Advanced Automatic Control
MDP 444

"If you have a smart project, you can say "I'm an engineer""

Lecture 5

Staff boarder

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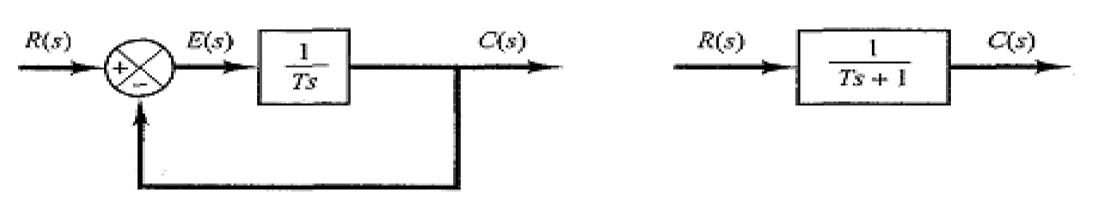
- **Lecture aims:**
  - Be familiar with the design formulas that relate the second-order pole locations to percent overshoot, settling time, rise time, and time to peak
  - Understand the concept of stability of dynamic systems

Time Response

- **Time response**
- Consider the first-order system. Physically, this system may represent an *RC* circuit, thermal system, or the like. A simplified block diagram is shown in Figure. The input-output relationship is given by

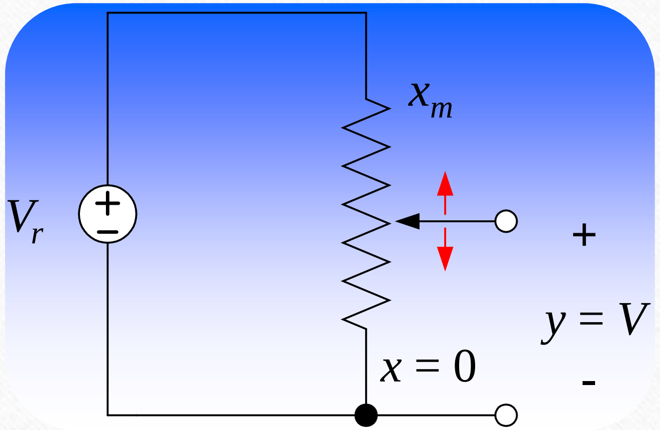
$$\frac{C(s)}{R(s)} = \frac{1}{Ts + 1}$$



- In the following, we shall analyze the system responses to such inputs as the unit-step, unit-ramp, and unit-impulse functions. The initial conditions are assumed to be zero.

Zero-order Systems

The behavior is characterized by its static sensitivity, K and remains constant regardless of input frequency (ideal dynamic characteristic).



A linear potentiometer used as position sensor is a zero-order sensor.

$$a_0 y(t) = b_0 x(t) \longrightarrow y(t) = Kx(t)$$

where K = static sensitivity = b_0/a_0

All the a's and b's other than a_0 and b_0 are zero.

$$V = V_r \cdot \frac{x}{x_m} \quad \text{here, } K = V_r / x_m$$

Where $0 \leq x \leq x_m$ and V_r is a reference voltage

First-Order Systems

All the a's and b's other than a_1, a_0 and b_0 are zero.

$$a_1 \frac{dy(t)}{dt} + a_0 = b_0 x(t)$$

$$\boxed{\tau \frac{dy(t)}{dt} + y(t) = Kx(t)} \quad \Longleftrightarrow \quad \boxed{\frac{y}{x}(S) = \frac{K}{\tau S + 1}}$$

Where $K = b_0/a_0$ is the static sensitivity

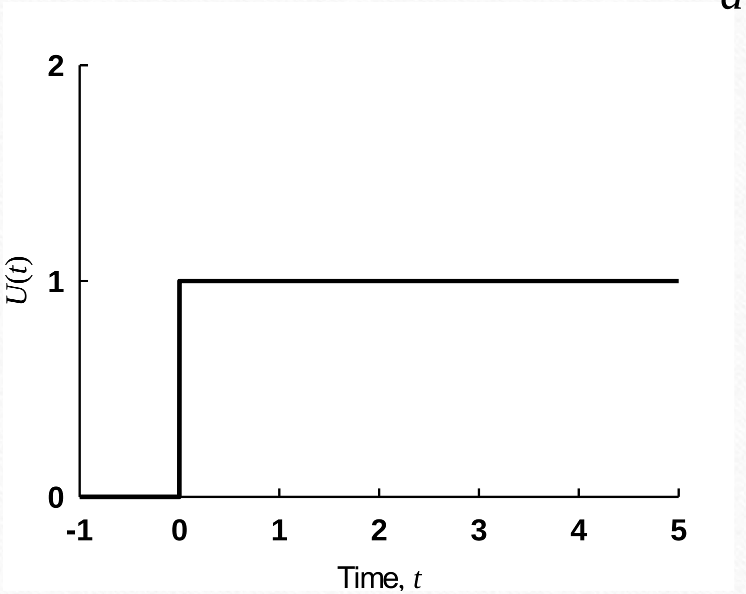
$\tau = a_1/a_0$ is the system's time constant (dimension of time)

First-Order Systems: Step Response

Assume for $t < 0$, $y = y_0$, at time = 0 the input quantity, x increases instantly by an amount A. Therefore $t > 0$

$$\tau \frac{dy(t)}{dt} + y(t) = KAU(t)$$

$$x(t) = AU(t) = \begin{cases} 0 & t \le 0 \\ A & t > 0 \end{cases}$$



The complete solution: $$\boxed{y(t) = \underbrace{Ce^{-t/\tau}}_{y_{ocf}} + \underbrace{KA}_{y_{opi}}}$$

y_{ocf} **Transient response**

y_{opi} **Steady state response**

Applying the initial condition, we get $C = y_0 - KA$, thus gives

$$\boxed{y(t) = KA + (y_0 - KA)e^{-t/\tau}}$$

Time Response

- **Unit-Step Response of First-Order Systems.**

Since the Laplace transform of the unit-step function is l/s, substituting R(s) = 1/s into Equation

$$\frac{C(s)}{R(s)} = \frac{1}{Ts+1} \qquad C(s) = \frac{1}{Ts+1}\frac{1}{s}$$

Expanding C(s)into partial fractions gives

$$C(s) = \frac{1}{s} - \frac{T}{Ts+1} = \frac{1}{s} - \frac{1}{s+(1/T)}$$

Taking the inverse Laplace transform of Equation (5-2), we obtain

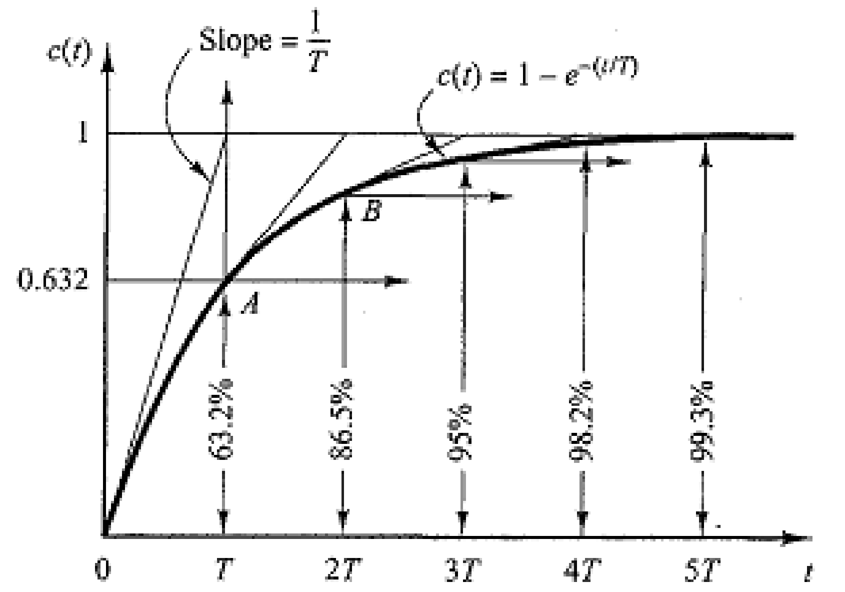
$$c(t) = 1 - e^{-t/T}, \qquad \text{for } t \geq 0$$

Time Response

- **Unit-Step Response of First-Order Systems.**

One important characteristic of such an exponential response curve c(t)is that at t = T the value of c(t)is 0.632,or the response c(t)has reached 63.2% of its total change

$$c(T) = 1 - e^{-1} = 0.632$$



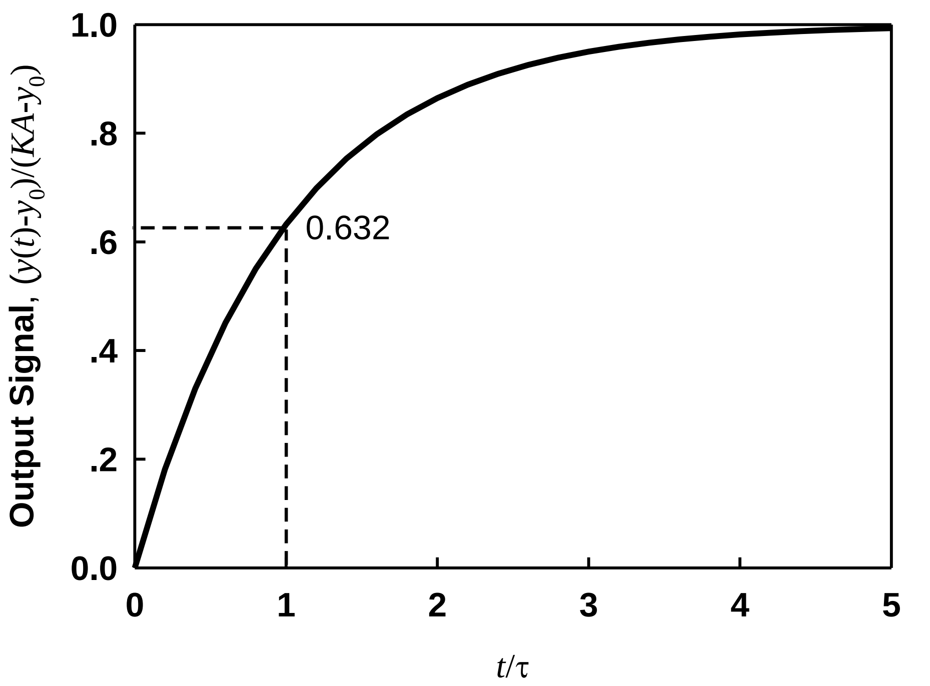
Time constant : T

Note that the smaller the time constant *T* ,the faster the system response.

First-Order Systems: Step Response

Non-dimensional step response of first-order instrument

$$\frac{y(t) - y_0}{KA - y_0} = 1 - e^{-t/\tau}$$



Time Response

- **Unit-Ramp Response of First-Order Systems.**

Since the Laplace transform of the unit-ramp function is l/s2, we obtain the output of the system

$$C(s) = \frac{1}{Ts + 1} \frac{1}{s^2}$$

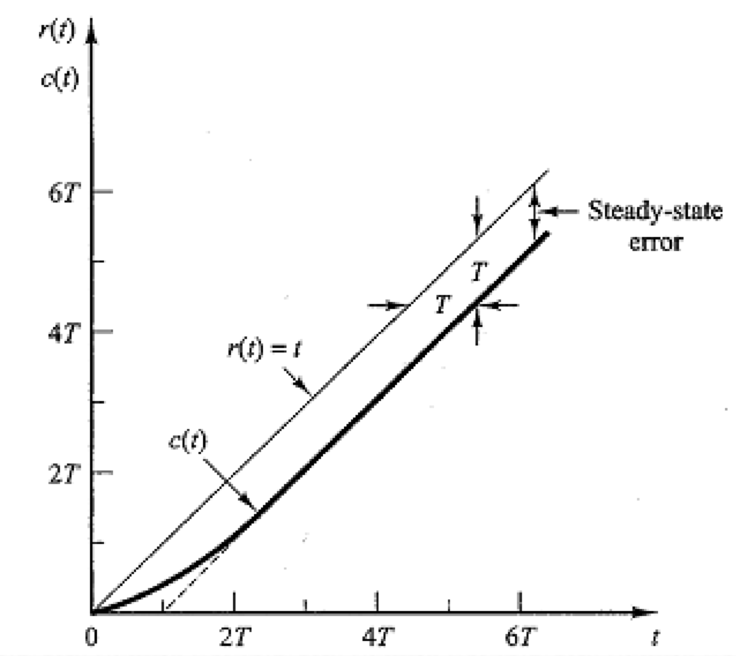
- Expanding C(s) into partial fractions gives

$$C(s) = \frac{1}{s^2} - \frac{T}{s} + \frac{T^2}{Ts + 1}$$

- Taking the inverse Laplace transform of Equation, we obtain

$$c(t) = t - T + Te^{-t/T}, \quad \text{for } t \geq 0$$

- The smaller the time constant T, the smaller the steady-state error in following the ramp input



Time Response

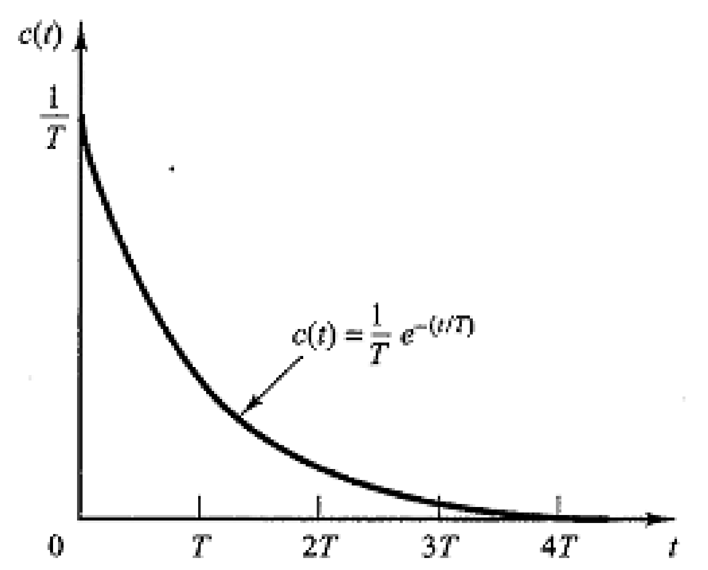
- **Unit-Impulse Response of First-Order Systems.**

For the unit-impulse input, *R(s)*= 1and the output of the system can be obtained as

$$C(s) = \frac{1}{Ts + 1}$$

- The inverse Laplace transform of Equation gives, and The response curve given by Equation is shown in Figure

$$c(t) = \frac{1}{T} e^{-t/T}, \qquad \text{for } t \geq 0$$



Time Response

- **Important Property of Linear Time-Invariant Systems.**
- In the analysis above, it has been shown that for the unit-ramp input the output *c (t)* is

$$c(t) = t - T + Te^{-t/T}, \qquad \text{for } t \geq 0$$

- For the **unit-step** input, which is the **derivative** of **unit-ramp** input, the output *c (t)* is

$$c(t) = 1 - e^{-t/T}, \qquad \text{for } t \geq 0$$

- Finally, for the **unit-impulse** input, which is the **derivative** of **unit-step** input, the output *c (t)* is

$$c(t) = \frac{1}{T} e^{-t/T}, \qquad \text{for } t \geq 0$$

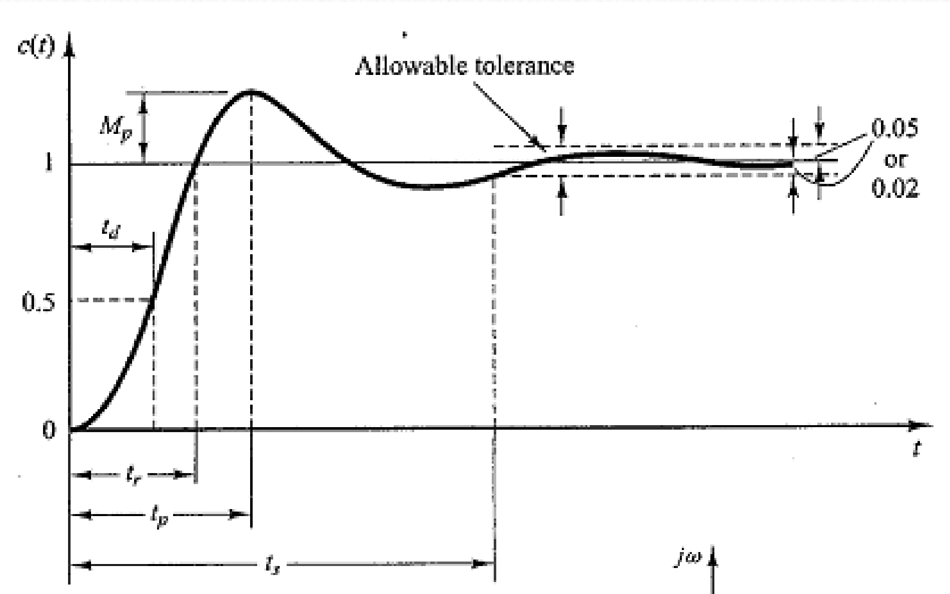
Time Response

Second-order systems

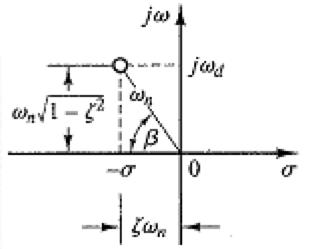
Frequently, the performance characteristics of a control system are specified in terms of the transient response to a unit-step input

1. **Delay** time, **td**: The delay time is the time required for the response to reach half the final value the very first time. Since the peak time corresponds to the first peak overshoot,

2. **Rise** time, **t***r:* The rise time is the time required for the response to rise from 10% to 90%, 5% to 95%,or 0% to 100% of its final value. the 10%to 90%rise time is commonly used. Clearly, for a small value of *tr,* ω_n must be large.



$$t_r = \frac{\pi - \beta}{\omega_d}$$



Time Response

Second-order systems

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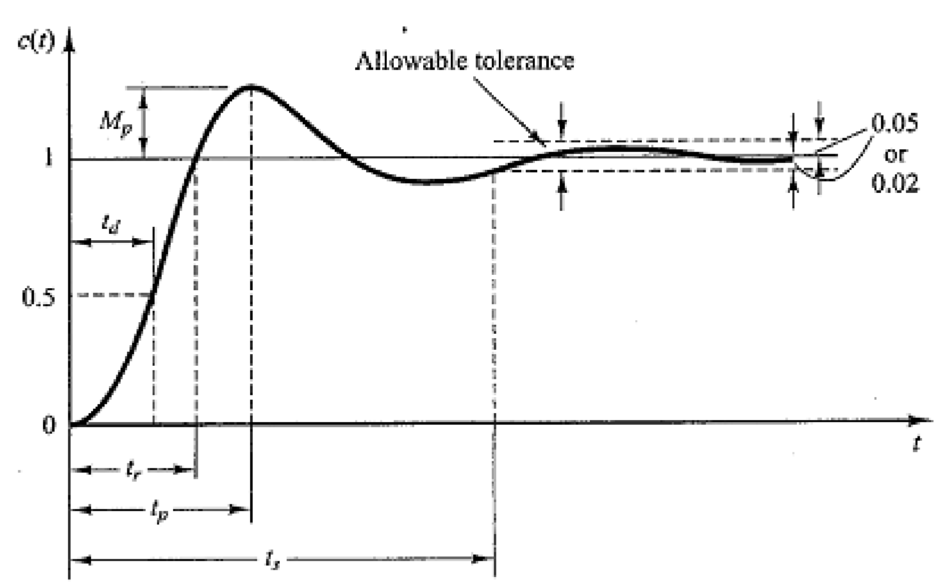


3. **Peak** time, **tp**: The peak time is the time required for the response to reach the first peak of the overshoot. $t_p = \dfrac{\pi}{\omega_d}$
4. **Maximum** (percent) **overshoot**, **Mp**: The maximum overshoot is the maximum peak value of the response curve measured from unity. $M_p \;\; e^{-(\zeta/\sqrt{1-\zeta^2})\pi}$
5. **Settling** time, ***ts:*** The settling time is the time required for the response curve to reach and stay within a range about the final value. The settling time corresponding to ±2% or ± *5%* tolerance band may be measured in terms of the time constant $T = 1/\zeta\omega_n$

$$t_s = 4T = \frac{4}{\sigma} = \frac{4}{\zeta\omega_n} \quad \text{(2\% criterion)}$$

$$t_s = 3T = \frac{3}{\sigma} = \frac{3}{\zeta\omega_n} \quad \text{(5\% criterion)}$$

Time Response

Second-order systems

Case 1 $(\zeta = 0)$

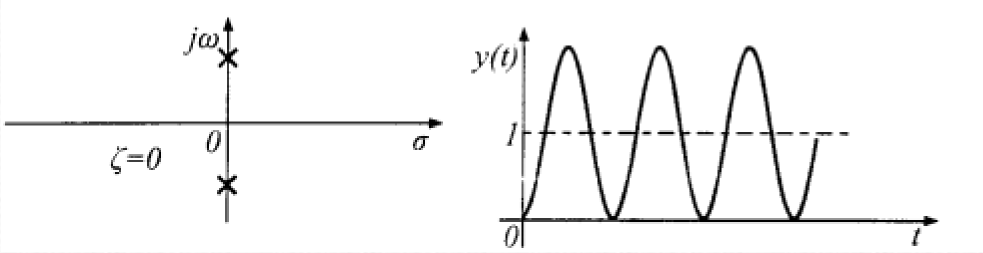
In this case the poles of G(s) are imaginary since $s_{1,2} = \pm j\omega_n$, and relation becomes

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

If we expand Y(s) in partial fractions, we have

$$Y(s) = \frac{1}{s} - \frac{s}{s^2 + \omega_n^2}, \qquad \text{and thus } y(t) = 1 - \cos \omega_n t$$

observe that the response y(t) is a sustained oscillation with constant frequency to ω_n and constant amplitude equal to 1. In this case, we say that the system is undamped



$$\sigma = \omega_n \zeta \text{ and } \omega_d = \omega_n \sqrt{1 - \zeta^2}$$

are called the attenuation or damping constant and the damped natural frequency of the system, respectively

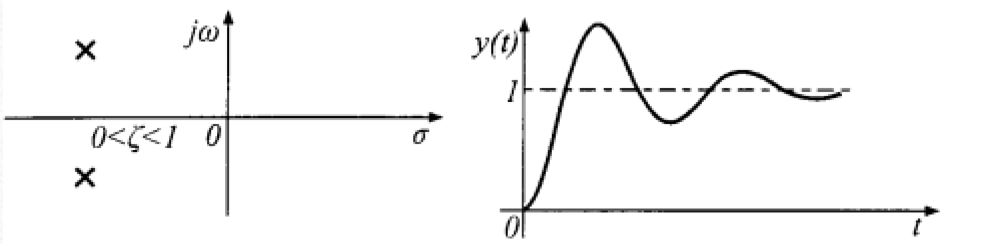
Time Response

Second-order systems

Case 2 $(0 < \zeta < 1)$

In this case the poles of G(s) are a complex conjugate pair since $s_{1,2} = -\sigma \pm j\omega_d$

, and relation becomes $$Y(s) = \frac{\omega_n^2}{s[(s+\sigma)^2 + \omega_d^2]}$$



$$\sigma = \omega_n \zeta \text{ and } \omega_d = \omega_n \sqrt{1-\zeta^2}$$

are called the attenuation or damping constant and the damped natural frequency of the system, respectively

If we expand Y(s) in partial fractions, we have

$$Y(s) = \frac{1}{s} - \frac{s+2\sigma}{(s+\sigma)^2+\omega_d^2} = \frac{1}{s} - \frac{s+\sigma}{(s+\sigma)^2+\omega_d^2} - \left[\frac{\sigma}{\omega_d}\right]\left[\frac{\omega_d}{(s+\sigma)^2+\omega_d^2}\right]$$

observe that the response y(t) is a damped oscillation which tends to 1 as t → ∞.

In this case, we say that the system is underdamped.

$$\varphi = \tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta}$$

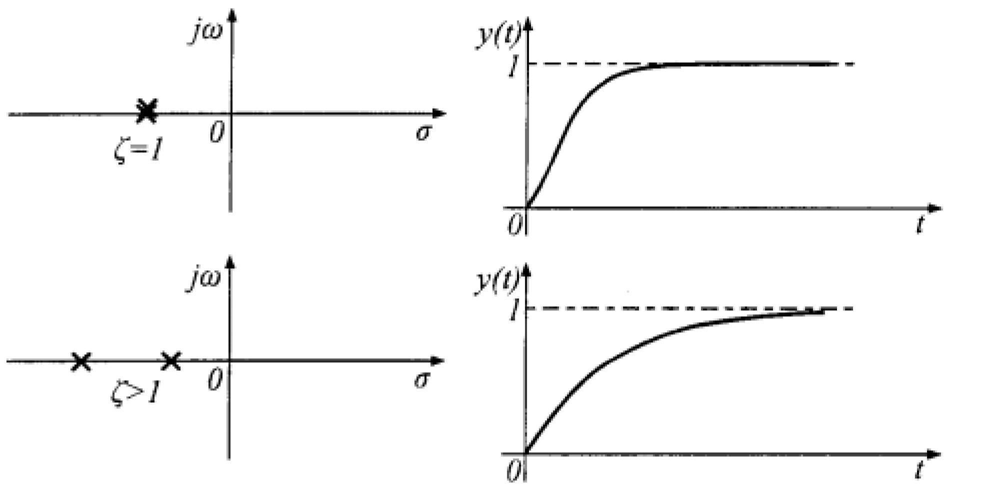
$$y(t) = 1 - e^{-\sigma t}\cos\omega_d t - \frac{\sigma}{\omega_d}e^{-\sigma t}\sin\omega_d t = 1 - \frac{e^{-\sigma t}}{\sqrt{1-\zeta^2}}\sin(\omega_d t + \varphi), = 1 - \frac{e^{-\sigma t}}{\sqrt{1-\zeta^2}}\sin(\omega_d t + \varphi),$$

Time Response

Second-order systems

Case 3 $(\zeta = 1)$

In this case the poles of G(s) are the real double pole $-\omega_n$, and relation becomes $Y(s) = \frac{\omega_n^2}{s(s+\omega_n)^2}$



If we expand Y(s) in partial fractions, we have

$$Y(s) = \frac{1}{s} - \frac{1}{s+\omega_n} - \frac{\omega_n^2}{(s+\omega_n)^2}, \quad \text{and thus } y(t) = 1 - e^{-\omega_n t} - \omega_n t e^{-\omega_n t}$$

we observe that the waveform of the response y(t) involves no oscillations, and asymptotically tends to 1 as $t \rightarrow \infty$.

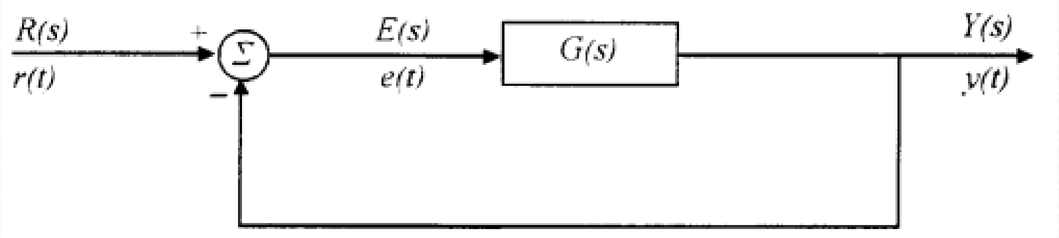
In this case we say that the system is critically damped

Model Examples

- DC- Motor Controller
- Response of 2nd order system without controller

Steady state error

Types of Systems and Error Constants



- In the design of a control system the steady-state performance is of special significance, since we seek a system whose output y(t).
- Consider the unity feedback system of Figure and assume that G(s) has the form

$$G(s) = K\frac{\prod_{i=1}^{m}(T_i' s + 1)}{s^j \prod_{i=1}^{q}(T_i s + 1)}, \quad \text{where } j + q = n \le m$$

- A system is called **type j** system when G(s) has j poles at the point s =0

Steady state error

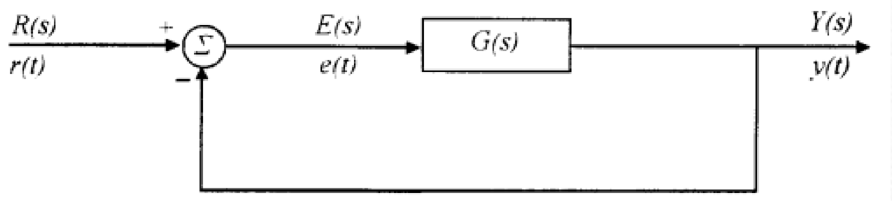
Types of Systems and Error Constants

- The position (or step) error constant Kp

$$K_p = \lim_{s\to 0} G(s).$$

- Substitute G(s) in Kp equation.

$$K_p = \lim_{s\to 0} G(s) = \lim_{s\to 0} K \frac{\prod_{i=1}^{m}(T_j' s + 1)}{s^j \prod_{i=1}^{q}(T_i s + 1)} = \begin{cases} K \text{ when } j = 0 \\ \infty \text{ when } j > 0 \end{cases}$$



$$G(s) = K \frac{\prod_{i=1}^{m}(T_i' s + 1)}{s^j \prod_{i=1}^{q}(T_i s + 1)}, \quad \text{where } j + q = n \leq m$$

Steady state error

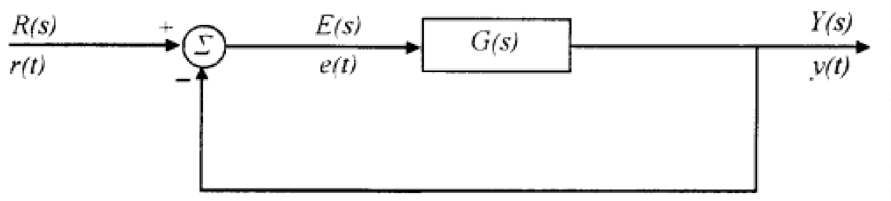
Types of Systems and Error Constants

- The speed (or velocity, or ramp) error constant Kv of a system

$$K_v = \lim_{s\to 0} sG(s)$$

- Substitute G(s) in Kv equation.

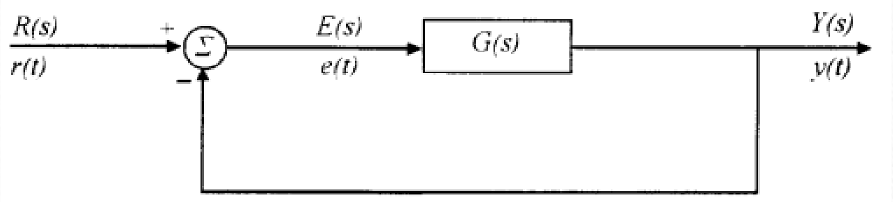
$$K_v = \lim_{s\to 0} sG(s) = \lim_{s\to 0} K \frac{\prod_{i=1}^{m}(T_i' s + 1)}{s^{j-1}\prod_{i=1}^{q}(T_i s + 1)} = \begin{cases} 0 \text{ when } j = 0 \\ K \text{ when } j = 1 \\ \infty \text{ when } j > 1 \end{cases}$$



$$G(s) = K \frac{\prod_{i=1}^{m}(T_i' s + 1)}{s^{j}\prod_{i=1}^{q}(T_i s + 1)}, \quad \text{where } j + q = n \leq m$$

Steady state error

Types of Systems and Error Constants



$$G(s) = K\frac{\prod_{i=1}^{m}(T_i' s + 1)}{s^j \prod_{i=1}^{q}(T_i s + 1)}, \quad \text{where } j + q = n \le m$$

- The acceleration (or parabolic) error constant Ka of a system

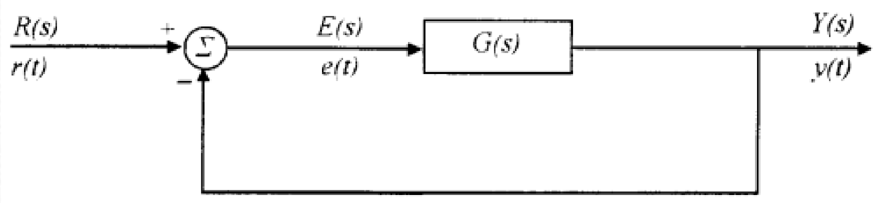
$$K_a = \lim_{s \to 0} s^2 G(s)$$

- Substitute G(s) in Ka equation.

$$K_a = \lim_{s \to 0} s^2 G(s) = \lim_{s \to 0} K \frac{\prod_{i=1}^{m}(T_i' s + 1)}{s^{j-2} \prod_{i=1}^{q}(T_i s + 1)} = \begin{cases} 0 \text{ when } j = 0, 1 \\ K \text{ when } j = 2 \\ \infty \text{ when } j > 2 \end{cases}$$

Steady state error

Consider the closed- loop system of unity feedback of Figure. The system error e(t) is defined as the difference between the command signal r(t) and the output of the system y(t).



$$e(t) = r(t) - y(t) \qquad e_{ss}(t) = r_{ss}(t) - y_{ss}(t)$$

The steady-state error $e_{ss}(t)$ is given by

$$e_{ss}(t) = \lim_{t\to\infty} e(t), \qquad r_{ss}(t) = \lim_{t\to\infty} r(t), \qquad \text{and} \qquad y_{ss}(t) = \lim_{t\to\infty} y(t)$$

In order to evaluate $e_{ss}(t)$, we work as follows

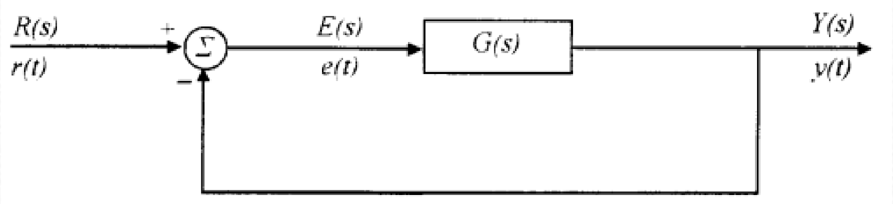
$$E(s) = \frac{R(s)}{1 + G(s)}$$

If we apply the final value theorem

$$e_{ss}(t) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} \frac{sR(s)}{1 + G(s)}$$

Steady state error

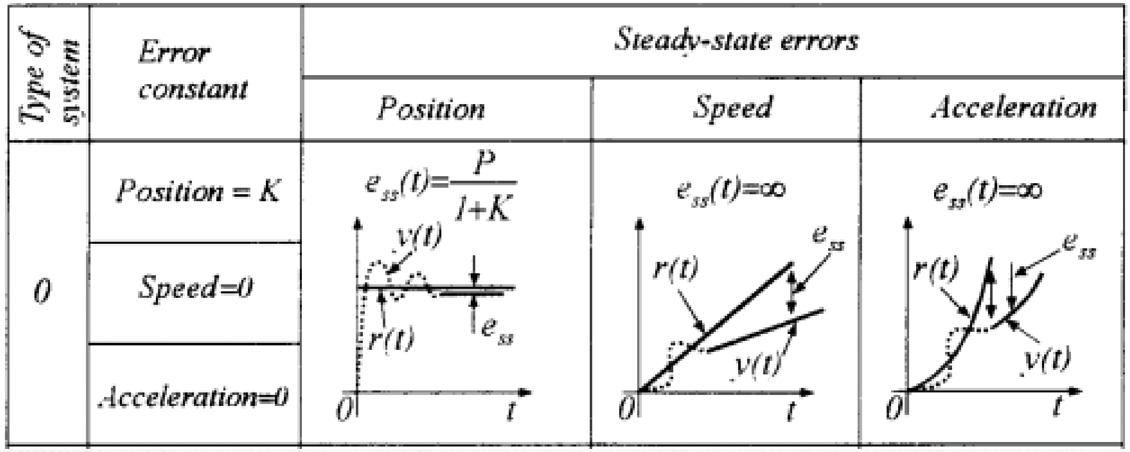
We will examine the steady-state error ess(t) for the following three special forms of the input r(t).



1. r(t) = P. In this case the input is a **step function** with amplitude P. Here, $e_{ss}(t)$ is called the position error.
   We have

$$e_{ss}(t) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} \frac{s[P/s]}{1+G(s)} = \frac{P}{1+\lim_{s\to 0} G(s)} = \frac{P}{1+K_p}$$

$$= \begin{cases} \dfrac{P}{1+K} & \text{when } j = 0 \\ 0 & \text{when } j > 0 \end{cases}$$



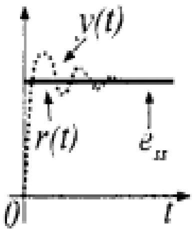
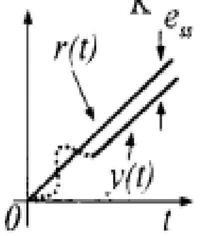
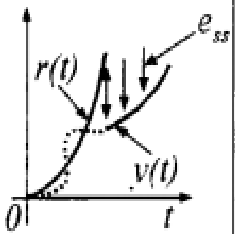
Type of system	Error constant	Steady-state errors		
		Position	Speed	Acceleration
0	Position = K	$e_{ss}(t)=\frac{P}{1+K}$	$e_{ss}(t)=\infty$	$e_{ss}(t)=\infty$
	Speed=0			
	Acceleration=0			

Steady state error

We will examine the steady-state error ess(t) for the following three special forms of the input r(t).

2. r(t) = Vt. In this case the input is a **ramp function** with slope equal to V.
Here $e_{ss}(t)$ is called the speed or velocity error. We have

$$e_{ss}(t) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} \frac{s[V/s^2]}{1+G(s)} = \frac{V}{\lim_{s\to 0} sG(s)} = \frac{V}{K_v} = \begin{bmatrix} \infty & \text{when } j = 0 \\ \frac{A}{K_v} & \text{when } j = 1 \\ 0 & \text{when } j > 1 \end{bmatrix}$$

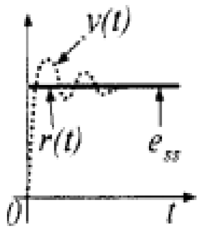
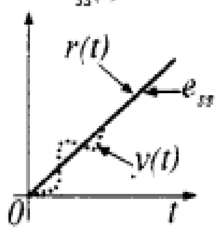
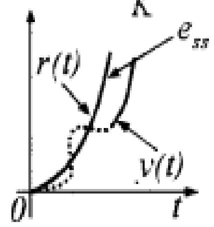
Type of system	Error constant	Steady-state errors		
		Position	Speed	Acceleration
1	Position=∞	$e_{ss}(t)=0$	$e_{ss}(t)=\frac{V}{K}$	$e_{ss}(t)=\infty$
	Speed=K			
	Acceleration=0			

Steady state error

We will examine the steady-state error ess(t) for the following three special forms of the input r(t).

3. r(t) = 1/2At^2. In this case the input is a **parabolic function**. Here, ess(t) is called the acceleration error. We have

$$e_{ss}(t) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} \frac{s[A/s^3]}{1+G(s)} = \frac{A}{\lim_{s\to 0} s^2G(s)} = \frac{A}{K_a} = \begin{bmatrix} \infty & \text{when } j = 0, 1 \\ \frac{A}{K} & \text{when } j = 2 \\ 0 & \text{when } j > 2 \end{bmatrix}$$

Type of system	Error constant	Steady-state errors		
		Position	Speed	Acceleration
2	Position=∞ Speed=∞ Acceleration=K	$e_{ss}(t)=0$ 	$e_{ss}(t)=0$ 	$e_{ss}(t)=\frac{A}{K}$ 

Steady state error

Remember that:

The terms ***position error, velocity error,*** **and** ***acceleration error*** mean steady-state deviations in the output position

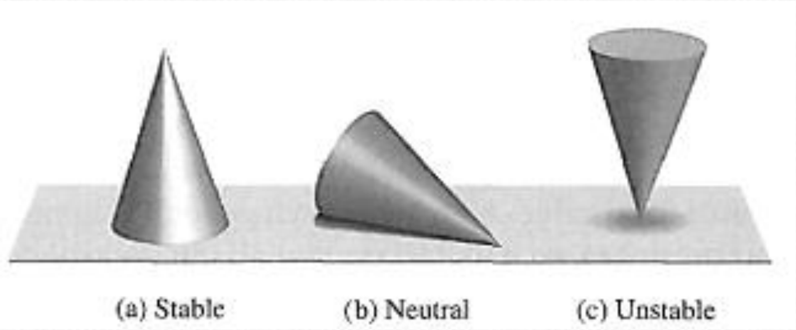
The error constants Kp, Kv, and *Ka* describe the ability of a unity-feedback system to reduce or eliminate steady-state error.

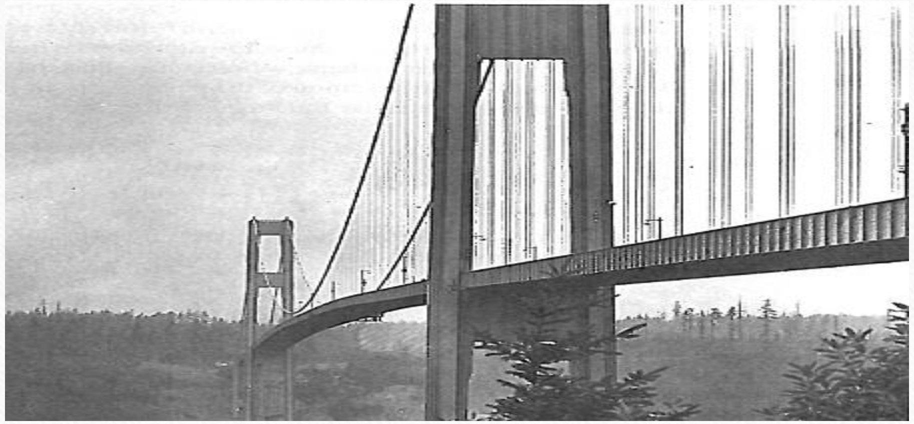
It is noted that to **improve** the steady state performance we can increase the type of the system by adding an **integrator** or integrators to the feedforward path.

	Step Input $r(t) = 1$	Ramp Input $r(t) = t$	Acceleration Input $r(t) = \frac{1}{2}t^2$
Type 0 system	$\frac{1}{1+K}$	∞	∞
Type 1 system	0	$\frac{1}{K}$	∞
Type 2 system	0	0	$\frac{1}{K}$

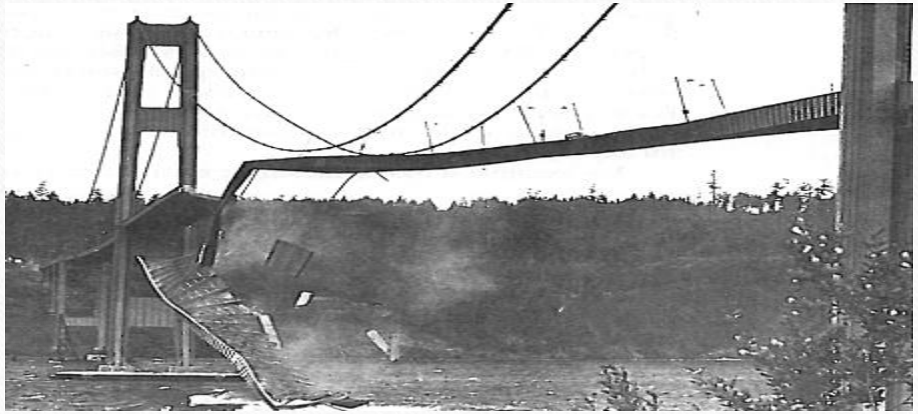
Stability Systems of Linear system

Definition :
The stability of a dynamic system is defined in a similar manner. The response to a displacement, or initial condition, will result in either a decreasing, neutral, or increasing response.





Stability of system after exciting force



Stability Systems of Linear system

Definition :

The characteristics equation of second order system

$$as^2 + bs + c = 0$$

The roots of the characteristic equation given in equation

$$s_1, s_2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

These roots determine the transient response of the system and for a second-order system can be written as

a) Overdamping

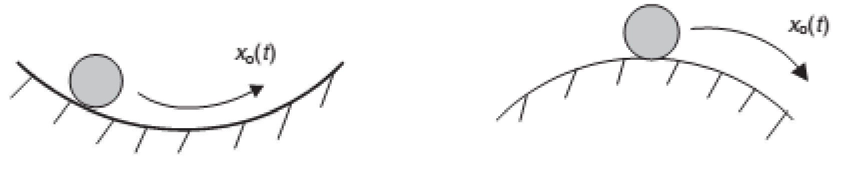
$$s_1 = -\sigma_1$$
$$s_2 = -\sigma_2$$

b) Critical damping

$$s_1 = s_2 = -\sigma$$

c) underdamping

$$s_1, s_2 = -\sigma \pm j\omega$$
$$s_1, s_2 = +\sigma \pm j\omega$$



(a) Stable (b) Unstable

Generally, if any of the roots of the characteristics equation have positive real parts, then the system will be unstable

It was stated that a control system is stable if and only if all closed-loop poles lie in the left-half s plane

Stability Systems of Linear system

Routh's Stability Criterion

absolute stability can be obtained directly from the coefficients of the characteristic equation.

The procedure in Routh's stability criterion is as follows:

1. Write the polynomial in s in the following form:

$$a_0 s^n + a_1 s^{n-1} + \cdots + a_{n-1} s + a_n = 0$$

where the coefficients are real quantities. Assume that ***a* ≠ 0; that is, any zero root has been removed.**

2. If any of the coefficients are zero or negative in the presence of at least one positive coefficient, there is a root or roots that are imaginary or that have positive

3. If all coefficients are positive, arrange the coefficients of the polynomial in rows and columns according to the following pattern:

s^n	a_0	a_2	a_4	a_6	$\cdots$
s^{n-1}	a_1	a_3	a_5	a_7	$\cdots$
s^{n-2}	b_1	b_2	b_3	b_4	$\cdots$
s^{n-3}	c_1	c_2	c_3	c_4	$\cdots$
s^{n-4}	d_1	d_2	d_3	d_4	$\cdots$
.	.	.			
.	.	.			
.	.	.			
s^2	e_1	e_2			
s^1	f_1				
s^0	g_1				

Stability Systems of Linear system

Routh's Stability Criterion

$$b_1 = \frac{a_1 a_2 - a_0 a_3}{a_1} \qquad c_1 = \frac{b_1 a_3 - a_1 b_2}{b_1}$$

$$b_2 = \frac{a_1 a_4 - a_0 a_5}{a_1} \qquad c_2 = \frac{b_1 a_5 - a_1 b_3}{b_1}$$

$$b_3 = \frac{a_1 a_6 - a_0 a_7}{a_1} \qquad c_3 = \frac{b_1 a_7 - a_1 b_4}{b_1}$$

s^n	a_0	a_2	a_4	a_6	$\cdots$
s^{n-1}	a_1	a_3	a_5	a_7	$\cdots$
s^{n-2}	b_1	b_2	b_3	b_4	$\cdots$
s^{n-3}	c_1	c_2	c_3	c_4	$\cdots$
s^{n-4}	d_1	d_2	d_3	d_4	$\cdots$
.	.	.			
.	.	.			
.	.	.			
s^2	e_1	e_2			
s^1	f_1				
s^0	g_1				

The Routh-Hurwitz criterion states that the number of roots of *q(s)* with positive real parts is equal to the number of changes in sign of the first column of the Routh array

The number of changes of sign in the first column of the array developed for the polynomial in s equal to the number of roots that are located to the right of the vertical line

Model Examples

- Pulse Width Modulation (PWM)