EE-2200 Spring-99

Lecture 11

Frequency Response of FIR

10-May-99

Info: Web-CT, Lab, HW

- Calendar:
  - Quiz #1 on 24-May (Monday)
- Prob Set #5 due FRIDAY
  - Includes 3 On-Line Problems due Wed.
- Lab #6: Frequency Response
  - Lab Quiz on Thursday 13-May
    - Another lab Quiz on 20-May

READING ASSIGNMENTS

- This Lecture:
  - Chapter 6, 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

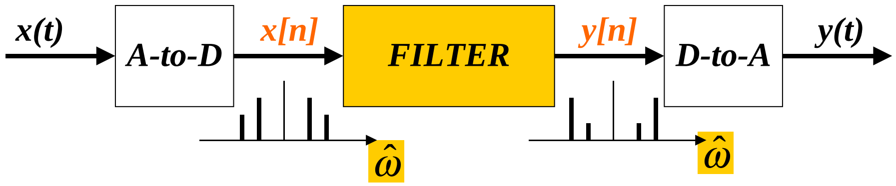
- SINUSOIDAL INPUT SIGNAL
  - DETERMINE FIR OUTPUT
- FREQUENCY RESPONSE of FIR
  - MAGNITUDE vs. Frequency
  - PHASE vs. Freq
  - PLOTTING:

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

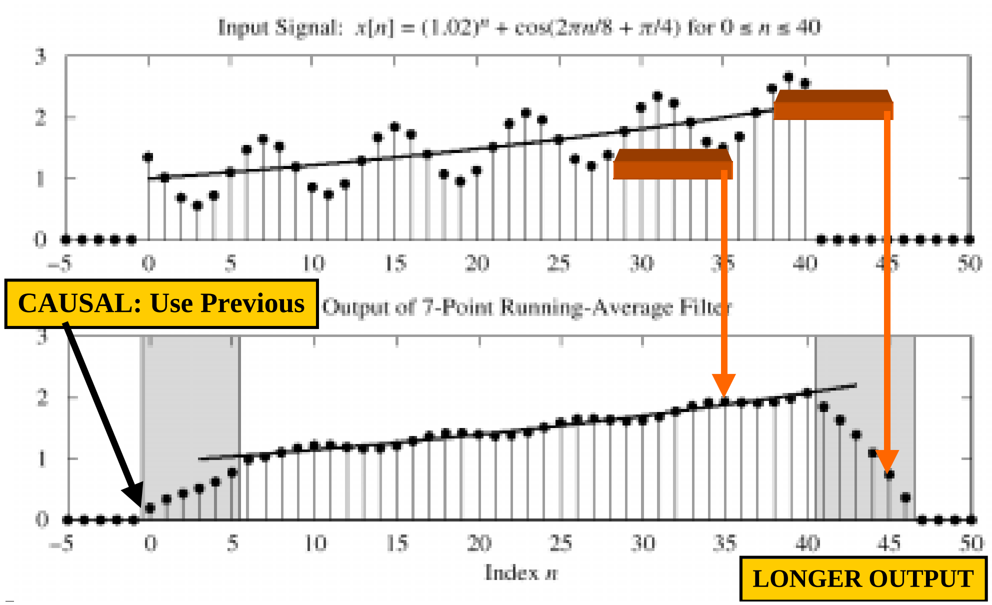
$$y[n] = \sum_{k=0}^{M} b_k x[n-k]$$

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

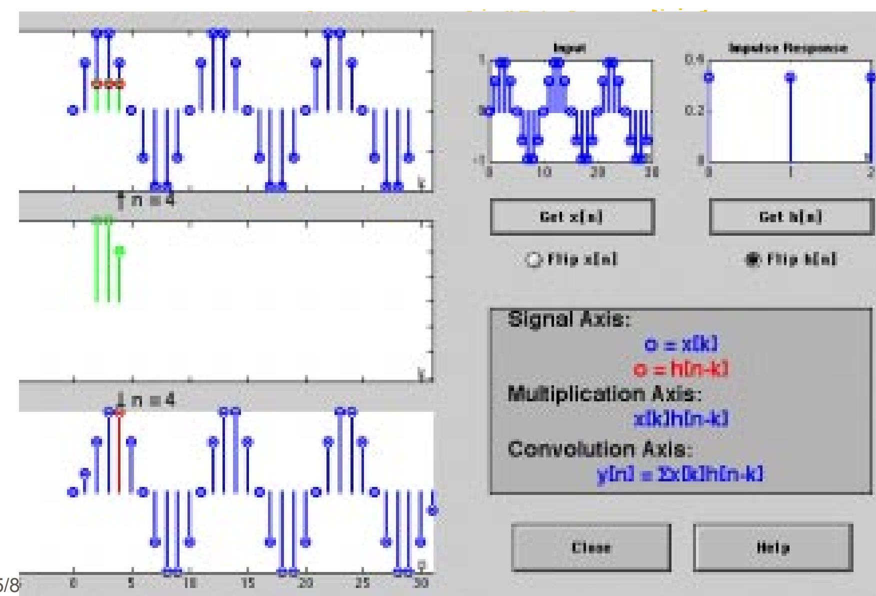
$$y[n] = \sum_{k=0}^{3} b_k x[n-k]$$

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

ANIMATION of FIR FILTER



CONVDEMO: MATLAB GUI



SPECIAL INPUT SIGNALS

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

COMPLEX EXPONENTIAL

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

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”

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

DERIVATION

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

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

FREQUENCY REPONSE

- At each frequency, we can define

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

← **FREQUENCY RESPONSE**

- 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

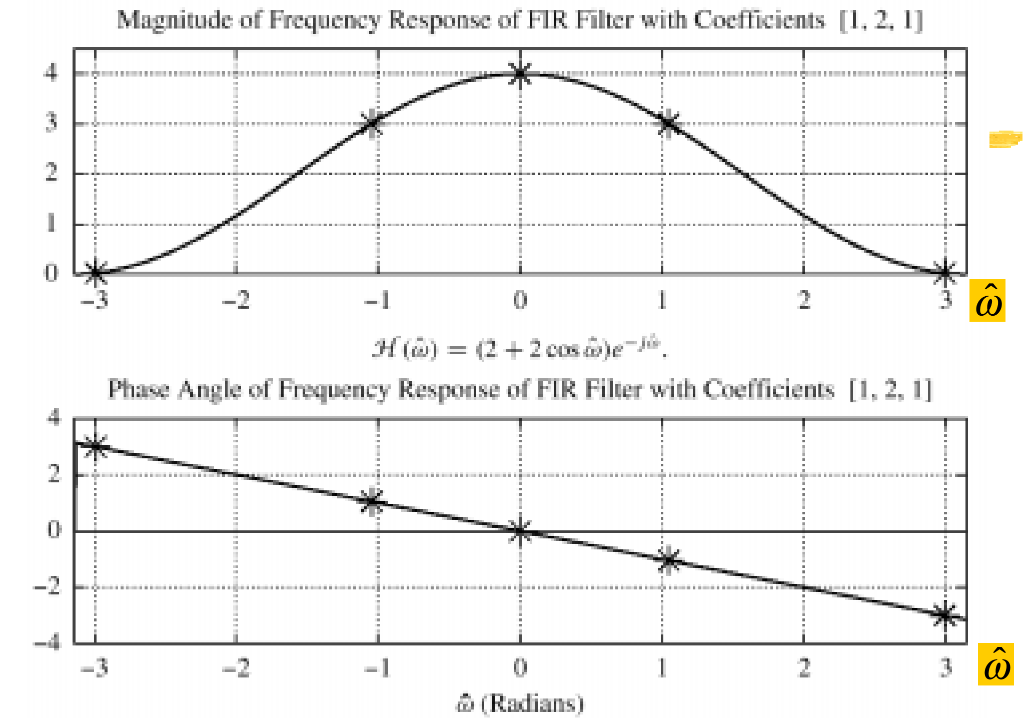
$$\mathcal{H}(\hat{\omega}) = 1 + 2e^{-j\hat{\omega}} + e^{-j\hat{\omega}2}$$

$$= e^{-j\hat{\omega}}\left(e^{j\hat{\omega}} + 2 + e^{-j\hat{\omega}}\right)$$

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

EXPLOIT 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

- `HH = freqz(bb,1,ww)`
  - VECTOR **bb** contains Filter Coefficients
  - DSP-First: `HH = 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.

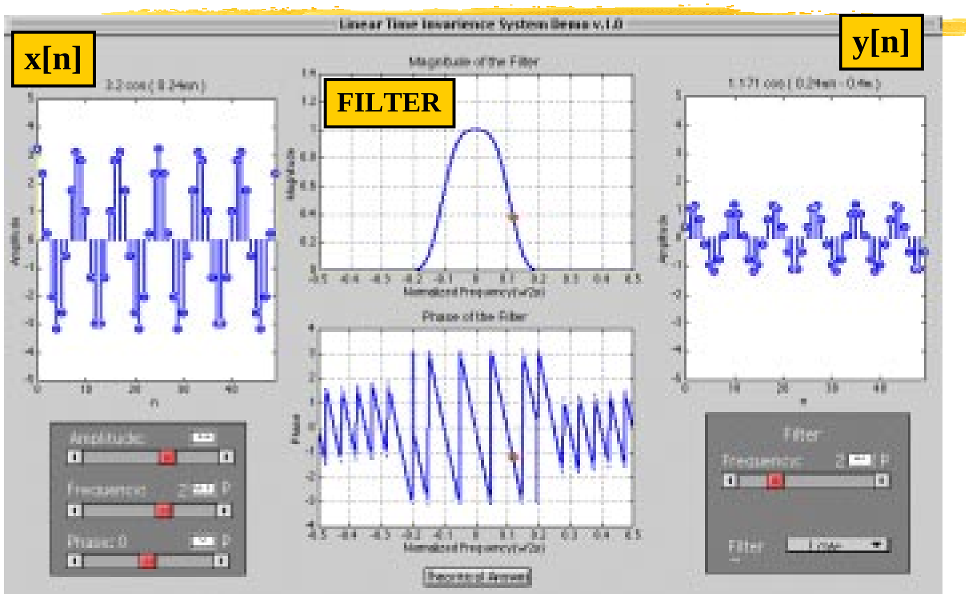
Example 6.2 Consider the complex input $x[n] = 2e^{j\pi/4}e^{j\pi n/3}$.
$|\mathcal{H}(\pi/3)| = 2 + 2\cos(\pi/3) = 3$ and $\angle\mathcal{H}(\hat{\omega}) = -\pi/3$.
Therefore, the output of the system for the given input is

$$y[n] = 3e^{-j\pi/3} \cdot 2e^{j\pi/4}e^{j\pi n/3}$$

$$= (3 \cdot 2) \cdot e^{(j\pi/4 - j\pi/3)}e^{j\pi n/3}$$

$$= 6e^{-j\pi/12}e^{j\pi n/3} = 6e^{j\pi/4}e^{j\pi(n-1)/3}$$

LTI Demo with Sinusoids



LTI SYSTEMS

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

Time & Frequency Relation

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

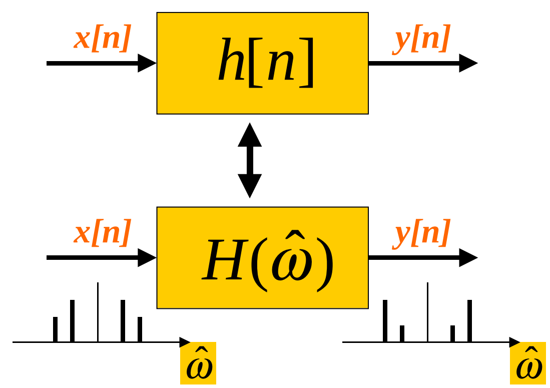
The frequency response of an LTI system

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

IMPULSE RESPONSE

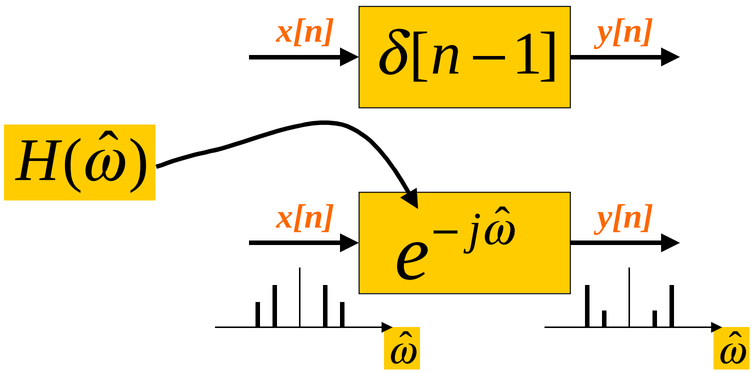
BLOCK DIAGRAMS

- Equivalent Representations



DELAY SYSTEM

- UNIT DELAY : Find $h[n]$ and $H(\hat{\omega})$



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 FREQUENCY RESPONSE ?

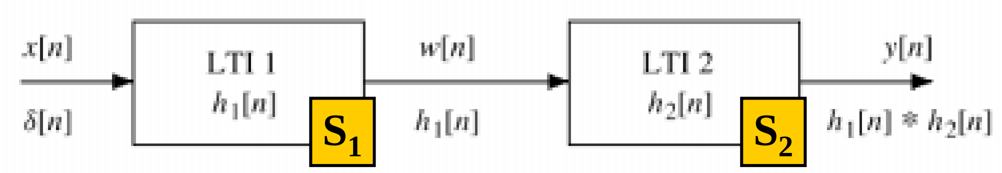
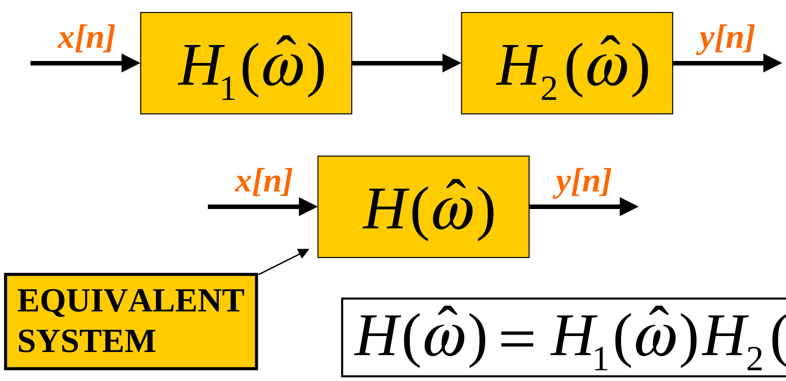


Figure 5.19 A Cascade of Two LTI Systems.

CASCADE EQUIVALENT

- MULTIPLY the Frequency Responses



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