Digital Signal Processing

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Lecture 14

Z Transforms: Introduction

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READING ASSIGNMENTS

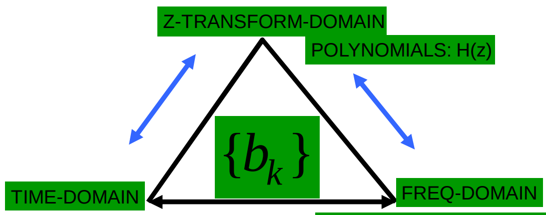
- This Lecture:
  - Chapter 7, Sects 7-1 through 7-5
- Other Reading:
  - Recitation: Ch. 7
    - CASCADING SYSTEMS
  - Next Lecture: Chapter 7, 7-6 to the end

LECTURE OBJECTIVES

- INTRODUCE the Z-TRANSFORM
  - Give Mathematical Definition
  - Show how the H(z) POLYNOMIAL simplifies analysis
    - **CONVOLUTION** is SIMPLIFIED !
- Z-Transform can be applied to
  - FIR Filter: $h[n] \rightarrow H(z)$
  - Signals: $x[n] \rightarrow X(z)$

$$H(z) = \sum_{n} h[n] z^{-n}$$

TWO (no, THREE) DOMAINS



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

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

Three main reasons for Z-Transform

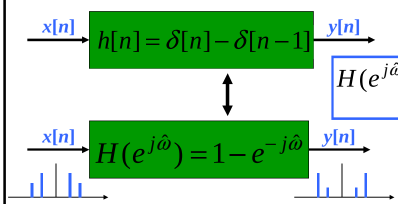
- Offers compact and convenient notation for describing digital signals and systems
- Widely used by DSP designers, and in the DSP literature
- Pole-zero description of a processor is a great help in visualizing its stability and frequency response characteristic

TRANSFORM CONCEPT

- Move to a new domain where
  - OPERATIONS are EASIER & FAMILIAR
  - Use POLYNOMIALS
- TRANSFORM both ways
  - $x[n] \rightarrow X(z)$ (into the z domain)
  - $X(z) \rightarrow x[n]$ (back to the time domain)

"TRANSFORM" EXAMPLE

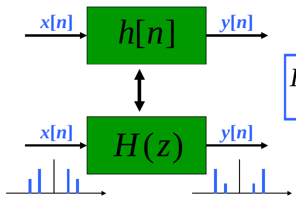
- Equivalent Representations



$$H(e^{j\hat{\omega}}) = \sum_n h[n] e^{-j\hat{\omega}n}$$

Z-TRANSFORM IDEA

- **POLYNOMIAL** REPRESENTATION



$$H(z) = \sum_n h[n] z^{-n}$$

Z-Transform DEFINITION

- POLYNOMIAL Representation of LTI SYSTEM: $H(z) = \sum_n h[n] z^{-n}$

APPLIES to Any SIGNAL

- EXAMPLE:

$\{h[n]\} = \{2, 0, -3, 0, 2\}$

$$H(z) = 2z^{-0} + 0z^{-1} - 3z^{-2} + 0z^{-3} + 2z^{-4}$$
$$= 2 - 3z^{-2} + 2z^{-4}$$
$$= 2 - 3(z^{-1})^2 + 2(z^{-1})^4$$

POLYNOMIAL in z^{-1}

Z-Transform EXAMPLE

- ANY SIGNAL has a z-Transform: $X(z) = \sum_n x[n] z^{-n}$

Example 7.1

n	$n < -1$	-1	0	1	2	3	4	5	$n > 5$
$x[n]$	0	0	2	4	6	4	2	0	0

$X(z) = ?$ $\quad X(z) = 2 + 4z^{-1} + 6z^{-2} + 4z^{-3} + 2z^{-4}$

Example 7.2

$X(z) = 1 - 2z^{-1} + 3z^{-3} - z^{-5}$

EXPONENT GIVES TIME LOCATION

$$x[n] = \begin{cases} 0 & n < 0 \\ 1 & n = 0 \\ -2 & n = 1 \\ 0 & n = 2 \\ 3 & n = 3 \\ 0 & n = 4 \\ -1 & n = 5 \\ 0 & n > 5 \end{cases}$$

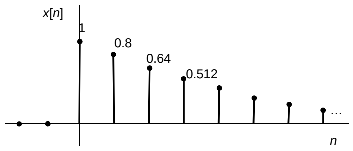
$x[n] = ?$

$$x[n] = \delta[n] - 2\delta[n-1] + 3\delta[n-3] - \delta[n-5]$$

13

Example

- Find the Z-Transform of the exponentially decaying signal shown in the following figure, expressing is as compact as possible.



14

- The Z-Transform of the signal:

$$X(z) = \sum_{n=0}^{\infty} x[n] z^{-n}$$
$$= 1 + 0.8z^{-1} + 0.64z^{-2} + 0.512z^{-3} + \cdots$$
$$= 1 + (0.8z^{-1}) + (0.64z^{-1})^2 + (0.512z^{-1})^3 + \cdots$$
$$= \frac{1}{1 - 0.8z^{-1}} = \frac{z}{z - 0.8}$$

15

Example

- Find and sketch, the signal corresponding to the Z-Transform:

$$X(z) = \frac{1}{z + 1.2}$$

16

- Recasting X(z) as a power series in z^{-1}, we obtain:

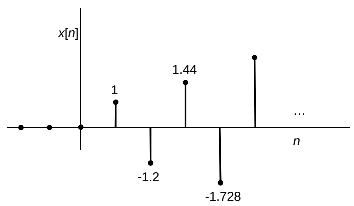
$$X(z) = \frac{1}{(z+1.2)} = \frac{z^{-1}}{(1+1.2z^{-1})} = z^{-1}(1+1.2z^{-1})^{-1}$$
$$= z^{-1}\{1 + (-1.2z^{-1}) + (-1.2z^{-1})^2 + (-1.2z^{-1})^3 + \cdots\}$$
$$= z^{-1} - 1.2z^{-2} + 1.44z^{-3} - 1.728z^{-4} + \cdots$$

- Succesive values of $x[n]$, starting at n=0, are therefore:

  0, 1, -1.2, 1.44, -1.728, $\cdots$

17

- $x[n]$ is shown in the following figure:



18

Z-Transform of FIR Filter

- CALLED the **SYSTEM FUNCTION**
  - $h[n]$ is same as $\{b_k\}$

SYSTEM FUNCTION

$$H(z)=\sum_{k=0}^{M} b_k z^{-k} = \sum_{k=0}^{M} h[k] z^{-k}$$

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

FIR DIFFERENCE EQUATION

CONVOLUTION

Z-Transform of FIR Filter

- Get $H(z)$ DIRECTLY from the $\{b_k\}$
- Example 7.3 in the book:

$$y[n]=6x[n]-5x[n-1]+x[n-2]$$

$$\{b_k\}=\{6,-5,1\}$$

$$H(z)=\sum b_k z^{-1} = 6-5z^{-1}+z^{-2}$$

Ex. DELAY SYSTEM

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

$x[n]$ → $\delta[n-1]$ → $y[n]=x[n-1]$

$$H(z)=\sum \delta[n-1] z^{-n} = z^{-1}$$

$x[n]$ → z^{-1} → $y[n]$

DELAY EXAMPLE

- UNIT DELAY: find $y[n]$ via polynomials
  - $x[n] = \{3,1,4,1,5,9,0,0,0,...\}$

$$Y(z)=z^{-1}X(z)$$

$$Y(z)=z^{-1}(3+z^{-1}+4z^{-2}+z^{-3}+5z^{-4}+9z^{-5})$$

$$Y(z)=0z^{0}+3z^{-1}+z^{-2}+4z^{-3}+z^{-4}+5z^{-5}+9z^{-6}$$

n	$n<0$	0	1	2	3	4	5	6	$n>6$
$y[n]$	0	0	3	1	4	1	5	9	0

DELAY PROPERTY

A delay of one sample multiplies the z-transform by z^{-1}.

$$x[n-1] \iff z^{-1}X(z)$$

Time delay of n_0 samples multiplies the z-transform by z^{-n_0}

$$x[n-n_0] \iff z^{-n_0}X(z)$$

GENERAL I/O PROBLEM

- Input is $x[n]$, find $y[n]$ (for FIR, $h[n]$)
- How to combine $X(z)$ and $H(z)$?

Example 7.5

$$x[n] = \delta[n-1]-\delta[n-2]+\delta[n-3]-\delta[n-4]$$

and $h[n] = \delta[n]+2\delta[n-1]+3\delta[n-2]+4\delta[n-3]$

$$X(z) = 0+1z^{-1}-1z^{-2}+1z^{-3}-1z^{-4}$$

and $H(z) = 1+2z^{-1}+3z^{-2}+4z^{-3}$

FIR Filter = CONVOLUTION

```
x[n], X(z)     0   +1   -1   +1   -1
h[n], H(z)     1    2    3    4
              -----------------------------------------
               0   +1   -1   +1   -1
                    0   +2   -2   +2   -2
                         0   +3   -3   +3   -3
                              0   +4   -4   +4   -4
              -----------------------------------------
 y[n], Y(z)    0   +1   +1   +2   +2   -3   +1   -4
```

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

CONVOLUTION

CONVOLUTION PROPERTY

- PROOF:

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

$$Y(z) = \sum_{k=0}^{M} h[k]\left(z^{-k}X(z)\right)$$

$$= \left(\sum_{k=0}^{M} h[k]z^{-k}\right) X(z) = H(z)X(z).$$

MULTIPLY Z-TRANSFORMS

CONVOLUTION EXAMPLE

- **MULTIPLY** the z-TRANSFORMS:

Example 7.5

$$x[n] = \delta[n-1] - \delta[n-2] + \delta[n-3] - \delta[n-4]$$

and $$h[n] = \delta[n] + 2\delta[n-1] + 3\delta[n-2] + 4\delta[n-3]$$

$$X(z) = 0 + 1z^{-1} - 1z^{-2} + 1z^{-3} - 1z^{-4}$$

and $$H(z) = 1 + 2z^{-1} + 3z^{-2} + 4z^{-3}$$

MULTIPLY *H(z)X(z)*

CONVOLUTION EXAMPLE

- Finite-Length input $x[n]$
- FIR Filter (L=4)

MULTIPLY Z-TRANSFORMS

$$Y(z) = H(z)X(z)$$

$$= (1 + 2z^{-1} + 3z^{-2} + 4z^{-3})(z^{-1} - z^{-2} + z^{-3} - z^{-4})$$

$$= z^{-1} + (-1+2)z^{-2} + (1-2+3)z^{-3} + (-1+2-3+4)z^{-4}$$

$$+ (-2+3-4)z^{-5} + (-3+4)z^{-6} + (-4)z^{-7}$$

$$= z^{-1} + z^{-2} + 2z^{-3} + 2z^{-4} - 3z^{-5} + z^{-6} - 4z^{-7}$$

y[*n*] = ?

CASCADE SYSTEMS

- Does the order of S_1 & S_2 matter?
  - NO, LTI SYSTEMS can be rearranged !!!
  - Remember: $h_1[n] * h_2[n]$
  - How to combine $H_1(z)$ and $H_2(z)$?

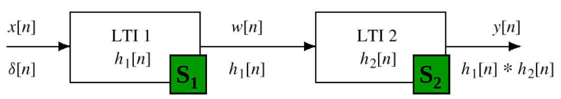
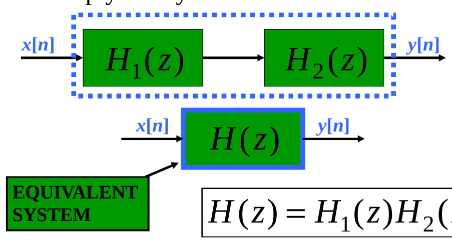


Figure 5.19 A Cascade of Two LTI Systems.

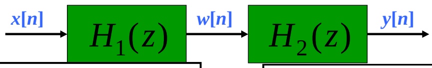
CASCADE EQUIVALENT

- Multiply the System Functions



$$H(z) = H_1(z)H_2(z)$$

CASCADE EXAMPLE



$$w[n] = x[n] - x[n-1]$$

$$y[n] = w[n] + w[n-1]$$

$$H_1(z) = 1 - z^{-1}$$

$$H_2(z) = 1 + z^{-1}$$

$$H(z) = (1 - z^{-1})(1 + z^{-1}) = 1 - z^{-2}$$

$$y[n] = x[n] - x[n-2]$$

31