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Principles of Automatic Control (1)
自动控制原理1

Topic 6
Steady-State Error
(Chapter 7 in text book)

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New terminologies in this topic

- Steady-state error 稳态误差
- Step input 阶越输入
- Ramp input 斜坡输入
- Parabolic input 抛物线输入
- Integration 积分
- System type 系统类型
- Static error constant 静态误差常数
- Position constant 位置常数
- Velocity constant 速度常数
- Acceleration constant 加速度常数
- Disturbance 干扰
- Geostationary orbit 地球静止轨道

Learning Outcomes for Topic 6

After completing this topic, you will be able to:

- Find the steady-state error for a unity feedback system;
- Specify a system's steady-state error performance;
- Design the gain of a closed-loop system to meet a steady-state error specification;
- Find the steady-state error for disturbance inputs.

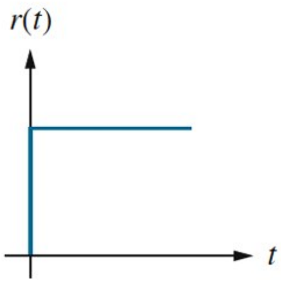
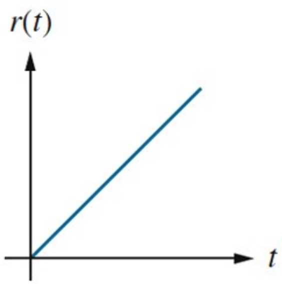
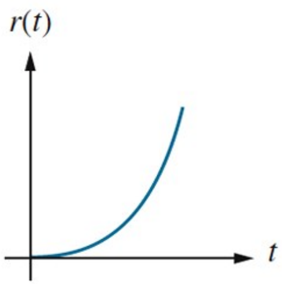
Outline

- Brief Introduction
- Steady-State Error for Unity Feedback Systems
- Static Error Constants and System Type
- Steady-State Error Specifications
- Steady-State Error for Disturbances
- Summary

Brief Introduction

- *Steady-state error* is a very important objective in designing control systems.
- *Steady-state error* is the difference between the input and the output for a prescribed test input as $t \to \infty$.
- Three test inputs are frequently used for steady-state error analysis and design.

TABLE 7.1 Test waveforms for evaluating steady-state errors of position control systems

Waveform	Name	Physical interpretation	Time function	Laplace transform
	Step	Constant position	1	$\frac{1}{s}$
	Ramp	Constant velocity	t	$\frac{1}{s^2}$
	Parabola	Constant acceleration	$\frac{1}{2}t^2$	$\frac{1}{s^3}$

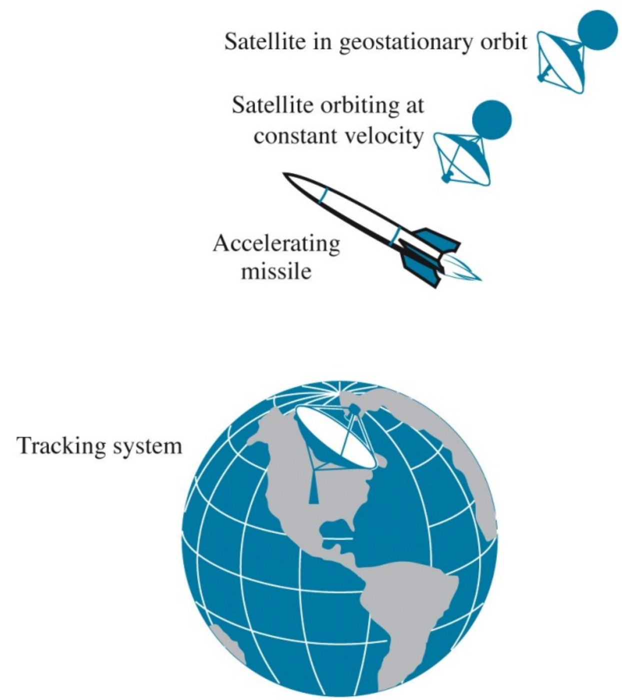


Figure 7.1

Application to Stable Systems

- Steady-state error is limited to stable systems, where the natural response approaches zero as $t \to \infty$.
- We must check the system for stability while performing steady-state error analysis and design.

Evaluating Steady-State Errors

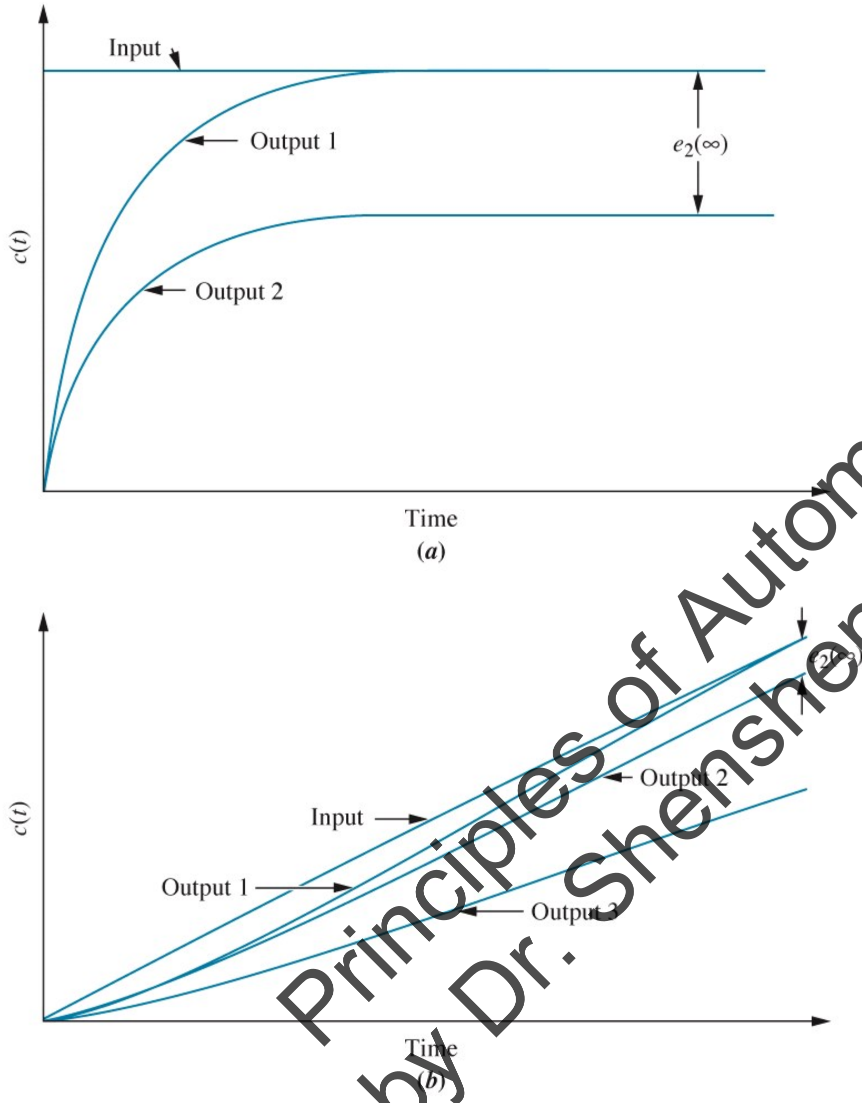


Figure 7.2

$$e_{ss} = \begin{cases} 0 \\ C \\ \infty \end{cases}$$

Two Representations for Closed-loop Control System Error

- *T(s):* Closed-loop transfer function
- *G(s):* Forward-path transfer function

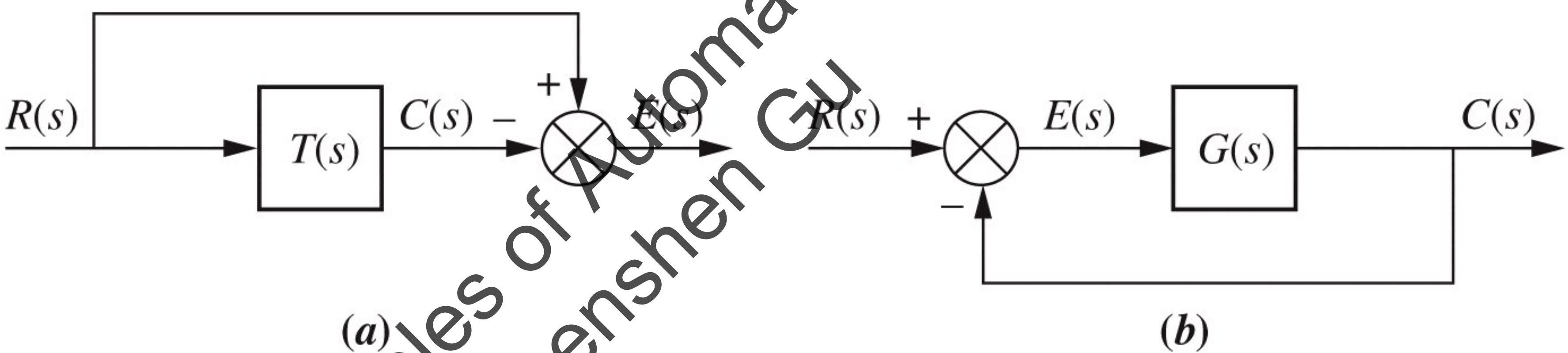
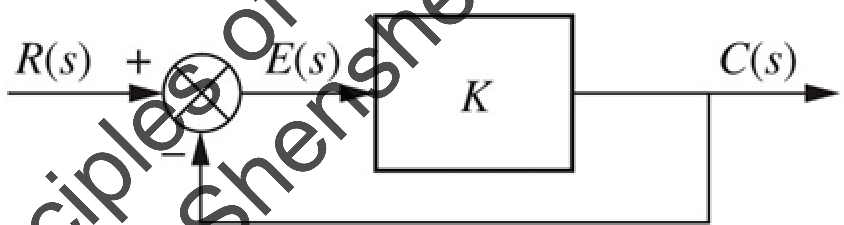


Figure 7.3

General representation **Representation for unity feedback systems**

Sources of Steady-State Error

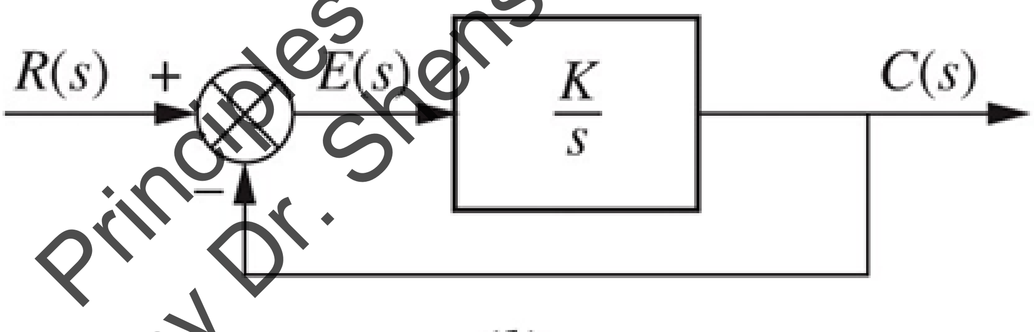
- Can occur from un-modelled non-linear characteristics, but that is not our focus.
- The steady-state errors we study here are errors that arise from the configuration of the system itself and the type of applied input.
- Feedback systems will **always have error for some type of input.**



(a)

- For the system shown with pure gain (K), the error can never be zero. For a step input, $K{*}e_{steady\text{-}state} = c_{steady\text{-}state}$

- Steady state error cannot be zero if c(t) ($t \to \infty$) has a finite value.
- If the forward-path gain is replaced by an integrator, there will be zero error in the steady state for a step input.
- As *c(t)* increases, *e(t)* will decrease, since *e(t)=r(t)-c(t).* This decrease will continue until there is zero error, but there will still be a value for *c(t)* since an integrator can have a constant output without any input.



(b)

Steady-State Error for Unity Feedback Systems

$$E(s) = R(s) - C(s)$$

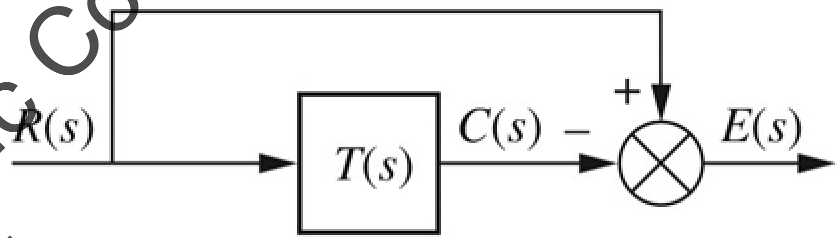
$$C(s) = R(s)T(s)$$

$$E(s) = R(s)\left[1 - T(s)\right]$$

Applying final value theorem

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

$$e(\infty) = \lim_{s \to 0} sR(s)\left[1 - T(s)\right]$$



(a)

Example 7.1

Steady-State Error in Terms of $T(s)$

PROBLEM: Find the steady-state error for the system of Figure 7.3(*a*) if $T(s) = 5/(s^2+7s+10)$ and the input is a unit step.

SOLUTION: From the problem statement, $R(s) = 1/s$ and $T(s) = 5/(s^2+7s+10)$. Substituting into Eq. (7.4) yields

$$E(s) = \frac{s^2+7s+5}{s(s^2+7s+10)} \qquad (7.7)$$

Since $T(s)$ is stable and, subsequently, $E(s)$ does not have right–half-plane poles or $j\omega$ poles other than at the origin, we can apply the final value theorem. Substituting Eq. (7.7) into Eq. (7.5) gives $e(\infty) = 1/2$.

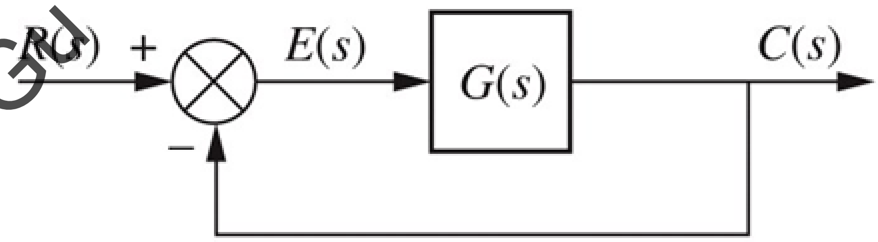
Steady-State Error in Terms of *G(s)*

- Many times we have the system configured as a unity feedback system with a forward transfer function, G(s). Although we can find the closed-loop transfer function, T(s), and then proceed as in the previous subsection, we find more insight for analysis and design by expressing the steady-state error in terms of G(s) rather than T(s).

$$E(s) = R(s) - C(s)$$

$$C(s) = E(s)G(s)$$

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



(b)

Applying Final Value Theorem

$$e(\infty) = \lim_{s\to 0} \frac{sR(s)}{1+G(s)}$$

Step Input

$$R(s)=\frac{1}{s}$$

$$e(\infty)=e_{\text{step}}(\infty)=\lim_{s\to 0}\frac{sR(s)}{1+G(s)}=\lim_{s\to 0}\frac{s(1/s)}{1+G(s)}=\frac{1}{1+\lim\limits_{s\to 0}G(s)}$$

$$G(s)=\frac{(s+z_1)(s+z_2)\cdots}{s^n(s+p_1)(s+p_2)\cdots}$$

$$\begin{cases} n=0\Rightarrow \quad \lim\limits_{s\to 0}G(s)=\dfrac{z_1z_2\cdots}{p_1p_2\cdots}\Rightarrow \quad e(\infty)=\text{nonzero finite error} \\ n\geq 1\Rightarrow \quad \lim\limits_{s\to 0}G(s)=\infty\Rightarrow \quad e(\infty)=0 \end{cases}$$

In summary, for a step input to a unity feedback system, the steady-state error will be zero if there is at least one pure integration in the forward path. If there are no integrations, then there will be a nonzero finite error.

Ramp Input

$$R(s)=\frac{1}{s^2}$$

$$e(\infty)=e_{\text{ramp}}(\infty)=\lim_{s\to 0}\frac{sR(s)}{1+G(s)}=\lim_{s\to 0}\frac{s\left(1/s^2\right)}{1+G(s)}=\lim_{s\to 0}\frac{1}{s+sG(s)}=\frac{1}{\lim_{s\to 0} sG(s)}$$

$$G(s)=\frac{(s+z_1)(s+z_2)\cdots}{s^n(s+p_1)(s+p_2)\cdots}$$

$$\begin{cases} n=0\Rightarrow & \lim_{s\to 0} sG(s)=0\Rightarrow & e(\infty)=\infty \\ n=1\Rightarrow & \lim_{s\to 0} sG(s)=\dfrac{z_1z_2\cdots}{p_1p_2\cdots}\Rightarrow & e(\infty)=\text{nonzero finite error} \\ n\geq 2\Rightarrow & \lim_{s\to 0} sG(s)=\infty\Rightarrow & e(\infty)=0 \end{cases}$$

Parabolic Input

$$R(s)=\frac{1}{s^3}$$

$$e(\infty)=e_{\text{parabola}}(\infty)=\lim_{s\to 0}\frac{sR(s)}{1+G(s)}=\lim_{s\to 0}\frac{s(1/s^3)}{1+G(s)}=\lim_{s\to 0}\frac{1}{s^2+s^2G(s)}=\frac{1}{\lim\limits_{s\to 0}s^2G(s)}$$

$$G(s)=\frac{(s+z_1)(s+z_2)\cdots}{s^n(s+p_1)(s+p_2)\cdots}$$

$$\begin{cases} n=0,1\Rightarrow & \lim\limits_{s\to 0}s^2G(s)=0\Rightarrow & e(\infty)=\infty \\ n=2\Rightarrow & \lim\limits_{s\to 0}s^2G(s)=\dfrac{z_1z_2\cdots}{p_1p_2\cdots}\Rightarrow & e(\infty)=\text{nonzero finite error} \\ n\geq 3\Rightarrow & \lim\limits_{s\to 0}s^2G(s)=\infty\Rightarrow & e(\infty)=0 \end{cases}$$

Example 7.2

Steady-State Errors for Systems with No Integrations

PROBLEM: Find the steady-state errors for inputs of $5u(t)$, $5tu(t)$, and $5t^2u(t)$ to the system shown in Figure 7.5. The function $u(t)$ is the unit step.

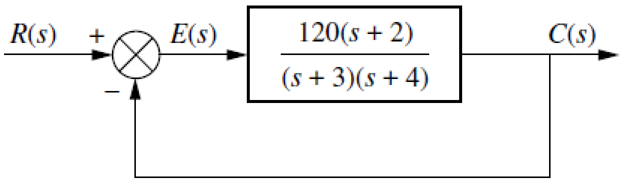


FIGURE 7.5 Feedback control system for Example 7.2

SOLUTION: First we verify that the closed-loop system is indeed stable. For this example we leave out the details. Next, for the input $5u(t)$, whose Laplace transform is $5/s$, the steady-state error will be five times as large as that given by Eq. (7.12), or

$$e(\infty) = e_{\text{step}}(\infty) = \frac{5}{1 + \lim_{s \to 0} G(s)} = \frac{5}{1 + 20} = \frac{5}{21} \tag{7.24}$$

which implies a response similar to output 2 of Figure 7.2(a).

For the input $5tu(t)$, whose Laplace transform is $5/s^2$, the steady-state error will be five times as large as that given by Eq. (7.16), or

$$e(\infty) = e_{\text{ramp}}(\infty) = \frac{5}{\lim_{s \to 0} sG(s)} = \frac{5}{0} = \infty \tag{7.25}$$

which implies a response similar to output 3 of Figure 7.2(b).

For the input $5t^2u(t)$, whose Laplace transform is $10/s^3$, the steady-state error will be 10 times as large as that given by Eq. (7.20), or

$$e(\infty) = e_{\text{parabola}}(\infty) = \frac{10}{\lim_{s \to 0} s^2G(s)} = \frac{10}{0} = \infty \tag{7.26}$$

Example 7.3

Steady-State Errors for Systems with One Integration

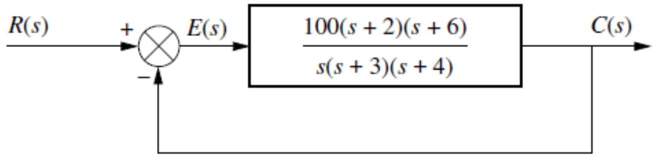


FIGURE 7.6 Feedback control system for Example 7.3

PROBLEM: Find the steady-state errors for inputs of $5u(t)$, $5tu(t)$, and $5t^2u(t)$ to the system shown in Figure 7.6. The function $u(t)$ is the unit step.

SOLUTION: First verify that the closed-loop system is indeed stable. For this example we leave out the details. Next note that since there is an integration in the forward path, the steady-state errors for some of the input waveforms will be less than those found in Example 7.2. For the input $5u(t)$, whose Laplace transform is $5/s$, the steady-state error will be five times as large as that given by Eq. (7.12), or

$$e(\infty) = e_{\text{step}}(\infty) = \frac{5}{1 + \lim\limits_{s\to 0} G(s)} = \frac{5}{\infty} = 0 \tag{7.27}$$

which implies a response similar to output 1 of Figure 7.2(*a*). Notice that the integration in the forward path yields zero error for a step input, rather than the finite error found in Example 7.2.

For the input $5tu(t)$, whose Laplace transform is $5/s^2$, the steady-state error will be five times as large as that given by Eq. (7.16), or

$$e(\infty) = e_{\text{ramp}}(\infty) = \frac{5}{\lim\limits_{s\to 0} sG(s)} = \frac{5}{100} = \frac{1}{20} \tag{7.28}$$

which implies a response similar to output 2 of Figure 7.2(*b*). Notice that the integration in the forward path yields a finite error for a ramp input, rather than the infinite error found in Example 7.2.

For the input, $5t^2u(t)$, whose Laplace transform is $10/s^3$, the steady-state error will be 10 times as large as that given by Eq. (7.20), or

$$e(\infty) = e_{\text{parabola}}(\infty) = \frac{10}{\lim\limits_{s\to 0} s^2G(s)} = \frac{10}{0} = \infty \tag{7.29}$$

Notice that the integration in the forward path does not yield any improvement in steady-state error over that found in Example 7.2 for a parabolic input.

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Skill-Assessment Exercise 7.1

WileyPLUS WPCS Control Solutions

PROBLEM: A unity feedback system has the following forward transfer function:

$$G(s) = \frac{10(s+20)(s+30)}{s(s+25)(s+35)}$$

a. Find the steady-state error for the following inputs: $15u(t)$, $15tu(t)$, and $15t^2u(t)$.

b. Repeat for

$$G(s) = \frac{10(s+20)(s+30)}{s^2(s+25)(s+35)(s+50)}$$

ANSWERS:

a. The closed-loop system is stable. For $15u(t)$, $e_{\text{step}}(\infty) = 0$; for $15tu(t)$, $e_{\text{ramp}}(\infty) = 2.1875$; for $15(t^2)u(t)$, $e_{\text{parabola}}(\infty) = \infty$.

b. The closed-loop system is unstable. Calculations cannot be made.

The complete solution is at www.wiley.com/college/nise.

7.1

a. First check stability.

$$T(s) = \frac{G(s)}{1+G(s)} = \frac{10s^2+500s+6000}{s^3+70s^2+1375s+6000} = \frac{10(s+30)(s+20)}{(s+26.03)(s+37.89)(s+6.085)}$$

Poles are in the lhp. Therefore, the system is stable. Stability also could be checked via Routh-Hurwitz using the denominator of $T(s)$. Thus,

$$15u(t): \quad e_{step}(\infty) = \frac{15}{1+\lim_{s\to 0} G(s)} = \frac{15}{1+\infty} = 0$$

$$15tu(t): \quad e_{ramp}(\infty) = \frac{15}{\lim_{s\to 0} sG(s)} = \frac{15}{\frac{10^*20^*30}{25^*35}} = 2.1875$$

$$15t^2u(t): \quad e_{parabola}(\infty) = \frac{15}{\lim_{s\to 0} s^2G(s)} = \frac{30}{0} = \infty, \text{ since } L\left[15t^2\right] = \frac{30}{s^3}$$

b. First check stability.

$$T(s) = \frac{G(s)}{1+G(s)} = \frac{10s^2+500s+6000}{s^5+110s^4+3875s^3+4.37e04s^2+500s+6000}$$
$$= \frac{10(s+30)(s+20)}{(s+50.01)(s+35)(s+25)(s^2-7.189e-04s+0.1372)}$$

From the second-order term in the denominator, we see that the system is unstable. Instability could also be determined using the Routh-Hurwitz criteria on the denominator of $T(s)$. Since the system is unstable, calculations about steady-state error cannot be made.

Static Error Constants and System Type

- We need to define parameters that we can use as steady-state error performance specifications. These steady-state error performance specifications are called static error constants.

$$e(\infty) = e_{\text{step}}(\infty) = \frac{1}{1 + \lim_{s\to 0} G(s)}$$

position constant →

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

$$e(\infty) = e_{\text{ramp}}(\infty) = \frac{1}{\lim_{s\to 0} sG(s)}$$

velocity constant →

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

$$e(\infty) = e_{\text{parabola}}(\infty) = \frac{1}{\lim_{s\to 0} s^2 G(s)}$$

acceleration constant →

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

- The three terms in the denominator that are taken to the limit determine the steady-state error. We call these limits ***static error constants***.

System Type

- The values of the static error constants, again, depend upon the form of G(s), especially the number of pure integrations in the forward path.
- We define system type to be the value of n in the denominator or, equivalently, the number of pure integrations in the forward path. Therefore, a system with n=0 is a Type 0 system. If n=1 or n=2, the corresponding system is a Type 1 or Type 2 system, respectively.

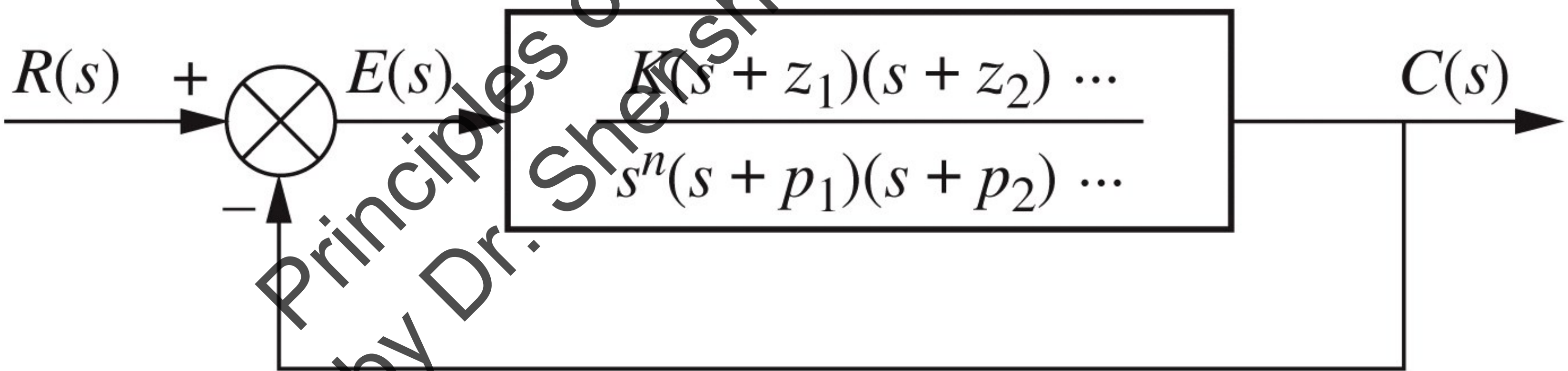
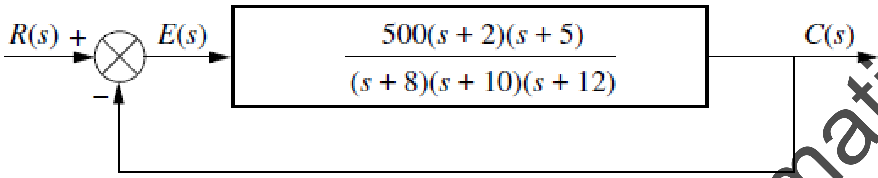


Figure 7.8

Example 7.4

Steady-State Error via Static Error Constants

PROBLEM: For each system of Figure 7.7, evaluate the static error constants and find the expected error for the standard step, ramp, and parabolic inputs.



SOLUTION: First verify that all closed-loop systems shown are indeed stable. For this example we leave out the details. Next, for Figure 7.7(*a*),

$$K_p = \lim_{s\to 0} G(s) = \frac{500 \times 2 \times 5}{8 \times 10 \times 12} = 5.208 \quad (7.36)$$

$$K_v = \lim_{s\to 0} sG(s) = 0 \quad (7.37)$$

$$K_a = \lim_{s\to 0} s^2 G(s) = 0 \quad (7.38)$$

Thus, for a step input,

$$e(\infty) = \frac{1}{1+K_p} = 0.161 \quad (7.39)$$

For a ramp input,

$$e(\infty) = \frac{1}{K_v} = \infty \quad (7.40)$$

For a parabolic input,

$$e(\infty) = \frac{1}{K_a} = \infty \quad (7.41)$$

- The following table ties together the concepts of steady-state error, static error constants, and system type. The table shows the static error constants and the steady-state errors as functions of input waveform and system type.

TABLE 7.2 Relationships between input, system type, static error constants, and steady-state errors

Input	Steady-state error formula	Type 0		Type 1		Type 2	
		Static error constant	Error	Static error constant	Error	Static error constant	Error
Step, $u(t)$	$\frac{1}{1+K_p}$	$K_p =$ Constant	$\frac{1}{1+K_p}$	$K_p = \infty$	0	$K_p = \infty$	0
Ramp, $tu(t)$	$\frac{1}{K_v}$	$K_v = 0$	∞	$K_v =$ Constant	$\frac{1}{K_v}$	$K_v = \infty$	0
Parabola, $\frac{1}{2}t^2u(t)$	$\frac{1}{K_a}$	$K_a = 0$	∞	$K_a = 0$	∞	$K_a =$ Constant	$\frac{1}{K_a}$

Table 7.2

Skill-Assessment Exercise 7.2

PROBLEM: A unity feedback system has the following forward transfer function:

$$G(s) = \frac{1000(s+8)}{(s+7)(s+9)}$$

a. Evaluate system type, K_p, K_v, and K_a.

b. Use your answers to **a.** to find the steady-state errors for the standard step, ramp, and parabolic inputs.

ANSWERS:

a. The closed-loop system is stable. System type = Type 0. $K_p = 127$, $K_v = 0$, and $K_a = 0$.

b. $e_{step}(\infty) = 7.8 \times 10^{-3}$, $e_{ramp}(\infty) = \infty$, and $e_{parabola}(\infty) = \infty$

The complete solution is at www.wiley.com/college/nise.

TryIt 7.1

Use MATLAB, the Control System Toolbox, and the following statements to find K_p, $e_{step}(\infty)$, and the closed-loop poles to check for stability for the system of Skill-Assessment Exercise 7.2.

```
numg=1000*[1 8];
deng=poly([-7 -9]);
G=tf(numg,deng);
Kp=dcgain(G)
estep=1/(1+Kp)
T=feedback(G,1);
poles=pole(T)
```

7.2

a. The system is stable, since

$$T(s) = \frac{G(s)}{1+G(s)} = \frac{1000(s+8)}{(s+9)(s+7)+1000(s+8)} = \frac{1000(s+8)}{s^2+1016s+8063}$$

and is of Type 0. Therefore,

$$K_p = \lim_{s\to 0} G(s) = \frac{1000{*}8}{7{*}9} = 127;\ K_v = \lim_{s\to 0} sG(s) = 0;$$

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

b.

$$e_{step}(\infty) = \frac{1}{1+\lim_{s\to 0} G(s)} = \frac{1}{1+127} = 7.8e-03$$

$$e_{ramp}(\infty) = \frac{1}{\lim_{s\to 0} sG(s)} = \frac{1}{0} = \infty$$

$$e_{parabola}(\infty) = \frac{1}{\lim_{s\to 0} s^2 G(s)} = \frac{1}{0} = \infty$$

Steady-State Error Specifications

- Static error constants can be used to specify the steady-state error characteristics of control systems.
- If a control system has the specification $K_v=1000$, we can draw several conclusions:
  - 1.The system is stable.
  - 2.The system is of Type 1, since only Type 1 systems have K_v's that are finite constants. Recall that $K_v=0$ for Type 0 systems, whereas $K_v=\infty$ for Type 2 systems.
  - 3.A ramp input is the test signal. Since K_v is specified as a finite constant, and the steady-state error for a ramp input is inversely proportional to K_v, we know the test input is a ramp.
  - 4.The steady-state error between the input ramp and the output ramp is $1/K_v$ per unit of input slope.

Example 7.6

Interpreting the Steady-State Error Specification

PROBLEM: What information is contained in the specification $K_p = 1000$?

SOLUTION: The system is stable. The system is Type 0, since only a Type 0 system has a finite K_p. Type 1 and Type 2 systems have $K_p = \infty$. The input test signal is a step, since K_p is specified. Finally, the error per unit step is

$$e(\infty) = \frac{1}{1+K_p} = \frac{1}{1+1000} = \frac{1}{1001} \tag{7.54}$$

Example 7.6

Gain Design to Meet a Steady-State Error Specification

PROBLEM: Given the control system in Figure 7.10, find the value of K so that there is 10% error in the steady state.

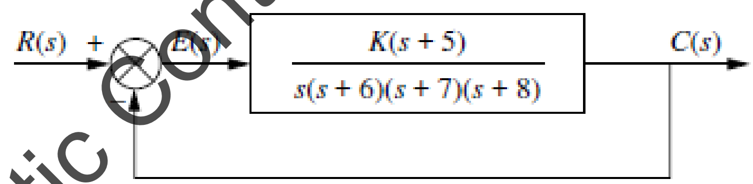


FIGURE 7.10 Feedback control system for Example 7.6

SOLUTION: Since the system is Type 1, the error stated in the problem must apply to a ramp input; only a ramp yields a finite error in a Type 1 system. Thus,

$$e(\infty) = \frac{1}{K_v} = 0.1 \tag{7.55}$$

Therefore,

$$K_v = 10 = \lim_{s \to 0} sG(s) = \frac{K \times 5}{6 \times 7 \times 8} \tag{7.56}$$

which yields

$$K = 672 \tag{7.57}$$

Applying the Routh-Hurwitz criterion, we see that the system is stable at this gain.

Although this gain meets the criteria for steady-state error and stability, it may not yield a desirable transient response. In Chapter 9 we will design feedback control systems to meet all three specifications.

Skill-Assessment Exercise 7.3

PROBLEM: A unity feedback system has the following forward transfer function:

$$G(s) = \frac{K(s+12)}{(s+14)(s+18)}$$

Find the value of K to yield a 10% error in the steady state.

ANSWER: $K = 189$

The complete solution is at www.wiley.com/college/nise.

WileyPLUS
WPCS
Control Solutions

TryIt 7.2

Use MATLAB, the Control System Toolbox, and the following statements to solve Skill-Assessment Exercise 7.3 and check the resulting system for stability.

```
numg=[1 12];
deng=poly([-14 -18]);
G=tf(numg,deng);
Kpdk=dcgain(G);
estep=0.1;
K=(1/estep-1)/Kpdk
T=feedback(G,1);
poles=pole(T)
```

7.3

System is stable for positive K. System is Type 0. Therefore, for a step input $e_{step}(\infty) = \frac{1}{1+K_p} = 0.1$. Solving for K_p yields $K_p = 9 = \lim_{s \to 0} G(s) = \frac{12K}{14*18}$; from which we obtain $K = 189$.

Steady-State Error for Disturbances

- Feedback control systems are used to compensate for disturbances or unwanted inputs that enter a system.
- The advantage of using feedback is that regardless of these disturbances, the system can be designed to follow the input with small or zero error.

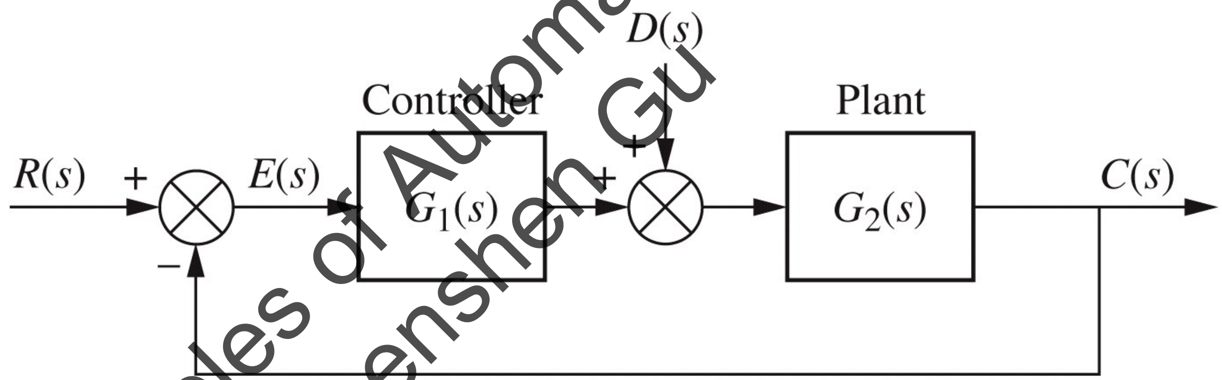


Figure 7.11

$$C(s) = E(s)G_1(s)G_2(s) + D(s)G_2(s)$$

$$C(s) = R(s) - E(s)$$

$$E(s) = \frac{1}{1+G_1(s)G_2(s)}R(s) - \frac{G_2(s)}{1+G_1(s)G_2(s)}D(s)$$

$$E(s)=\frac{1}{1+G_1(s)G_2(s)}R(s)-\frac{G_2(s)}{1+G_1(s)G_2(s)}D(s)$$

Applying final value theorem

$$e(\infty)=\lim_{s\to 0} sE(s)=\lim_{s\to 0}\frac{s}{1+G_1(s)G_2(s)}R(s)-\lim_{s\to 0}\frac{sG_2(s)}{1+G_1(s)G_2(s)}D(s)$$

$$=e_R(\infty)+e_D(\infty)$$

Steady-state error due to *R(s)*

$$e_R(\infty)=\lim_{s\to 0}\frac{s}{1+G_1(s)G_2(s)}R(s)$$

Steady-state error due to *D(s)*

$$e_D(\infty)=-\lim_{s\to 0}\frac{sG_2(s)}{1+G_1(s)G_2(s)}D(s)$$

Steady-state error component due to a step disturbance

$$e_D(\infty)=-\frac{1}{\lim_{s\to 0}\frac{1}{G_2(s)}+\lim_{s\to 0}G_1(s)}$$

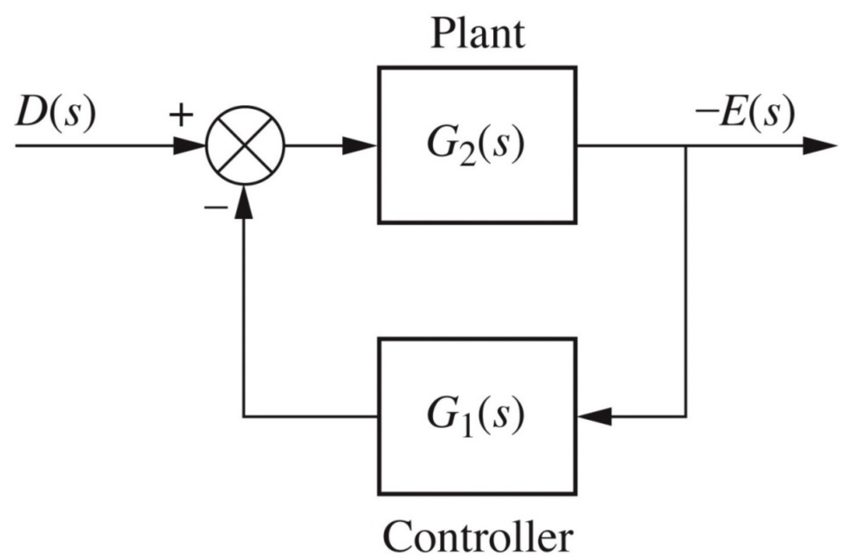


Figure 7.12

Example 7.7

Steady-State Error Due to Step Disturbance

PROBLEM: Find the steady-state error component due to a step disturbance for the system of Figure 7.13.

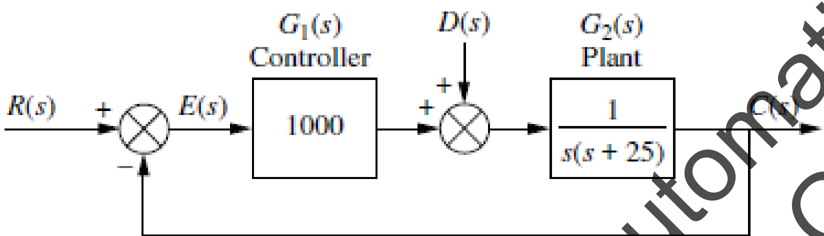


FIGURE 7.13 Feedback control system for Example 7.7

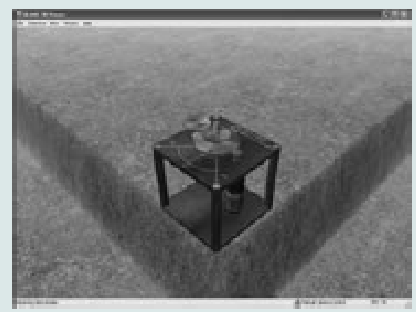
SOLUTION: The system is stable. Using Figure 7.12 and Eq. (7.62), we find

$$e_D(\infty) = -\frac{1}{\lim\limits_{s\to 0}\frac{1}{G_2(s)} + \lim\limits_{s\to 0} G_1(s)} = -\frac{1}{0+1000} = -\frac{1}{1000} \qquad (7.63)$$

The result shows that the steady-state error produced by the step disturbance is inversely proportional to the dc gain of $G_1(s)$. The dc gain of $G_2(s)$ is infinite in this example.

Virtual Experiment 7.1
Steady-State Error

Put theory into practice finding the steady-state error of the Quanser Rotary Servo when subject to an input or a disturbance by simulating it in LabVIEW. This analysis becomes important when developing controllers for bottle labelling machines or robot joint control.



Virtual experiments are found on WileyPLUS.

Skill-Assessment Exercise 7.4

PROBLEM: Evaluate the steady-state error component due to a step disturbance for the system of Figure 7.14.

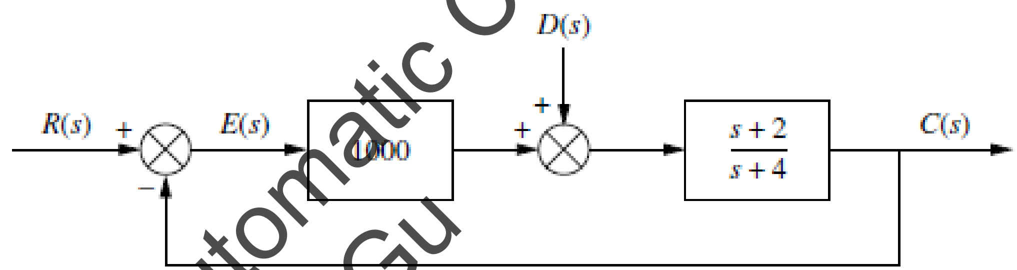


FIGURE 7.14 System for Skill-Assessment Exercise 7.4

ANSWER: $e_D(\infty) = -9.98 \times 10^{-4}$

The complete solution is at www.wiley.com/college/nise.

7.4

System is stable. Since $G_1(s) = 1000$, and $G_2(s) = \dfrac{(s+2)}{(s+4)}$,

$$e_D(\infty) = -\frac{1}{\lim\limits_{s\to 0}\dfrac{1}{G_2(s)} + \lim\limits_{s\to 0} G_1(s)} = \frac{1}{2+1000} = -9.98e-04$$

Summary

- The steady-state errors studied resulted strictly from the system configuration.
- The greater the number of pure integrations a system has in the forward path, the higher the degree of accuracy, assuming the system is stable.
- The static error constants are the steady-state error specifications for control systems.
- The system type is the number of pure integrations in the forward path, assuming a unity feedback system. Increasing the system type decreases the steady-state error as long as the system remains stable.

Summary(Cont.)

- Increasing system gain increases the static error constant. Thus, in general, increasing system gain decreases the steady-state error as long as the system remains stable.
- We also saw how feedback decreases a system's steady-state error caused by disturbances. With feedback, the effect of a disturbance can be reduced by system gain adjustments.