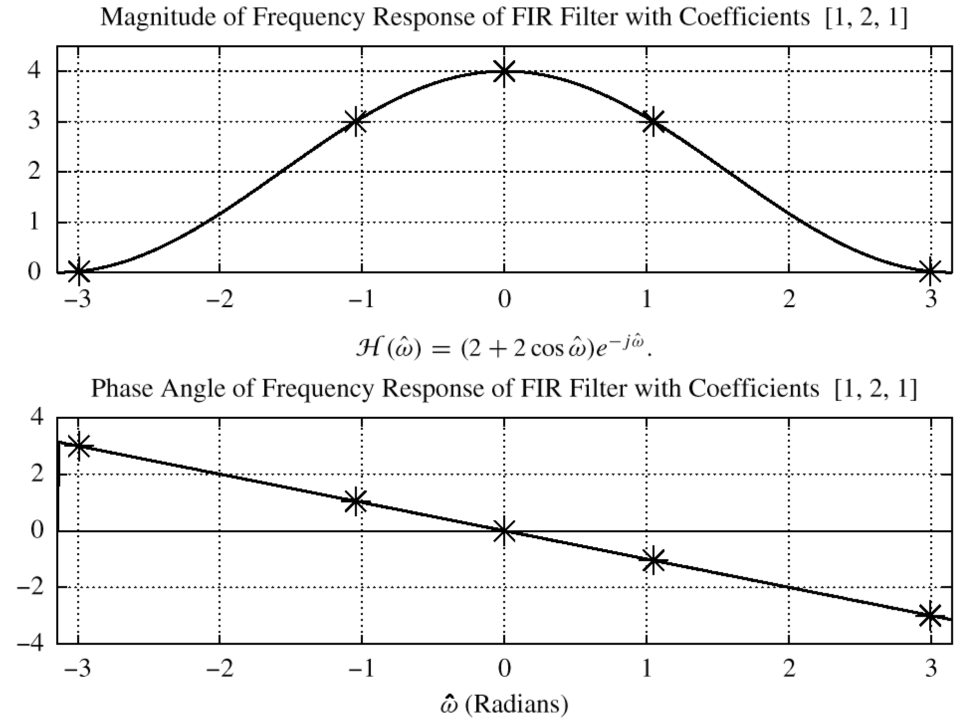
$$\mathcal{H}(\hat{\omega}) = 1 + 2e^{-j\hat{\omega}} + e^{-j\hat{\omega}2}$$

To obtain formulas for the magnitude and phase of the frequency response

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

SYMMETRY

Since $(2 + 2\cos\hat{\omega}) \geq 0$ for frequencies $-\pi < \hat{\omega} \leq \pi$, the magnitude is $|\mathcal{H}(\hat{\omega})| = (2 + 2\cos\hat{\omega})$ and the phase is $\angle\mathcal{H}(\hat{\omega}) = -\hat{\omega}$.



MATLAB: FREQUENCY RESPONSE

- `yy = freqz(bb,1,ww)`
  - VECTOR **bb** contains Filter Coefficients
  - DSP-First: `yy = freekz(bb,1,ww)`
- FILTER COEFFICIENTS $\{b_k\}$

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

EXAMPLE 6.2

- Find y[n] when x[n] = complex exp.

Example 6.2 Consider the complex input $x[n] = 2e^{j\pi/4}e^{j\pi n/3}$.

$$|\mathcal{H}(\pi/3)| = 2 + 2\cos(\pi/3) = 3 \text{ and } \angle\mathcal{H}(\hat{\omega}) = -\pi/3.$$

Therefore, the output of the system for the given input is

$$\begin{aligned}y[n] &= 3e^{-j\pi/3} \cdot 2e^{j\pi/4}e^{j\pi n/3} \\ &= (3 \cdot 2) \cdot e^{(j\pi/4 - j\pi/3)}e^{j\pi n/3} \\ &= 6e^{-j\pi/12}e^{j\pi n/3} = 6e^{j\pi/4}e^{j\pi(n-1)/3}\end{aligned}$$

LTI SYSTEMS

- LTI:
  - Linear & Time-Invariant
- COMPLETELY CHARACTERIZED by:
  - FREQUENCY RESPONSE
  - IMPULSE RESPONSE h[n]
- Two DOMAINS: time & frequency
  - Go back and forth

Time & Frequency

- Frequency Reponse from h[n]
  - Here is the FIR case:

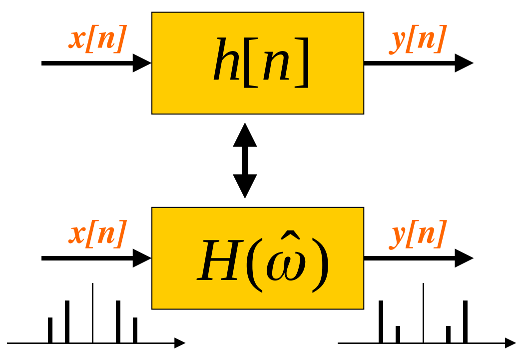
The frequency response of an LTI system

$$\mathcal{H}(\hat{\omega}) = \sum_{k=0}^{M} b_k e^{-j\hat{\omega}k} = \sum_{k=0}^{M} h[k] e^{-j\hat{\omega}k} \qquad (6.1.4)$$

IMPULSE RESPONSE

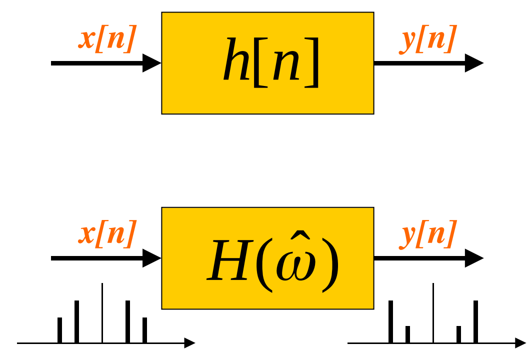
BLOCK DIAGRAMS

- Equivalent Representations



DELAY SYSTEM ??

- UNIT DELAY: find h[n] and $H(\omega)$



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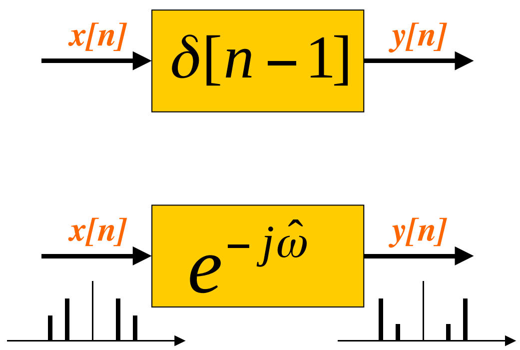


CASCADE SYSTEMS

- 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 FREQUENCY RESPONSE ?

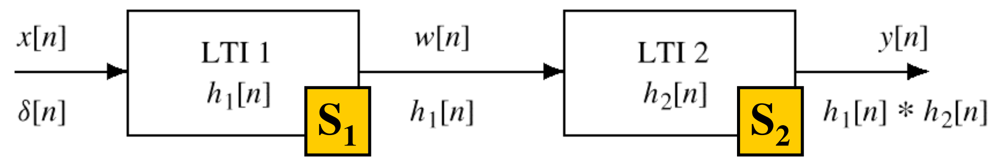
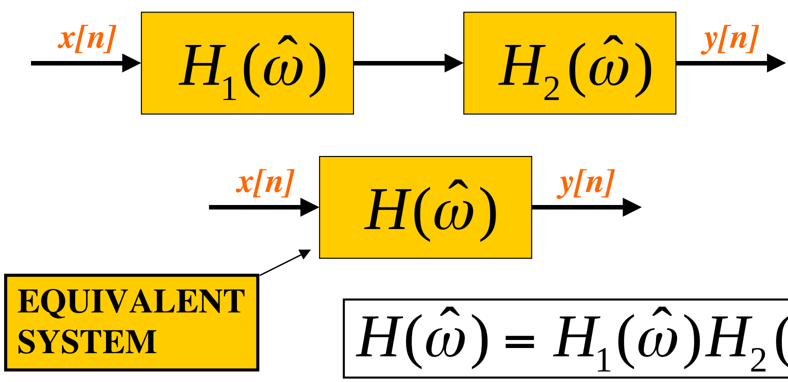


Figure 5.19 A Cascade of Two LTI Systems.

CASCADE EQUIVALENT

- Multiply the Frequency Responses



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