Figure 10.1
The HP 35670A Dynamic Signal Analyzer obtains frequency response data from a physical system. The displayed data can be used to analyze, design, or determine a mathematical model for the system.

Courtesy of Hewlett-Packard.

Figure 10.2 Sinusoidal frequency response: **a.** system; **b.** transfer function; **c.** input and output waveforms

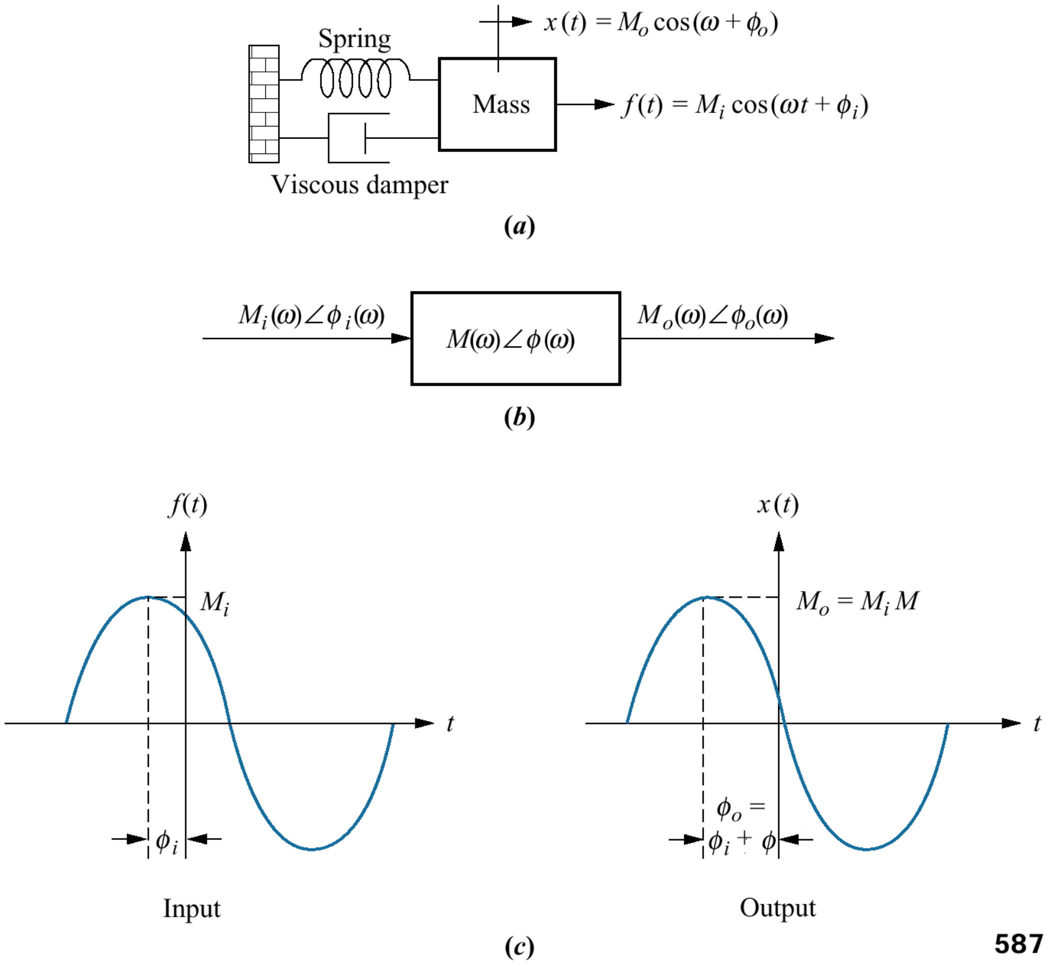


Figure 10.3
System with sinusoidal input

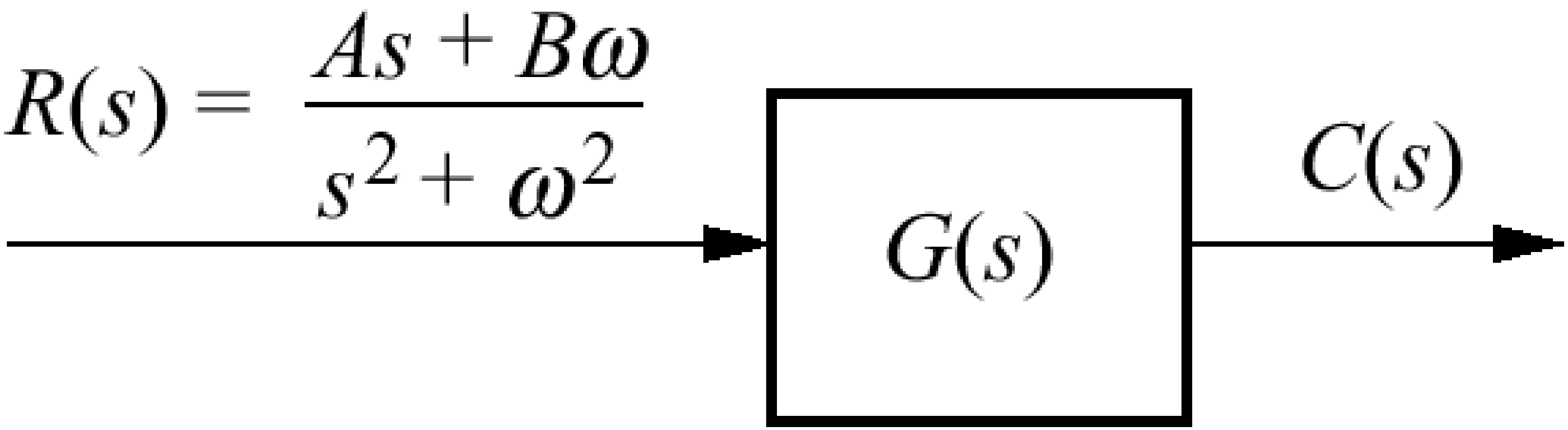


Figure 10.4
Frequency response plots for $G(s) = 1/(s + 2)$: separate magnitude and phase

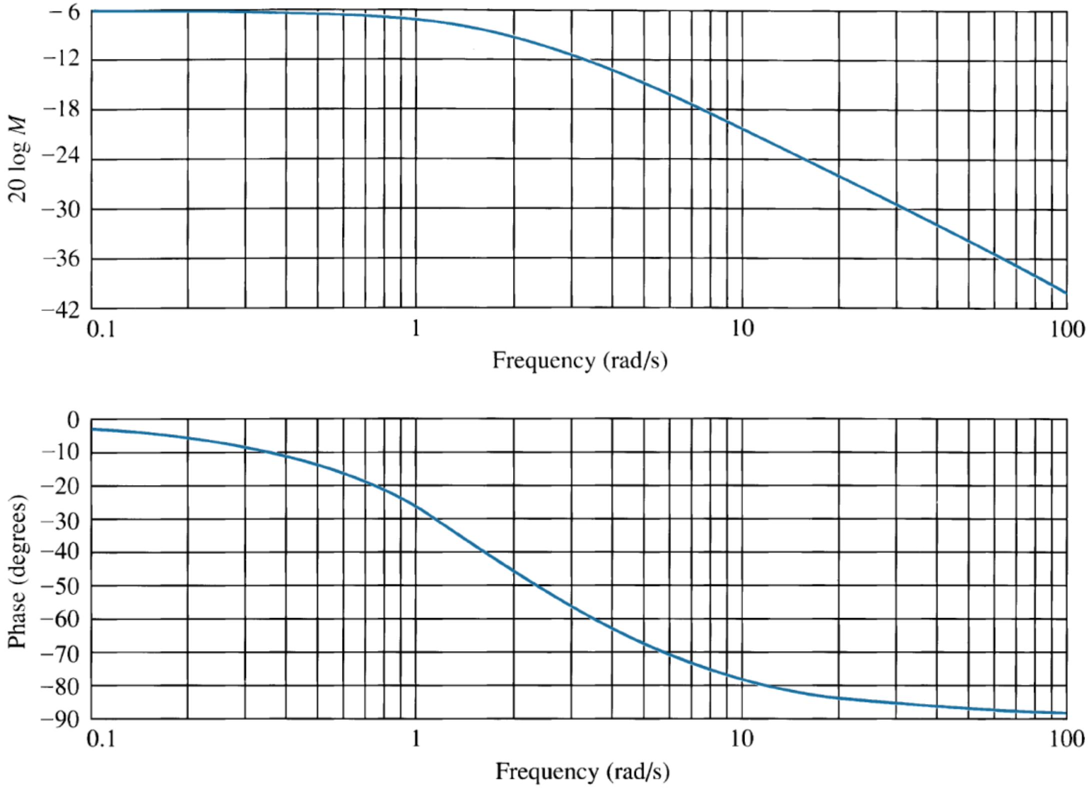
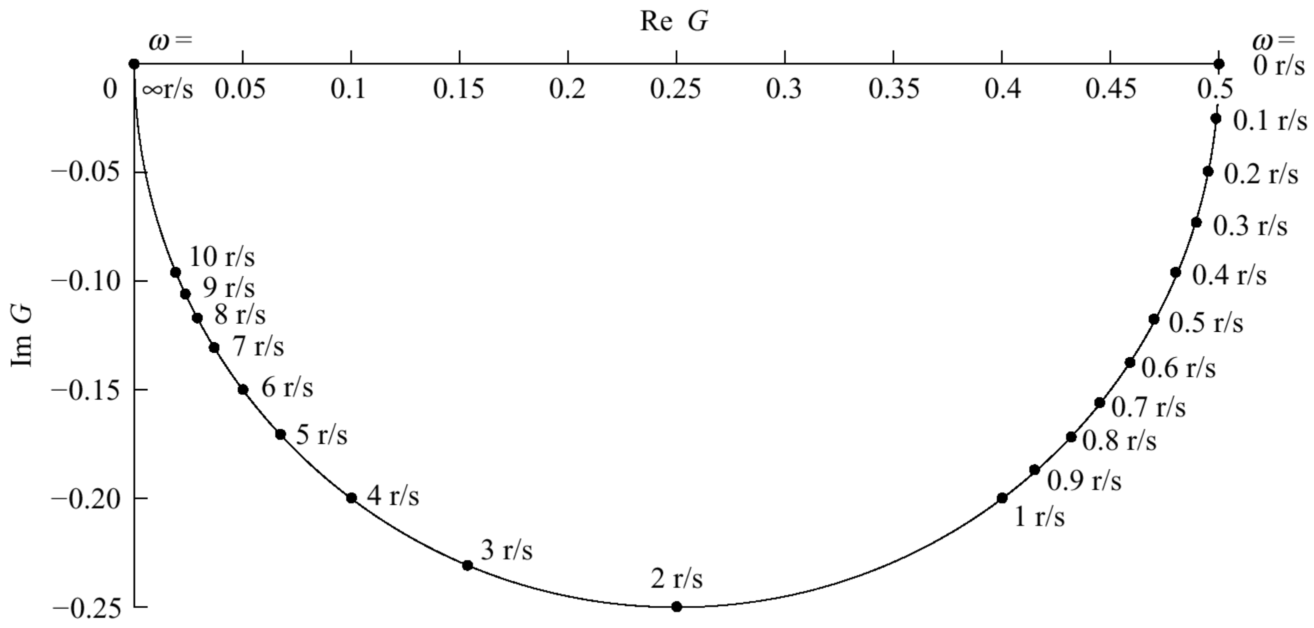
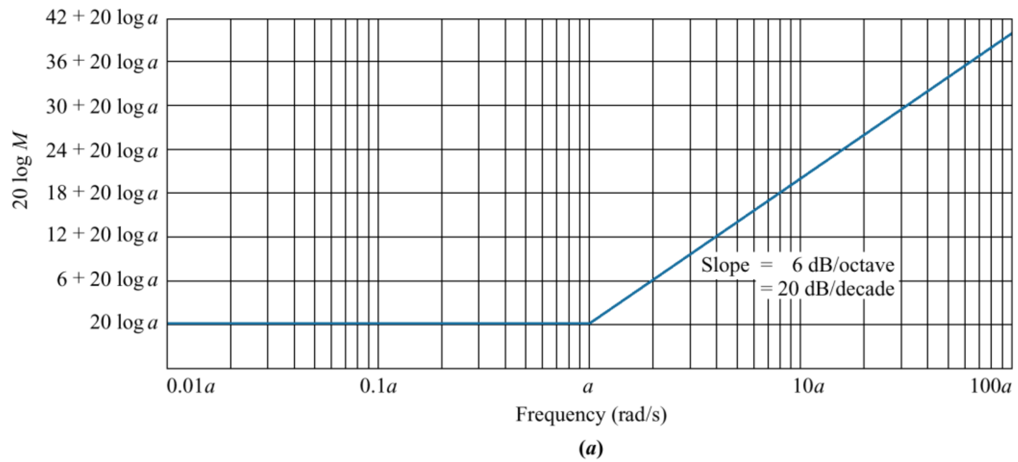


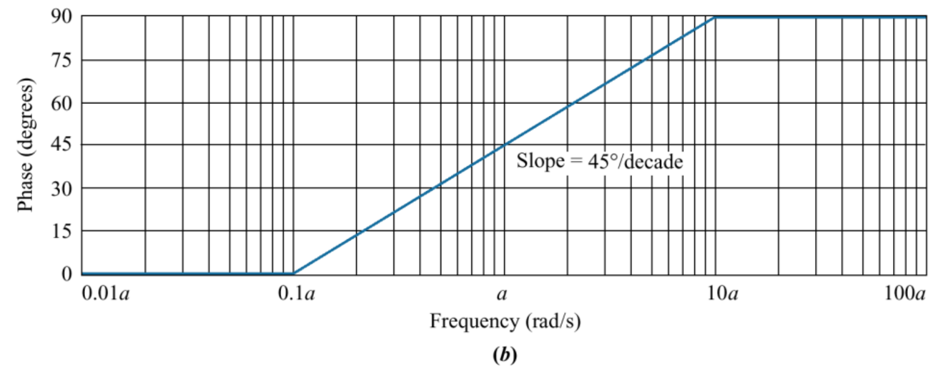
Figure 10.5
Frequency response plots for $G(s) = 1/(s + 2)$: polar plot



Note: r/s = rad/s

Figure 10.6
Bode plots of
(s + a):
a. magnitude plot;
b. phase plot**.**





Frequency a (rad/s)	$20 \log \frac{M}{a}$ (dB) Asymptotic	Actual	Phase (degrees) Asymptotic	Actual
0.01	0	0.00	0.00	0.57
0.02	0	0.00	0.00	1.15
0.04	0	0.01	0.00	2.29
0.06	0	0.02	0.00	3.43
0.08	0	0.03	0.00	4.57
0.1	0	0.04	0.00	5.71
0.2	0	0.17	13.55	11.31
0.4	0	0.64	27.09	21.80
0.6	0	1.34	35.02	30.96
0.8	0	2.15	40.64	38.66
1	0	3.01	45.00	45.00
2	6	6.99	58.55	63.43
4	12	12.30	72.09	75.96
6	15.56	15.68	80.02	80.54
8	18	18.13	85.64	82.87
10	20	20.04	90.00	84.29
20	26.02	26.03	90.00	87.14
40	32.04	32.04	90.00	88.57
60	35.56	35.56	90.00	89.05
80	38.06	38.06	90.00	89.28
100	40	40.00	90.00	89.43

Table 10.1

Asymptotic and actual nor frequency response data for (s + a)

Figure 10.7

Asymptotic and actual normalized and scaled magnitude response of
$(s + a)$

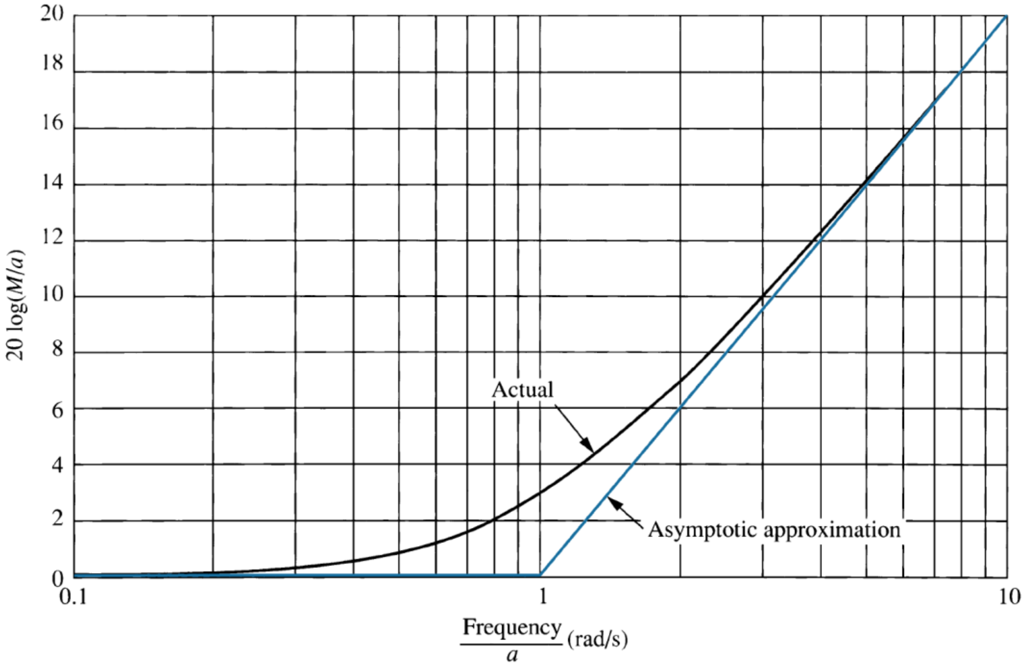


Figure 10.8

Asymptotic and actual normalized and scaled phase response of (s + a)

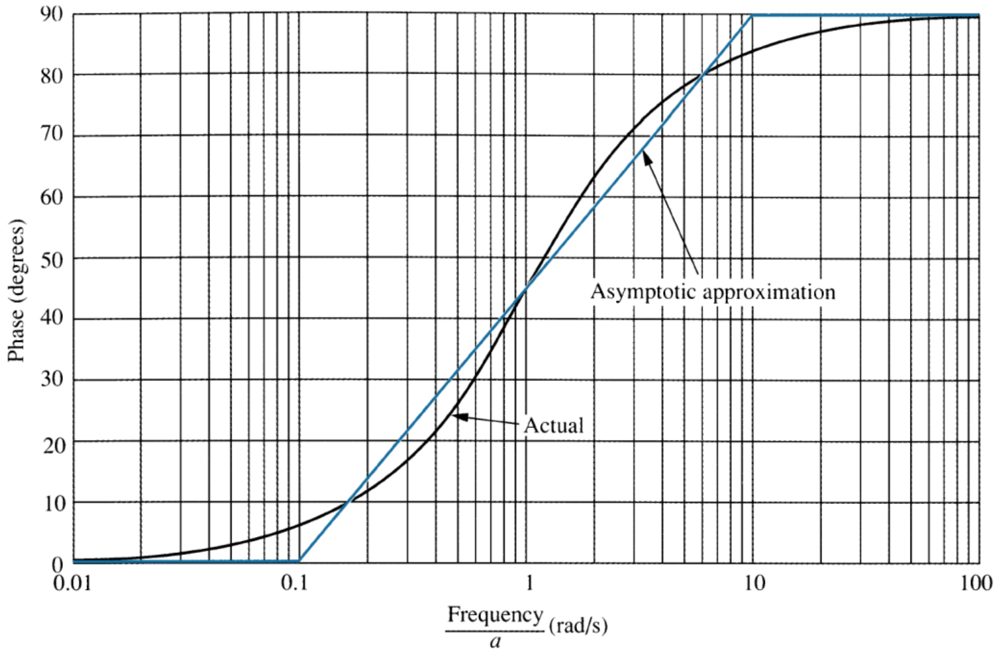


Figure 10.9

Normalized and scaled Bode plots for

a. $G(s) = s$;

b. $G(s) = 1/s$;

c. $G(s) = (s + a)$;

d. $G(s) = 1/(s + a)$

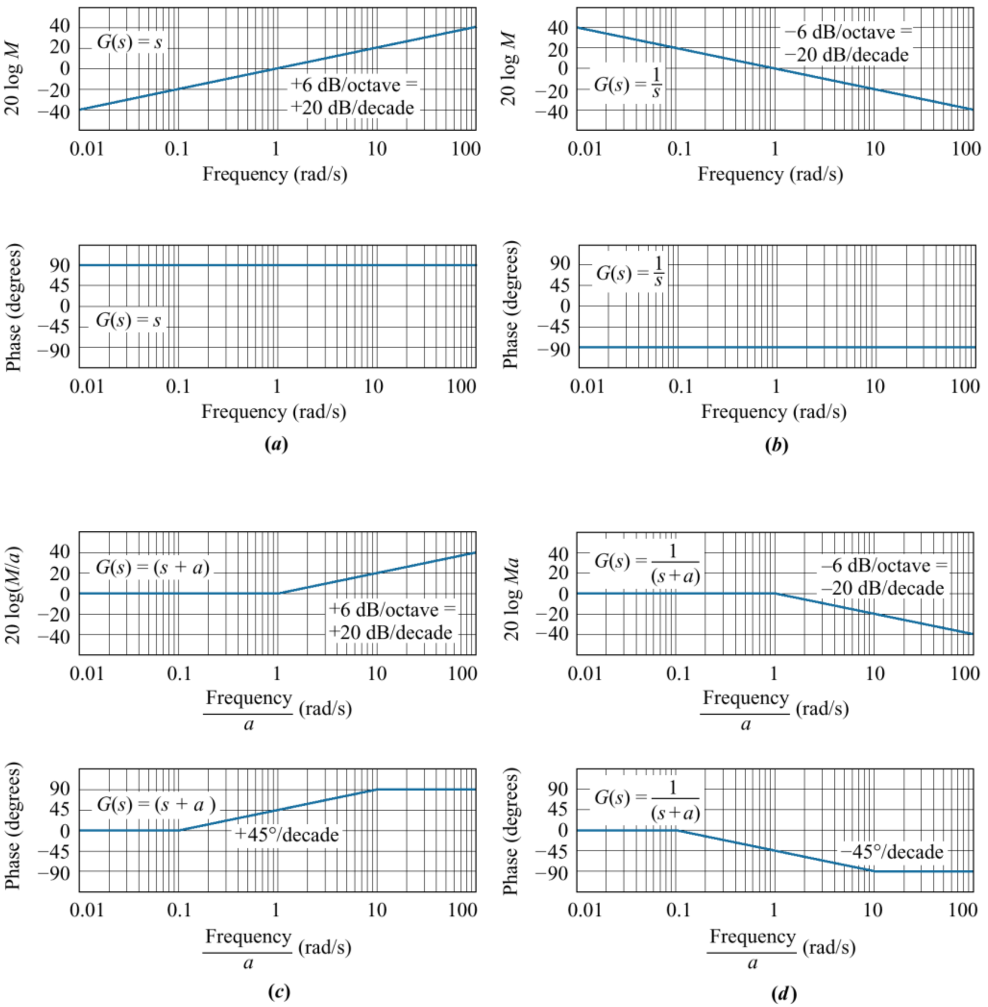


Figure 10.10 Closed-loop
unity
feedback system

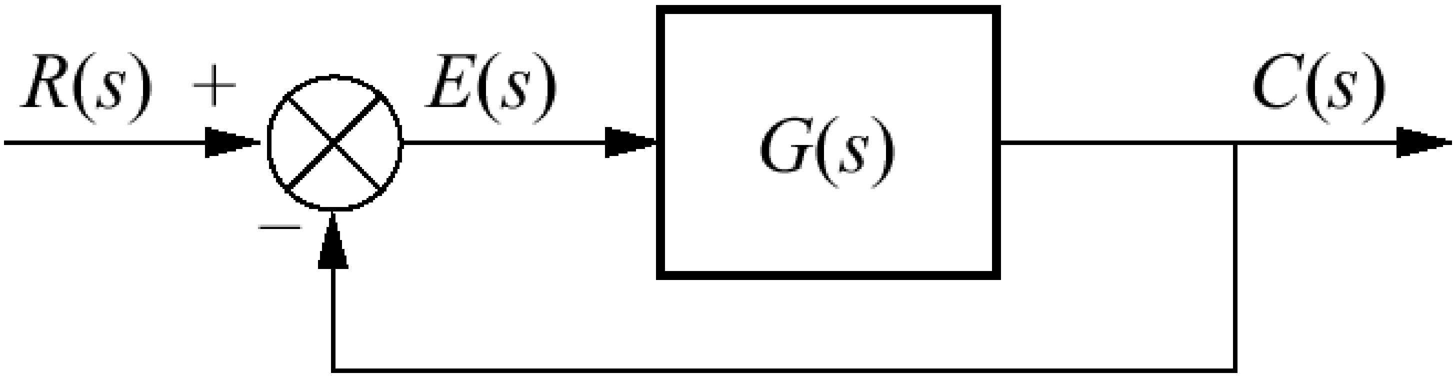


Figure 10.11

Bode
log-magnitude
plot for Example 10.2:
a. components;
b. composite

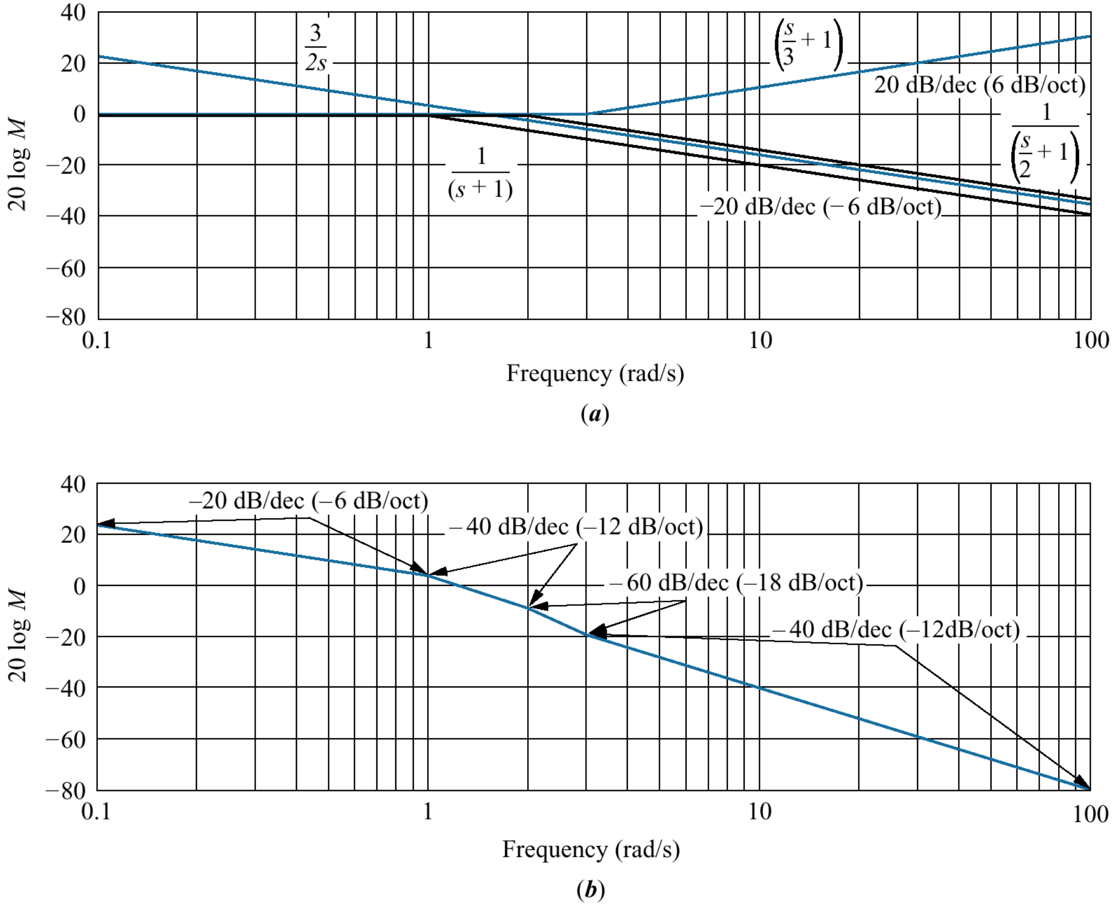


Figure 10.12

Bode phase plot for Example 10.2:
a. components;
b. composite

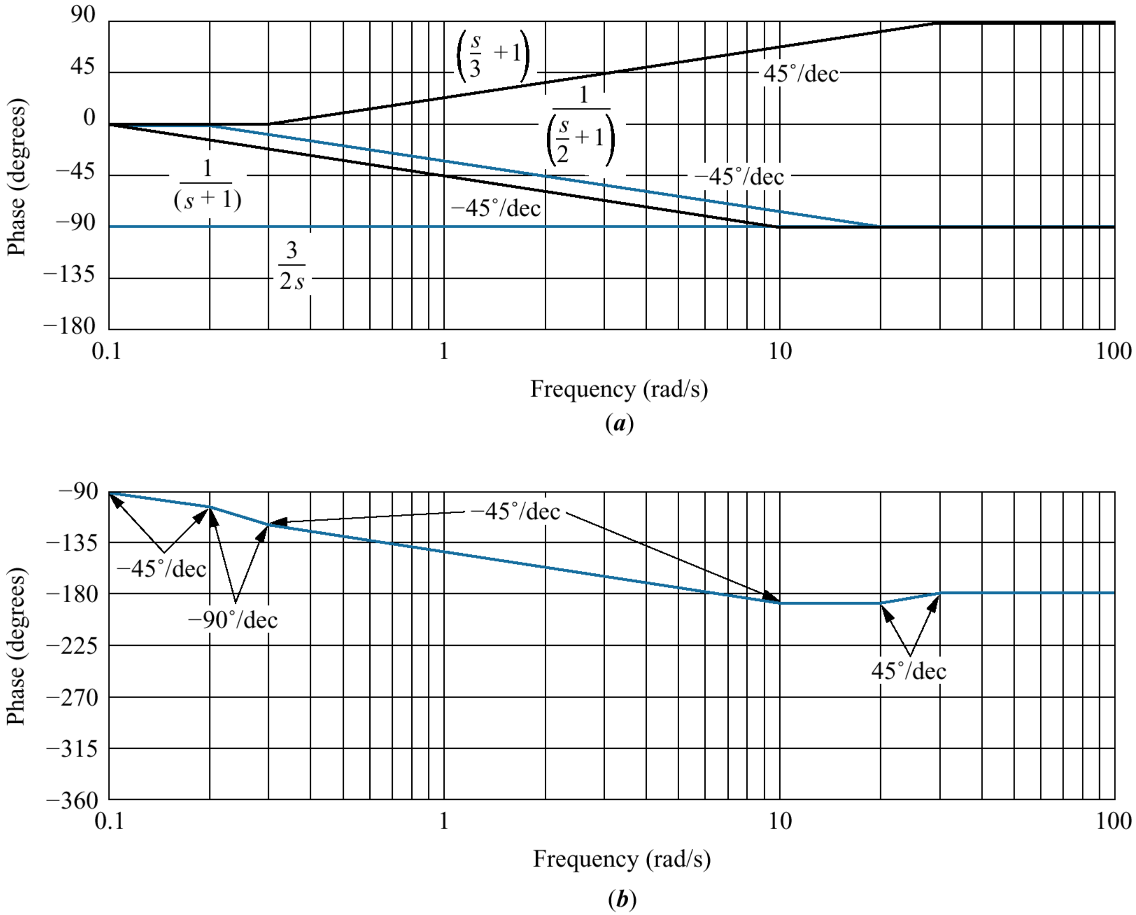


Figure 10.13
Bode asymptotes for normalized and scaled $G(s) =$

$$s^2 + 2\zeta\omega_n s + \omega_n^2:$$

a. magnitude;
b. phase

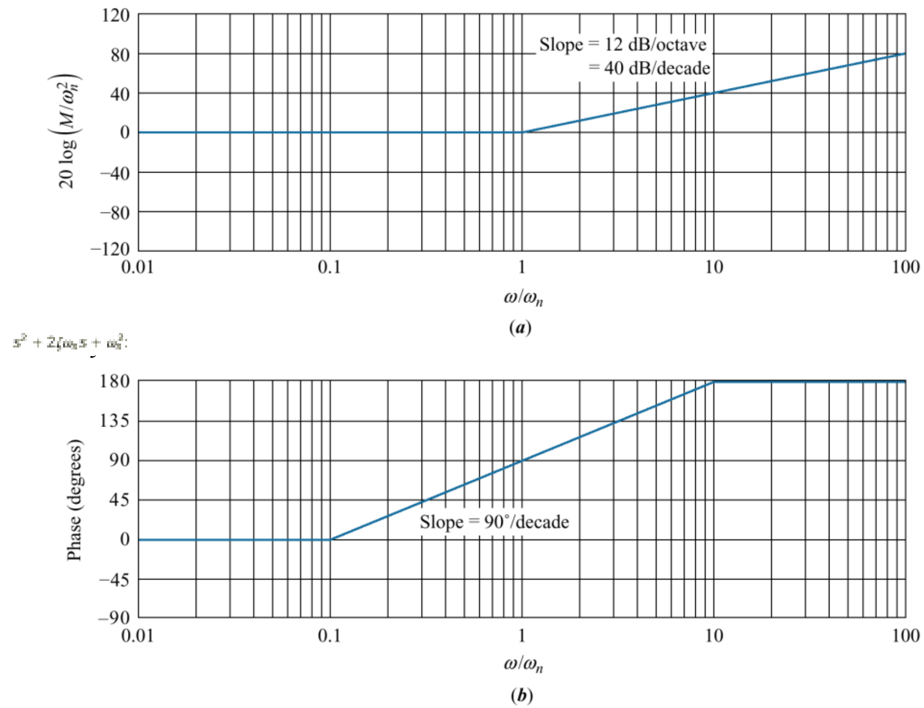


Table 10.4
Data for normalized and scaled log-magnitude and phase plots for $(s^2 + 2\zeta\omega_n s + \omega_n^2)$. Mag = 20 $\log(M/\omega_n^2)$
(table continues)

Freq. ω/ω_n	Mag (dB) $\zeta = 0.1$	Phase (deg) $\zeta = 0.1$	Mag (dB) $\zeta = 0.2$	Phase (deg) $\zeta = 0.2$	Mag (dB) $\zeta = 0.3$	Phase (deg) $\zeta = 0.3$
0.10	−0.09	1.16	−0.08	2.31	−0.07	3.47
0.20	−0.35	2.39	−0.32	4.76	−0.29	7.13
0.30	−0.80	3.77	−0.74	7.51	−0.65	11.19
0.40	−1.48	5.44	−1.36	10.78	−1.17	15.95
0.50	−2.42	7.59	−2.20	14.93	−1.85	21.80
0.60	−3.73	10.62	−3.30	20.56	−2.68	29.36
0.70	−5.53	15.35	−4.70	28.77	−3.60	39.47
0.80	−8.09	23.96	−6.35	41.63	−4.44	53.13
0.90	−11.64	43.45	−7.81	62.18	−4.85	70.62
1.00	−13.98	90.00	−7.96	90.00	−4.44	90.00
1.10	−10.34	133.67	−6.24	115.51	−3.19	107.65
1.20	−6.00	151.39	−3.73	132.51	−1.48	121.43
1.30	−2.65	159.35	−1.27	143.00	0.35	131.50
1.40	0.00	163.74	0.92	149.74	2.11	138.81
1.50	2.18	166.50	2.84	154.36	3.75	144.25
1.60	4.04	168.41	4.54	157.69	5.26	148.39
1.70	5.67	169.80	6.06	160.21	6.64	151.65
1.80	7.12	170.87	7.43	162.18	7.91	154.26
1.90	8.42	171.72	8.69	163.77	9.09	156.41
2.00	9.62	172.41	9.84	165.07	10.19	158.20
3.00	18.09	175.71	18.16	171.47	18.28	167.32
4.00	23.53	176.95	23.57	173.91	23.63	170.91
5.00	27.61	177.61	27.63	175.24	27.67	172.87
6.00	30.89	178.04	30.90	176.08	30.93	174.13
7.00	33.63	178.33	33.64	176.66	33.66	175.00
8.00	35.99	178.55	36.00	177.09	36.01	175.64
9.00	38.06	178.71	38.07	177.42	38.08	176.14
10.00	39.91	178.84	39.92	177.69	39.93	176.53

Freq. ω/ω_n	Mag (dB) $\zeta = 0.5$	Phase (deg) $\zeta = 0.5$	Mag (dB) $\zeta = 0.7$	Phase (deg) $\zeta = 0.7$	Mag (dB) $\zeta = 1$	Phase (deg) $\zeta = 1$
0.10	−0.04	5.77	0.00	8.05	0.09	11.42
0.20	−0.17	11.77	0.00	16.26	0.34	22.62
0.30	−0.37	18.25	0.02	24.78	0.75	33.40
0.40	−0.63	25.46	0.08	33.69	1.29	43.60
0.50	−0.90	33.69	0.22	43.03	1.94	53.13
0.60	−1.14	43.15	0.47	52.70	2.67	61.93
0.70	−1.25	53.92	0.87	62.51	3.46	69.98
0.80	−1.14	65.77	1.41	72.18	4.30	77.32
0.90	−0.73	78.08	2.11	81.42	5.15	83.97
1.00	0.00	90.00	2.92	90.00	6.02	90.00
1.10	0.98	100.81	3.83	97.77	6.89	95.45
1.20	2.13	110.14	4.79	104.68	7.75	100.39
1.30	3.36	117.96	5.78	110.76	8.60	104.86
1.40	4.60	124.44	6.78	116.10	9.43	108.92
1.50	5.81	129.81	7.76	120.76	10.24	112.62
1.60	6.98	134.27	8.72	124.85	11.03	115.99
1.70	8.10	138.03	9.66	128.45	11.80	119.07
1.80	9.17	141.22	10.56	131.63	12.55	121.89
1.90	10.18	143.95	11.43	134.46	13.27	124.48
2.00	11.14	146.31	12.26	136.97	13.98	126.87
3.00	18.63	159.44	19.12	152.30	20.00	143.13
4.00	23.82	165.07	24.09	159.53	24.61	151.93
5.00	27.79	168.23	27.96	163.74	28.30	157.38
6.00	31.01	170.27	31.12	166.50	31.36	161.08
7.00	33.72	171.70	33.80	168.46	33.98	163.74
8.00	36.06	172.76	36.12	169.92	36.26	165.75
9.00	38.12	173.58	38.17	171.05	38.28	167.32
10.00	39.96	174.23	40.00	171.95	40.09	168.58

Table 10.4 *(continued)*

Figure 10.14

Normalized and scaled log-magnitude response for

$$(s^2 + 2\zeta\omega_n s + \omega_n^2)$$

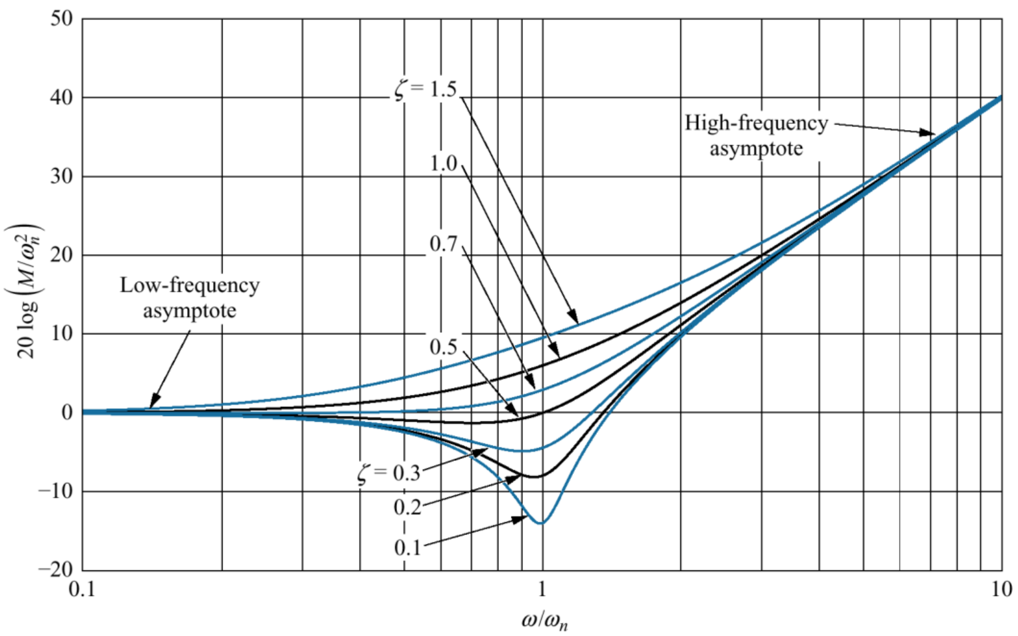


Figure 10.15

Scaled phase response for

$$(s^2 + 2\zeta\omega_n s + \omega_n^2)$$

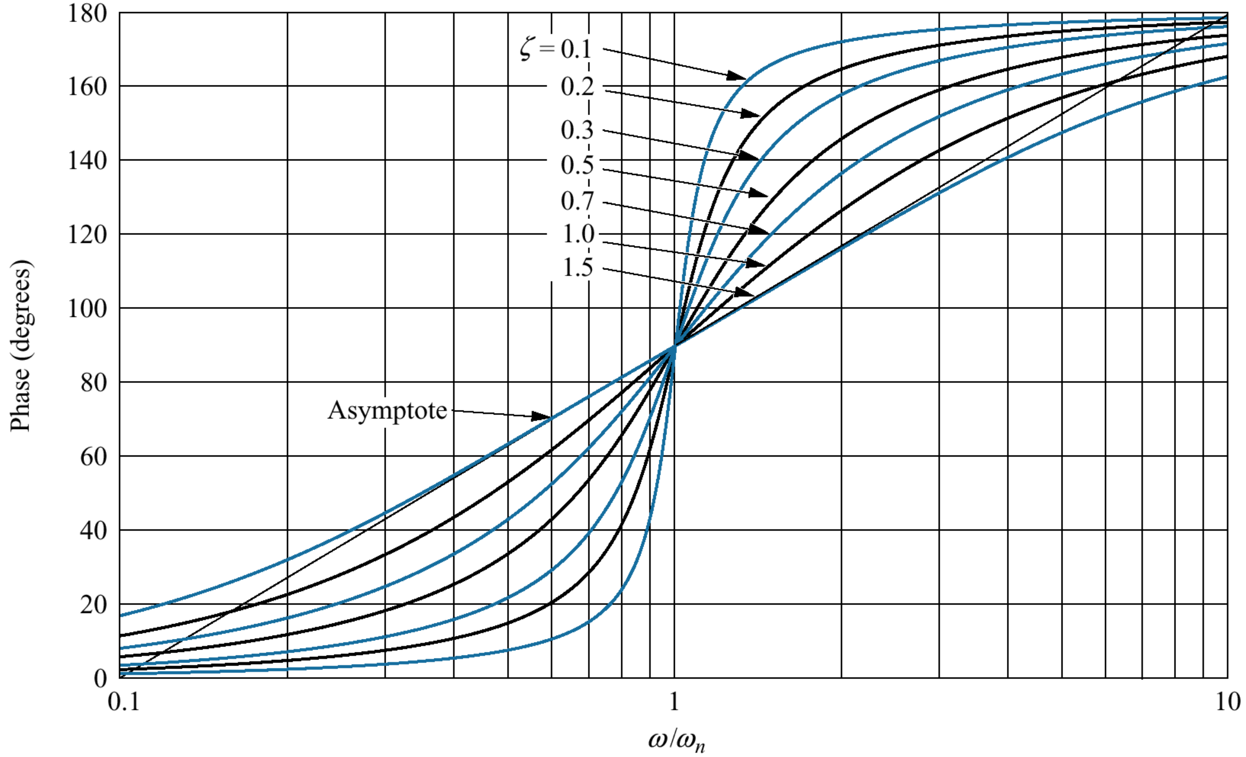


Table 10.5
Data for normalized and scaled log-magnitude and phase plots for $1/(s^2 + 2\zeta\omega_n s + \omega_n^2)$. Mag = $20 \log(M/\omega_n^2)$
(table continues)

Freq. ω/ω_n	**Mag (dB)** $\zeta = 0.1$	**Phase (deg)** $\zeta = 0.1$	**Mag (dB)** $\zeta = 0.2$	**Phase (deg)** $\zeta = 0.2$	**Mag (dB)** $\zeta = 0.3$	**Phase (deg)** $\zeta = 0.3$
0.10	0.09	−1.16	0.08	−2.31	0.07	−3.47
0.20	0.35	−2.39	0.32	−4.76	0.29	−7.13
0.30	0.80	−3.77	0.74	−7.51	0.65	−11.19
0.40	1.48	−5.44	1.36	−10.78	1.17	−15.95
0.50	2.42	−7.59	2.20	−14.93	1.85	−21.80
0.60	3.73	−10.62	3.30	−20.56	2.68	−29.36
0.70	5.53	−15.35	4.70	−28.77	3.60	−39.47
0.80	8.09	−23.96	6.35	−41.63	4.44	−53.13
0.90	11.64	−43.45	7.81	−62.18	4.85	−70.62
1.00	13.98	−90.00	7.96	−90.00	4.44	−90.00
1.10	10.34	−133.67	6.24	−115.51	3.19	−107.65
1.20	6.00	−151.39	3.73	−132.51	1.48	−121.43
1.30	2.65	−159.35	1.27	−143.00	−0.35	−131.50
1.40	0.00	−163.74	−0.92	−149.74	−2.11	−138.81
1.50	−2.18	−166.50	−2.84	−154.36	−3.75	−144.25
1.60	−4.04	−168.41	−4.54	−157.69	−5.26	−148.39
1.70	−5.67	−169.80	−6.06	−160.21	−6.64	−151.65
1.80	−7.12	−170.87	−7.43	−162.18	−7.91	−154.26
1.90	−8.42	−171.72	−8.69	−163.77	−9.09	−156.41
2.00	−9.62	−172.41	−9.84	−165.07	−10.19	−158.20
3.00	−18.09	−175.71	−18.16	−171.47	−18.28	−167.32
4.00	−23.53	−176.95	−23.57	−173.91	−23.63	−170.91
5.00	−27.61	−177.61	−27.63	−175.24	−27.67	−172.87
6.00	−30.89	−178.04	−30.90	−176.08	−30.93	−174.13
7.00	−33.63	−178.33	−33.64	−176.66	−33.66	−175.00
8.00	−35.99	−178.55	−36.00	−177.09	−36.01	−175.64
9.00	−38.06	−178.71	−38.07	−177.42	−38.08	−176.14
10.00	−39.91	−178.84	−39.92	−177.69	−39.93	−176.53

Freq. ω/ω_n	Mag (dB) $\zeta = 0.5$	Phase (deg) $\zeta = 0.5$	Mag (dB) $\zeta = 0.7$	Phase (deg) $\zeta = 0.7$	Mag (dB) $\zeta = 1$	Phase (deg) $\zeta = 1$
0.10	0.04	−5.77	0.00	−8.05	−0.09	−11.42
0.20	0.17	−11.77	0.00	−16.26	−0.34	−22.62
0.30	0.37	−18.25	−0.02	−24.78	−0.75	−33.40
0.40	0.63	−25.46	−0.08	−33.69	−1.29	−43.60
0.50	0.90	−33.69	−0.22	−43.03	−1.94	−53.13
0.60	1.14	−43.15	−0.47	−52.70	−2.67	−61.93
0.70	1.25	−53.92	−0.87	−62.51	−3.46	−69.98
0.80	1.14	−65.77	−1.41	−72.18	−4.30	−77.32
0.90	0.73	−78.08	−2.11	−81.42	−5.15	−83.97
1.00	0.00	−90.00	−2.92	−90.00	−6.02	−90.00
1.10	−0.98	−100.81	−3.83	−97.77	−6.89	−95.45
1.20	−2.13	−110.14	−4.79	−104.68	−7.75	−100.39
1.30	−3.36	−117.96	−5.78	−110.76	−8.60	−104.86
1.40	−4.60	−124.44	−6.78	−116.10	−9.43	−108.92
1.50	−5.81	−129.81	−7.76	−120.76	−10.24	−112.62
1.60	−6.98	−134.27	−8.72	−124.85	−11.03	−115.99
1.70	−8.10	−138.03	−9.66	−128.45	−11.80	−119.07
1.80	−9.17	−141.22	−10.56	−131.63	−12.55	−121.89
1.90	−10.18	−143.95	−11.43	−134.46	−13.27	−124.48
2.00	−11.14	−146.31	−12.26	−136.97	−13.98	−126.87
3.00	−18.63	−159.44	−19.12	−152.30	−20.00	−143.13
4.00	−23.82	−165.07	−24.09	−159.53	−24.61	−151.93
5.00	−27.79	−168.23	−27.96	−163.74	−28.30	−157.38
6.00	−31.01	−170.27	−31.12	−166.50	−31.36	−161.08
7.00	−33.72	−171.70	−33.80	−168.46	−33.98	−163.74
8.00	−36.06	−172.76	−36.12	−169.92	−36.26	−165.75
9.00	−38.12	−173.58	−38.17	−171.05	−38.28	−167.32
10.00	−39.96	−174.23	−40.00	−171.95	−40.09	−168.58

Table 10.5 *(continued)*

Figure 10.16

Normalized and scaled log magnitude response for $1/(s^2 + 2\zeta\omega_n s + \omega_n^2)$

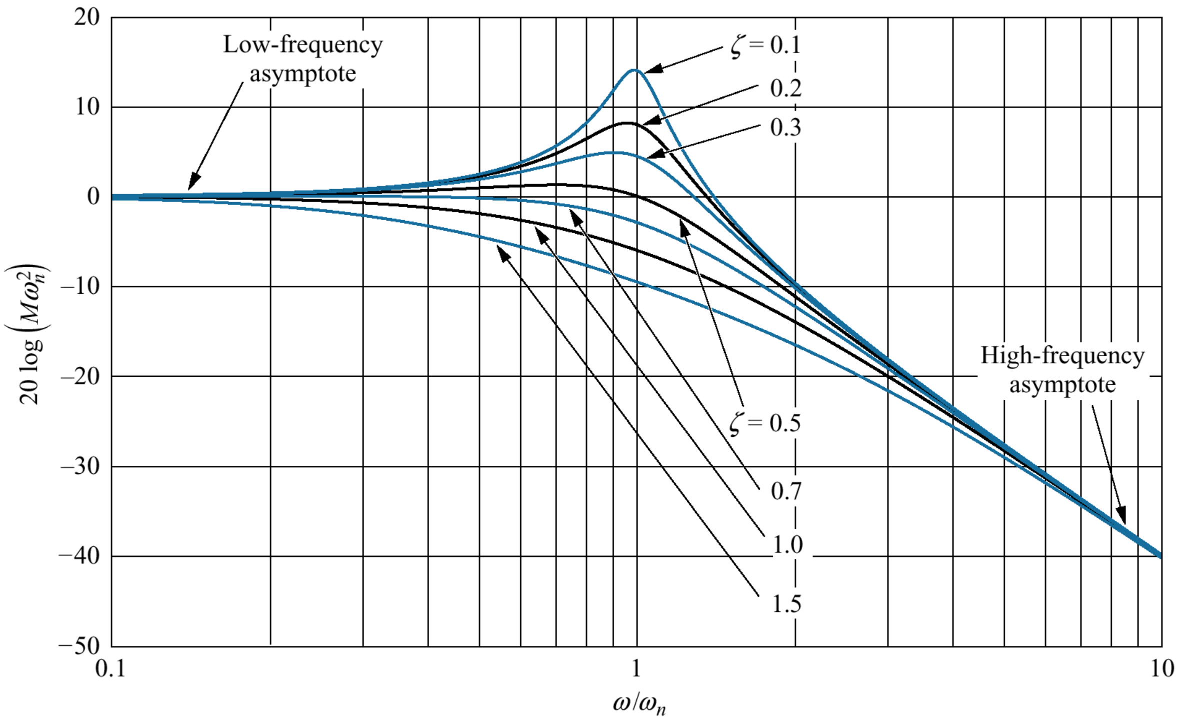


Figure 10.17

Scaled phase response for

$$1/(s^2 + 2\zeta\omega_n s + \omega_n^2)$$

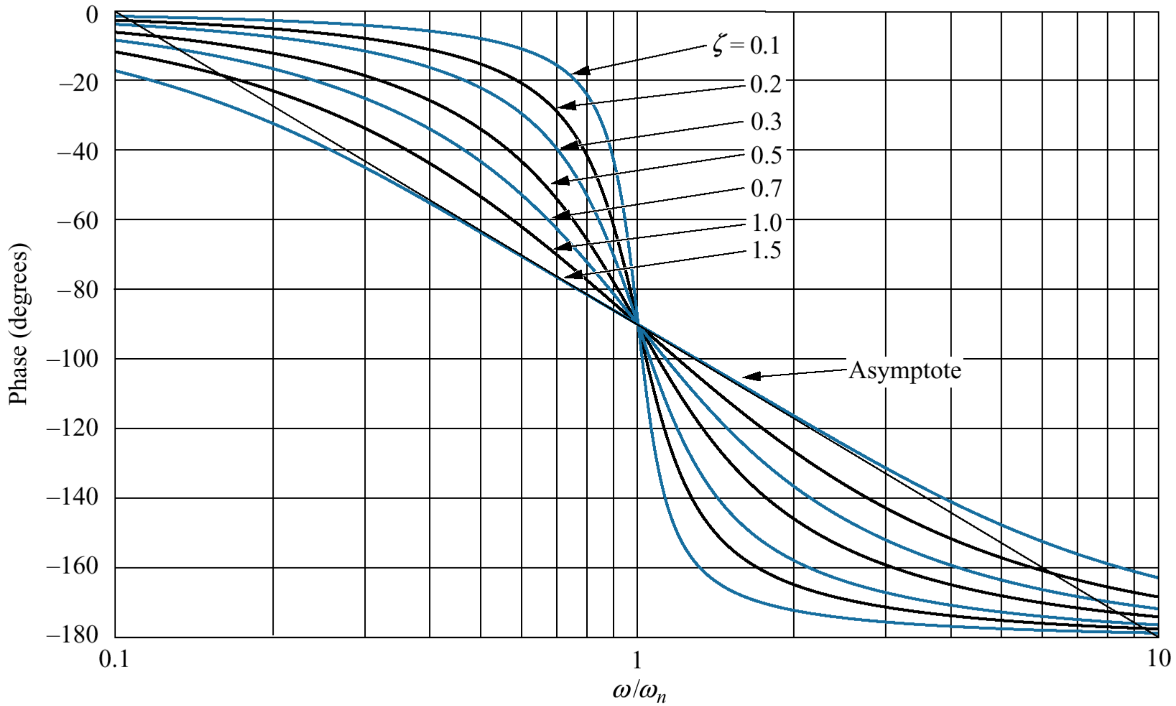


Figure 10.18

Bode magnitude plot for $G(s) = (s + 3)/[(s + 2)(s^2 + 2s + 25)]$:

a. components;

b. composite

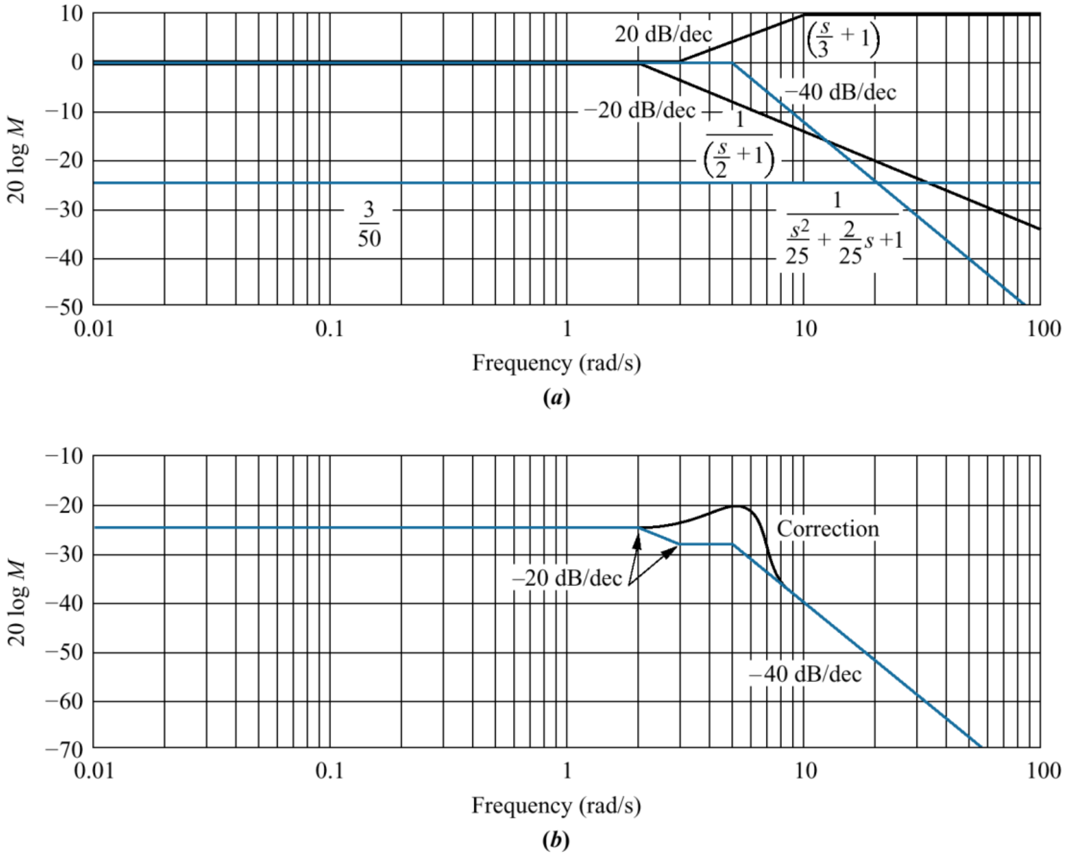


Table 10.7

Phase diagram slopes for Example 10.3

	Start: pole at -2	**Start: zero at -3**	**Start: ω_n at -5**	**End: pole at -2**	**End: zero at -3**	**End: $\omega_n = 5$**
Frequency (rad/s)	0.2	0.3	0.5	20	30	50
Pole at -2	-45	-45	-45	0		
Zero at -3		45	45	45	0	
$\omega_n = 5$			-90	-90	-90	0
Total slope (deg/dec)	-45	0	-90	-45	-90	0

Figure 10.19
Bode phase plot for
$G(s) =$
$(s + 3)/[(s + 2)$
$(s^2 + 2s + 25)]$:
a. components;
b. composite

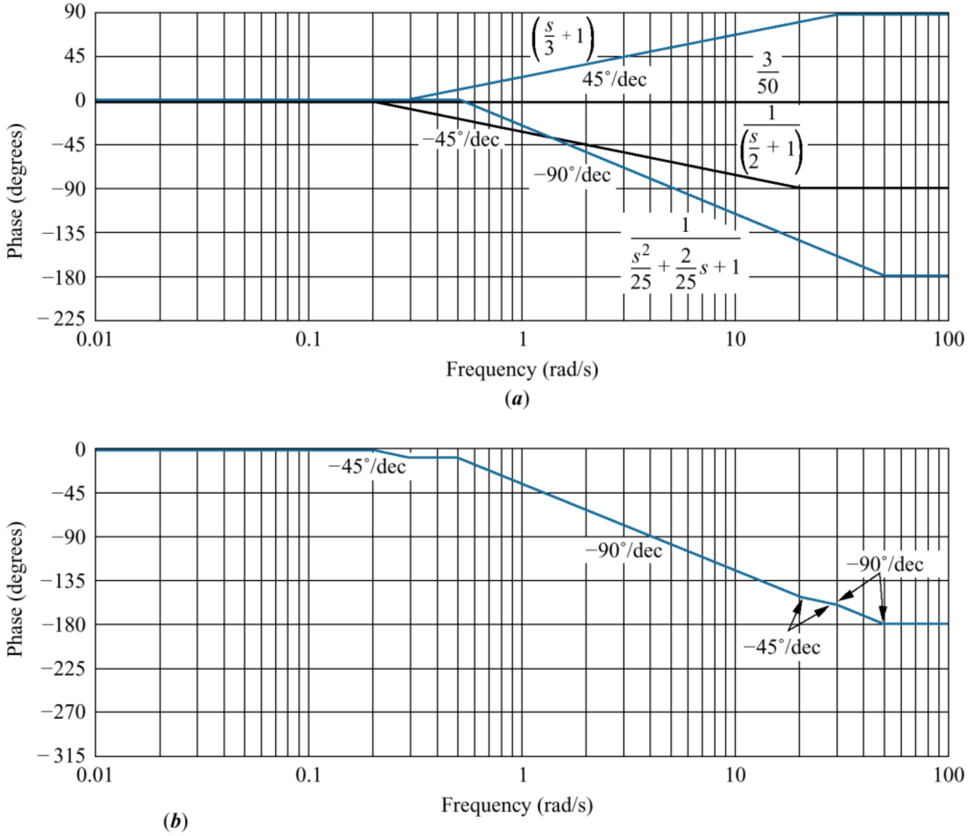


Figure 10.20
Closed-loop control system

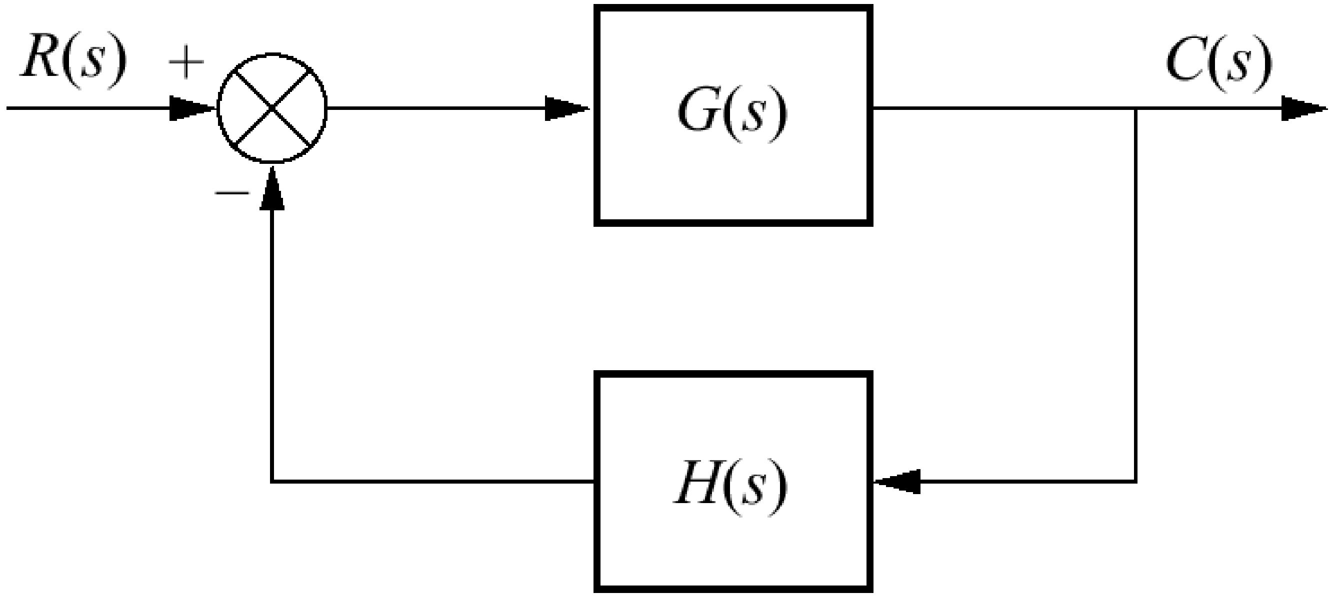


Figure 10.21
Mapping contour *A* through function *F*(*s*) to contour *B*

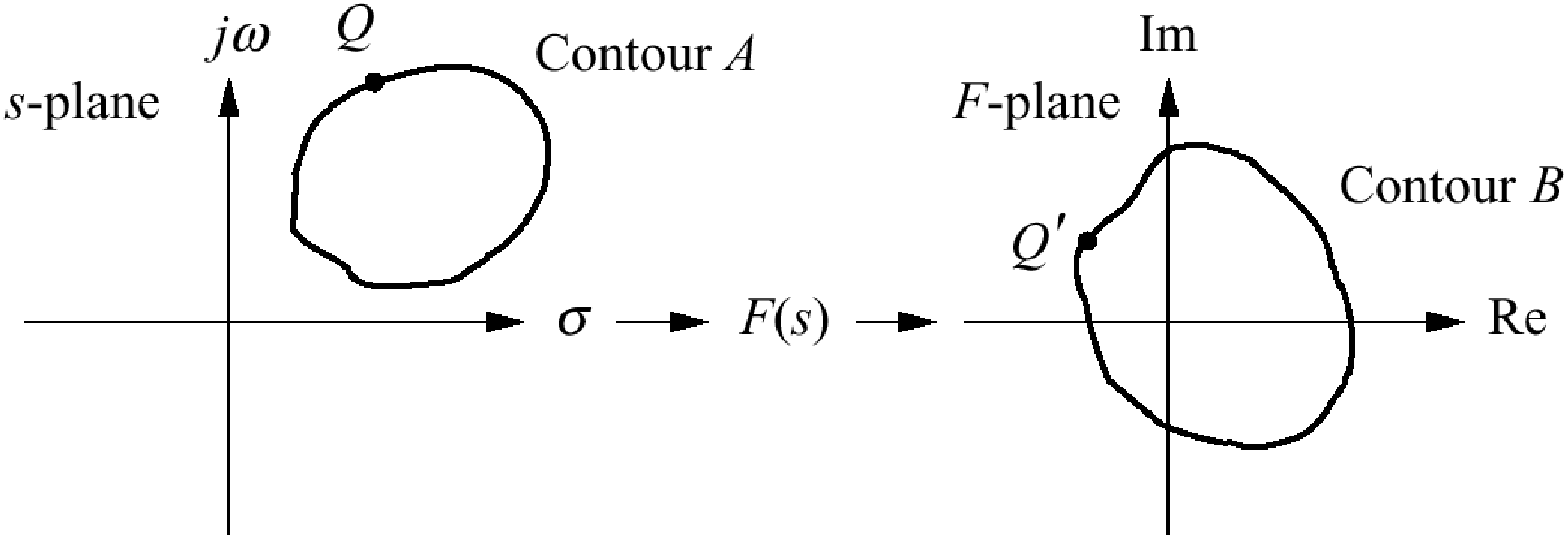


Figure 10.22
Examples of contour mapping

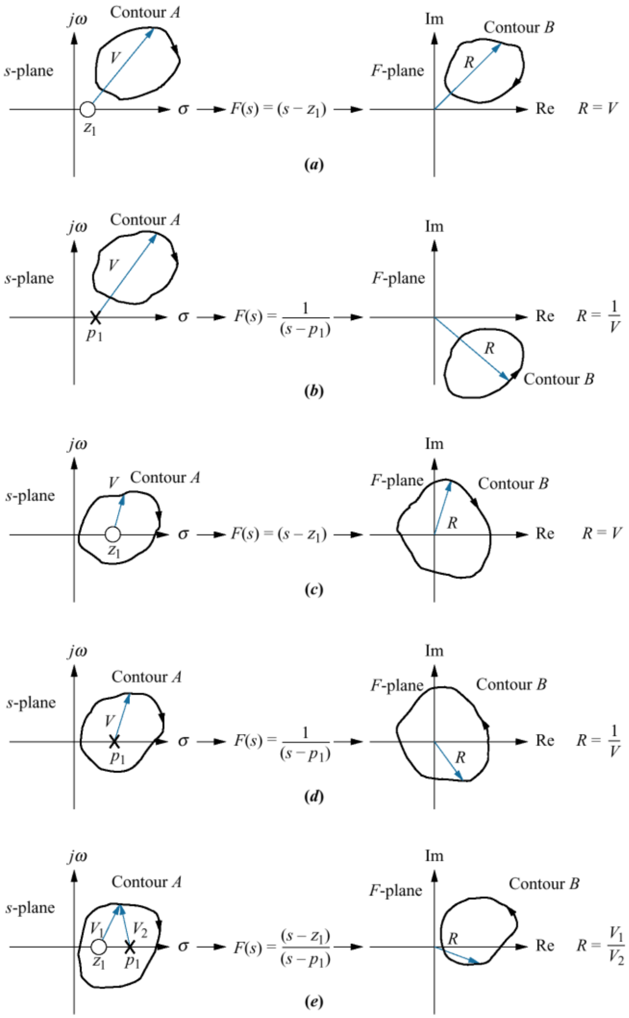


Figure 10.23
Vector representation of mapping

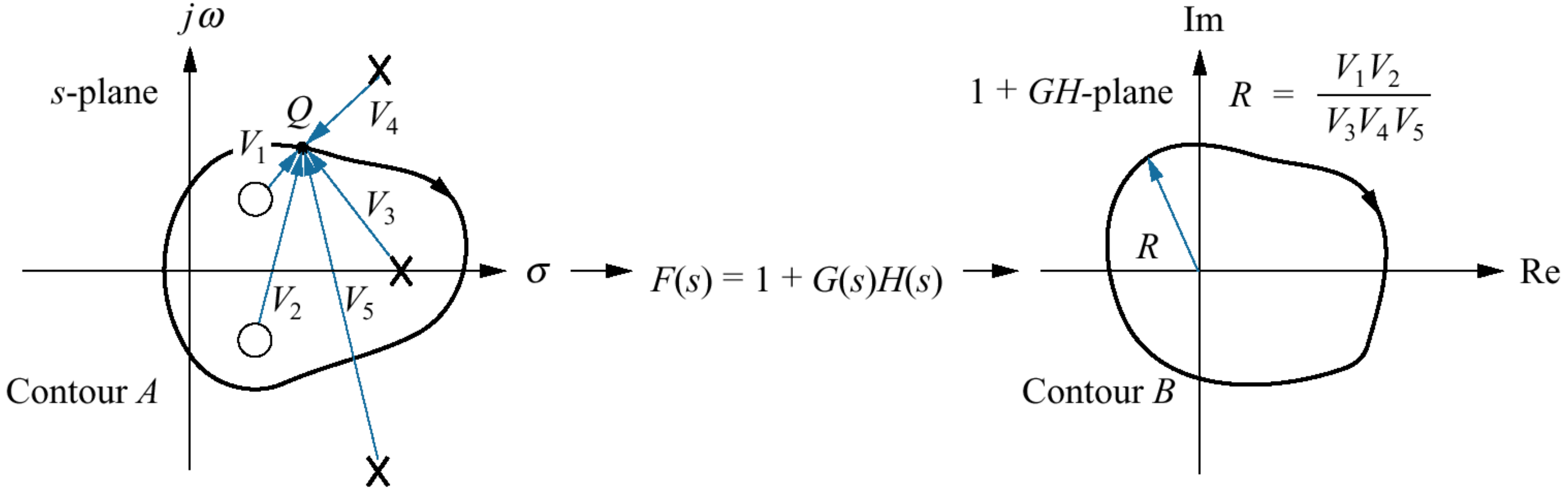


Figure 10.24
Contour enclosing
right half-plane
to determine stability

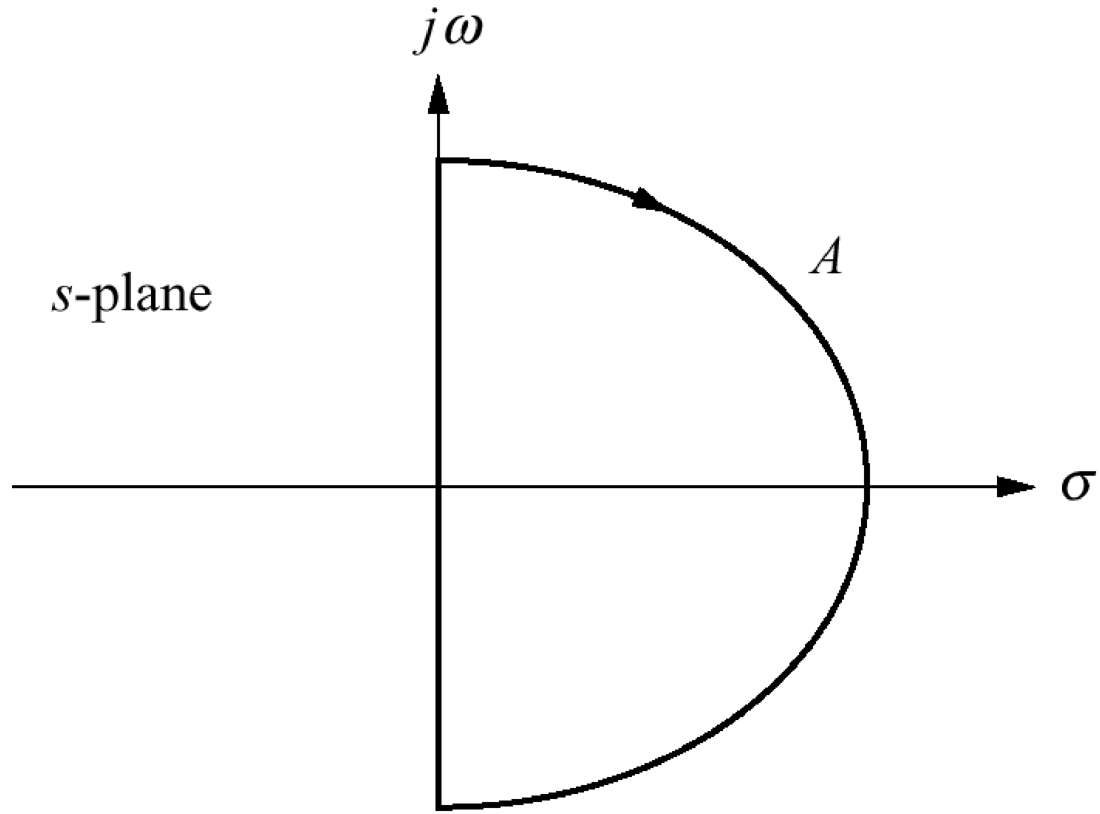


Figure 10.25

Mapping examples:

a. contour does not enclose closed-loop poles;

b. contour does enclose closed-loop poles

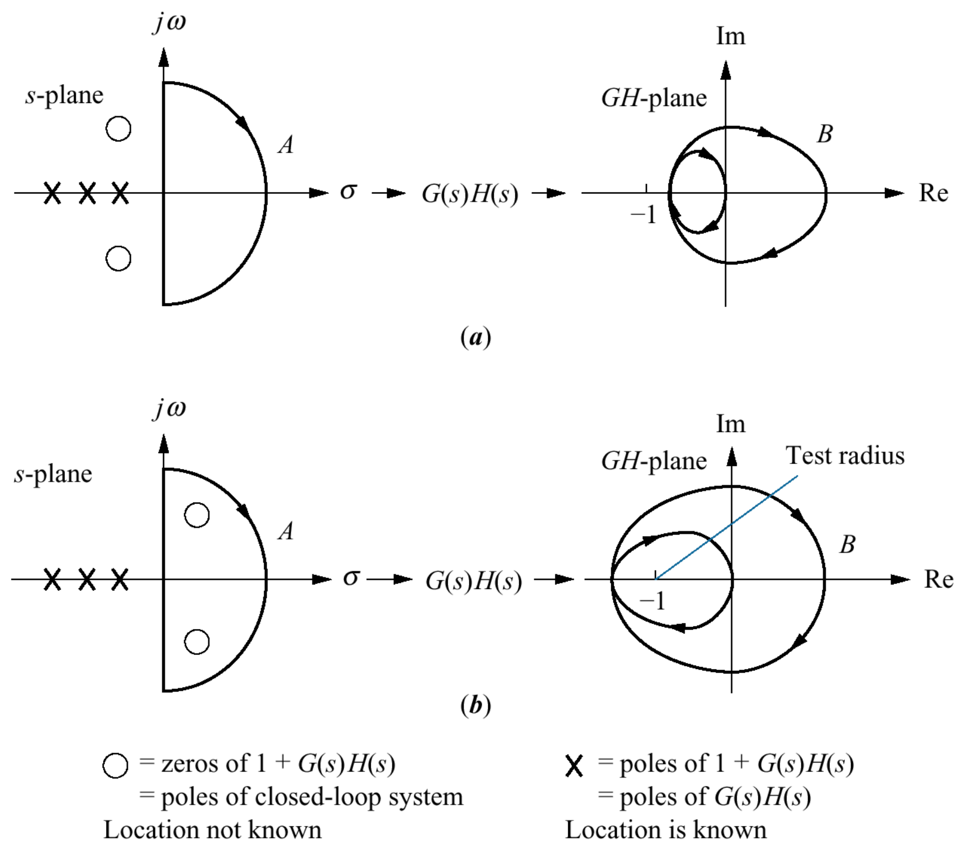


Figure 10.26
a. Turbine and generator;
b. block diagram of speed control system for Example 10.4

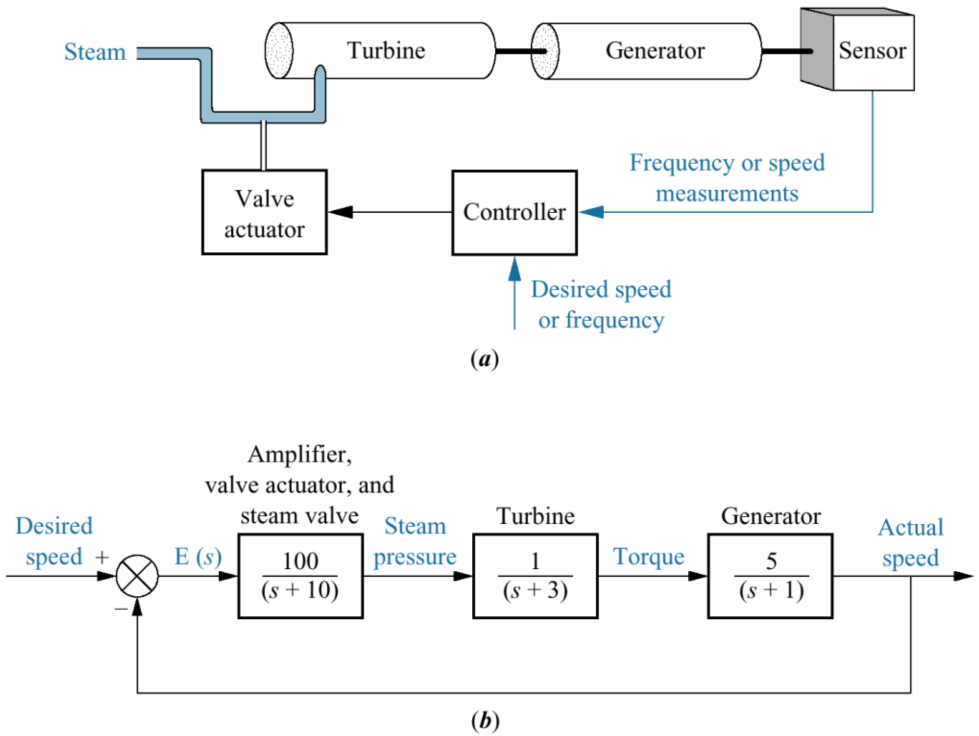


Figure 10.27

Vector evaluation of the Nyquist diagram for Example 10.4:

a. vectors on contour at low frequency;

b. vectors on contour around infinity;

c. Nyquist diagram

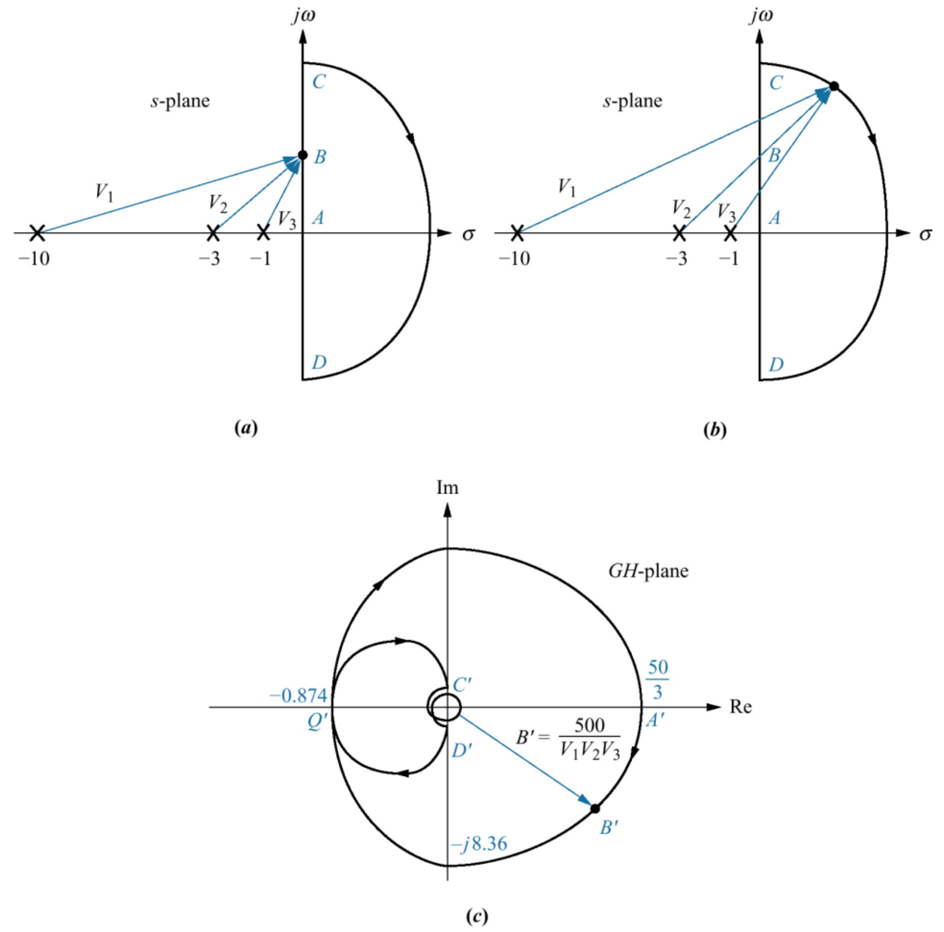


Figure 10.28

Detouring around open-loop poles:

a. poles on contour;

b. detour right;

c. detour left

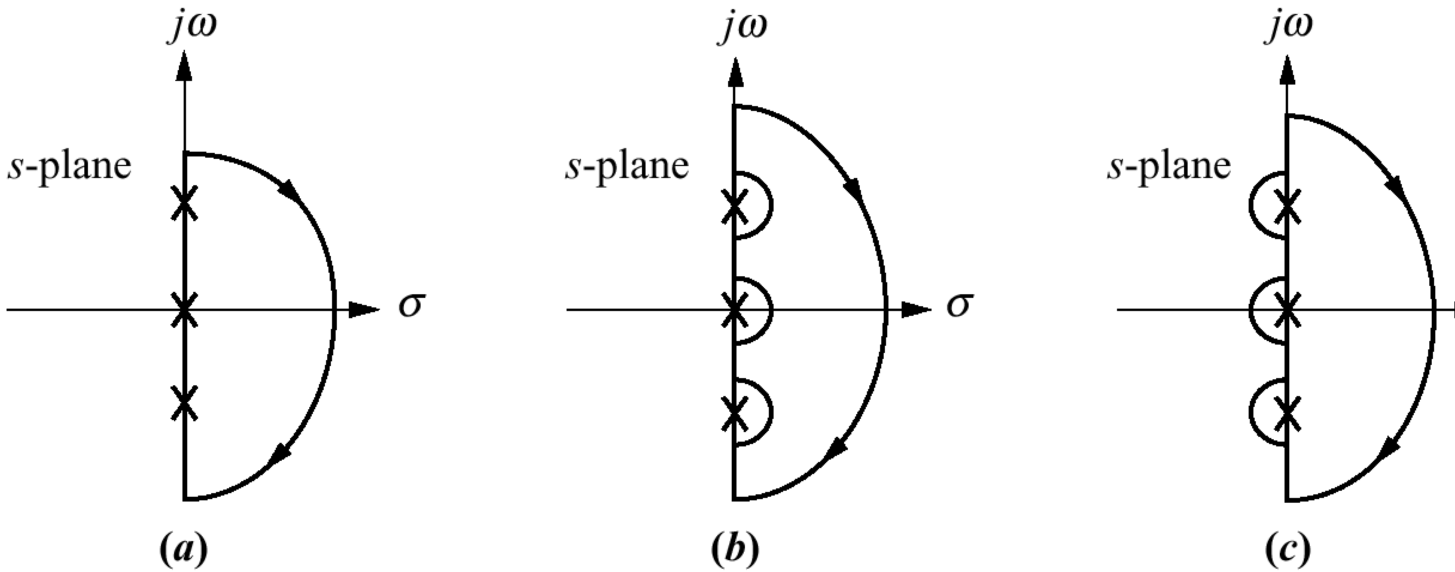
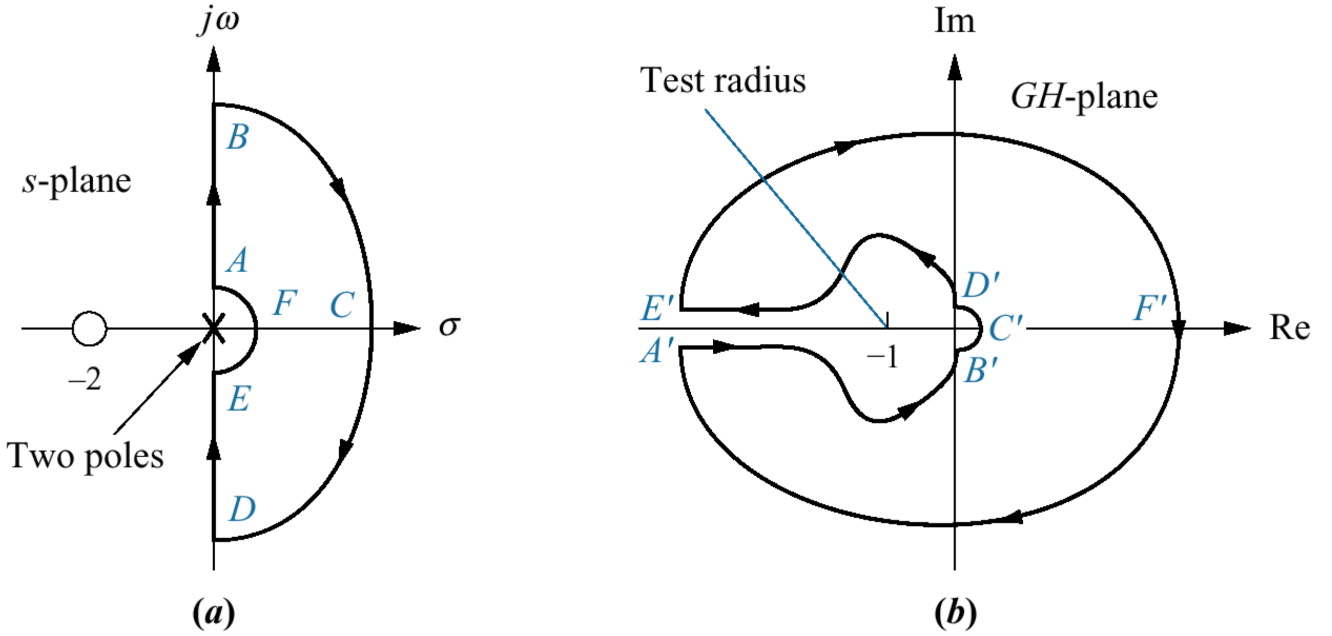


Figure 10.29

a. Contour for Example 10.5;

b. Nyquist diagram for Example 10.5



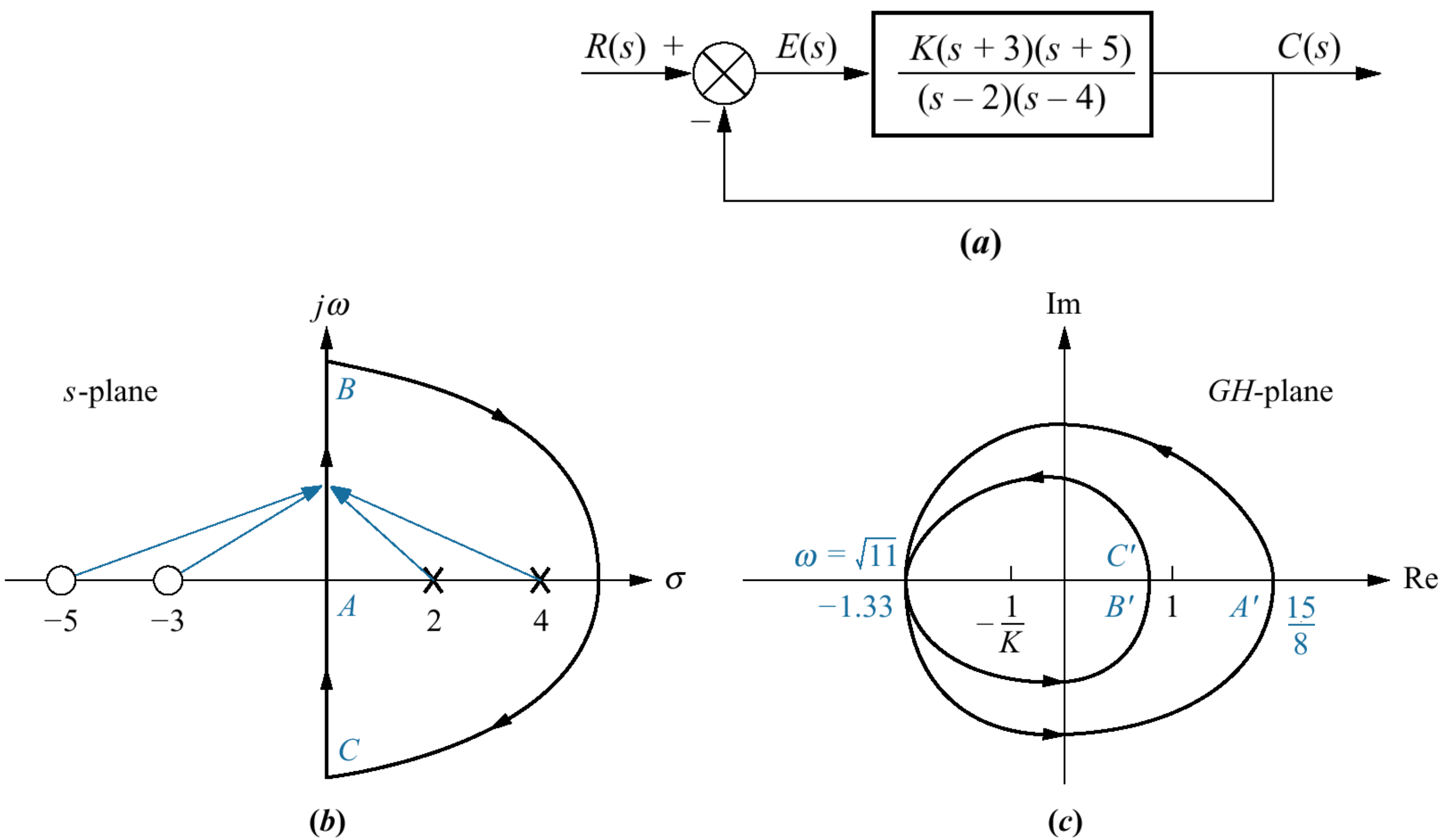


Figure 10.30

Demonstrating Nyquist stability:
a. system;
b. contour;
c. Nyquist diagram

Figure 10.31

a. Contour for Example 10.6;

b. Nyquist diagram

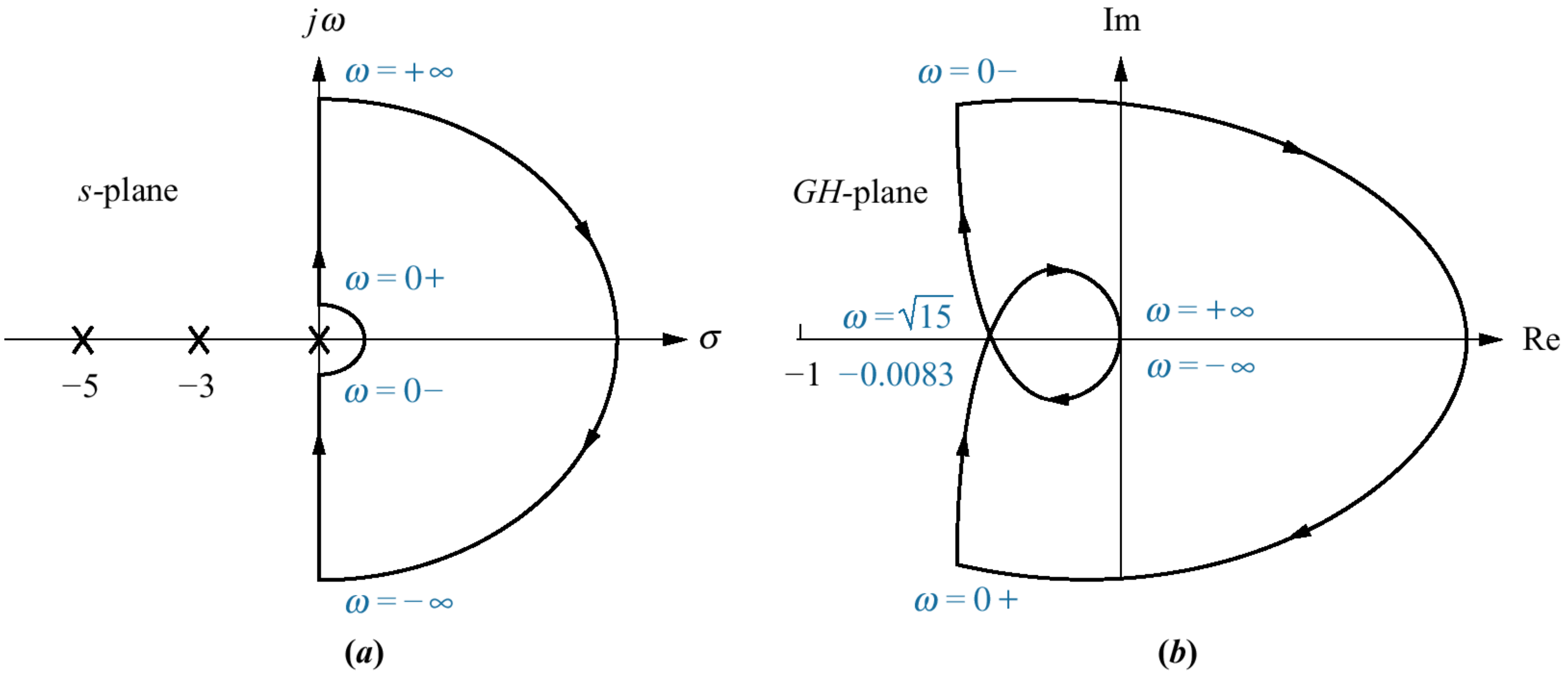


Figure 10.32

a. Contour and root locus of system that
is stable for small gain and unstable for large gain;
b. Nyquist diagram

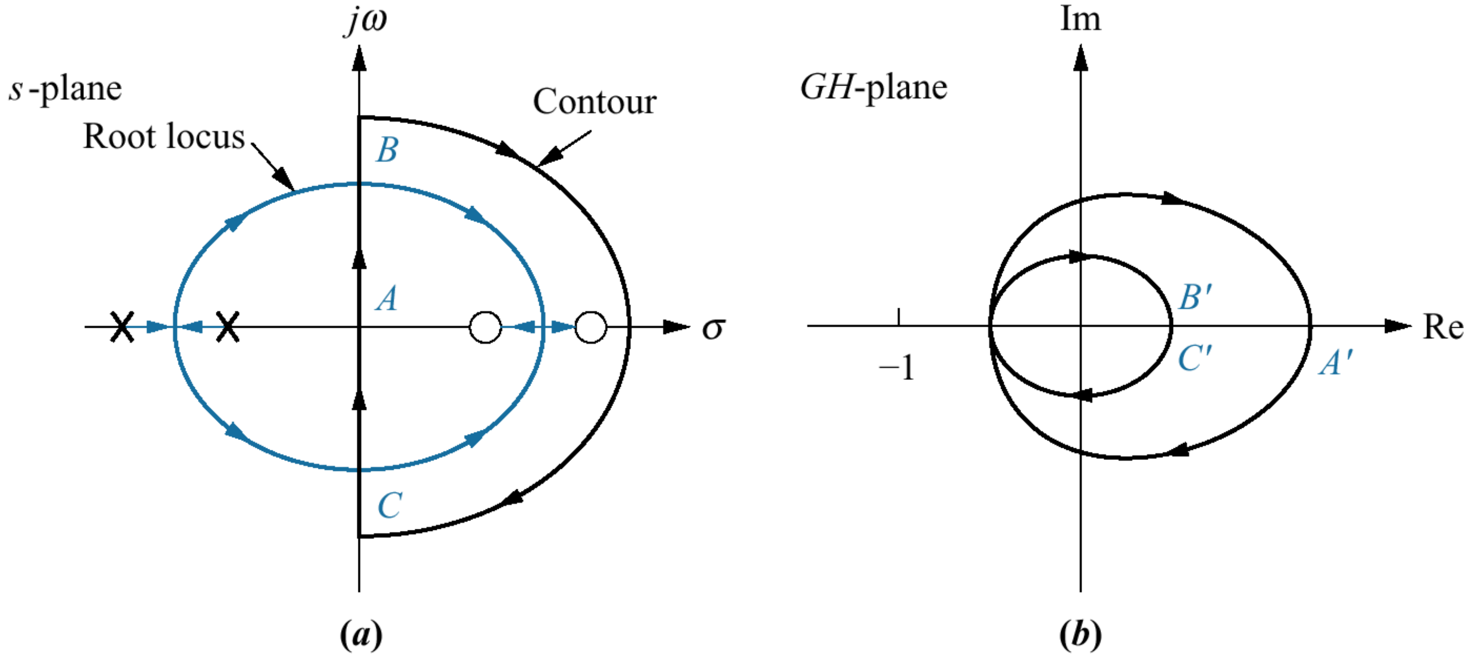


Figure 10.33

a. Contour and root locus of system that is unstable for small gain and stable for large gain;
b. Nyquist diagram

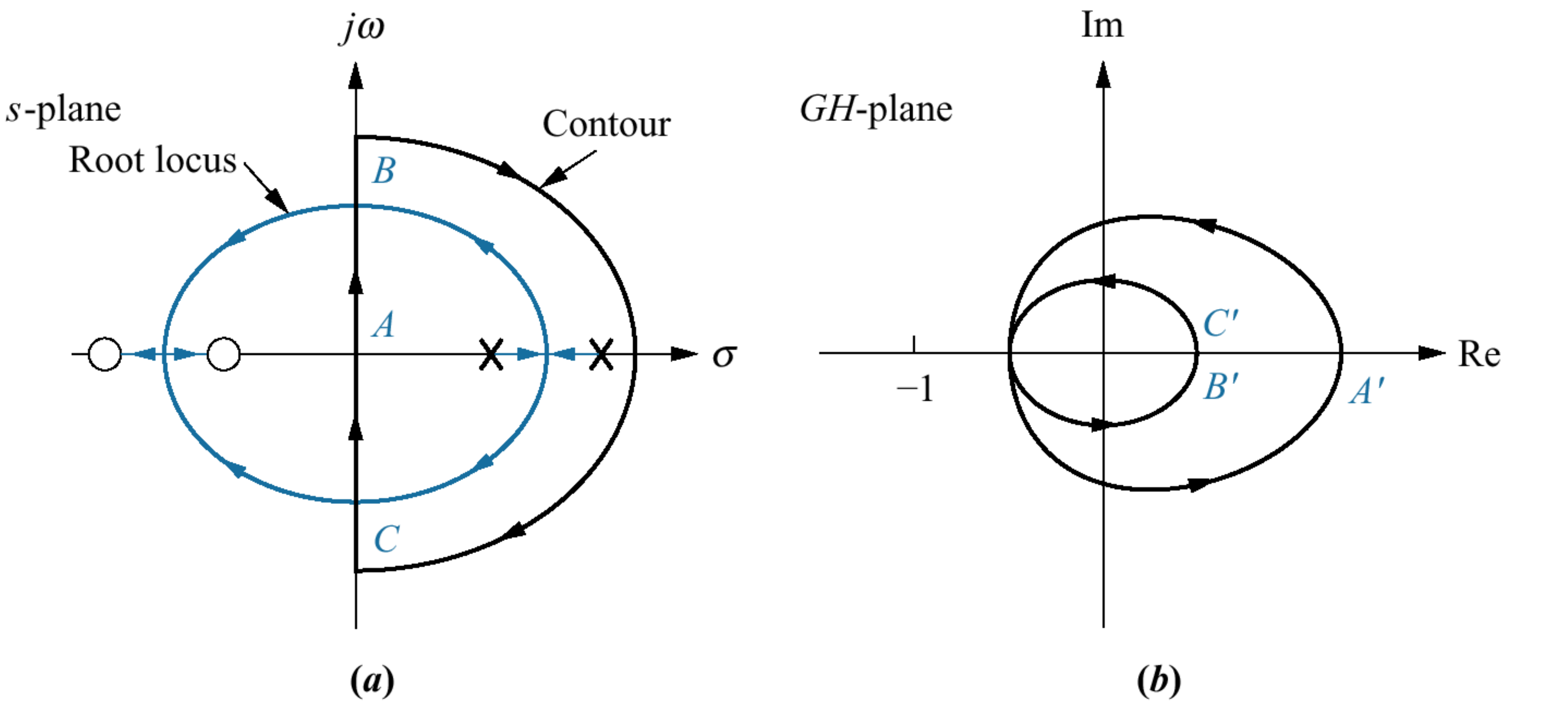


Figure 10.34

a. Portion of contour to be mapped for Example 10.7;
b. Nyquist diagram of mapping of positive imaginary axis

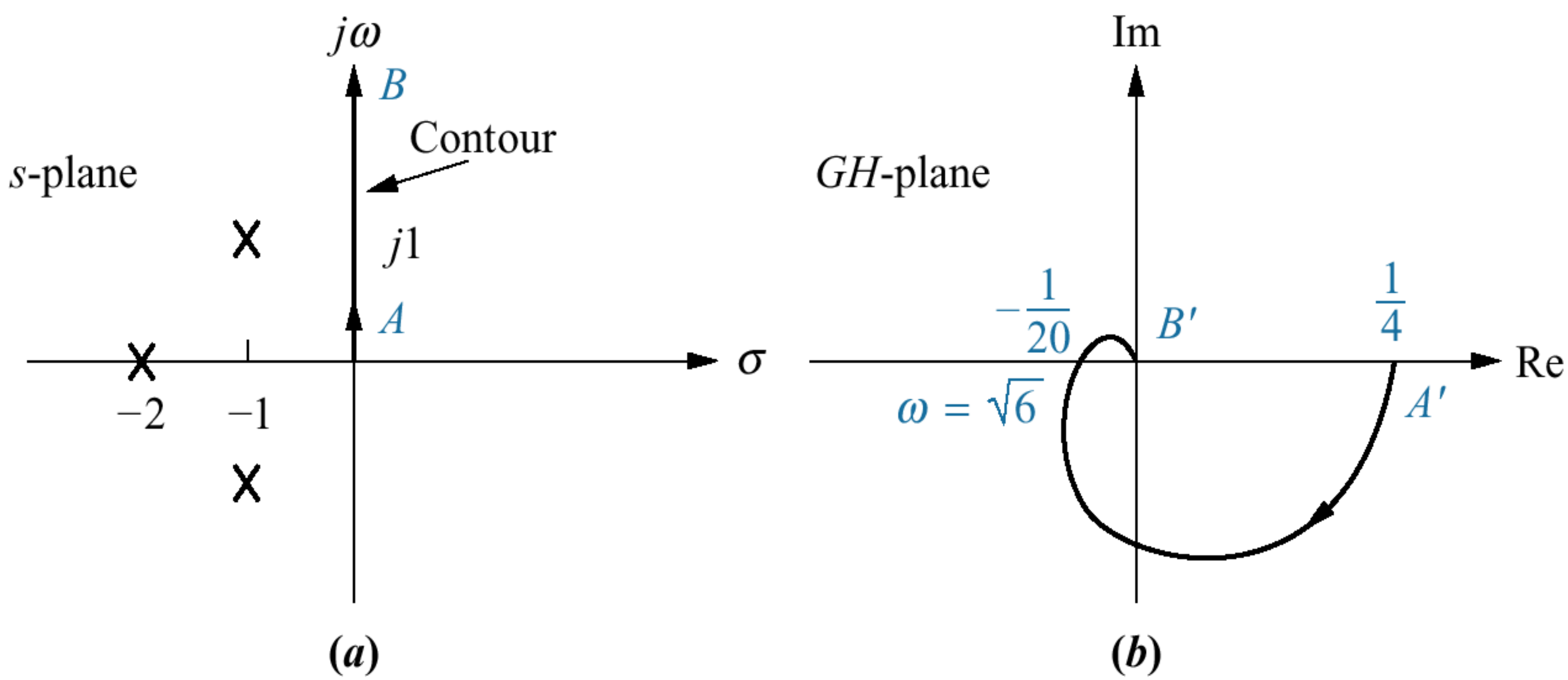


Figure 10.35
Nyquist diagram showing gain and phase margins

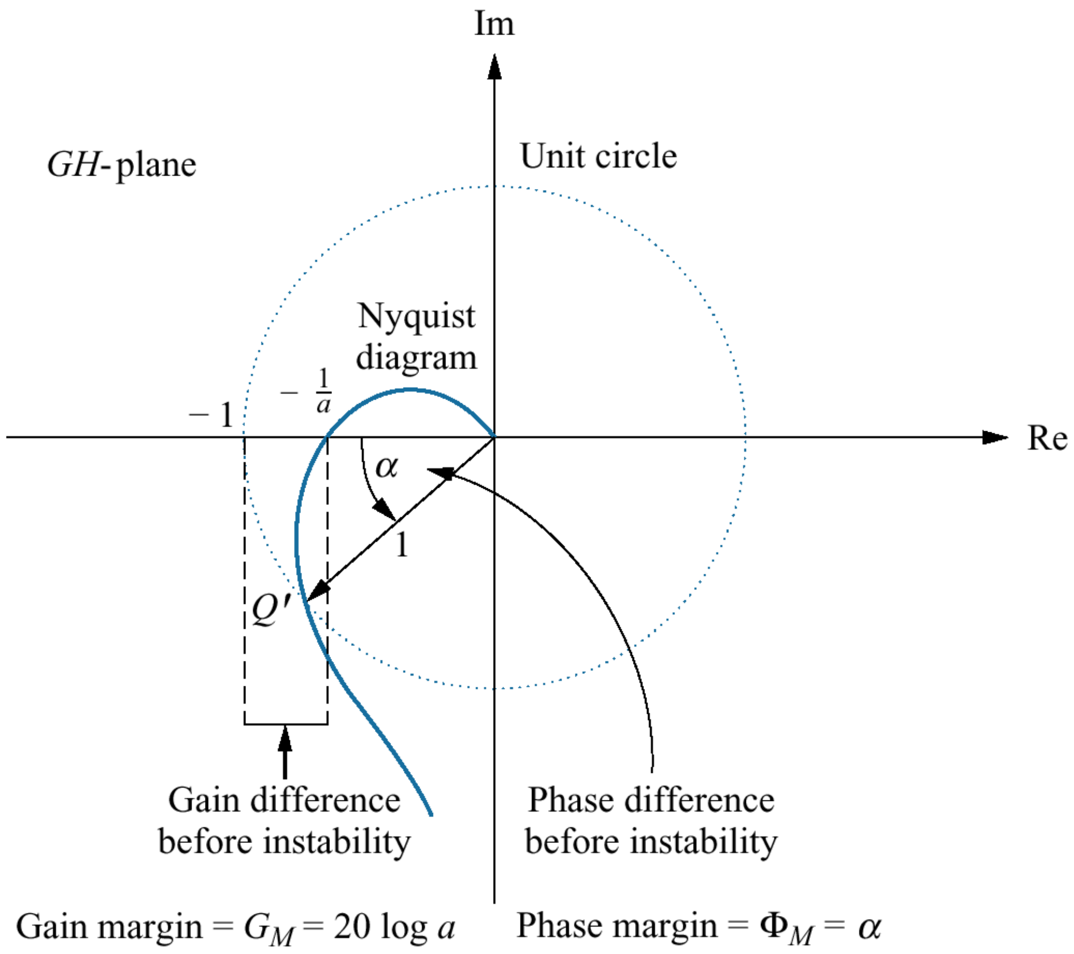


Figure 10.36

Bode
log-magnitude
and phase diagrams
for the system
of Example 10.9

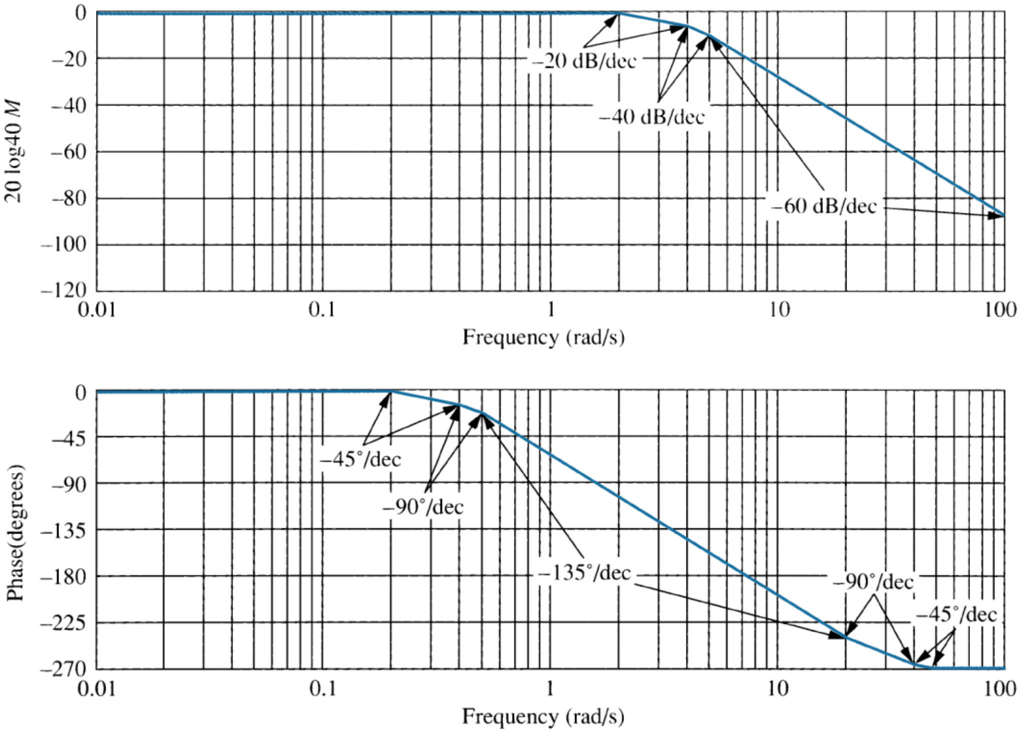


Figure 10.37
Gain and phase margins on the Bode diagrams

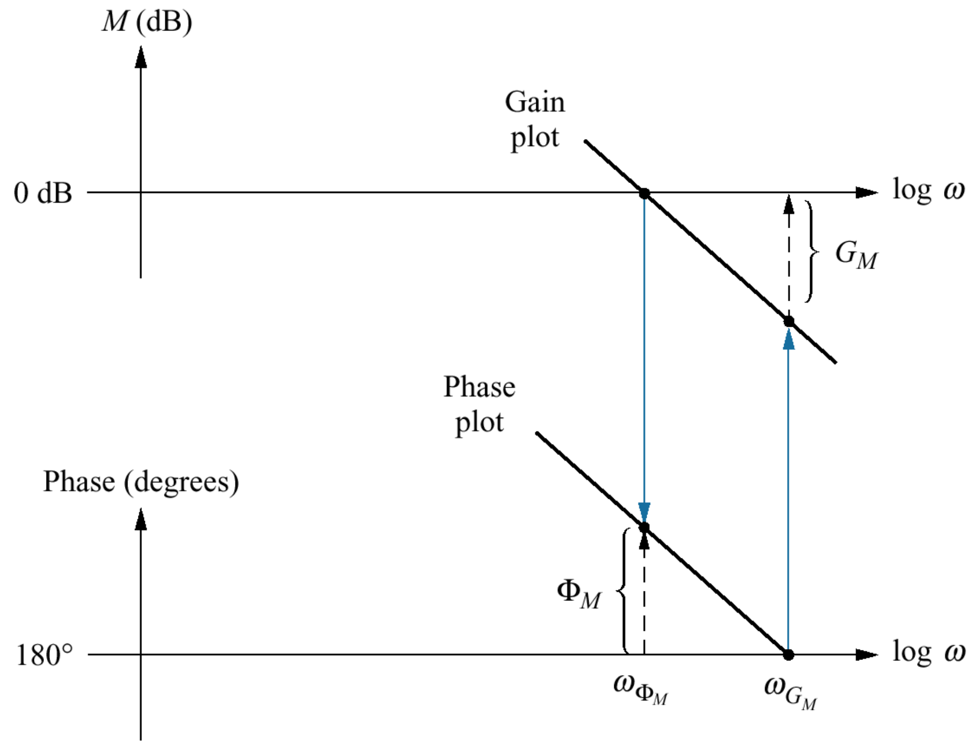


Figure 10.38
Second-order closed-loop system

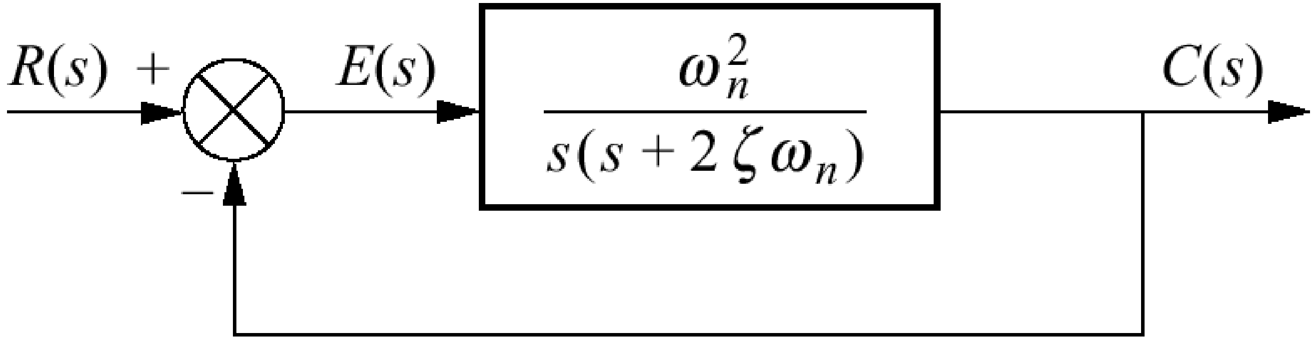


Figure 10.39

Representative log-magnitude plot of Eq. (10.51)

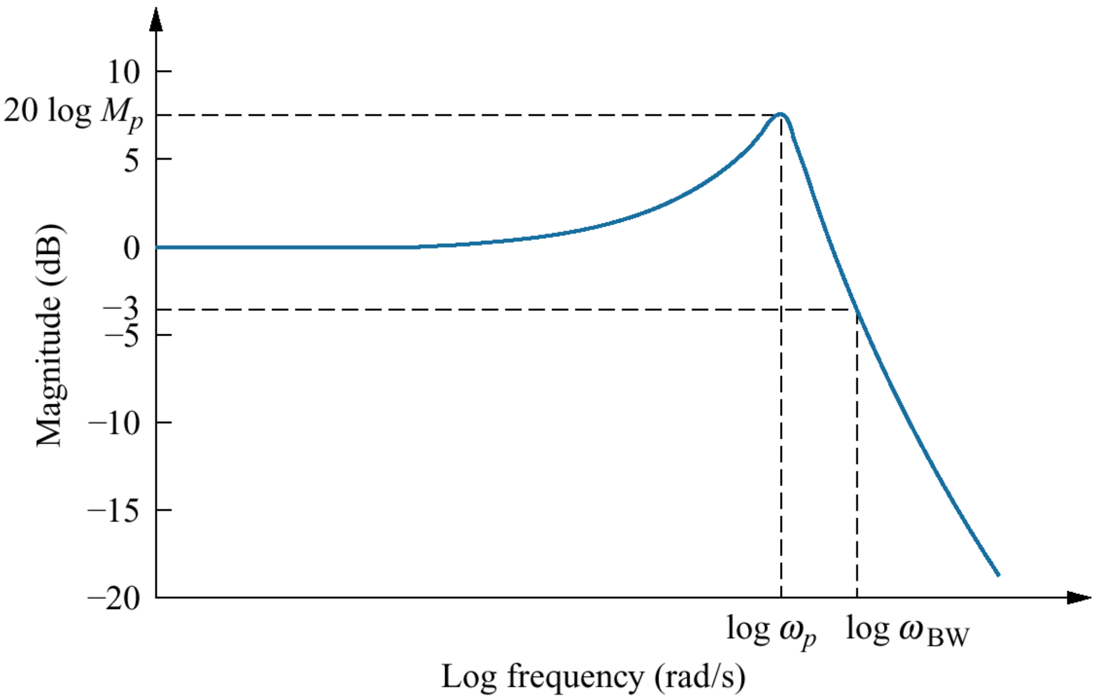


Figure 10.40

Closed-loop frequency percent overshoot for a two-pole system

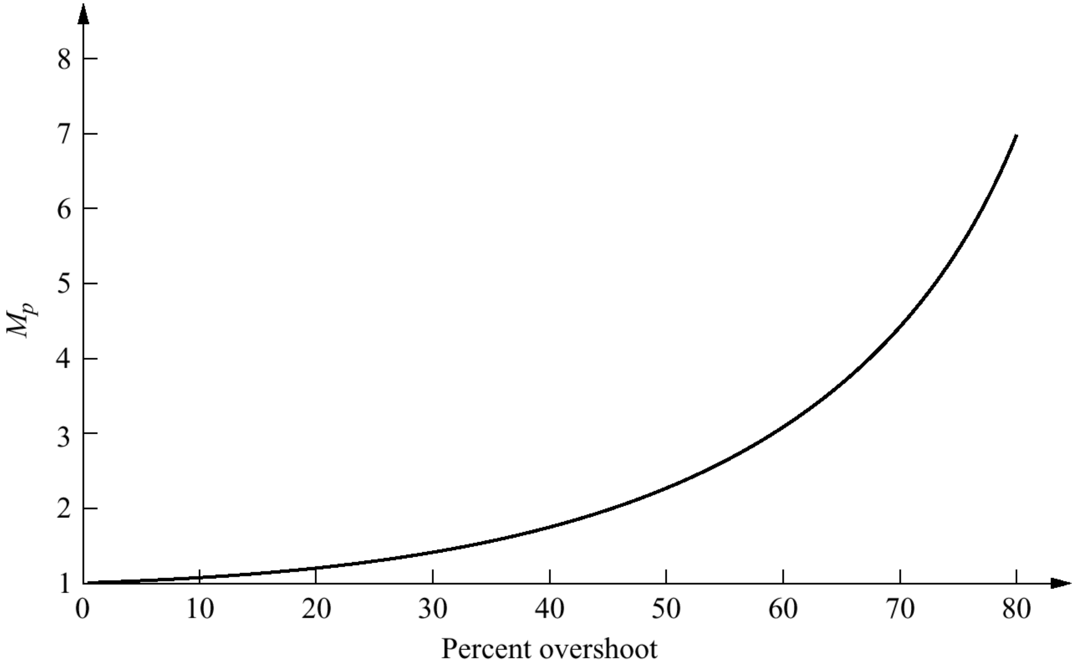


Figure 10.41 Normalized bandwidth vs. damping ratio for:
a. settling time;
b. peak time;
c. rise time

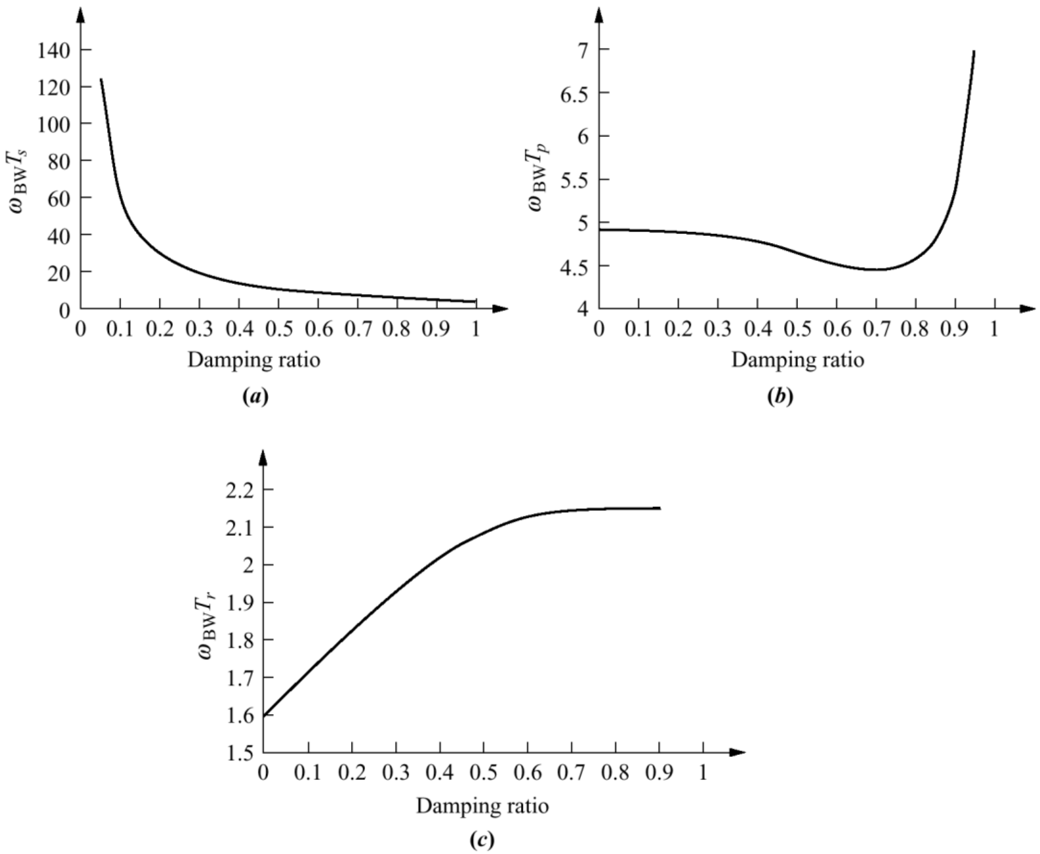


Figure 10.42

Constant *M* circles

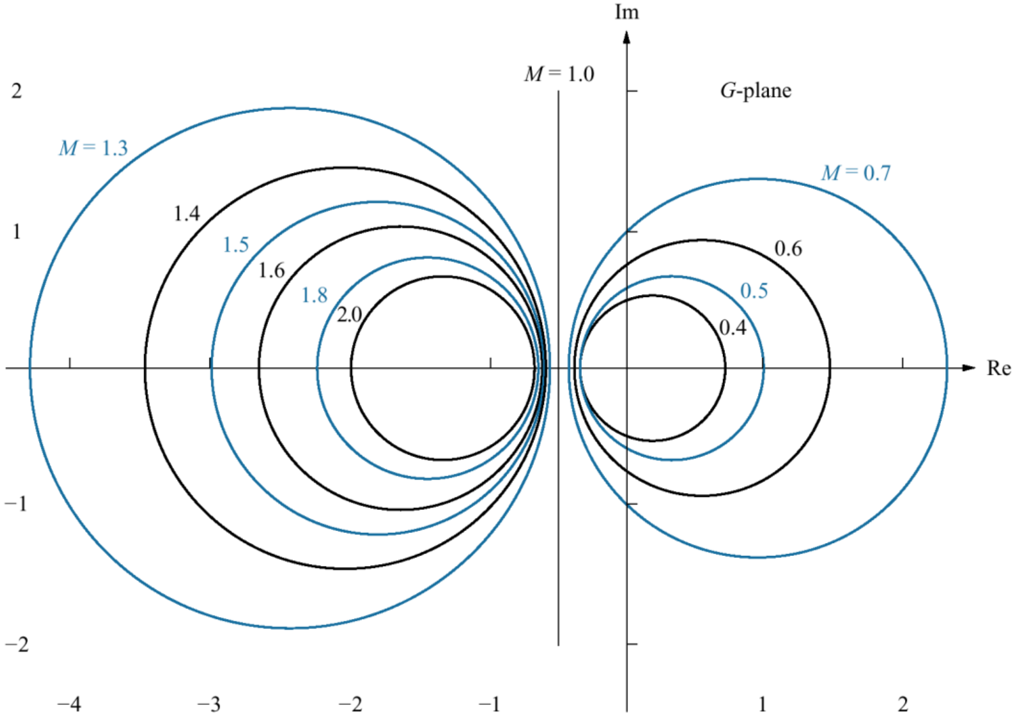


Figure 10.43

Constant *N* circles

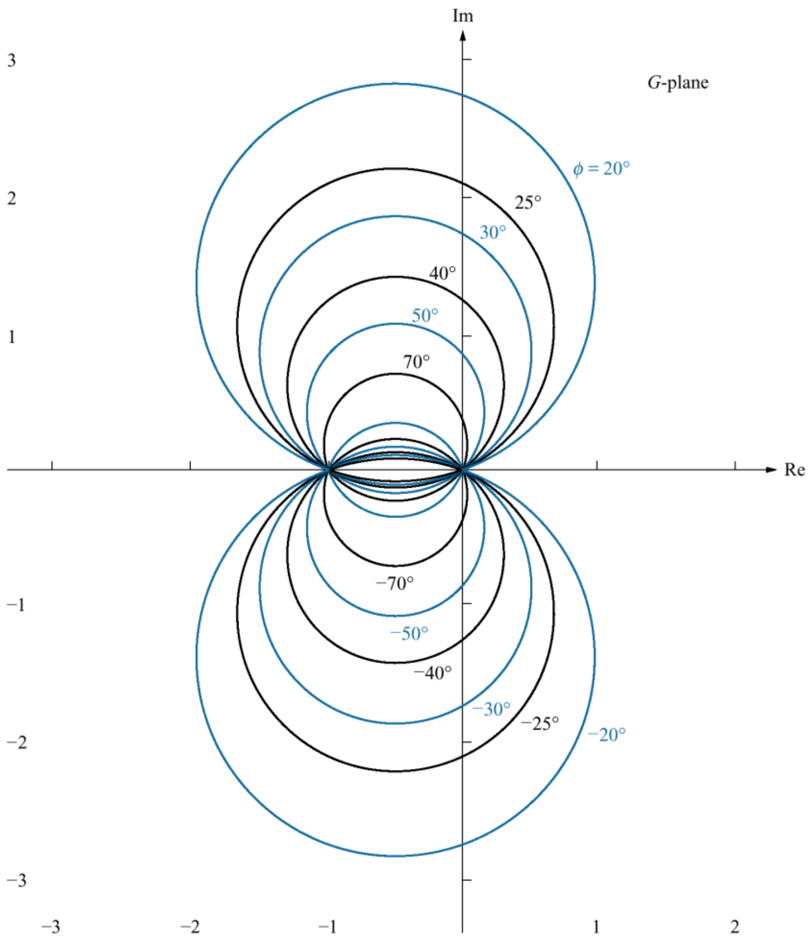


Figure 10.44

Nyquist diagram
for Example 10.11 and
constant
M and *N* circles

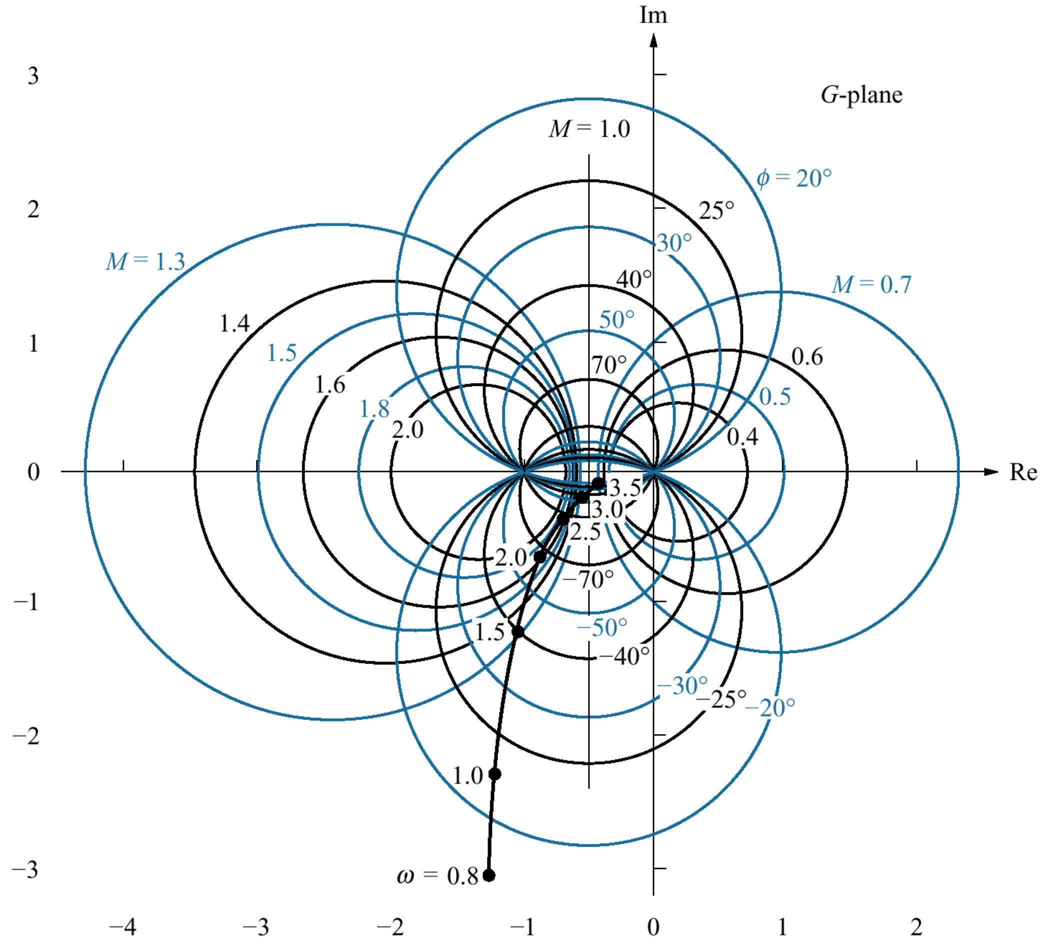


Figure 10.45
Closed-loop frequency response for Example 10.11

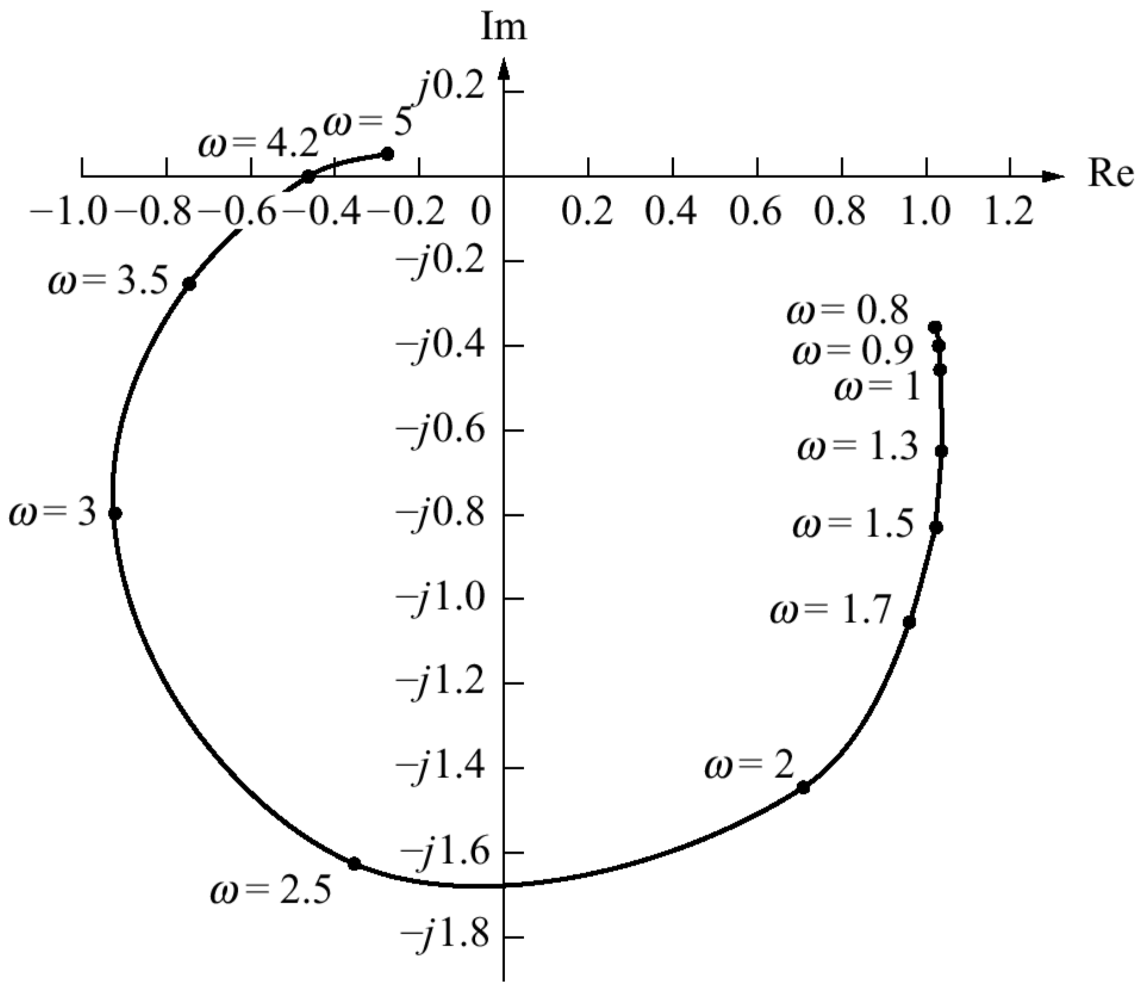


Figure 10.46

Nichols chart

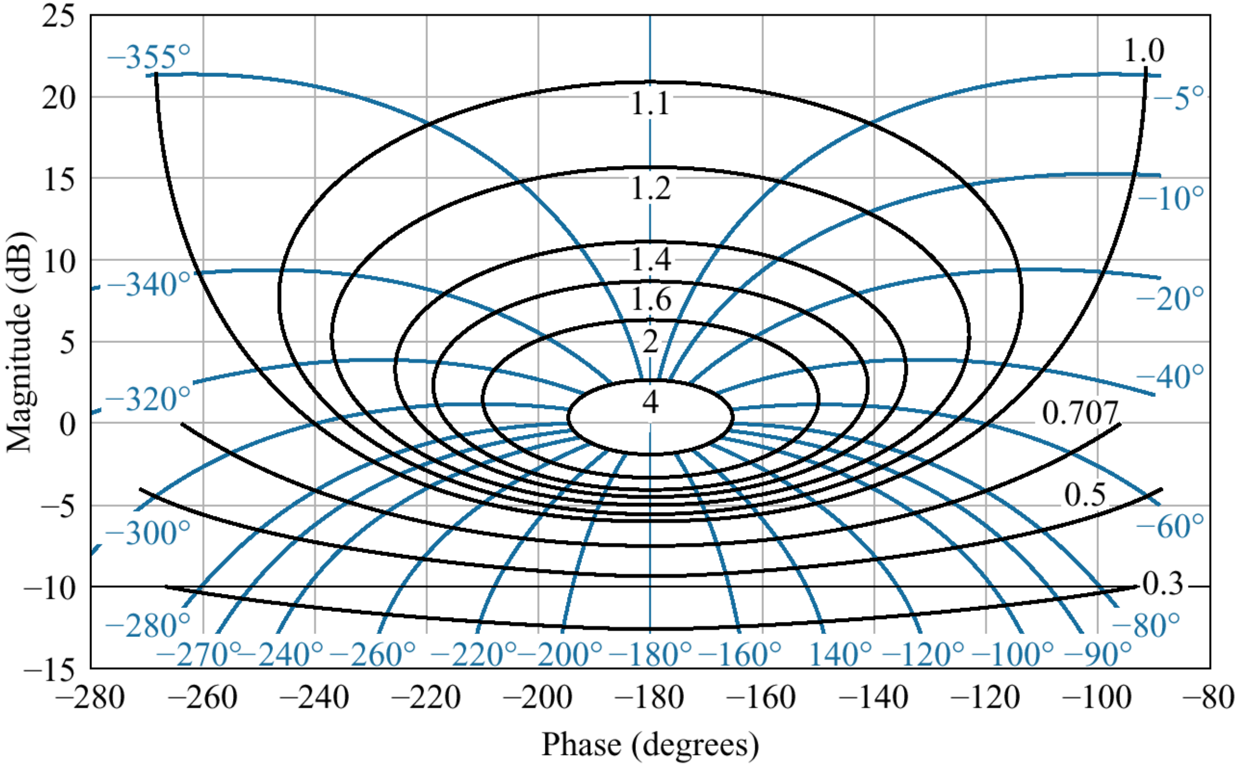
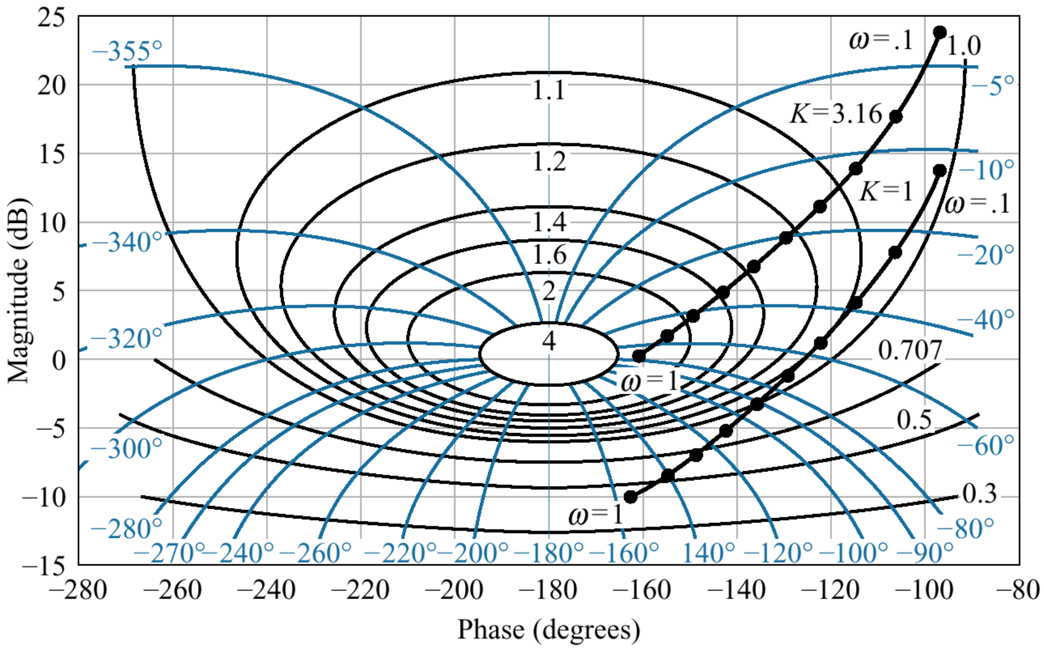


Figure 10.47

Nichols chart with frequency response for
$G(s) = K/[s(s + 1)(s + 2)]$ superimposed.
Values for $K = 1$ and $K = 3.16$ are shown.



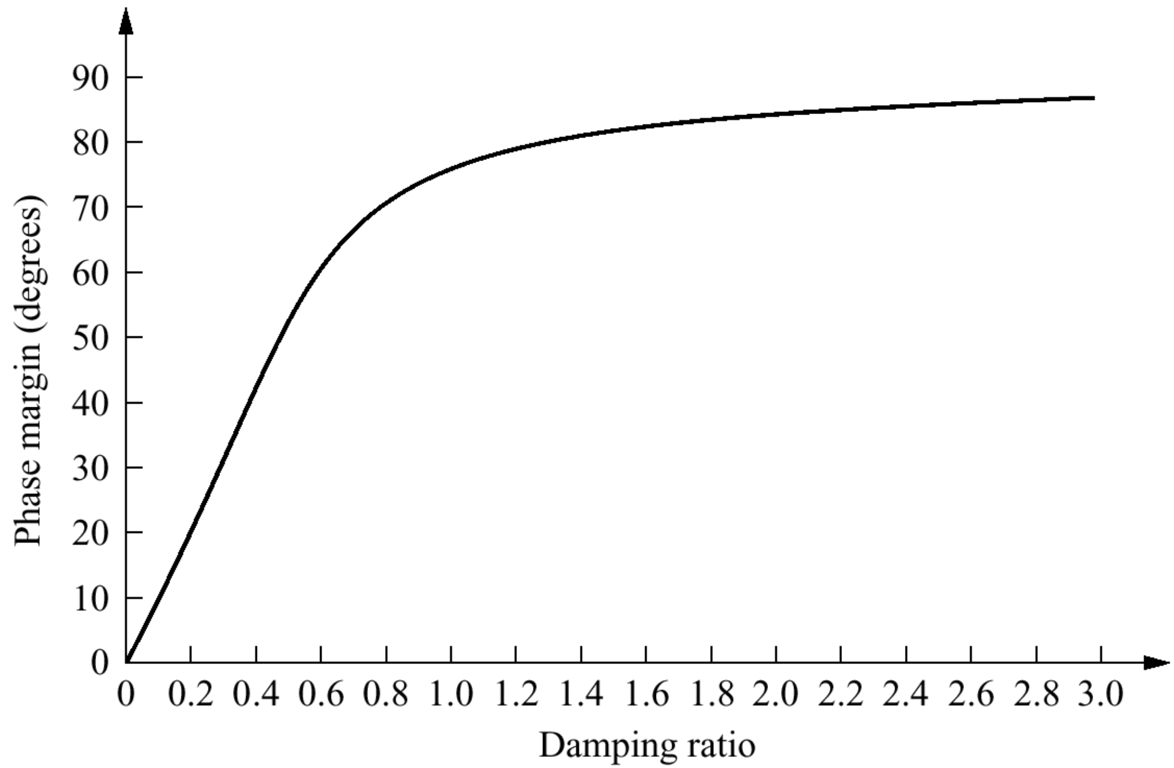


Figure 10.48

Phase margin vs. damping ratio

Figure 10.49
Open-loop gain vs. open-loop phase angle for –3 dB closed-loop gain

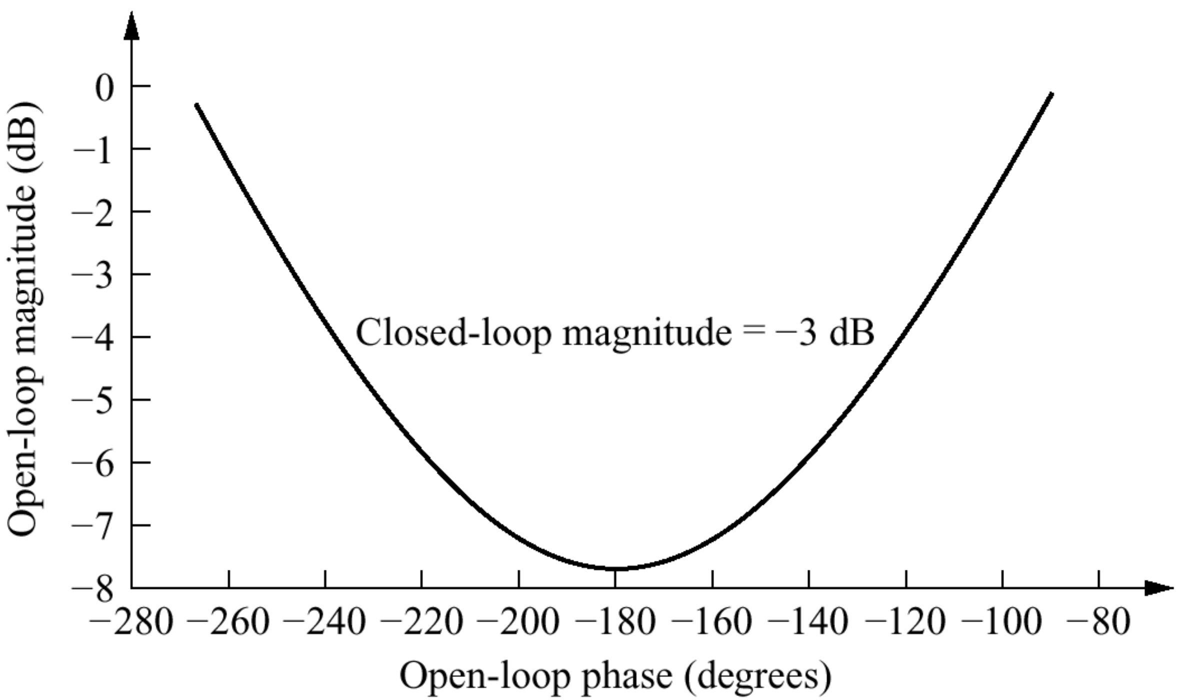
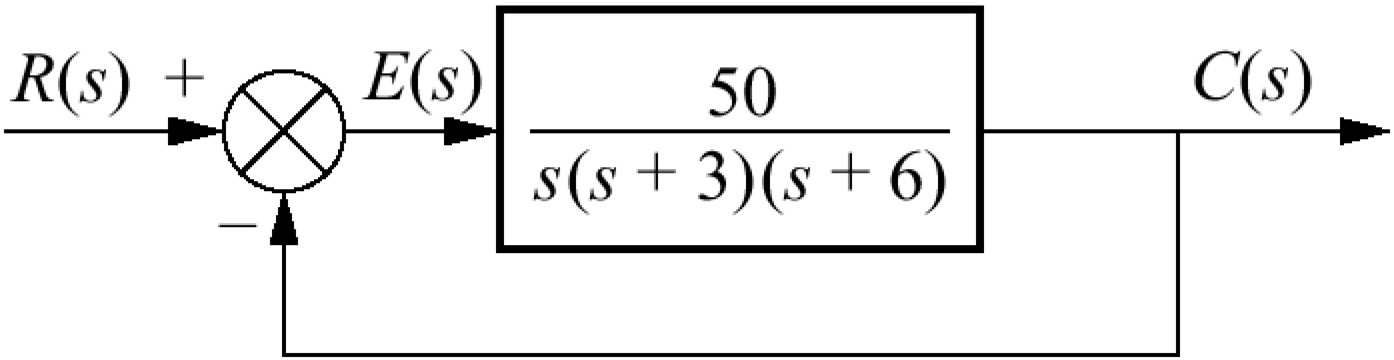


Figure 10.50

a. Block diagram

(figure continues)



(*a*)

Figure 10.50 *(continued)*
b. Bode diagrams for system of Example 10.13

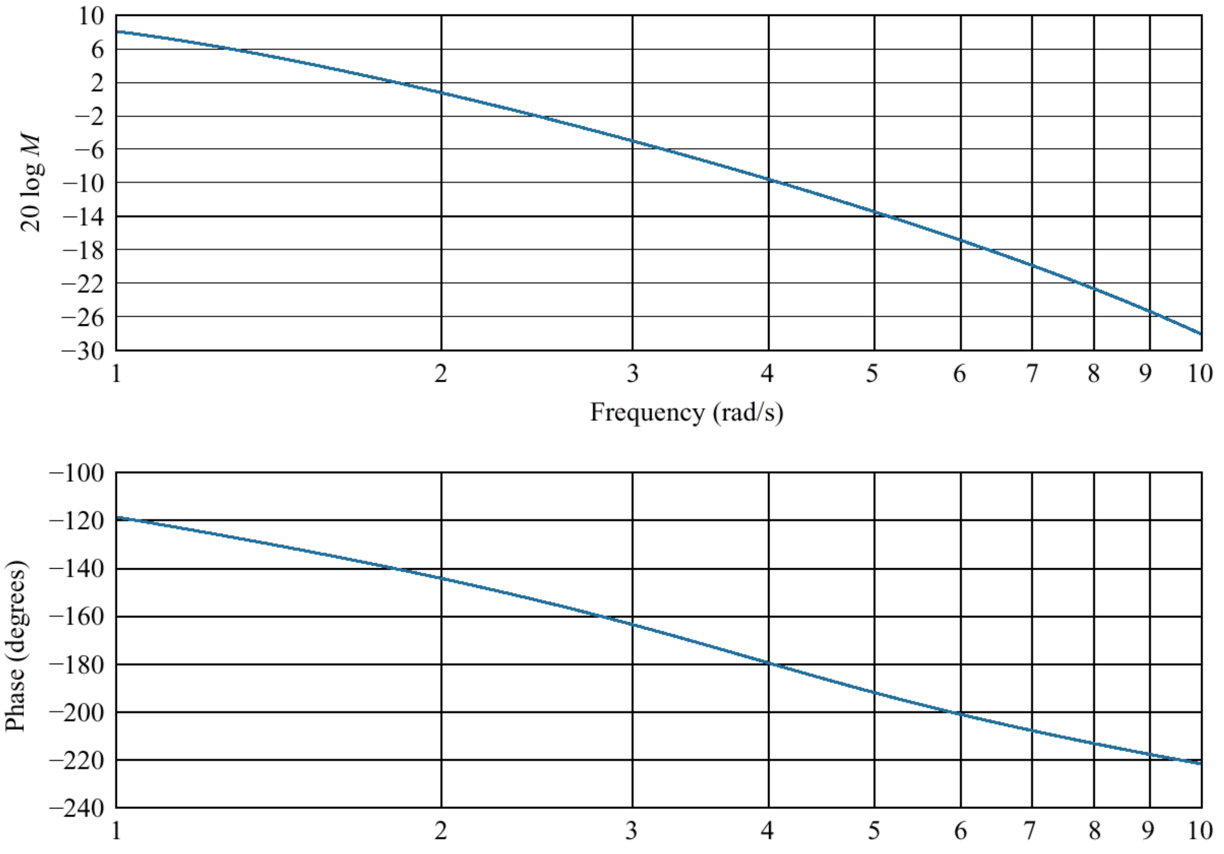


Figure 10.52
Bode log-magnitude plots for Example 10.14

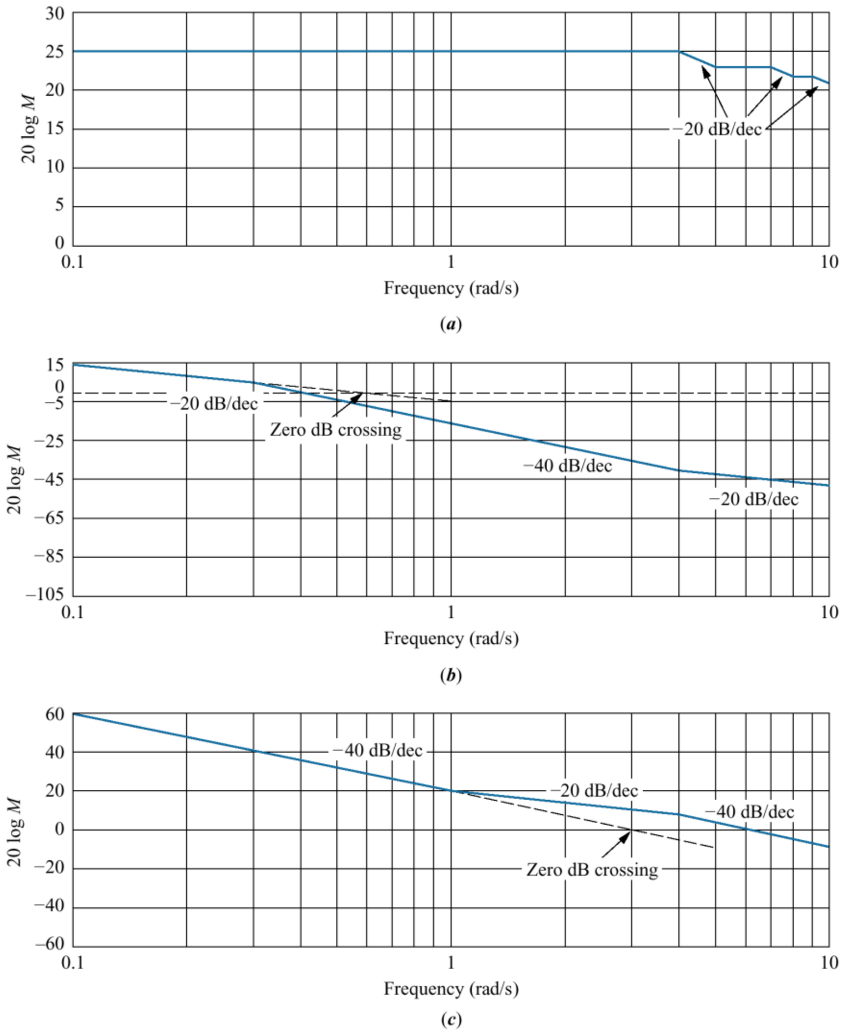


Figure 10.53

Bode log-magnitude plot for Skill-Assessment Exercise 10.10

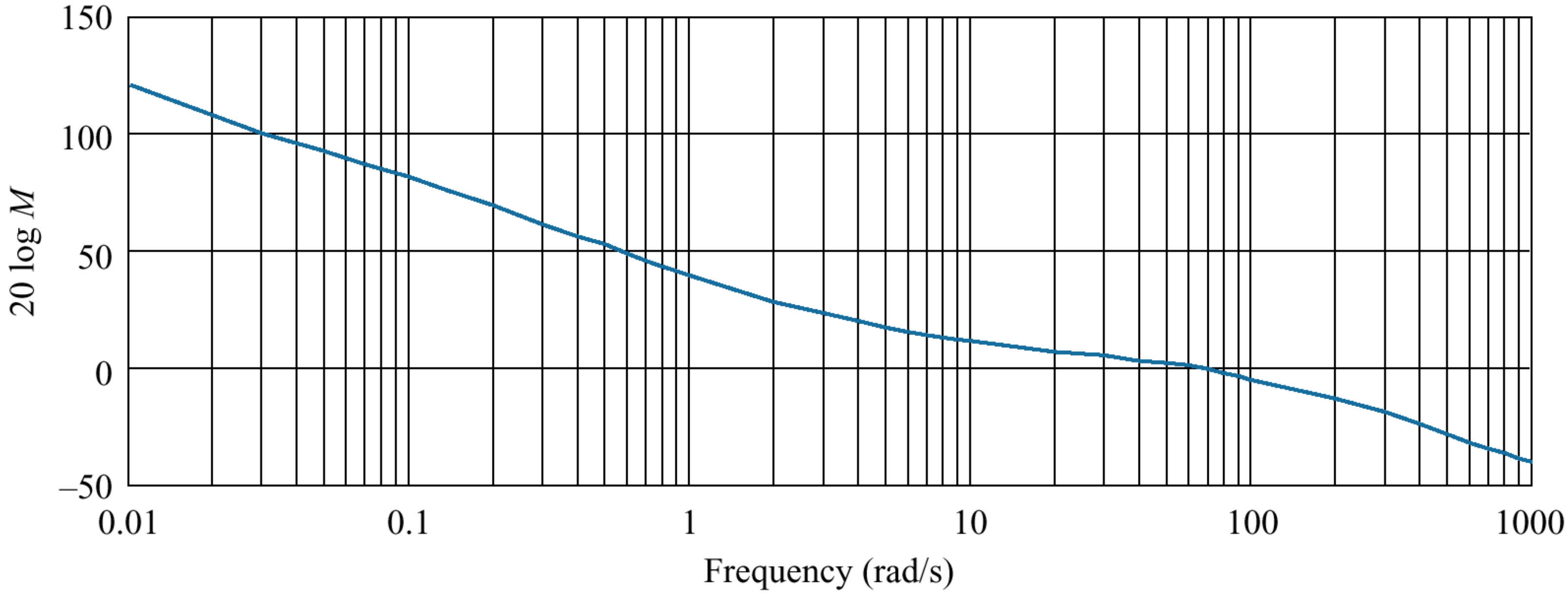


Figure 10.54
Effect of delay upon frequency response

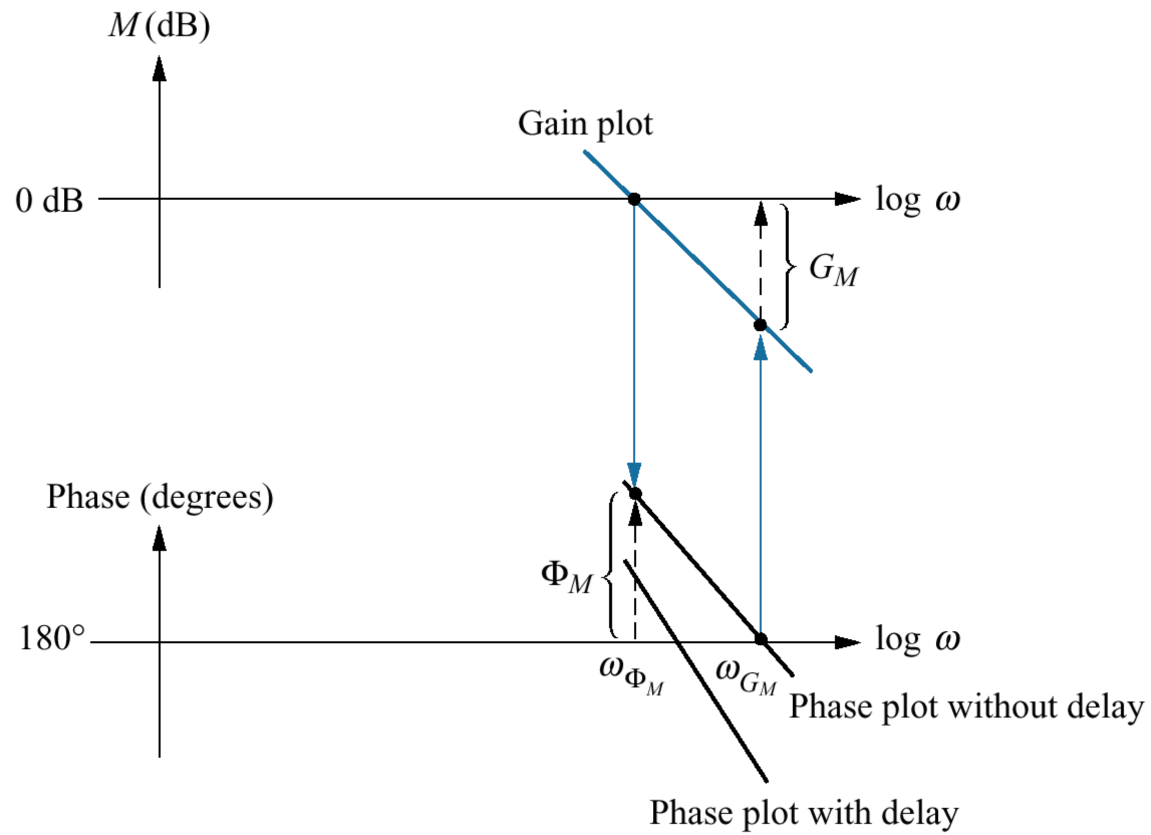
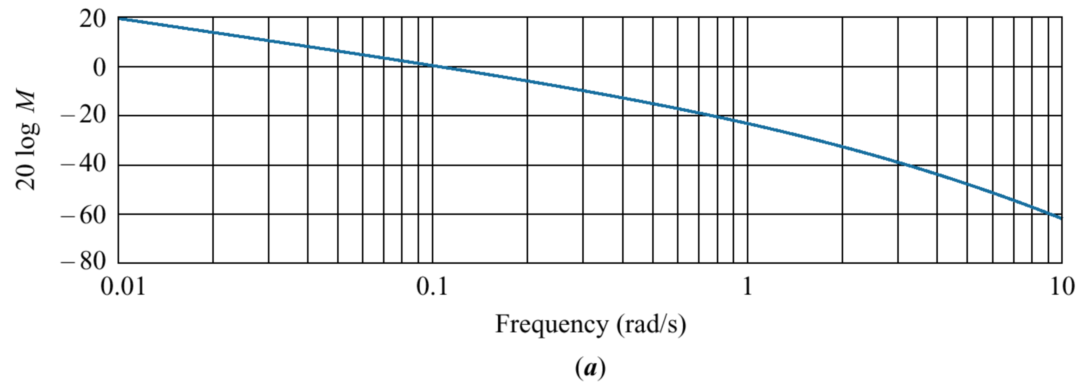


Figure 10.55

Frequency response plots for $G(s) = K/[s(s+1)(s+10)]$ with a delay of 1 second and $K = 1$:

a. magnitude plot;

b. phase plot



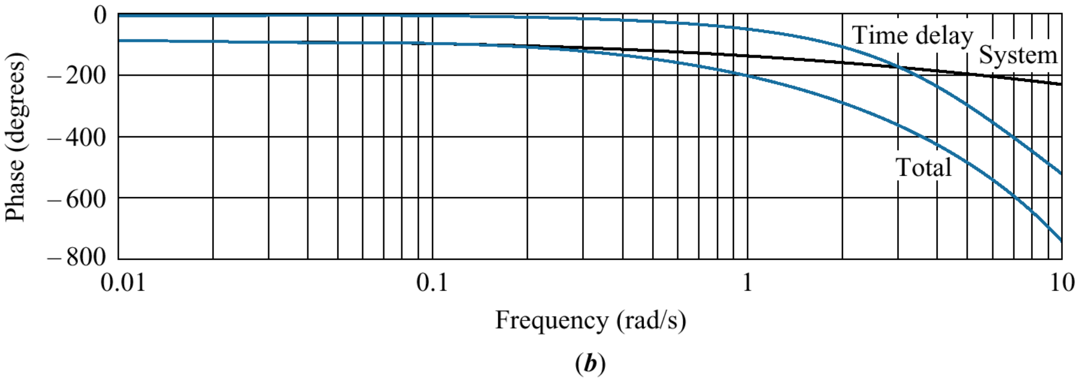


Figure 10.56

Step response for closed-loop system with $G(s) = 5/[s(s+1)(s+10)]$:

a. with a 1 second delay;

b. without delay

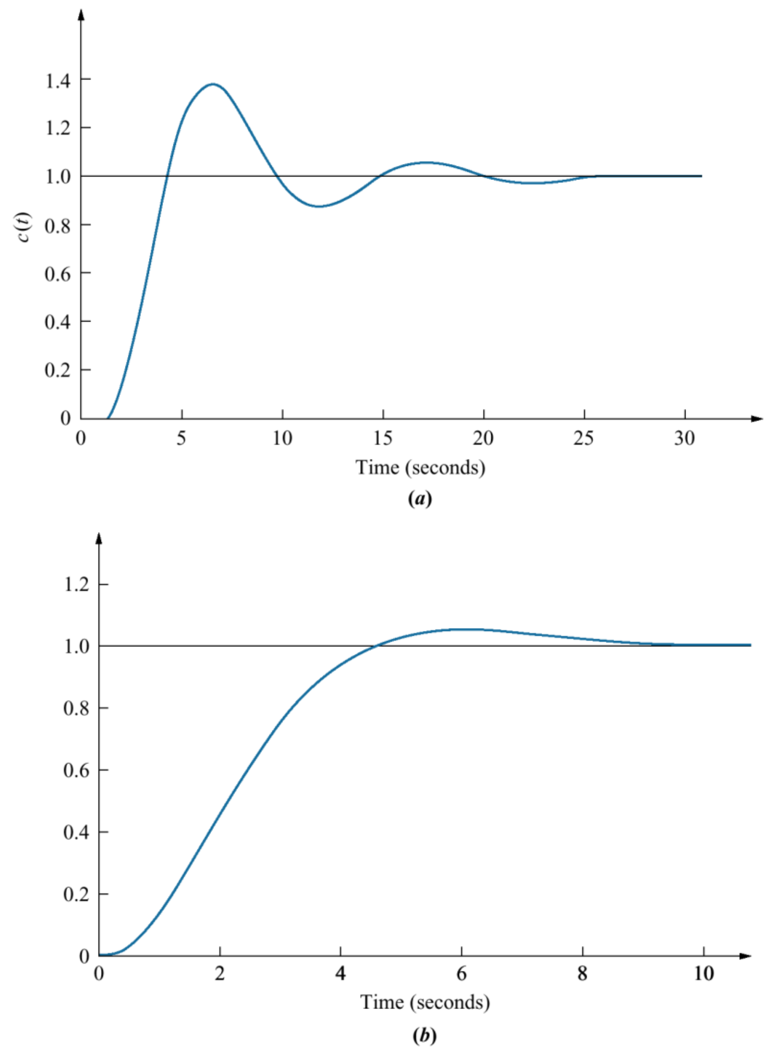


Figure 10.57

Bode plots for subsystem with undetermined transfer function

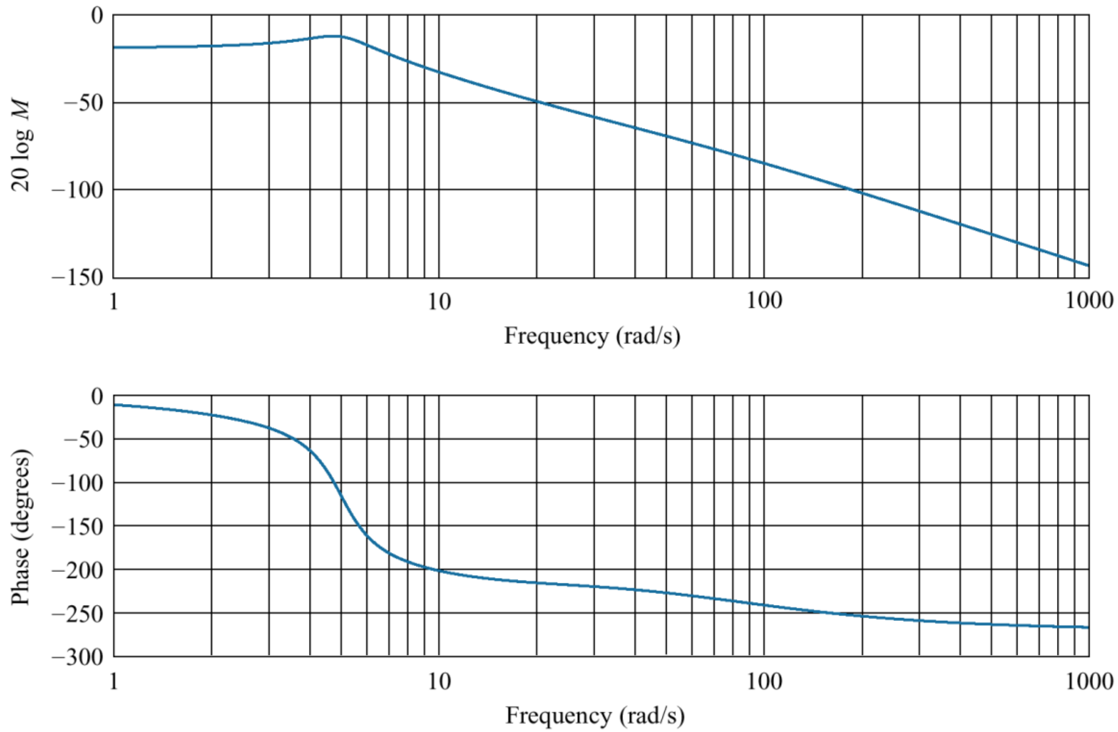


Figure 10.58
Original Bode plots minus response of $G_1(s) = 25/(s^2 + 2.4s + 25)$

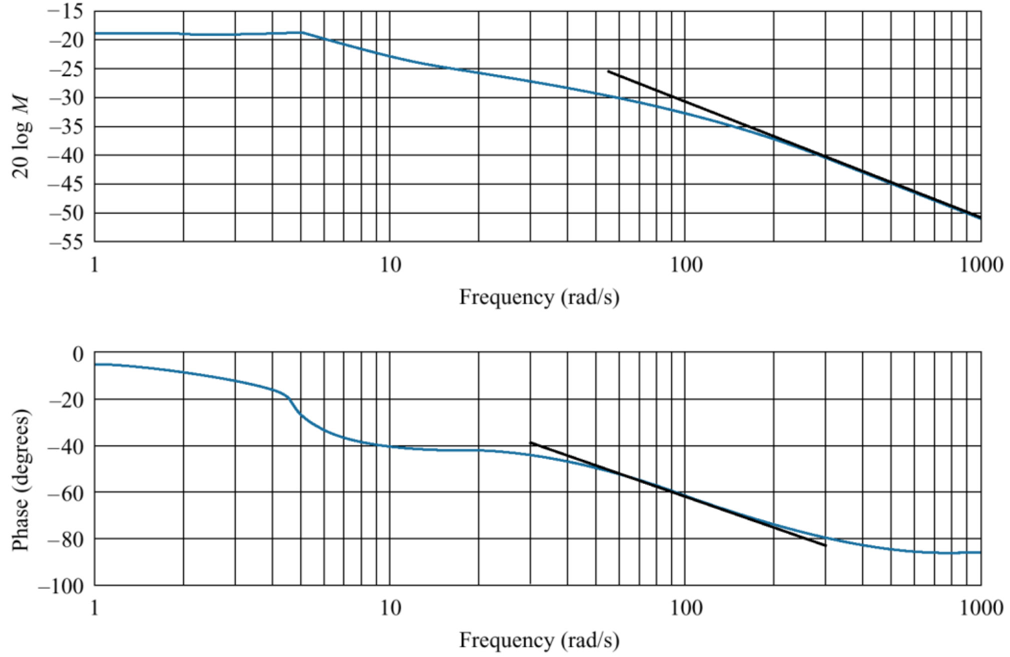


Figure 10.59

Original Bode plot minus response of $G_1(s)G_2(s) = [25/(s^2 + 2.4s + 25)] \cdot [90/(s + 90)]$

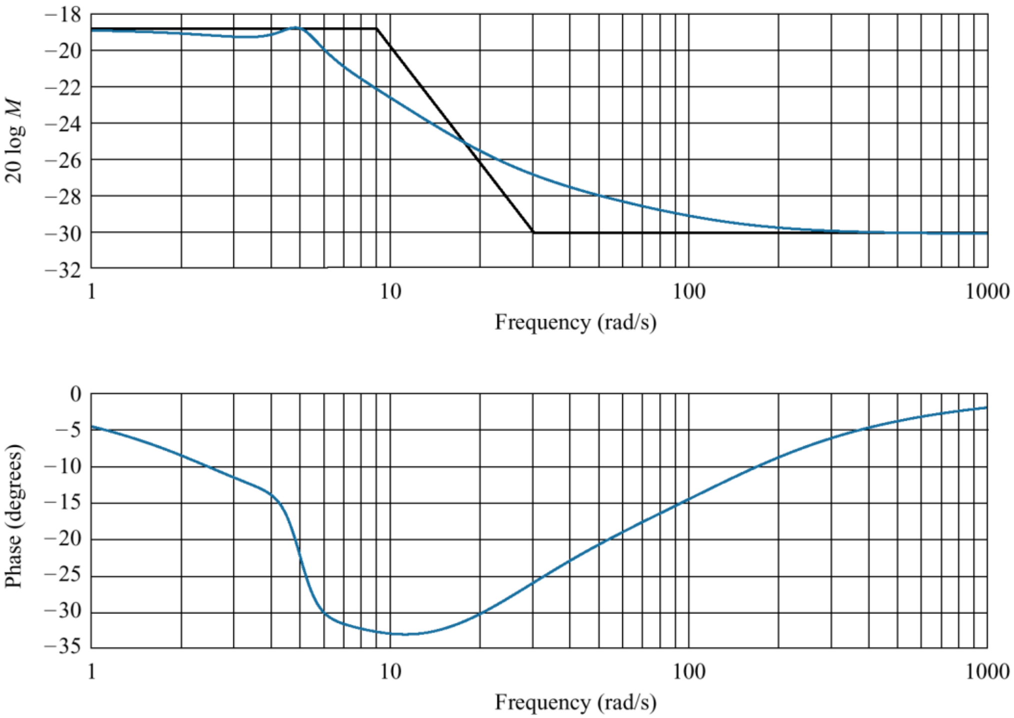


Figure 10.60

Bode plots for Skill-Assessment Exercise 10.12

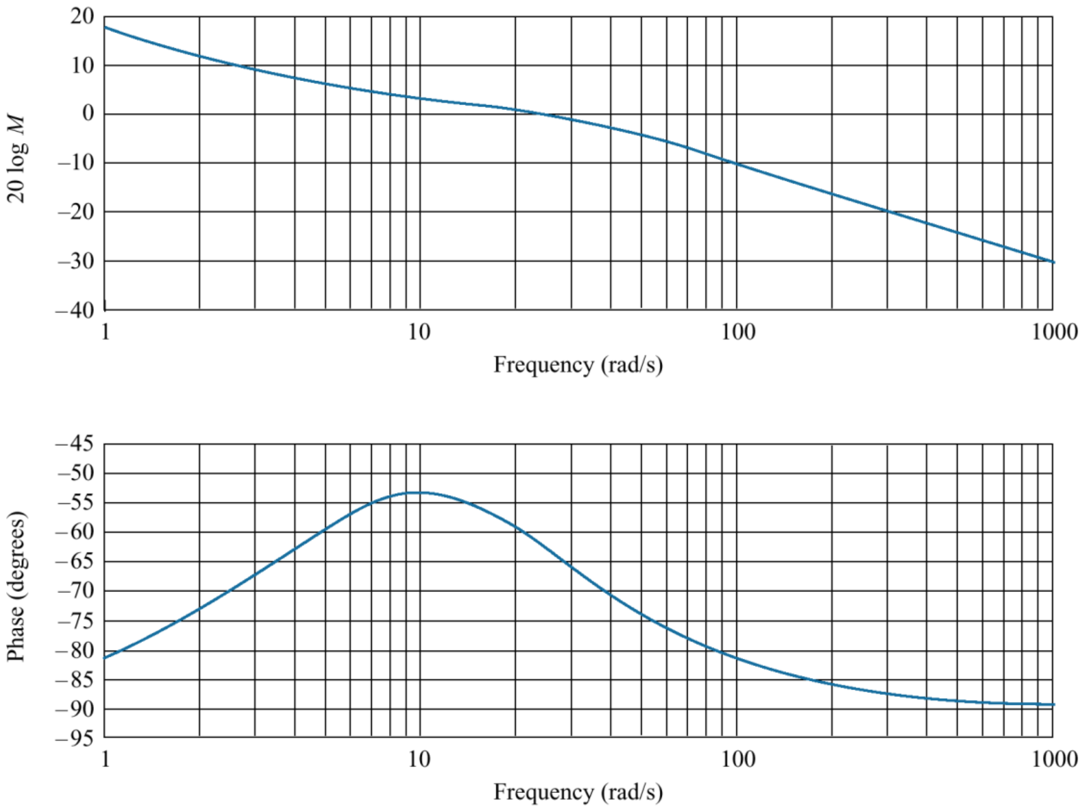
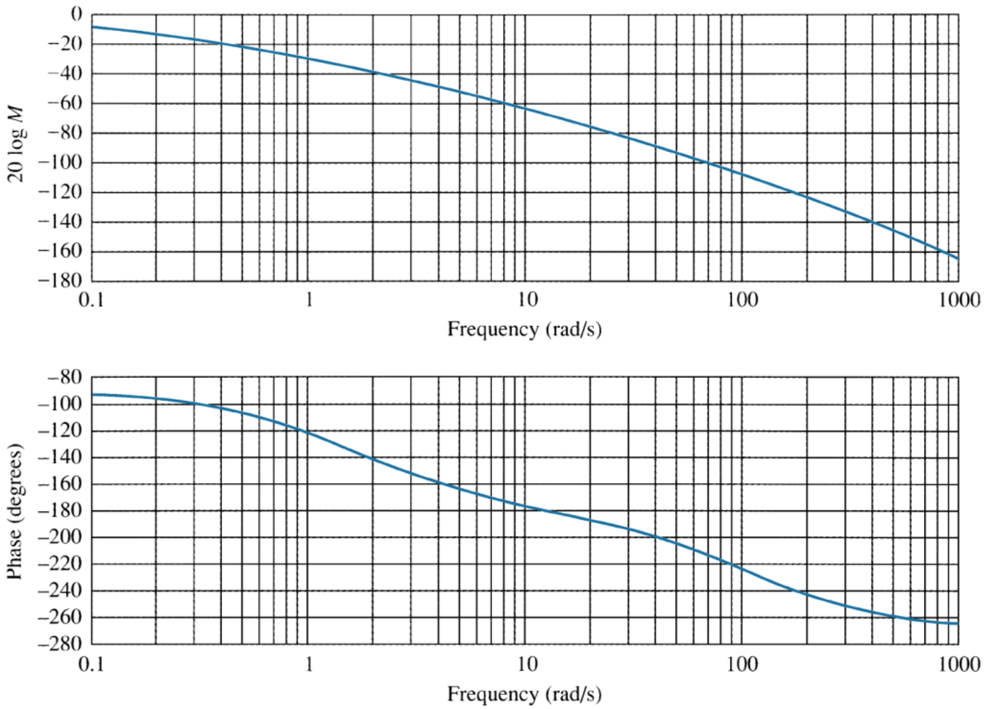


Figure 10.61 Open-loop frequency response plots for the antenna control system (K = 1)



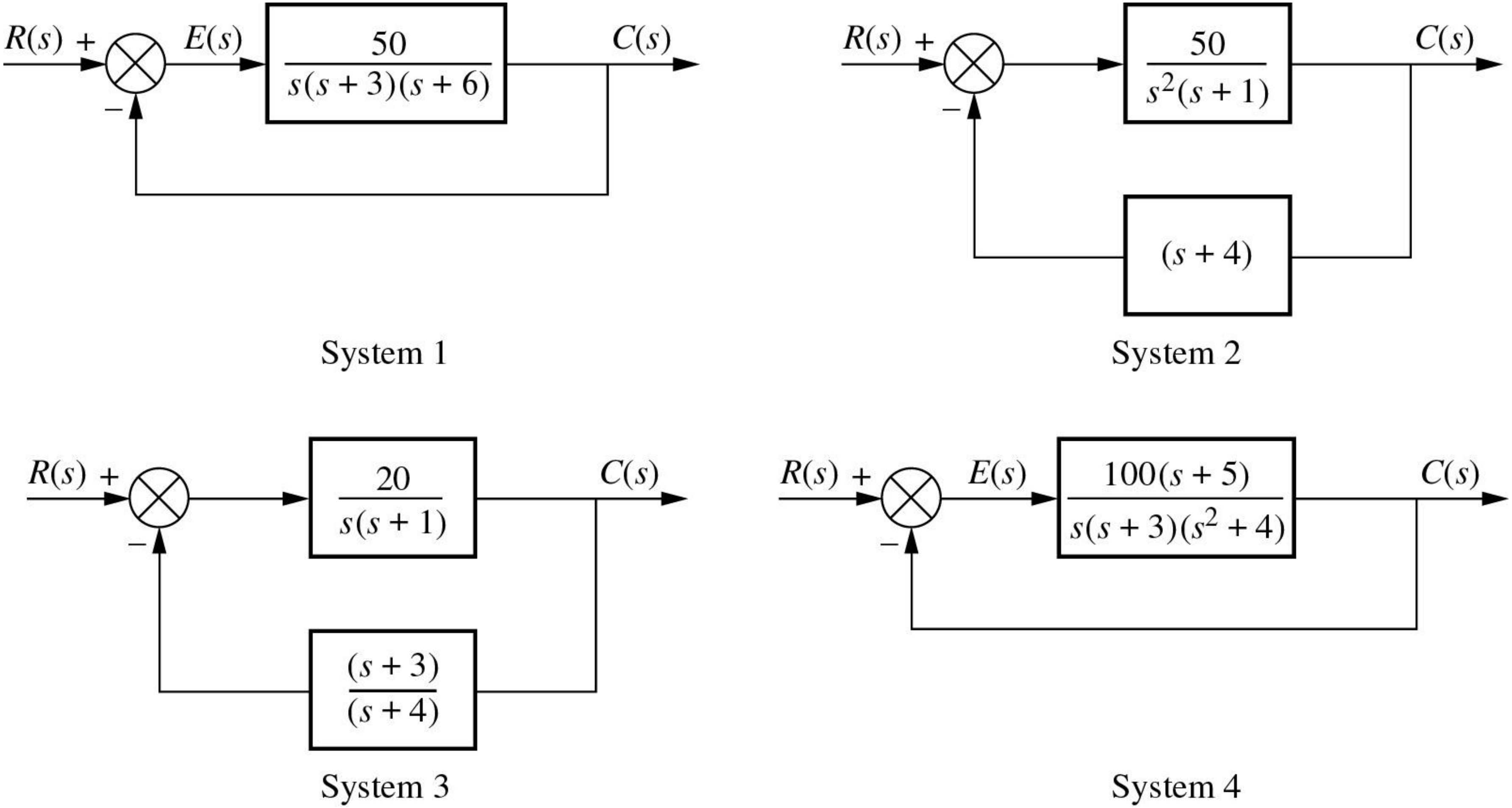
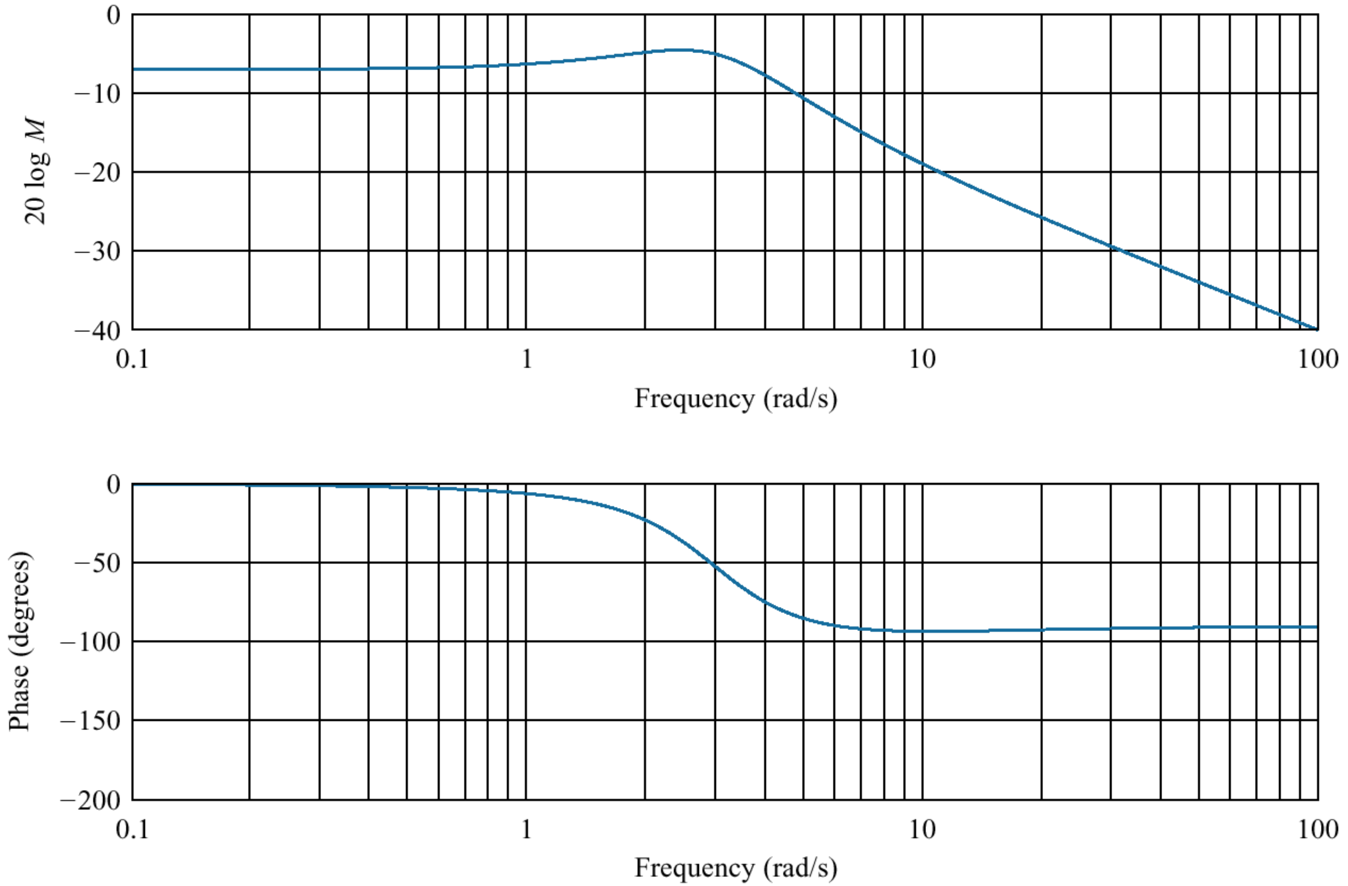


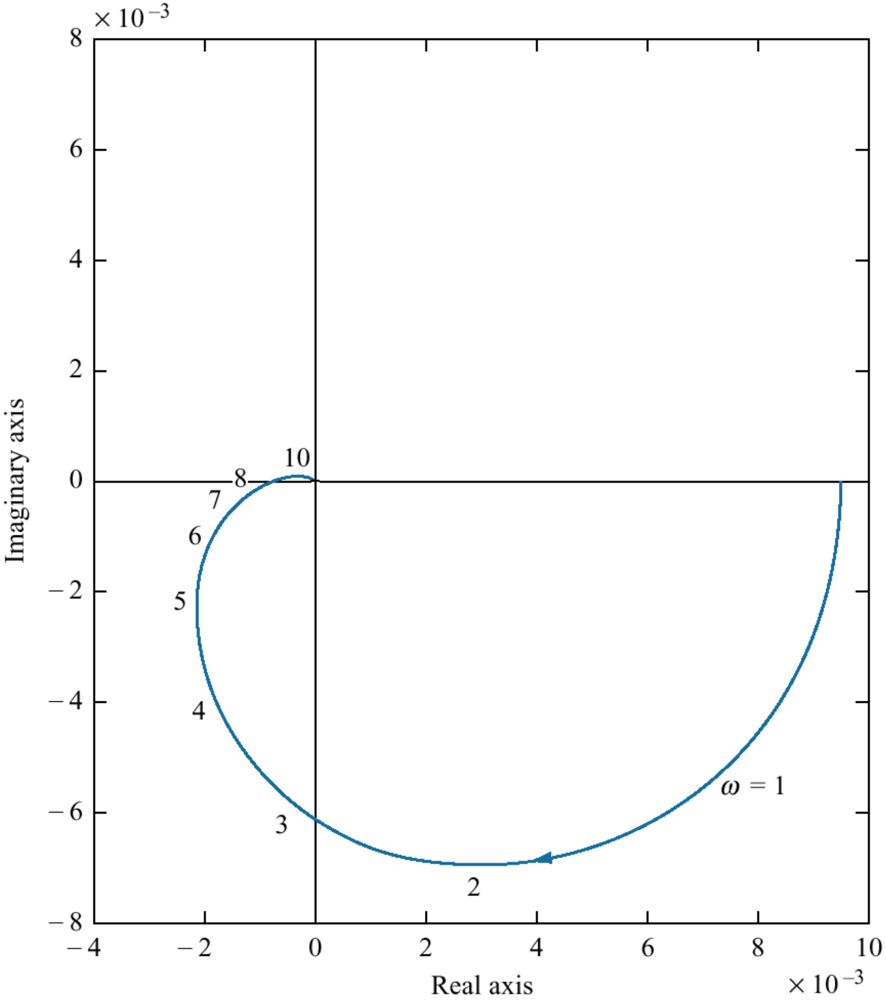
Figure P10-1 (p. 675)

Figure P10.2



0
−10
−20
−30
−40
20 log M
0.1
1
10
100
Frequency (rad/s)
0
−50
−100
−150
−200
Phase (degrees)
0.1
1
10
100
Frequency (rad/s)

Figure P10.3



× 10^−3
8
6
4
2
0
− 2
− 4
− 6
− 8
Imaginary axis
10
8
7
6
5
4
3
2
ω = 1
− 4
− 2
0
2
4
6
8
10
Real axis
× 10^−3

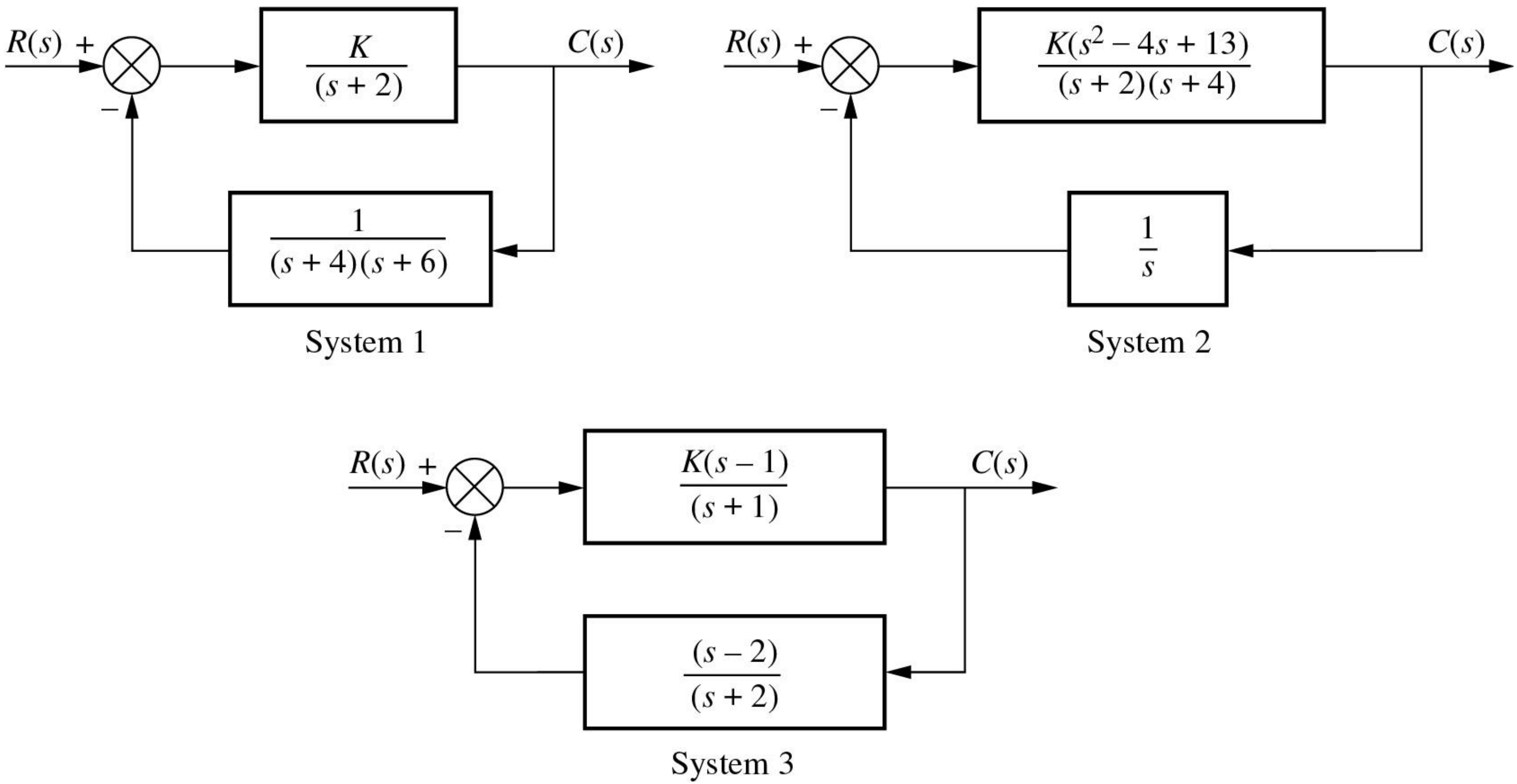


Figure P10-4 (p. 677)

Figure P10.5

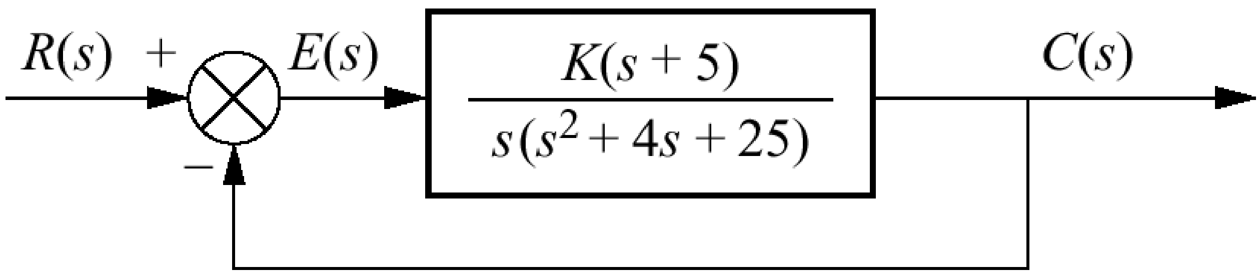
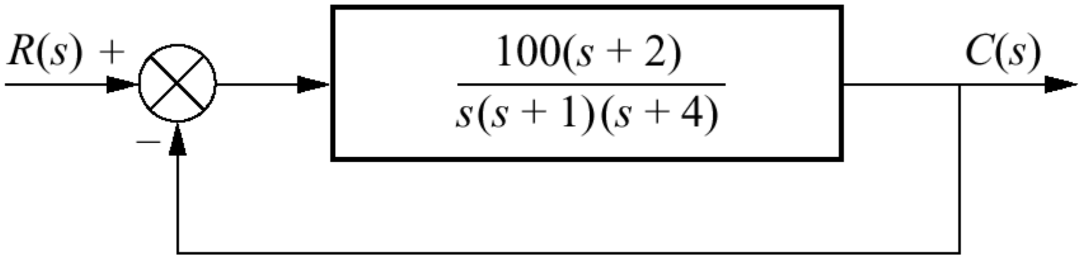
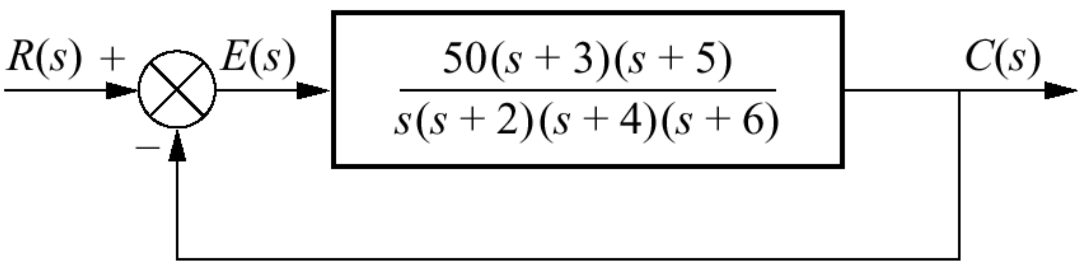


Figure P10.6



System 1



System 2

Figure P10.7

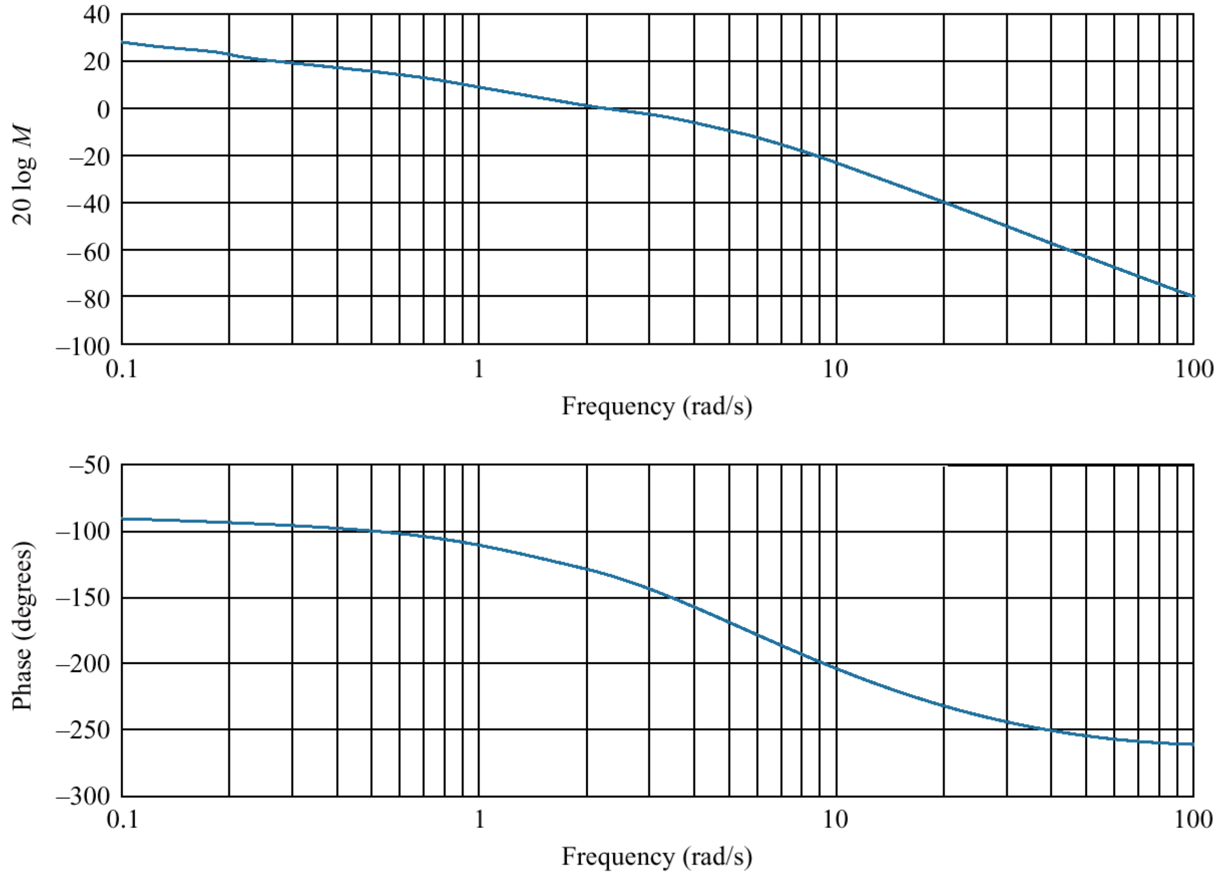
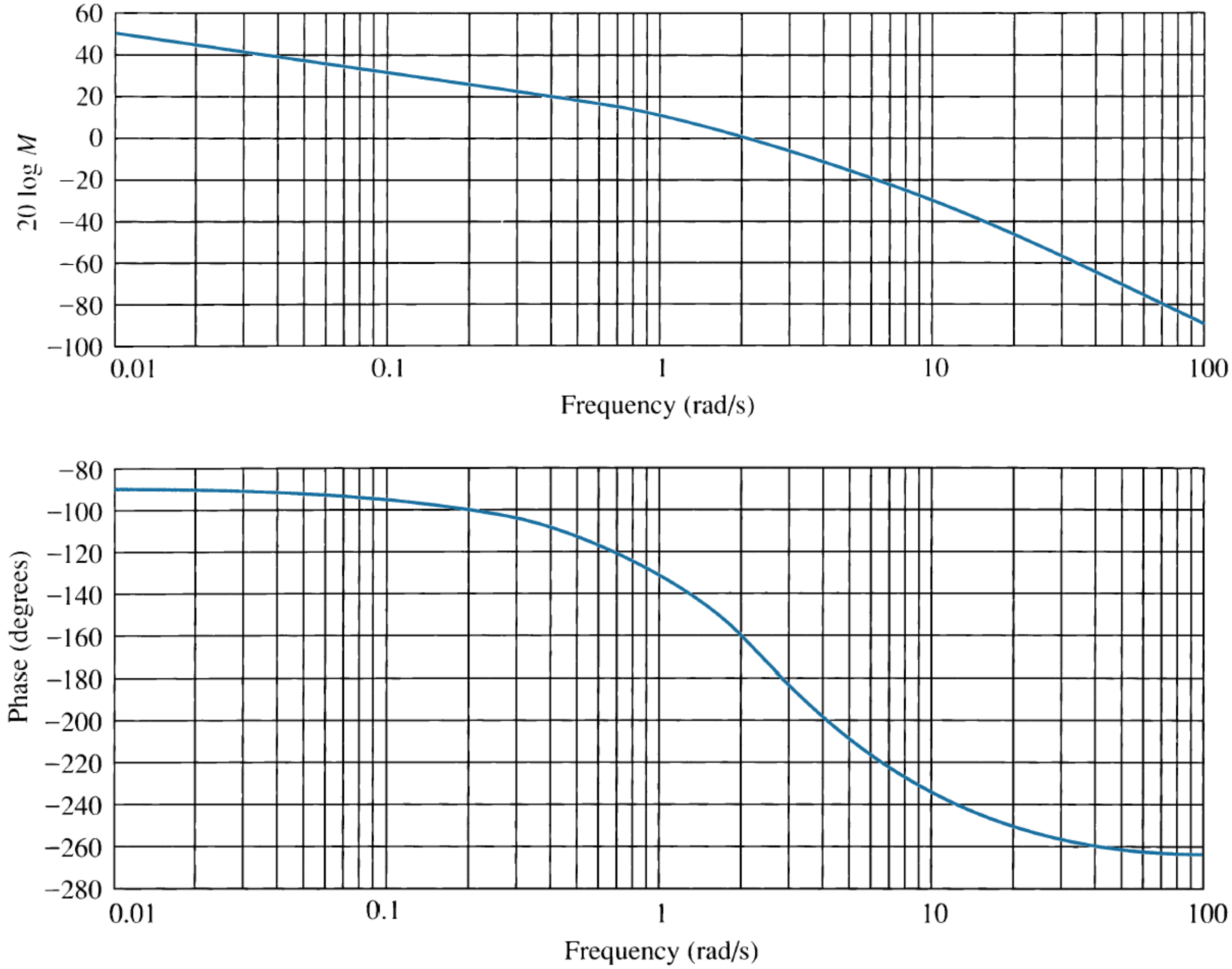


Figure P10.7

Figure P10.8



20 log M
60
40
20
0
−20
−40
−60
−80
−100
0.01
0.1
1
10
100
Frequency (rad/s)
Phase (degrees)
−80
−100
−120
−140
−160
−180
−200
−220
−240
−260
−280
0.01
0.1
1
10
100
Frequency (rad/s)

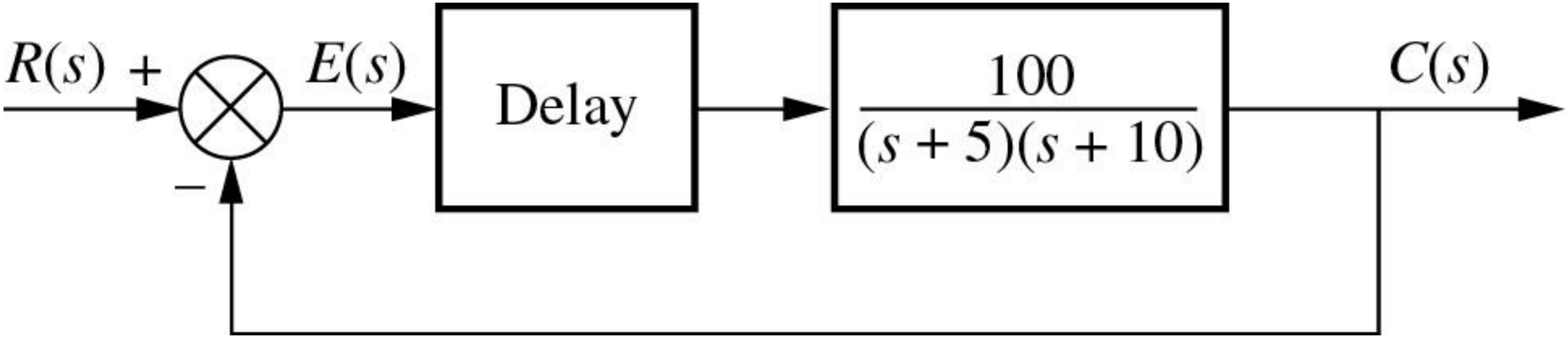


Figure P10-9 (p. 681)

Figure P

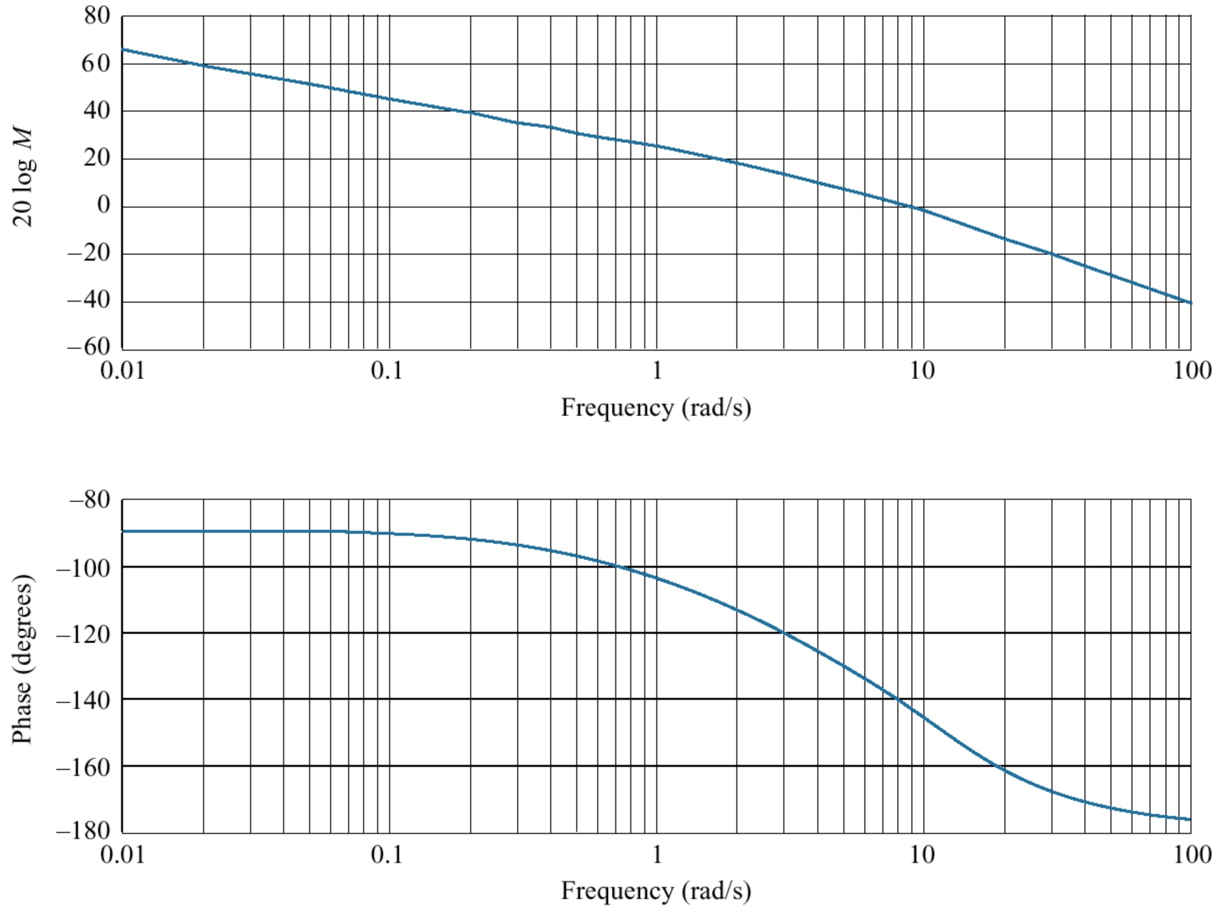


Figure P10.10

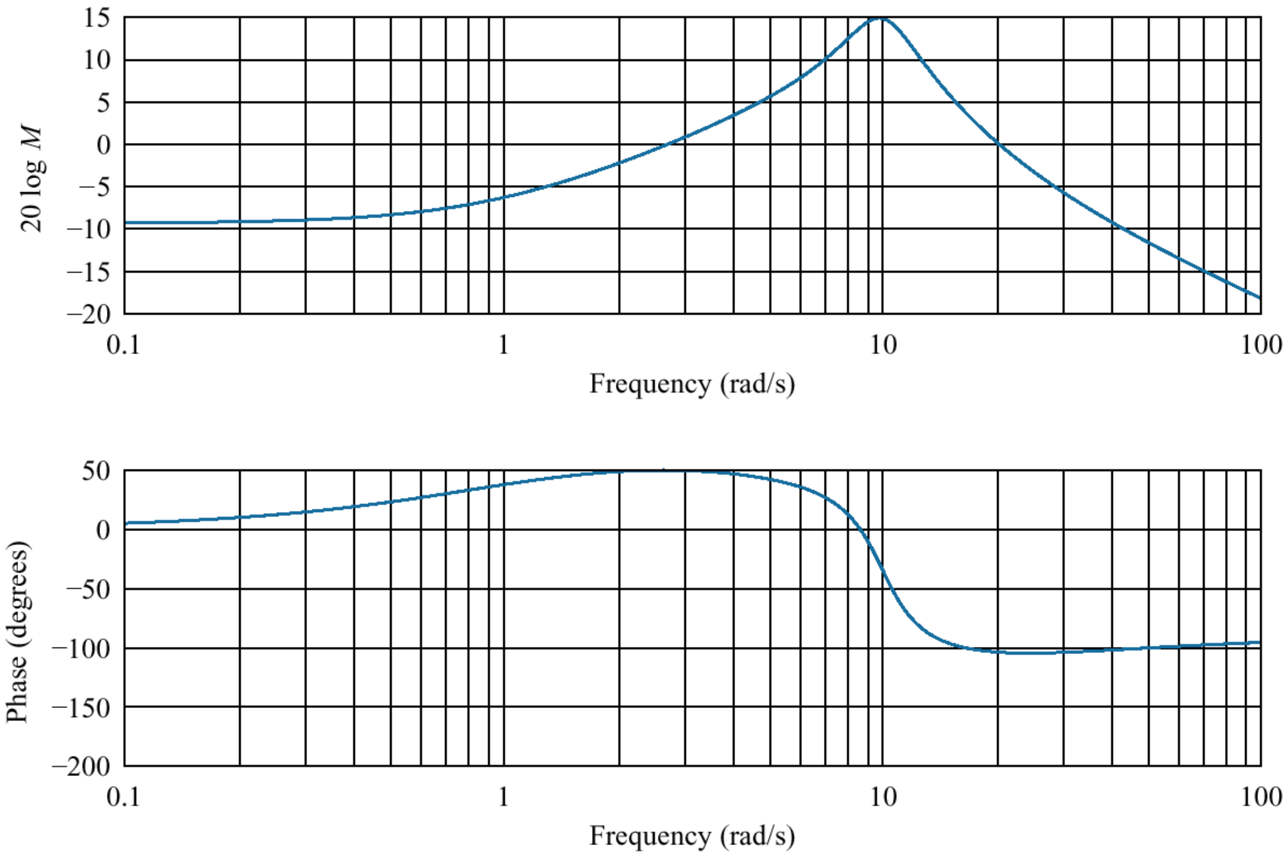


Figure P10.11

Figure P10.12
Soft Arm position control system block diagram

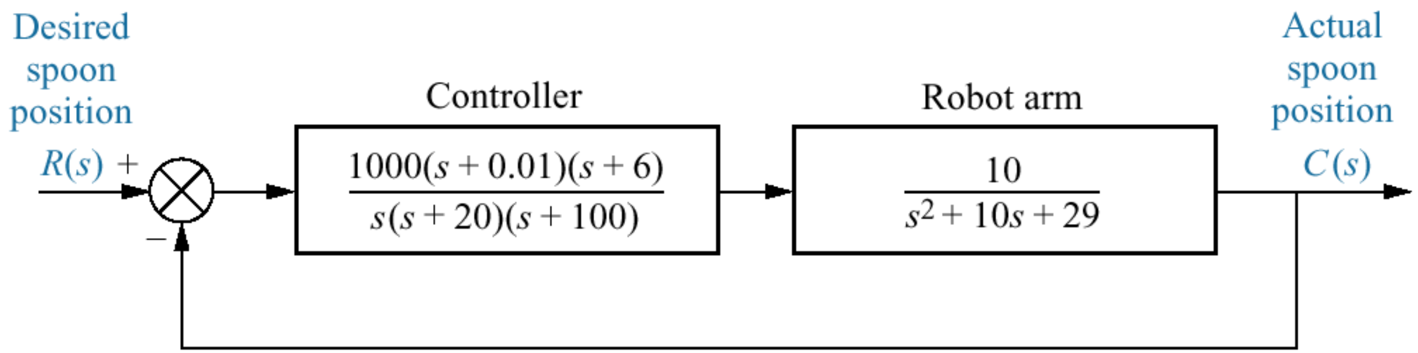


Figure P10.13
Floppy disk drive
block diagram

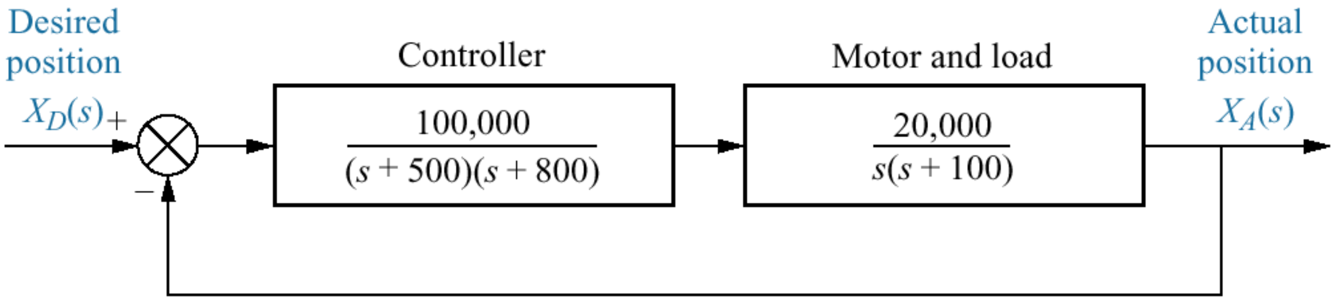


Figure P10.14

AdeptOne, a four- or five-axis industrial robot, is used for assembly, packaging, and other manufacturing tasks.

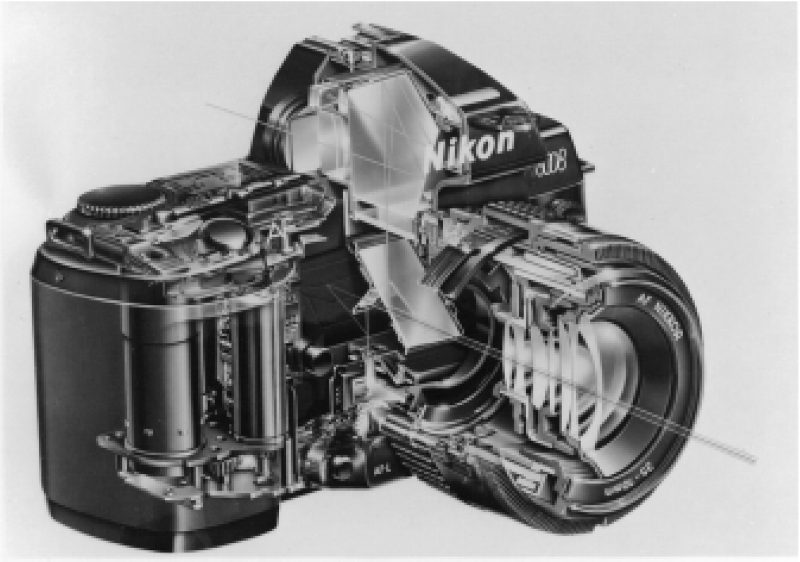
Figure P10.15

a. A cutaway view of a Nikon 35-mm camera showing parts of the CCD automatic focusing system;

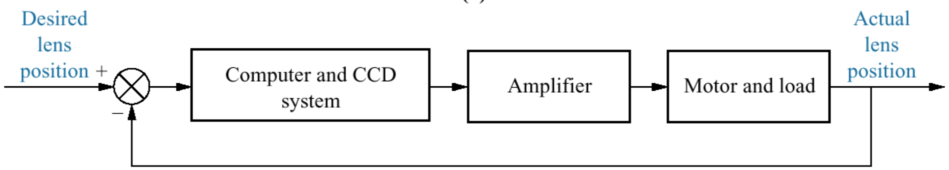
b. functional block diagram;

c. block diagram

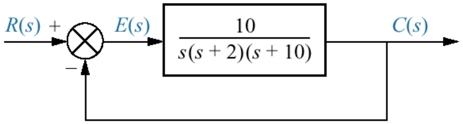
Courtesy of Nikon, Inc.



(*a*)



(*b*)



(*c*)

Figure P10.16
Block diagram of a ship's roll stabilizing system

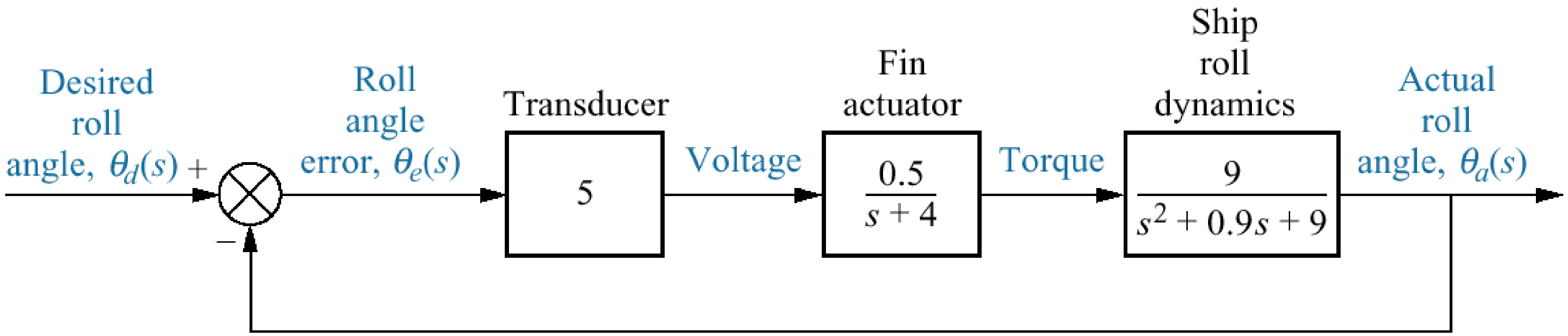


Table 10.2 Bode magnitude plot: slope contribution from each pole and zero in Example 10.2

Description	Frequency (rad/s) 0.1 (Start: Pole at 0)	1 (Start: Pole at −1)	2 (Start: Pole at −2)	3 (Start: Zero at −3)
Pole at 0	−20	−20	−20	−20
Pole at −1	0	−20	−20	−20
Pole at −2	0	0	−20	−20
Zero at −3	0	0	0	20
Total slope (dB/dec)	−20	−40	−60	−40

Table 10.2

Bode magnitude plot: slop contribution from each pole and zero in Example 10.2

Table 10.3 Bode phase plot: slope contribution from each pole and zero in Example 10.2

Description	Frequency (rad/s)					
	0.1 (Start: Pole at −1)	**0.2 (Start: Pole at −2)**	**0.3 (Start: Zero at −3)**	**0 (End: Pole at −1)**	**20 (End: Pole at −2)**	**30 (End: Zero at −3)**
Pole at −1	−45	−45	−45	0		
Pole at −2		−45	−45	−45	0	
Zero at −3			45	45	45	0
Total slope (deg/dec)	−45	−90	−45	0	45	0

Table 10.3

Bode phase plot: slop contribution from each pole and zero in Example 10.2

Table 10.6 Magnitude diagram slopes for Example 10.3

Description	Frequency (rad/s)			
	0.01 (Start: Plot)	2 (Start: Pole at −2)	3 (Start: Zero at −3)	5 (Start: $\omega_n = 5$)
Pole at −2	0	−20	−20	−20
Zero at −3	0	0	20	20
$\omega_n = 5$	0	0	0	−40
Total slope (dB/dec)	0	−20	0	−40

Table 10.6

Magnitude diagram slopes for Example 10.3