ECE-2025 Fall-2009

Lecture 13

Frequency Response of FIR

9-Oct-09

Lab & HW Info

- Lab #5
  - **Formal** Lab Report (150 pts)
  - Due starting on 13-Oct (Tues)
  - **Listening Test** when report is turned in
- Lab #7 starts on 13-Oct
- HW #7 due week of 12-Oct
- Quiz #2 on 23-Oct (Friday)
  - Coverage: HW #4, #5, #6, #7 and #8
    - Chapters 3(FourierSeries), 4(Sampling), 5(FIR Filters) and 6(Frequency Response)

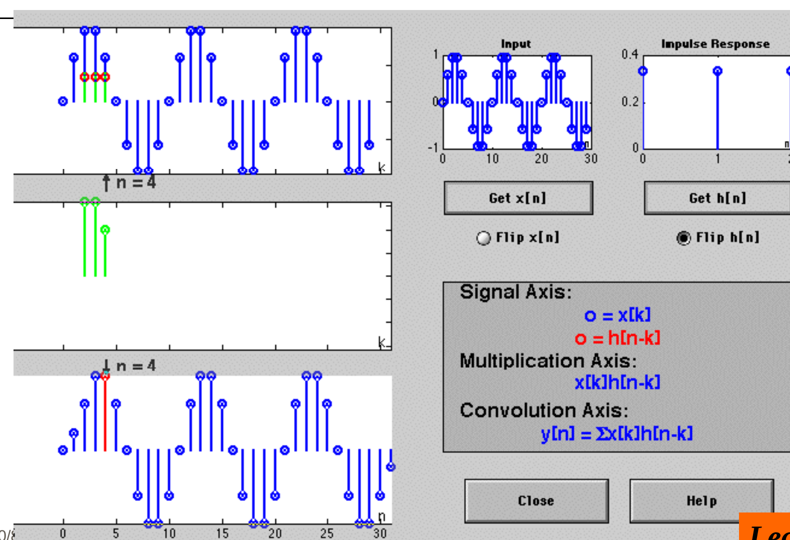
Lecture

Switching Lab Partners

- Choose a new partner
  - Must **change** partners
  - Starts with Lab #7 (week of 13-Oct)
- Fill out on-line form no later than Friday, 9-Oct
  - Go to **Quizzes/Tests** on t-square
  - Both partners must fill out the form
  - Both partners must be in the **same** lab section
- No chosen partner?
  - Then assignments will be made at random.

Lecture

DCONVDEMO: MATLAB GUI



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

MAG

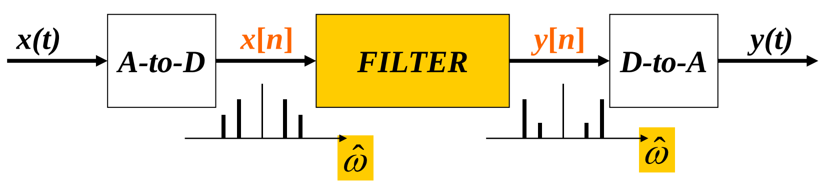
PHASE

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

DOMAINS: Time & Frequency

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

DIGITAL “FILTERING”



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

FILTERING EXAMPLE

- 7-point AVERAGER
  - Removes cosine
    - By making its amplitude (A) smaller

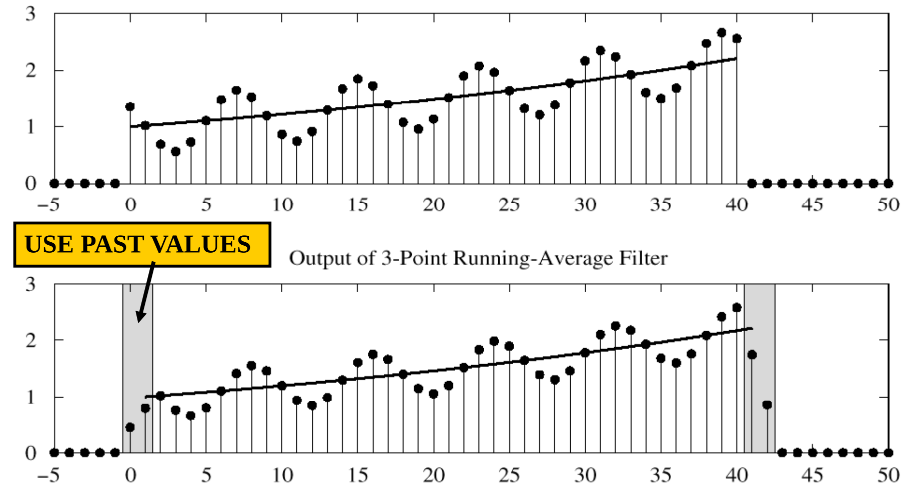
$$y_7[n] = \sum_{k=0}^{6} \left(\tfrac{1}{7}\right) x[n-k]$$

- 3-point AVERAGER
  - Changes A slightly

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

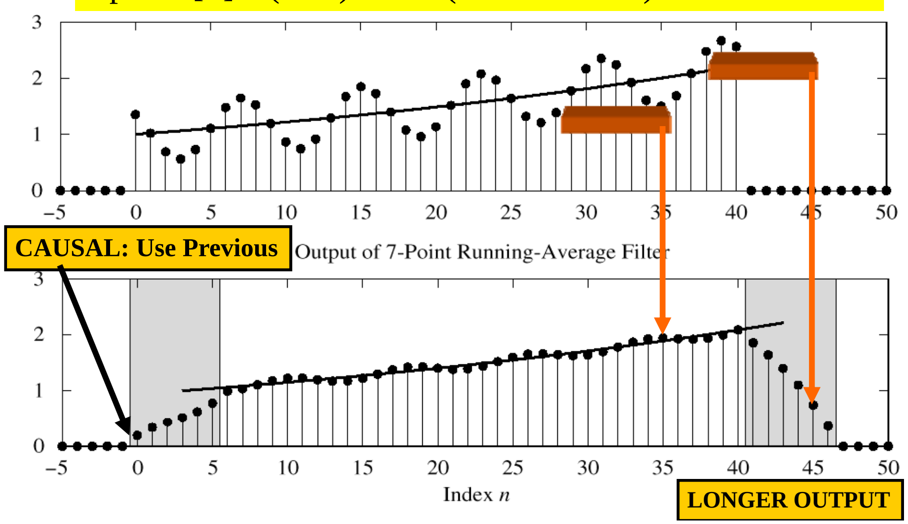
3-pt AVG EXAMPLE

$\text{Input}: x[n] = (1.02)^n + \cos(2\pi n/8 + \pi/4) \quad \text{for } 0 \le n \le 40$



7-pt FIR EXAMPLE (AVG)

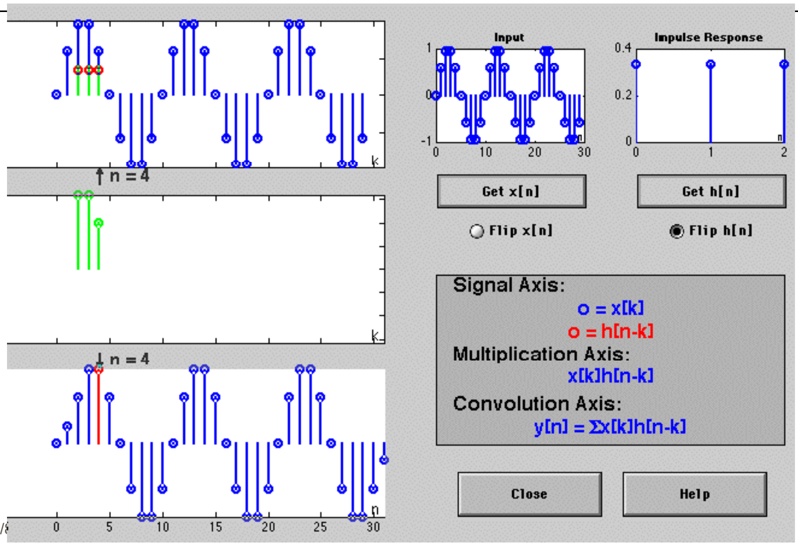
$\text{Input}: x[n] = (1.02)^n + \cos(2\pi n/8 + \pi/4) \quad \text{for } 0 \le n \le 40$



SINUSOIDAL RESPONSE

- 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**

DCONVDEMO: MATLAB GUI



COMPLEX EXPONENTIAL

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

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"

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

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

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

FREQUENCY RESPONSE

- At each frequency, we can DEFINE

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

FREQUENCY RESPONSE

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

EXAMPLE 6.1

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

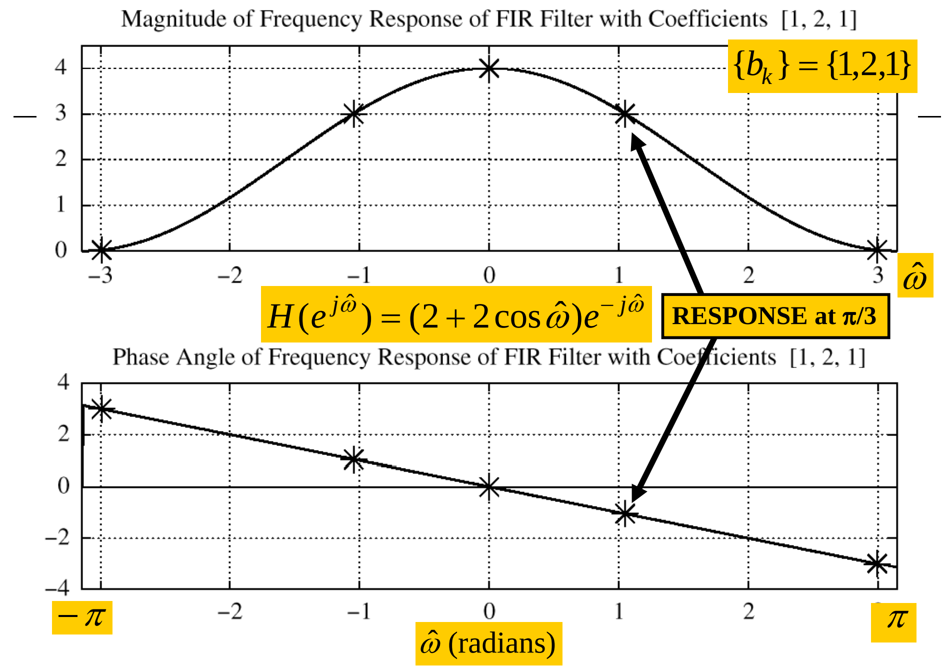
$$H(e^{j\hat{\omega}}) = 1 + 2e^{-j\hat{\omega}} + e^{-j2\hat{\omega}}$$
$$= e^{-j\hat{\omega}}(e^{j\hat{\omega}} + 2 + e^{-j\hat{\omega}})$$
$$= e^{-j\hat{\omega}}(2 + 2\cos\hat{\omega})$$

EXPLOIT SYMMETRY

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

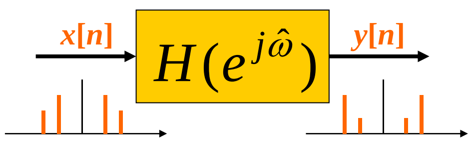
Magnitude is $\left|H(e^{j\hat{\omega}})\right| = (2 + 2\cos\hat{\omega})$

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



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 $\hat{\omega} = \pi/3$

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

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

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

EX: COSINE INPUT

Find $y[n]$ when $x[n] = 2\cos(\frac{\pi}{3}n + \frac{\pi}{4})$

$$2\cos(\tfrac{\pi}{3}n + \tfrac{\pi}{4}) = e^{j(\pi n/3+\pi/4)} + e^{-j(\pi n/3+\pi/4)}$$
$$\Rightarrow x[n] = x_1[n] + x_2[n]$$

Use Linearity

$$y_1[n] = H(e^{j\pi/3})e^{j(\pi n/3+\pi/4)}$$
$$y_2[n] = H(e^{-j\pi/3})e^{-j(\pi n/3+\pi/4)}$$
$$\Rightarrow y[n] = y_1[n] + y_2[n]$$

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

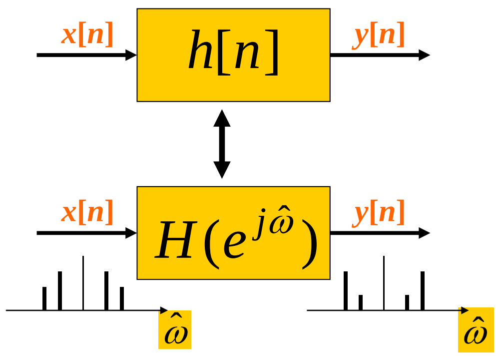
- Get Frequency Response from h[n]
  - Here is the FIR case:

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

IMPULSE RESPONSE

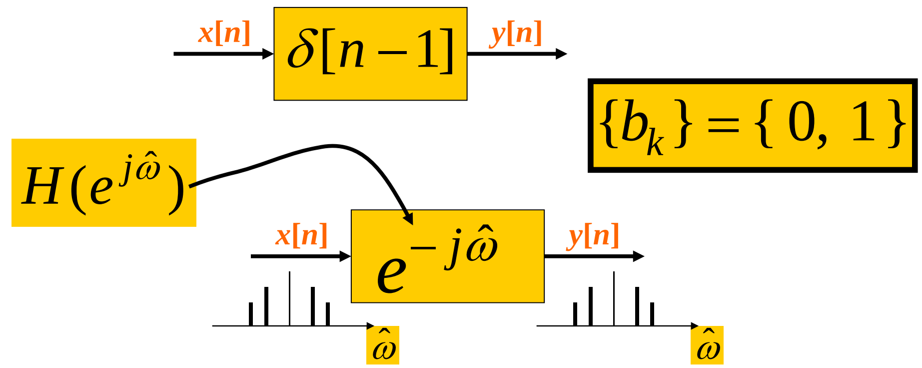
BLOCK DIAGRAMS

- Equivalent Representations



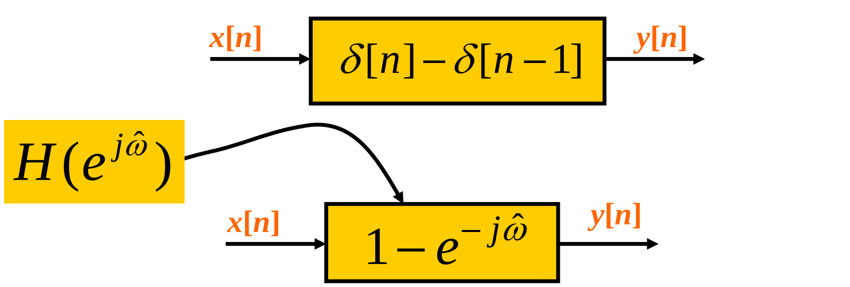
UNIT-DELAY SYSTEM

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

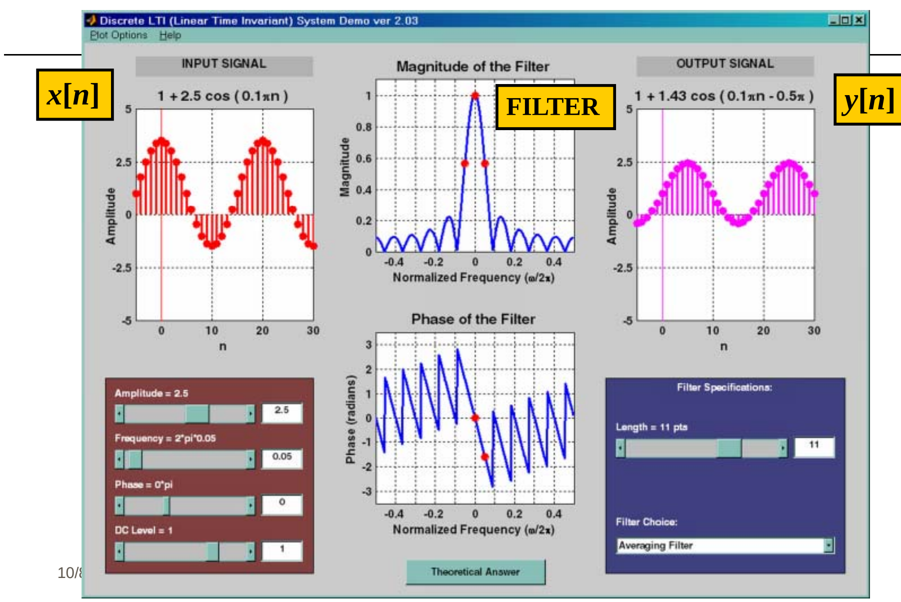


FIRST DIFFERENCE SYSTEM

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 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 ?

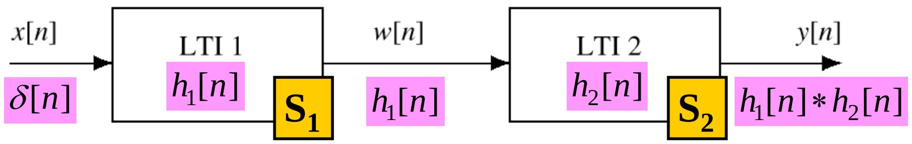


Figure 5.19 A Cascade of Two LTI Systems.

CASCADE EQUIVALENT

- MULTIPLY the Frequency Responses