

# ELC 4351: Digital Signal Processing

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## 1 Inverse Systems and Deconvolution

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- Deconvolution — The inverse system operation that takes  $y(n)$  and produces  $x(n)$ .
- System Identification — In short, to find  $h(n)$  or  $H(\omega)$ .

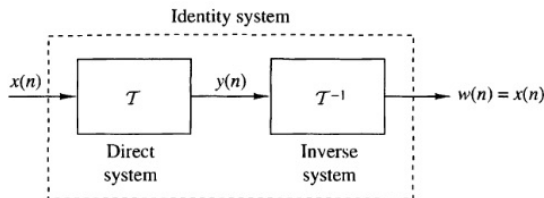
# Invertibility of Linear Time-Invariant Systems

A system is said to be *invertible* if there is a one-to-one correspondence between its input and output signals.

An invertible system:  $\mathcal{T}$

The inverse system:  $\mathcal{T}^{-1}$

$$w(n) = \mathcal{T}^{-1}[y(n)] = \mathcal{T}^{-1}\{\mathcal{T}[x(n)]\} = x(n)$$





# Invertibility of Linear Time-Invariant Systems

LTI system  $\mathcal{T}$  has impulse response  $h(n)$ ; the inverse system  $\mathcal{T}^{-1}$  has impulse response  $h_I(n)$ .

$$w(n) = h_I(n) \otimes h(n) \otimes x(n) = x(n)$$

$$h(n) \otimes h_I(n) = \delta(n)$$

$$H(z)H_I(z) = 1$$

Therefore,

$$H_I(z) = \frac{1}{H(z)}$$

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$$H_I(z) = \frac{1}{H(z)}$$

If  $H(z)$  has a rational system function

$$H(z) = \frac{B(z)}{A(z)}$$

then

$$H_I(z) = \frac{A(z)}{B(z)}$$

- The zeros of  $H(z)$  become the poles of the inverse system, and vice versa.
- If  $H(z)$  is an FIR system, then  $H_I(z)$  is an all-pole system, and vice versa.

# Invertibility of Linear Time-Invariant Systems

$$h(n) \otimes h_I(n) = \delta(n)$$

We assume that the system and its inverse are causal. Then this equation simplifies to

$$\sum_{k=0}^n h(k)h_I(n-k) = \delta(n)$$

For  $n = 0$ ,  $h_I(0) = 1/h(0)$ .

For  $n \geq 1$ ,  $h_I(n)$  can be obtained recursively

$$h_I(n) = \sum_{k=1}^n \frac{h(k)h_I(n-k)}{h(0)}, \quad n \geq 1$$

# Minimum-Phase, Maximum-Phase, and Mixed-Phase Systems

e.g.,

$$H_1(z) = 1 + \frac{1}{2}z^{-1}$$

$$H_2(z) = \frac{1}{2} + z^{-1}$$

$$|H_1(\omega)| = |H_2(\omega)| = \sqrt{\frac{5}{4} + \cos \omega}$$

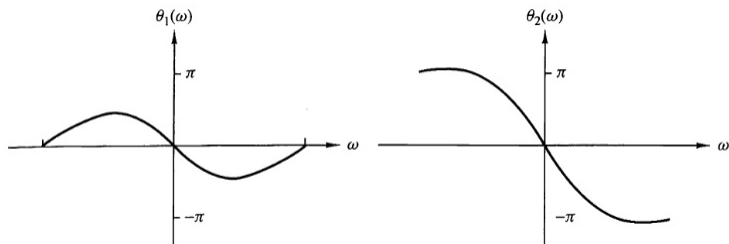
$$\angle H_1(\omega) = -\omega + \tan^{-1} \frac{\sin \omega}{0.5 + \cos \omega}$$

$$\angle H_2(\omega) = -\omega + \tan^{-1} \frac{\sin \omega}{2 + \cos \omega}$$

# Minimum-Phase, Maximum-Phase, and Mixed-Phase Systems

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Minimum-phase:  $\angle H(\pi) - \angle H(0) = 0$ ; Maximum-phase:  
 $\angle H(\pi) - \angle H(0) = \pi$ .

# Minimum-Phase, Maximum-Phase, and Mixed-Phase Systems

For an FIR system that has  $M$  zeros,

$$H(\omega) = b_0(1 - z_1 e^{-j\omega})(1 - z_2 e^{-j\omega}) \cdots (1 - z_M e^{-j\omega})$$

- When all zeros are inside the unit circle, Minimum-phase:  
 $\angle H(\pi) - \angle H(0) = 0$ ;
- When all zeros are outside the unit circle, Maximum-phase:  
 $\angle H(\pi) - \angle H(0) = M\pi$ .

If the FIR system with  $M$  zeros has some of its zeros inside the unit circle and the remaining zeros outside the unit circle, it is called a mixed-phase system or a nonminimum-phase system.

# Minimum-Phase, Maximum-Phase, and Mixed-Phase Systems

Since the derivative of the phase characteristic of the system is a measure of the time delay that signal frequency components undergo in passing through the system,

- a minimum-phase characteristic implies a minimum delay function;
- a maximum-phase characteristic implies that the delay characteristic is also maximum.

Because

$$|H(\omega)|^2 = H(z)H(z^{-1})|_{z=e^{j\omega}},$$

if we replace a zero  $z_k$  of the system by its inverse  $1/z_k$ , the magnitude characteristic of the system does not change.

Place zeros inside unit circle for minimum phase.

# Minimum-Phase, Maximum-Phase, and Mixed-Phase Systems

Extend to IIR systems that have rational system functions

$$H(z) = \frac{B(z)}{A(z)}$$

It is minimum-phase, if all its poles and zeros are inside the unit circle.

For a stable and causal system, the system is maximum phase if all the zeros are outside the unit circle.

- A stable pole-zero system that is minimum phase has a stable inverse which is also minimum phase. *Why?*
- Maximum-phase systems and mixed-phase systems result in unstable inverse systems.



# Decomposition of Nonminimum-phase Pole-zero Systems.

Any nonminimum-phase pole-zero system can be expressed as

$$H(z) = H_{min}(z)H_{ap}(z)$$

$H(z)$  is causal and stable.

$B(z) = B_1(z)B_2(z)$ , where  $B_1(z)$  has all its roots inside the unit circle,  $B_2(z)$  has all its roots outside the unit circle.

Then,

$$H_{min}(z) = \frac{B_1(z)B_2(z^{-1})}{A(z)}$$

$$H_{ap}(z) = \frac{B_2(z)}{B_2(z^{-1})}$$

$H_{ap}(z)$  is a stable, all-pass, maximum-phase system.

Group delay:  $\tau_g(\omega) = \tau_g^{min}(\omega) + \tau_g^{ap}(\omega)$

# System Identification and Deconvolution

$$y(n) = h(n) \otimes x(n)$$

$$H(z) = \frac{Y(z)}{X(z)}$$

The system can be identified uniquely if it is known causal.  
Alternatively, if the system is causal,

$$y(n) = \sum_{k=0}^n h(k)x(n-k), \quad n \geq 0$$

hence, recursively, we have

$$h(0) = \frac{y(0)}{x(0)}$$

$$h(n) = \frac{y(n) - \sum_{k=0}^{n-1} h(k)x(n-k)}{x(0)}, \quad n \geq 1$$

# System Identification and Deconvolution

The crosscorrelation method is an effective and practical method for system identification.

$$r_{yx}(m) = \sum_{k=0}^{\infty} h(k)r_{xx}(m-k) = h(m) \otimes r_{xx}(m)$$

$$S_{yx}(\omega) = H(\omega)S_{xx}(\omega) = H(\omega)|X(\omega)|^2$$

Therefore,

$$H(\omega) = \frac{S_{yx}(\omega)}{S_{xx}(\omega)} = \frac{S_{yx}(\omega)}{|X(\omega)|^2}$$