Xi'an Jiaotong-Liverpool University
西交利物浦大学

MEC208 Instrumentation and Control System

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Contents Covered in Exam

State Variable Models

Feedback Control System Characteristics

Time-Domain Performance of Feedback Control System

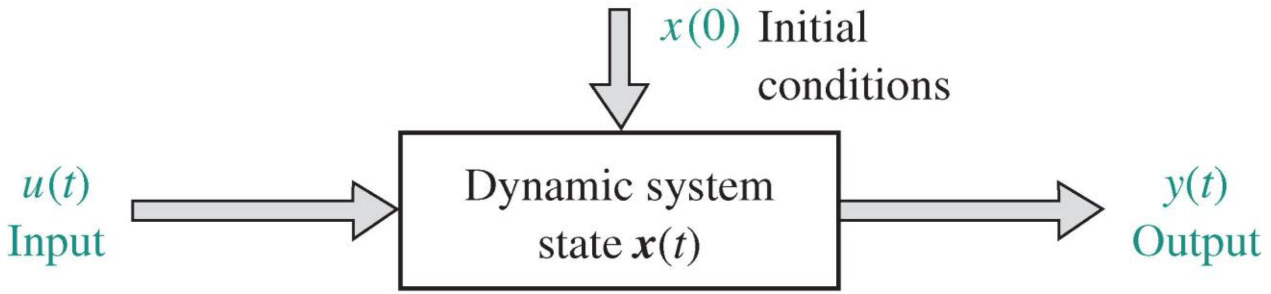
State Variable Models

- State Variables
- State-space Modeling
- State Space Representation in Matrix Form
- Time-domain response (Solution of State-space Models)
- Conversion between State-space Model and Transfer Function

State of a System

The **State** of a system is a set of variables whose values, together with the input signals and the equations describing the dynamics, will provide the future state and output of the system;

It is the <u>minimum information</u> needed about the system in order to determine its future behavior.



State variables: $[x_1(t), x_2(t), x_3(t), \dots x_n(t)]$ $\quad \boldsymbol{x}(t)$

Input signals: $[u_1(t), u_2(t), \dots u_m(t)]$ $\quad \boldsymbol{u}(t)$

Output signals: $[y_1(t), y_2(t), \dots y_p(t)]$ $\quad \boldsymbol{y}(t)$

State-space Modelling

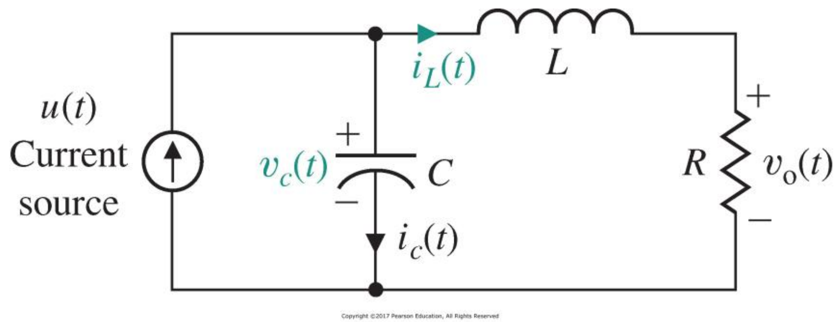
First-order linear differential equations:

$$\begin{cases} \dot{x}_1(t) = a_{11}x_1(t) + a_{12}x_2(t) + \cdots + a_{1n}x_n(t) + b_{11}u_1(t) + \cdots + b_{1m}u_m(t) \\ \dot{x}_2(t) = a_{21}x_1(t) + a_{22}x_2(t) + \cdots + a_{2n}x_n(t) + b_{21}u_1(t) + \cdots + b_{2m}u_m(t) \\ \vdots \\ \dot{x}_n(t) = a_{n1}x_1(t) + a_{n2}x_2(t) + \cdots + a_{nn}x_n(t) + b_{n1}u_1(t) + \cdots + b_{nm}u_m(t) \end{cases}$$

$$\begin{cases} y_1(t) = c_{11}x_1(t) + c_{12}x_2(t) + \cdots + c_{1n}x_n(t) + d_{11}u_1(t) + \cdots + d_{1m}u_m(t) \\ y_2(t) = c_{21}x_1(t) + c_{22}x_2(t) + \cdots + c_{2n}x_n(t) + d_{21}u_1(t) + \cdots + d_{2m}u_m(t) \\ \vdots \\ y_n(t) = c_{n1}x_1(t) + c_{n2}x_2(t) + \cdots + c_{nn}x_n(t) + d_{n1}u_1(t) + \cdots + d_{nm}u_m(t) \end{cases}$$

**note: boldface small letter: vector; boldface capital letter: matrix.*

Example 9.3 revisit



input: source current u(t)

output: resistor voltage v_o(t)

Ordinary Differential Equations:

$$i_c(t) = C\frac{dv_c}{dt} = u(t) - i_L(t)$$

$$L\frac{di_L}{dt} = -Ri_L(t) + v_c(t)$$

Output: $v_o(t) = Ri_L(t)$

- Choose variables, let $x_1(t) = v_c(t)$, $x_2(t) = i_L(t), y(t) = v_o(t)$

$$\frac{dx_1}{dt} = -\frac{1}{C}x_2(t) + \frac{1}{C}u(t)$$

$$\frac{dx_2}{dt} = \frac{1}{L}x_1(t) - \frac{R}{L}x_2(t)$$

$$y(t) = v_o(t) = Rx_2(t)$$

$\rightarrow$

$$\dot{x}_1 = -\frac{1}{C}x_2 + \frac{1}{C}u$$

$$\dot{x}_2 = \frac{1}{L}x_1 - \frac{R}{L}x_2$$

$$y = Rx_2$$

Process of State-space Modelling

Model the system by linear ordinary differential equations (ODEs)

Define a set of state variables

Substitute the state variables into the ODEs and rewrite ODEs into

Rewrite ODEs into a set of first order differential equations

Don’t forget about the output equations

For a system, the number of state variables required is equal to the number of independent energy-storage elements.

State-space Representation in Matrix Form

Linear first-order differential equations:

$$\dot{x}_1(t) = a_{11}x_1(t) + a_{12}x_2(t) + \cdots + a_{1n}x_n(t) + b_{11}u_1(t) + \cdots + b_{1m}u_m(t)$$

$$\dot{x}_2(t) = a_{21}x_1(t) + a_{22}x_2(t) + \cdots + a_{2n}x_n(t) + b_{21}u_1(t) + \cdots + b_{2m}u_m(t)$$

$$\vdots$$

$$\dot{x}_n(t) = a_{n1}x_1(t) + a_{n2}x_2(t) + \cdots + a_{nn}x_n(t) + b_{n1}u_1(t) + \cdots + b_{nm}u_m(t)$$

State Space Equations:

System matrix

$$\boxed{\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)}$$

Input matrix

Output matrix

$$\boxed{\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t)}$$

Feed-forward matrix

Dimensions: $\mathbf{x}(n \times 1), \mathbf{u}(m \times 1), \mathbf{y}(p \times 1); \mathbf{A}(n \times n), \mathbf{B}(n \times m), \mathbf{C}(p \times n), \mathbf{D}(p \times m).$

**note: boldface small letter: vector; boldface capital letter: matrix.*

Time-domain response

$$\boxed{\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)}$$

$$s\mathbf{X}(s) - \mathbf{x}(0) = \mathbf{A}\mathbf{X}(s) + \mathbf{B}\mathbf{U}(s),$$

$$\mathbf{X}(s) = [s\mathbf{I} - \mathbf{A}]^{-1}\mathbf{x}(0) + [s\mathbf{I} - \mathbf{A}]^{-1}\mathbf{B}\mathbf{U}(s)$$

State transition matrix

$$\boldsymbol{\Phi}(s) = [s\mathbf{I} - \mathbf{A}]^{-1}$$

Then:

$$\mathbf{x}(t) = \boldsymbol{\Phi}(t)\mathbf{x}(0) + \int_0^t \boldsymbol{\Phi}(t-\tau)\mathbf{B}\mathbf{u}(\tau)\, d\tau$$

If $\boldsymbol{u}(t) = 0$, then

unforced response $\mathbf{x}(t) = \boldsymbol{\Phi}(t)\mathbf{x}(0)$

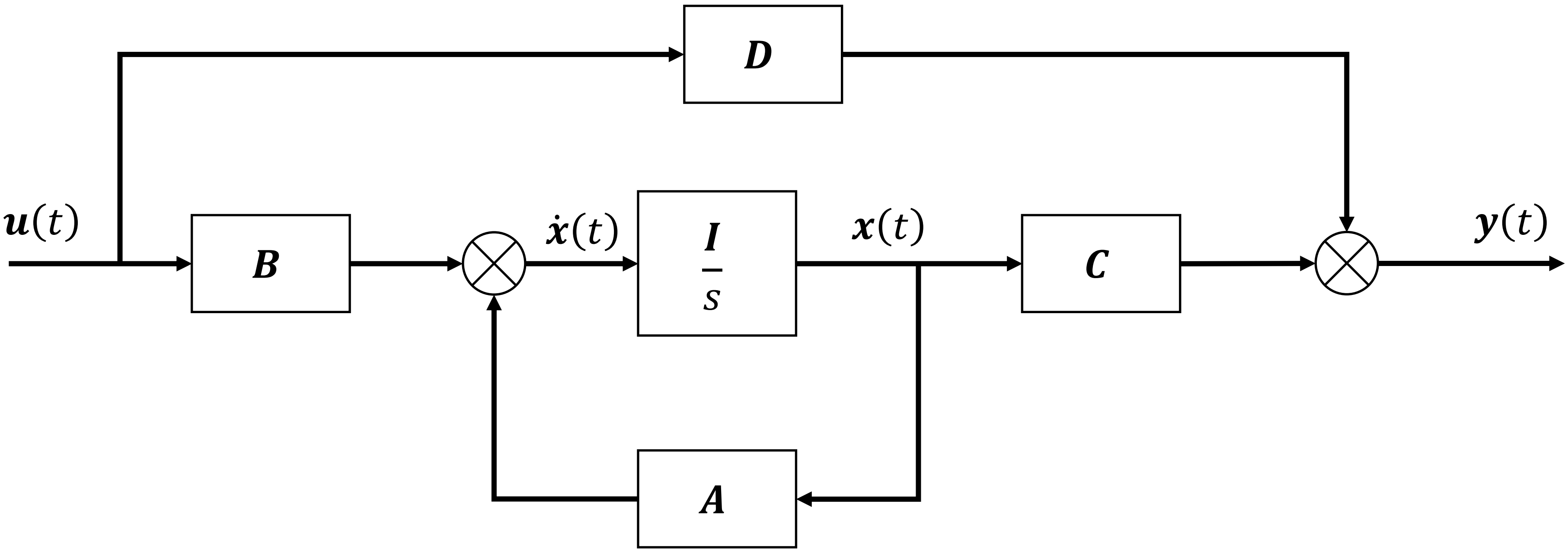
If $\boldsymbol{u}(t) \neq 0$, then

forced response $\mathbf{x}(t) = \boldsymbol{\Phi}(t)\mathbf{x}(0) + \int_0^t \boldsymbol{\Phi}(\tau)\mathbf{B}\mathbf{u}(t-\tau)\, d\tau$ Equivalent form

Covert State-space Model to Transfer Function

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)$$
$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t)$$

$$s\boldsymbol{X}(s) = \mathbf{A}\mathbf{X}(s) + \mathbf{B}\mathbf{U}(s)$$
$$\boldsymbol{Y}(s) = \mathbf{C}\mathbf{X}(s) + \mathbf{D}\mathbf{U}(s)$$



$$\mathbf{Y}(s) = (\mathbf{C}[s\mathbf{I} - \mathbf{A}]^{-1}\mathbf{B} + \mathbf{D})\mathbf{U}(s)$$

$$\mathbf{G}(s) = \mathbf{C}[s\mathbf{I} - \mathbf{A}]^{-1}\mathbf{B} + \mathbf{D}$$

Covert Transfer Function to State-space Model

Method 1: to develop graphic model of the system and use this model to determine state variables.

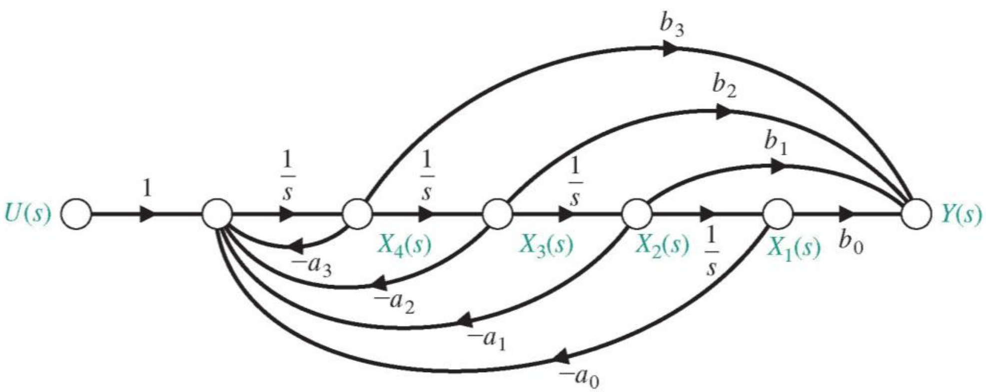
$$G(s)=\frac{Y(s)}{U(s)}=\frac{b_m s^m+b_{m-1}s^{m-1}+\cdots+b_1 s+b_0}{s^n+a_{n-1}s^{n-1}+\cdots+a_1 s+a_0}\quad n\ge m$$

Divided by s^n

$$G(s)=\frac{b_m s^{-(n-m)}+b_{m-1}s^{-(n-m+1)}+\cdots+b_1 s^{-(n-1)}+b_0 s^{-n}}{1+a_{n-1}s^{-1}+\cdots+a_1 s^{-(n-1)}+a_0 s^{-n}}$$

$$G(s)=\frac{b_3 s^3+b_2 s^2+b_1 s+b_0}{s^4+a_3 s^3+a_2 s^2+a_1 s+a_0}$$

$$=\frac{b_3 s^{-1}+b_2 s^{-2}+b_1 s^{-3}+b_0 s^{-4}}{1+a_3 s^{-1}+a_2 s^{-2}+a_1 s^{-3}+a_0 s^{-4}}.$$



$$\dot{x}_1=x_2$$
$$\dot{x}_2=x_3$$
$$\dot{x}_3=x_4$$
$$\dot{x}_4=-a_0x_1-a_1x_2-a_2x_3-a_3x_4+u$$
$$y=b_0x_1+b_1x_2+b_2x_3+b_3x_4$$

$$\boldsymbol{A}=\begin{bmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\-a_0&-a_1&-a_2&-a_3\end{bmatrix}\quad \boldsymbol{B}=\begin{bmatrix}0\\0\\0\\1\end{bmatrix}$$

$$\boldsymbol{C}=[b_0\quad b_1\quad b_2\quad b_3]\qquad \boldsymbol{D}=[0]$$

Covert Transfer Function to State-space Model

Method 2: State-space Model can be also obtained by introducing an intermediate variable $Z(s)$.

For simplicity, assume $n = 4$:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{b_3 s^3 + b_2 s^2 + b_1 s + b_0}{s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \frac{Z(s)}{Z(s)}$$

$$Y(s) = (b_3 s^3 + b_2 s^2 + b_1 s + b_0) Z(s)$$

$$U(s) = (s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0) Z(s)$$

Then taking inverse Laplace transform of both equations:

$$y = b_3 \frac{d^3 z}{dt^3} + b_2 \frac{d^2 z}{dt^2} + b_1 \frac{dz}{dt} + b_0 z$$

$$u = \frac{d^4 z}{dt^4} + a_3 \frac{d^3 z}{dt^3} + a_2 \frac{d^2 z}{dt^2} + a_1 \frac{dz}{dt} + a_0 z$$

Covert Transfer Function to State-space Model

$$y = b_3\frac{d^3z}{dt^3} + b_2\frac{d^2z}{dt^2} + b_1\frac{dz}{dt} + b_0z \qquad u = \frac{d^4z}{dt^4} + a_3\frac{d^3z}{dt^3} + a_2\frac{d^2z}{dt^2} + a_1\frac{dz}{dt} + a_0z.$$

Define the four state variables as follows:

$$\begin{aligned} x_1 &= z \\ x_2 &= \dot{x}_1 = \dot{z} \\ x_3 &= \dot{x}_2 = \ddot{z} \\ x_4 &= \dot{x}_3 = \dddot{z}. \end{aligned}$$

Then the differential equation can be written equivalently as

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= x_3, \\ \dot{x}_3 &= x_4, \end{aligned}$$

and

$$\dot{x}_4 = -a_0x_1 - a_1x_2 - a_2x_3 - a_3x_4 + u,$$

and the corresponding output equation is

$$y = b_0x_1 + b_1x_2 + b_2x_3 + b_3x_4.$$

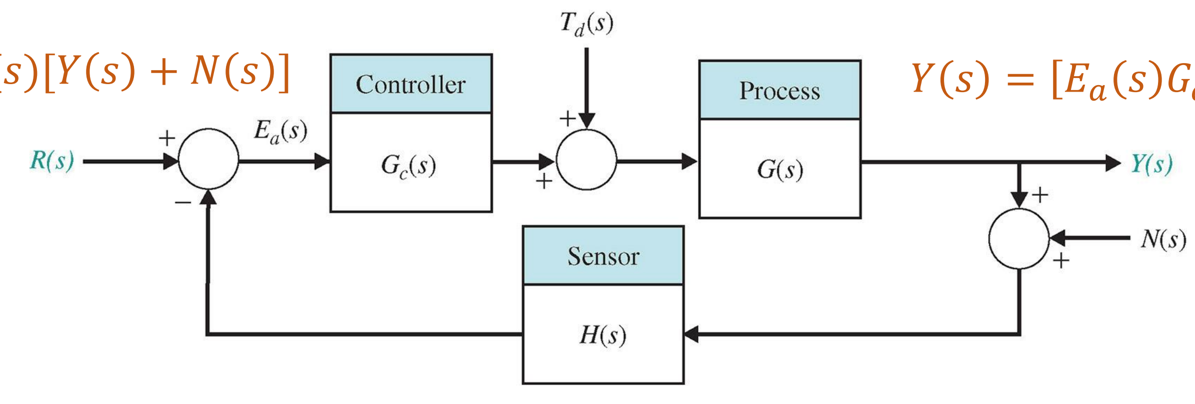
Method 3: Select state variable with physical meanings.

Feedback Control System Characteristics

- Error Signal Analysis
- Sensitivity of Control System to Parameter Variations
- Disturbance Rejection and Measurement Noise Attenuation
- Control of the Transient Response and Steady-state Error
- “Cost” of Feedback

Error Signal Analysis

$E_a(s) = R(s) - H(s)[Y(s) + N(s)]$



(b)

$Y(s) = [E_a(s)G_c(s) + T_d(s)]G(s)$

Tracking error definition: $E(s) = R(s) - Y(s)$

To facilitate our discussion, unity feedback system is assumed, i.e., $H(s) = 1$.

The output can be obtained from the block diagram:

$$Y(s) = \frac{G_c(s)G(s)}{1 + G_c(s)G(s)}R(s) + \frac{G(s)}{1 + G_c(s)G(s)}T_d(s) - \frac{G_c(s)G(s)}{1 + G_c(s)G(s)}N(s)$$

Therefore:

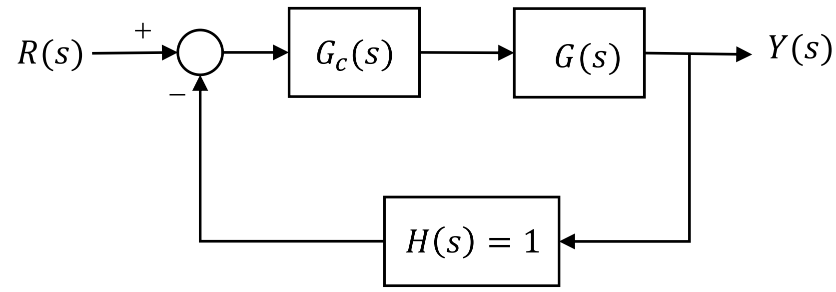
$$E(s) = R(s) - Y(s) = \frac{1}{1 + G_c(s)G(s)}R(s) - \frac{G(s)}{1 + G_c(s)G(s)}T_d(s) + \frac{G_c(s)G(s)}{1 + G_c(s)G(s)}N(s)$$

$$E(s) = \frac{1}{1 + L(s)}R(s) - \frac{G(s)}{1 + L(s)}T_d(s) + \frac{L(s)}{1 + L(s)}N(s)$$

where **loop gain** $L(s) = G_c(s)G(s)H(s) = G_c(s)G(s)$

Definition of System Sensitivity

By definition: $S = \dfrac{\partial T / T}{\partial G / G}$, where system transfer function $T(s) = \dfrac{Y(s)}{R(s)}$



In the limit, for small incremental changes:

$$S = \frac{\partial T / T}{\partial G / G} = \frac{\partial \ln T}{\partial \ln G}$$

System sensitivity is the ratio of the change in the system transfer function *T*(*s*) to the change of a process transfer function *G*(*s*) (or parameter) for a small incremental change.

Sensitivity for OL system: 1

Sensitivity for CL system: since $T(s) = \dfrac{G_c(s)G(s)}{1 + G_c(s)G(s)}$

$$S_G^T = \frac{\partial T \cdot G}{\partial G \cdot T} = \frac{G_c}{[1 + G_c G]^2} \cdot \frac{1 + G_c G}{G_c} \quad \rightarrow \quad S_G^T = \frac{1}{1 + G_c G}$$

To determine the influence of process parameter α (of $G(s)$), use chain rule:

$$S_\alpha^T = S_G^T \, S_\alpha^G$$

Disturbance Rejection

Feedback control reduces the negative effect of disturbance signals:

- A disturbance signal is an unwanted input signal that affects the output signal.
- Many control systems are subject to extraneous disturbance signals that cause the system to provide an inaccurate output.
  - Electronic amplifiers have inherent noise generated within the integrated circuits or transistors;
  - Radar antennas are subject to wind gusts;
  - Many systems generate unwanted distortion signals due to nonlinear elements.
- The benefit of feedback systems is that the effect of distortion, noise, and unwanted disturbances can be effectively reduced.

To analyze rejection of disturbance, assume $R(s) = N(s) = 0$.

$$E(s) = -S(s)G(s)T_d(s) = -\frac{G(s)}{1 + L(s)}T_d(s)$$

For a fixed $G(s)$ and a given $T_d(s)$, as the loop gain $L(s)$ increases, the effect of $T_d(s)$ on the tracking error decreases. For good disturbance rejection, we require a large loop gain over the frequencies of interest associated with the expected disturbance signals.

Measurement Noise Attenuation

A noise signal that is prevalent in many systems is the noise generated by the **measurement sensor.**

To analyze attenuation of measurement noise, assume $R(s) = T_d(s) = 0$.

$$E(s) = C(s)N(s) = \frac{L(s)}{1 + L(s)} N(s)$$

As the loop gain $L(s)$ decreases, the effect of $N(s)$ on the tracking error decreases. For effective measurement noise attenuation, we need a small loop gain over the frequencies associated with the expected noise signals.

How to realize disturbance rejection and measurement noise attenuation at the same time?

- In practice, disturbances are often at low frequencies, while measurement noise signals are often at high frequencies.
- Therefore, the controller should be of high gain at low frequencies and low gain at high frequencies.

Control of Transient Response

One of the most important characteristics of control systems is their **transient response**, which is a function of time.

Another purpose of control systems is to provide a desired satisfactory transient response:

- If an OL control system does not provide a satisfactory transient response, then the process, $G(s)$, may need to be replaced with a more suitable process;
- By contrast, a CL system can often be adjusted to yield the desired response by adjusting the feedback loop parameters (e.g., controller and feedback path parameters).

A feedback control system is valuable because it provides the engineer with the ability to **adjust/manipulate** the transient response.

Steady-state Error (and Output)

The **steady-state error (output)** is the error (output) value after the transient response has decayed, leaving only the continuous response.

Final Value Theorem (only for stable system):

$$\lim_{t\to\infty} e(t) = \lim_{s\to 0} sE(s)$$

Assume a unit step input as a comparable input ($r(t) = 1, t > 0; R(s) = \frac{1}{s}$):

Open-loop:

$$E_{OL}(s) = R(s) - Y(s) = \big(1 - G_c(s)G(s)\big)R(s)$$

$$e_{OL}(\infty) = \lim_{s\to 0} s\big(1 - G_c(s)G(s)\big)\left(\frac{1}{s}\right) = 1 - G_c(0)G(0)$$

To calculate **steady-state output** towards input *R*, simply use:

$$\lim_{t\to\infty} y(t) = \lim_{s\to 0} sY(s) = \lim_{s\to 0} sT_{CL}R(s)$$

Closed-loop (assume $T_d(s) = N(s) = 0$, and $H(s) = 1$):

$$E_{CL}(s) = \frac{1}{1 + G_c(s)G(s)}R(s)$$

$$e_{CL}(\infty) = \lim_{s\to 0} s\frac{1}{1+G_c(s)G(s)}\frac{1}{s} = \frac{1}{1+G_c(0)G(0)}$$

Large $L(0) = G_c(0)G(0)$ will lead to small steady-state error.

"Cost" of Feedback Control

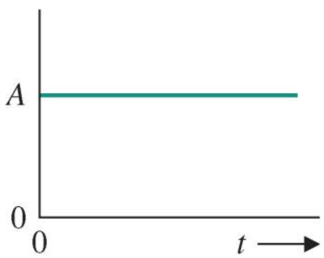
- **Increased number of components and complexity in the system.**
  - To add feedback, it is necessary to consider several "physical" feedback components, e.g. sensors. The sensor is often the most expensive component in a control system, which may introduce noise, inaccuracy, and robustness issues.
- **Loss of Gain.**
  - Loop gain: $G_c(s)G(s)$
  - Closed-loop gain: $\frac{G_c(s)G(s)}{1+G_c(s)G(s)}$
- **Introduction of the possibility of instability.**
  - Even if an open-loop system is stable, the closed-loop system may not be always stable (will be discussed in later chapters).

Time-Domain Performance of Feedback Control System

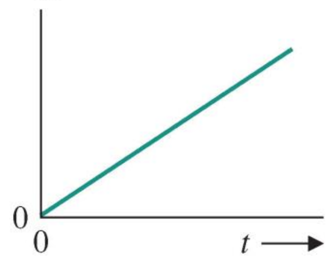
- Test Input Signals
- Performance of First-Order and Second-Order System
- Effects of a Third Pole and a Zero on the Second-Order System Response
- Pole Location on the s-plane and the Transient Response
- Steady-State Error of Feedback Control Systems

Test Input Signal in Time- and *s*-Domain

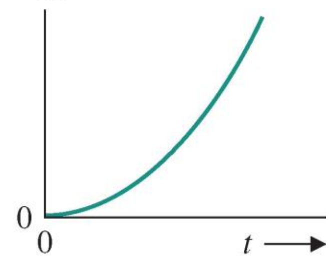
Step



Ramp



Parabolic



Unit impulse

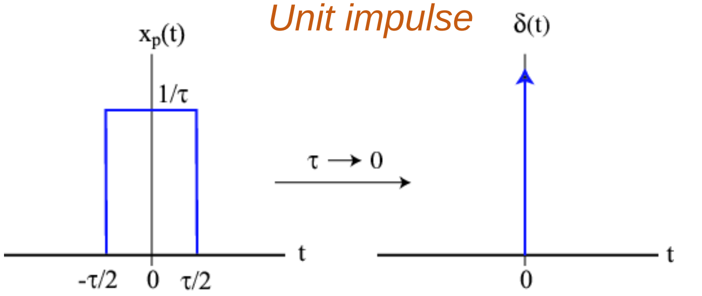


Table 5.1 Test Signal Inputs

Test Signal	$r(t)$	$R(s)$
Step	$r(t) = A, t > 0$ $= 0, t < 0$	$R(s) = A/s$
Ramp	$r(t) = At, t > 0$ $= 0, t < 0$	$R(s) = A/s^2$
Parabolic	$r(t) = At^2, t > 0$ $= 0, t < 0$	$R(s) = 2A/s^3$

$$r(t) = \delta(t)$$

$$\delta(t) = \begin{cases} 0, & t \neq 0 \\ +\infty, & t = 0 \end{cases}$$

$$R(s) = 1$$

Note: this is a continuous-time impulse.

First-order System: Unit-step Time Response

Normalized form $\dfrac{Y(s)}{R(s)} = \dfrac{1}{Ts+1}$

T - time constant

Unit-step time response

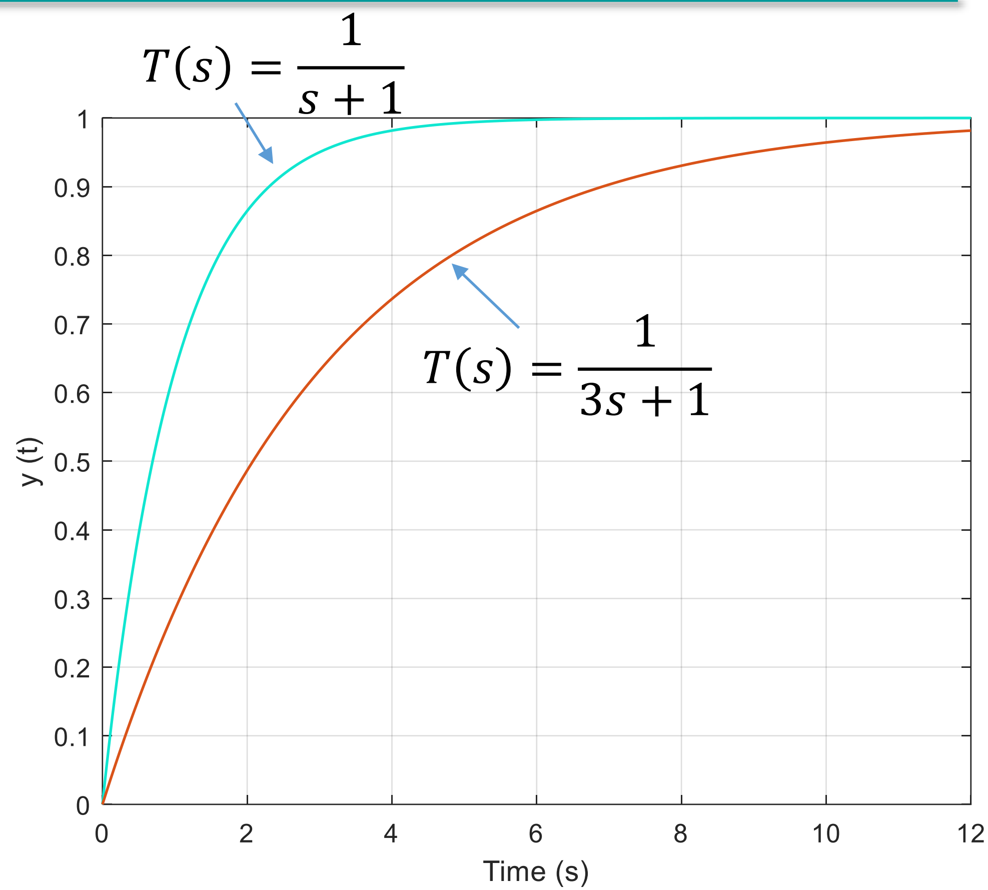
$$y(t) = 1 - e^{-t/T}$$

Time points of interest

$$y(T) = 0.632$$

$$y(3T) = 0.95$$

$$y(4T) = 0.982$$



Second-Order system

The **normalized form** is :

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

ω_n – Natural frequency

ζ – Damping ratio/coefficient

$\zeta > 1 \quad \textit{overdamped}$

$\zeta = 1 \quad \textit{critical damped}$

$\zeta < 1 \quad \textit{under damped}$

Unit-step time response:

$\zeta > 1$

$$y(t) = 1 - Ae^{-\frac{1}{T_1}t} - Be^{-\frac{1}{T_2}t}$$

One component can be ignored if T_1 and T_2 are far away enough to each other

$\zeta < 1$

$$\boxed{y(t) = 1 - e^{-\zeta\omega_n t}\left(\cos\sqrt{1-\zeta^2}\,\omega_n t + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin\sqrt{1-\zeta^2}\,\omega_n t\right)}$$

Second-Order system - under damped

$\zeta < 1$

$$y(t) = 1 - e^{-\zeta\omega_n t}\left(\cos\sqrt{1-\zeta^2}\,\omega_n t + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin\sqrt{1-\zeta^2}\,\omega_n t\right)$$

Peak Time:

$$T_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}}$$

Rise Time:

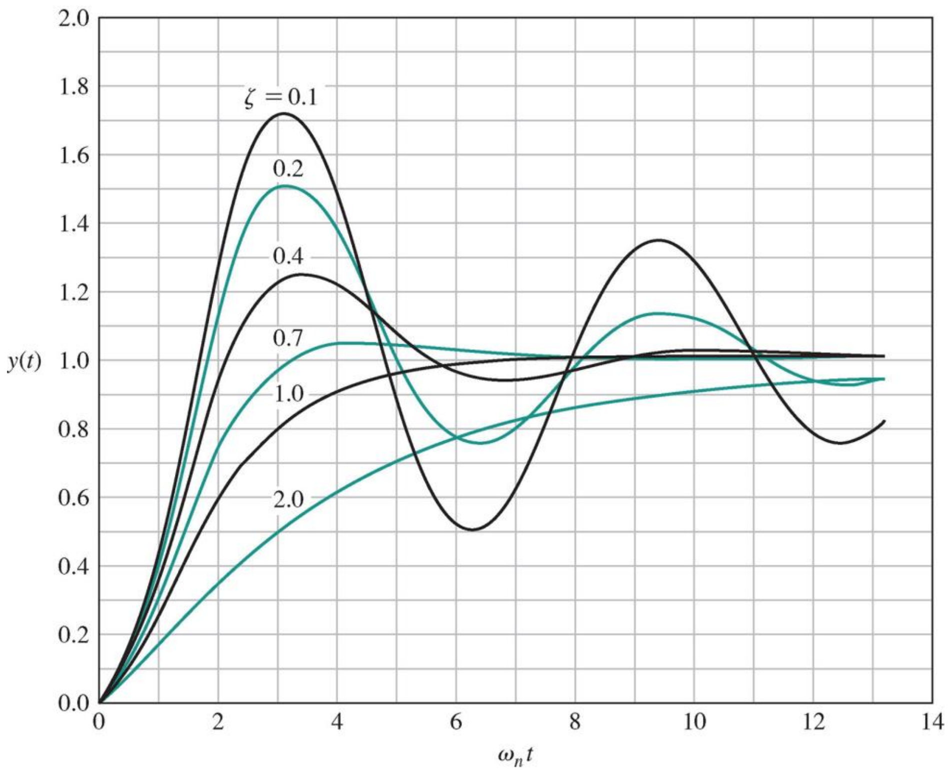
$$T_{r1} = \frac{2.16\zeta + 0.60}{\omega_n} \quad (0.3 < \zeta < 0.8)$$

2% Settling Time:

$$\boxed{T_s = \frac{4}{\zeta\omega_n}}$$

Percent Overshoot:

$$\boxed{P.O. = 100e^{-\zeta\pi/\sqrt{1-\zeta^2}}}$$

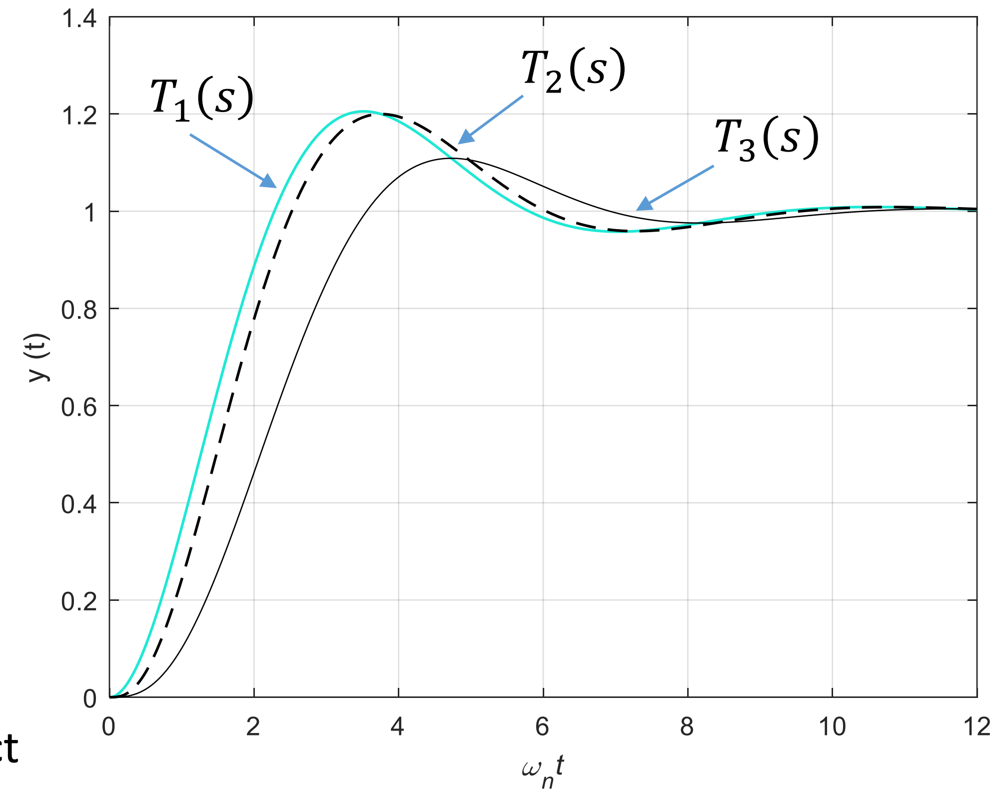


Additional pole – Underdamped Second-Order system

$$T_1(s) = \frac{1}{s^2 + 0.9s + 1}$$

$$T_2(s) = \frac{1}{(s^2 + 0.9s + 1)(0.22s + 1)}$$

$$T_3(s) = \frac{1}{(s^2 + 0.9s + 1)(s + 1)}$$

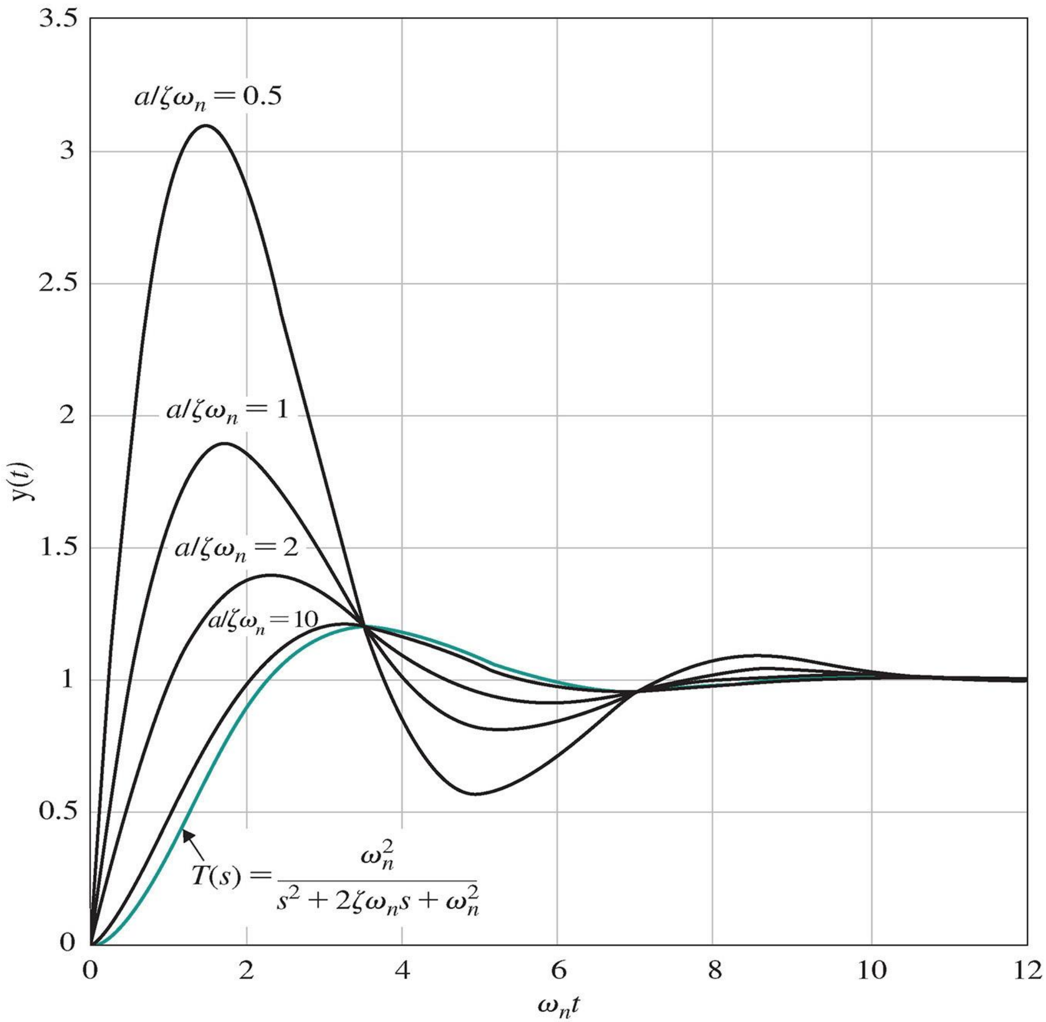


- Additional pole to the second-order system results in small overshoot and larger peak time
- If the pole's real part is faraway from the real part of original poles, the effect is minor and can be neglected

Additional zero – Underdamped Second-Order system

$$T(s) = \frac{\frac{{\omega_n}^2}{a}(s+a)}{s^2 + 2\zeta\omega_n s + {\omega_n}^2}$$

- Additional zero to the second-order system results in larger overshoot and smaller peak time
- If the zero's real part is faraway from the real part of original poles, the effect is minor and can be neglected

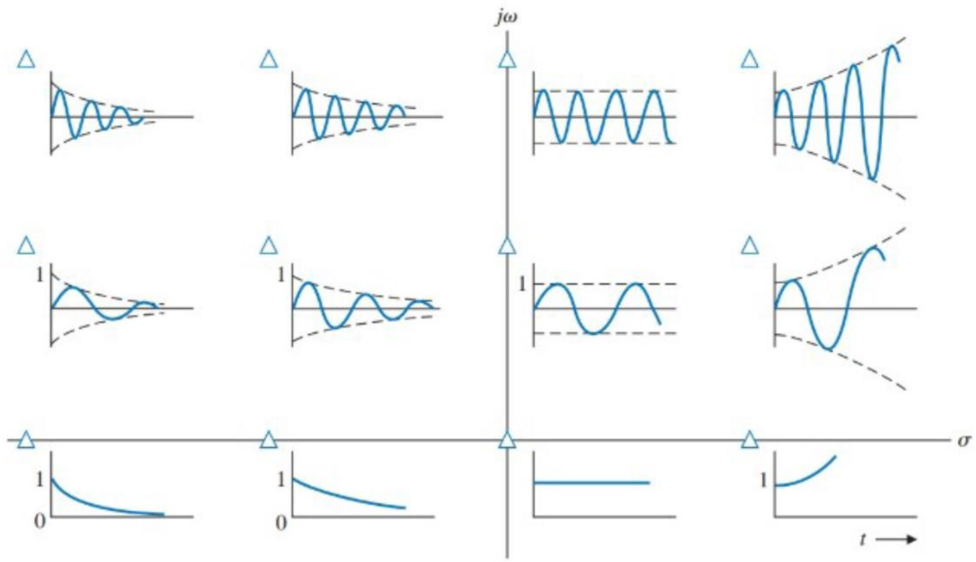


Higher-order system – Unit-step Response

If the system (with DC gain = 1) has no repeated roots, its unit step response can be formulated as a partial fraction expansion as:

$$Y(s) = \frac{1}{s} + \sum_{i=1}^{M} \frac{A_i}{s+\sigma_i} + \sum_{K=1}^{N} \frac{B_k s + C_k}{s^2 + 2\alpha_k s + ({\alpha_k}^2 + {\omega_k}^2)}$$

$$y(t) = 1 + \sum_{i=1}^{M} A_i e^{-\sigma_i t} + \sum_{k=1}^{N} D_k e^{-\alpha_k t} \sin(\omega_k t + \theta_k)$$



Steady-State Error

$$e_{ss} = \lim_{s\to 0} s \frac{A/s}{1 + G_c(s)G(s)} = \frac{A}{1 + \lim_{s\to 0} G_c(s)G(s)}$$

$$G_c(s)G(s) = \frac{K\prod_{i=1}^{M}(s+z_i)}{s^{N}\prod_{k=1}^{Q}(s+p_k)}$$

The number of integration indicates a system with **type number** that is equal to ***N***, which determines the steady-state error of the system.

Table 5.2 Summary of Steady-State Errors

Number of Integrations in $G_c(s)G(s)$, Type Number	Input		
	Step, $r(t) = A$, $R(s) = A/s$	Ramp, $r(t) = At$, $R(s) = A/s^2$	Parabola, $r(t) = At^2/2$, $R(s) = A/s^3$
0	$e_{ss} = \frac{A}{1+K_p}$	∞	∞
1	$e_{ss} = 0$	$\frac{A}{K_v}$	∞
2	$e_{ss} = 0$	0	$\frac{A}{K_a}$

Good luck with your exam

Office hour: 2-4 pm Thursday SC554E