Chapter 10

Frequency Response Techniques

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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.

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

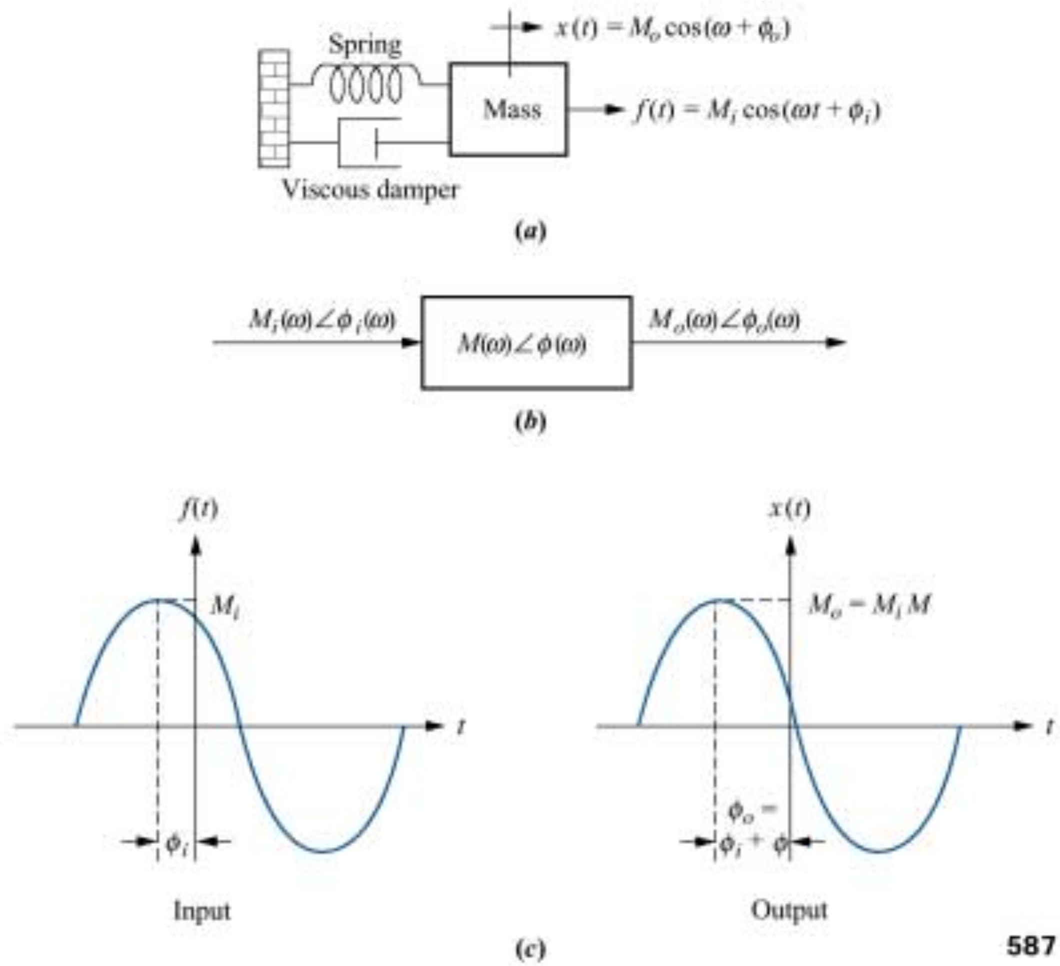

Figure 10.3
System with sinusoidal input

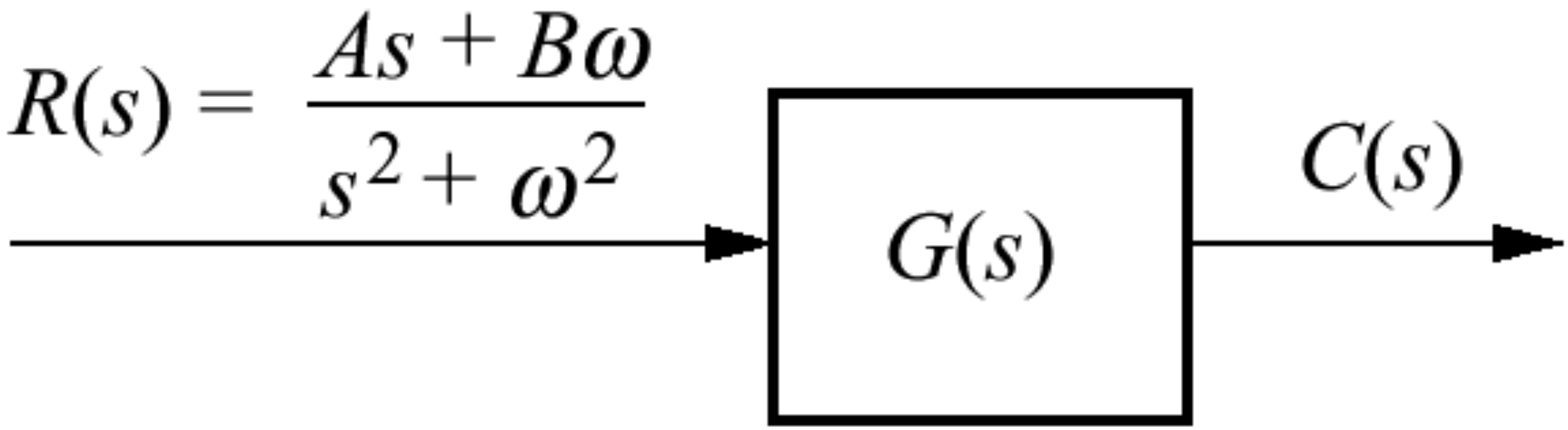

Figure 10.4
Frequency response plots for $G(s) = 1/(s+2)$: separate magnitude and phase

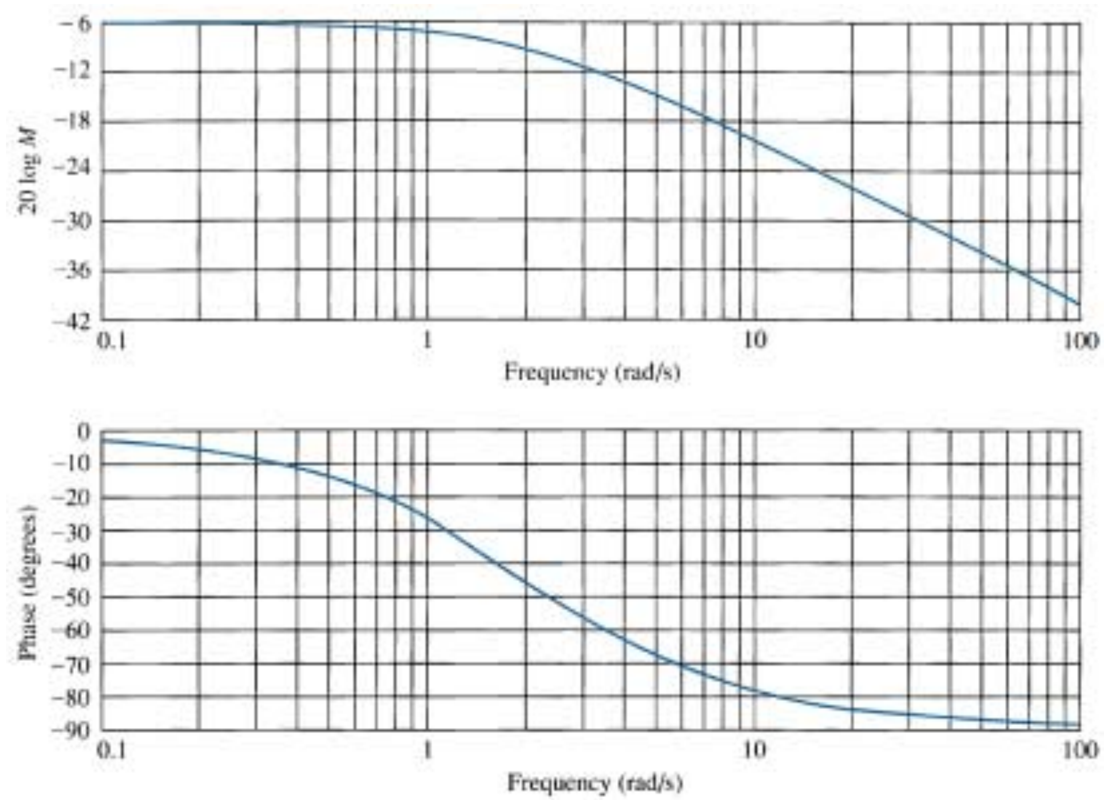

Figure 10.5
Frequency response plots for $G(s) = 1/(s+2)$: polar plot

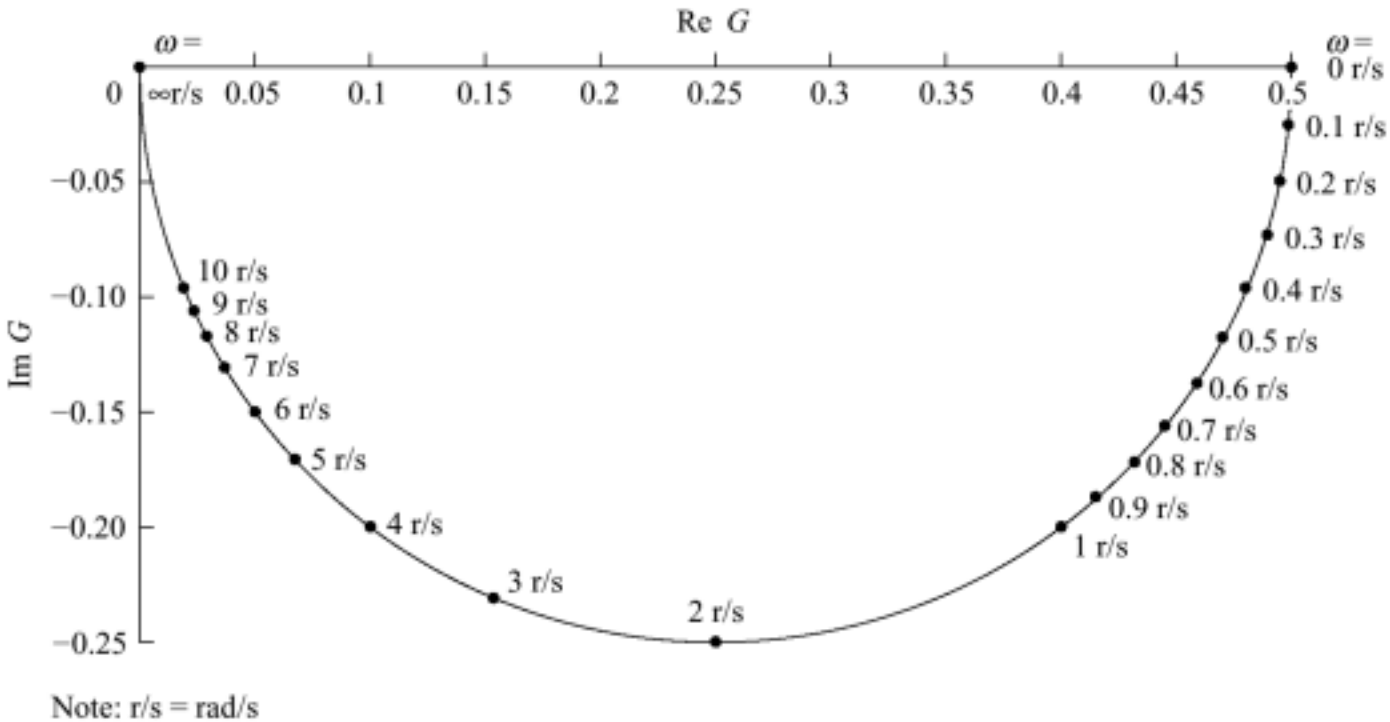

Figure 10.6
Bode plots of (s + a):
a. magnitude plot;
b. phase plot.

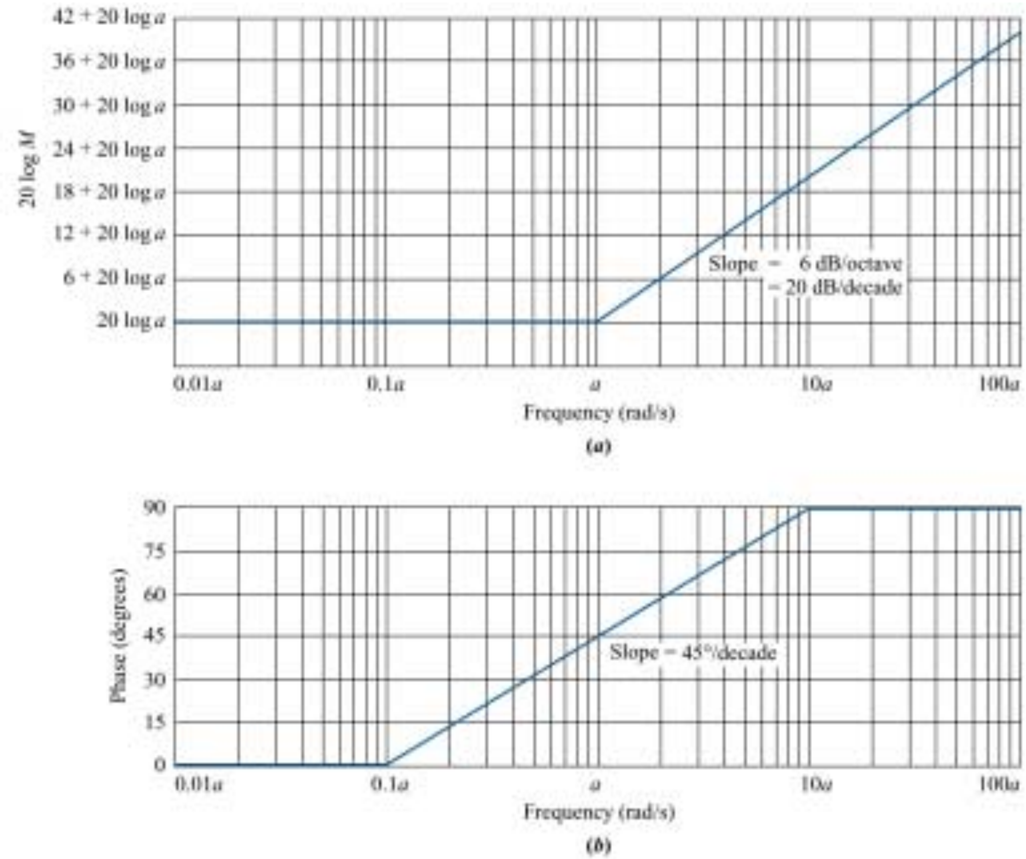

Figure 10.7
Asymptotic and actual normalized and scaled magnitude response of (s + a)

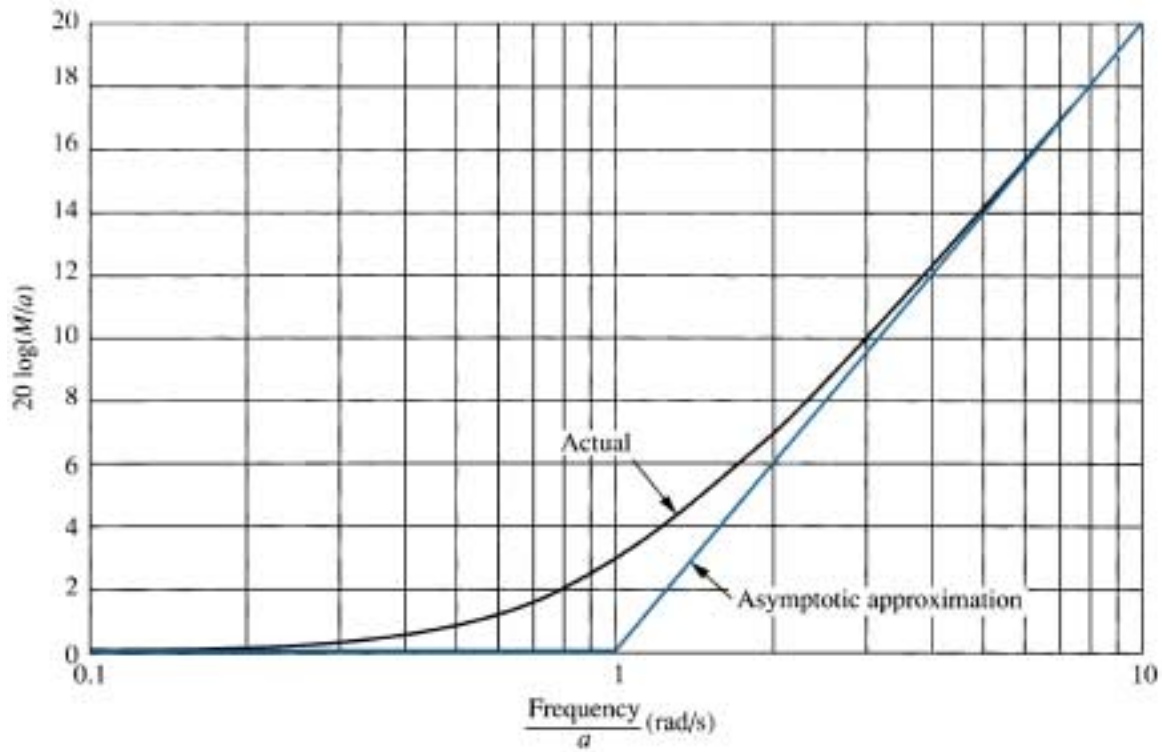

Figure 10.8
Asymptotic and actual normalized and scaled phase response of (s + a)

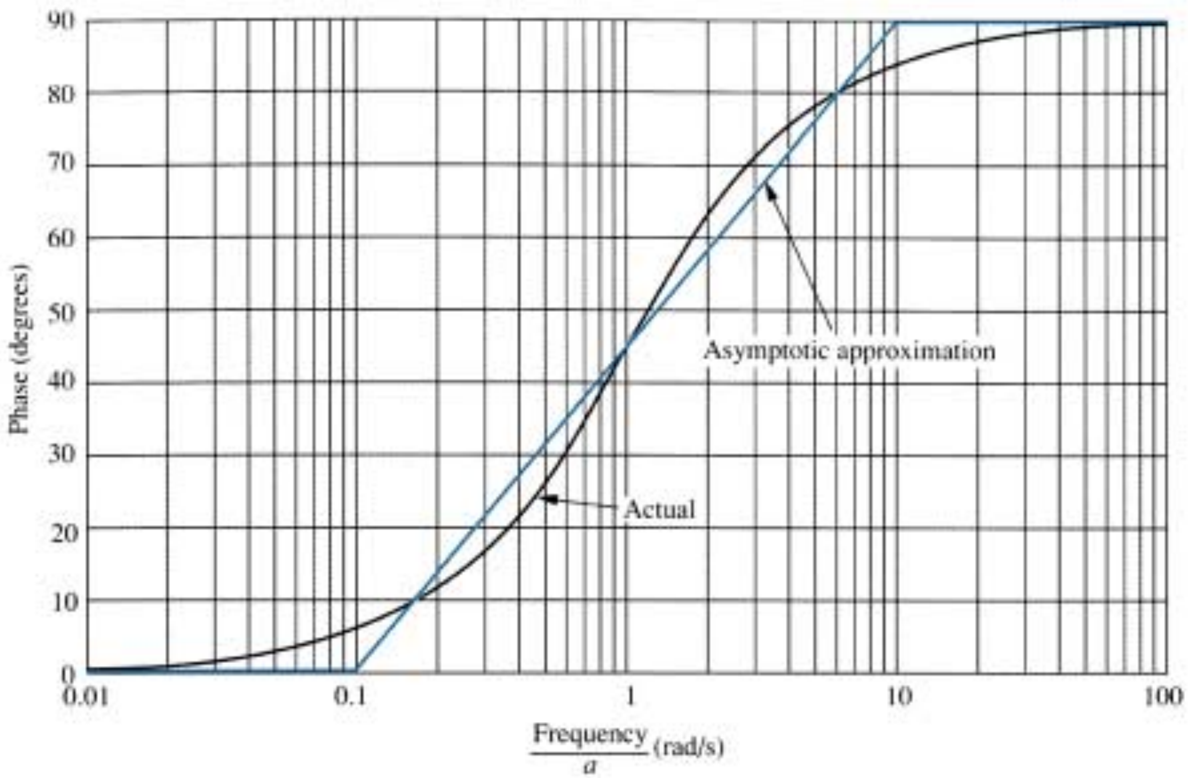

Figure 10.9
Normalized and scaled Bode plots for
a. $G(s) = s$;
b. $G(s) = 1/s$;
c. $G(s) = (s + a)$;
d. $G(s) = 1/(s + a)$

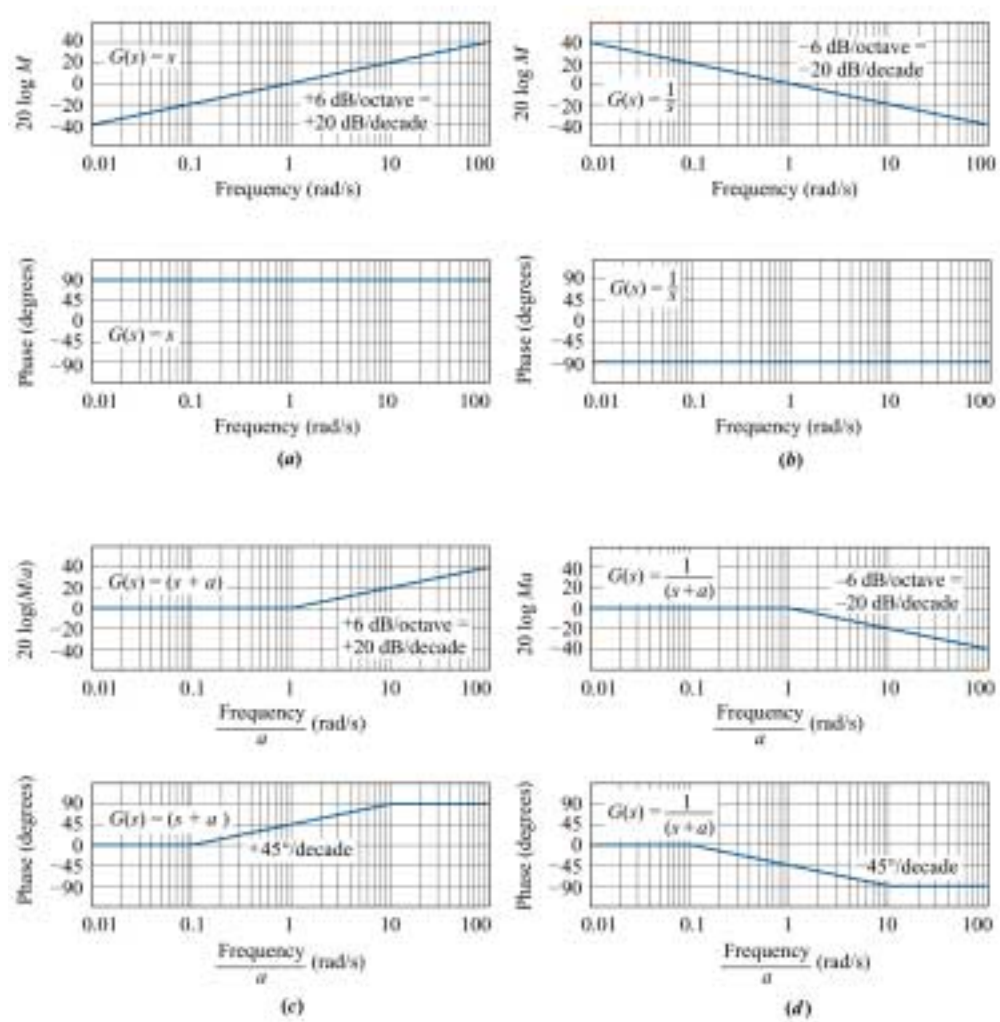

Figure 10.10 Closed-loop unity feedback system

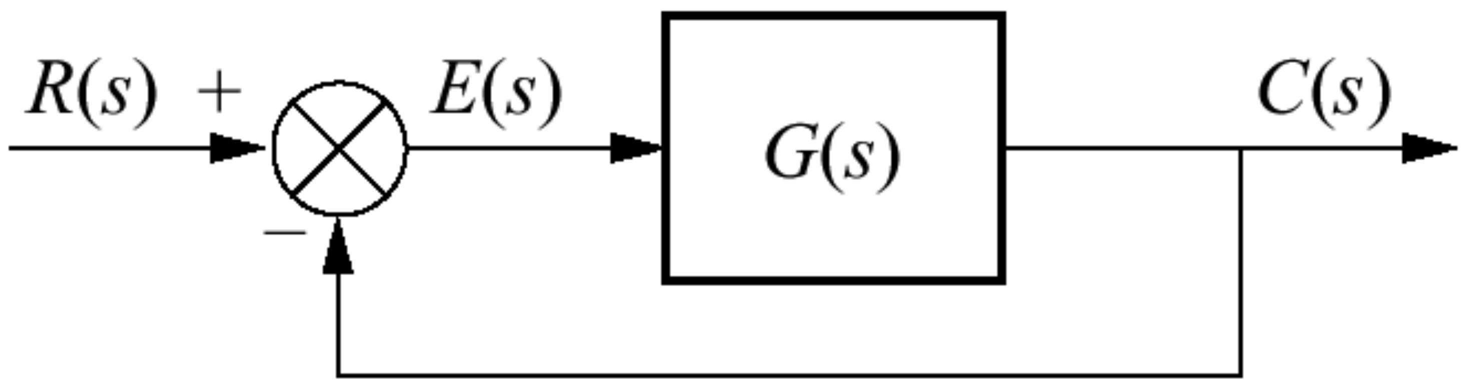

Figure 10.11 Bode log-magnitude plot for Example 10.2:
a. components;
b. composite

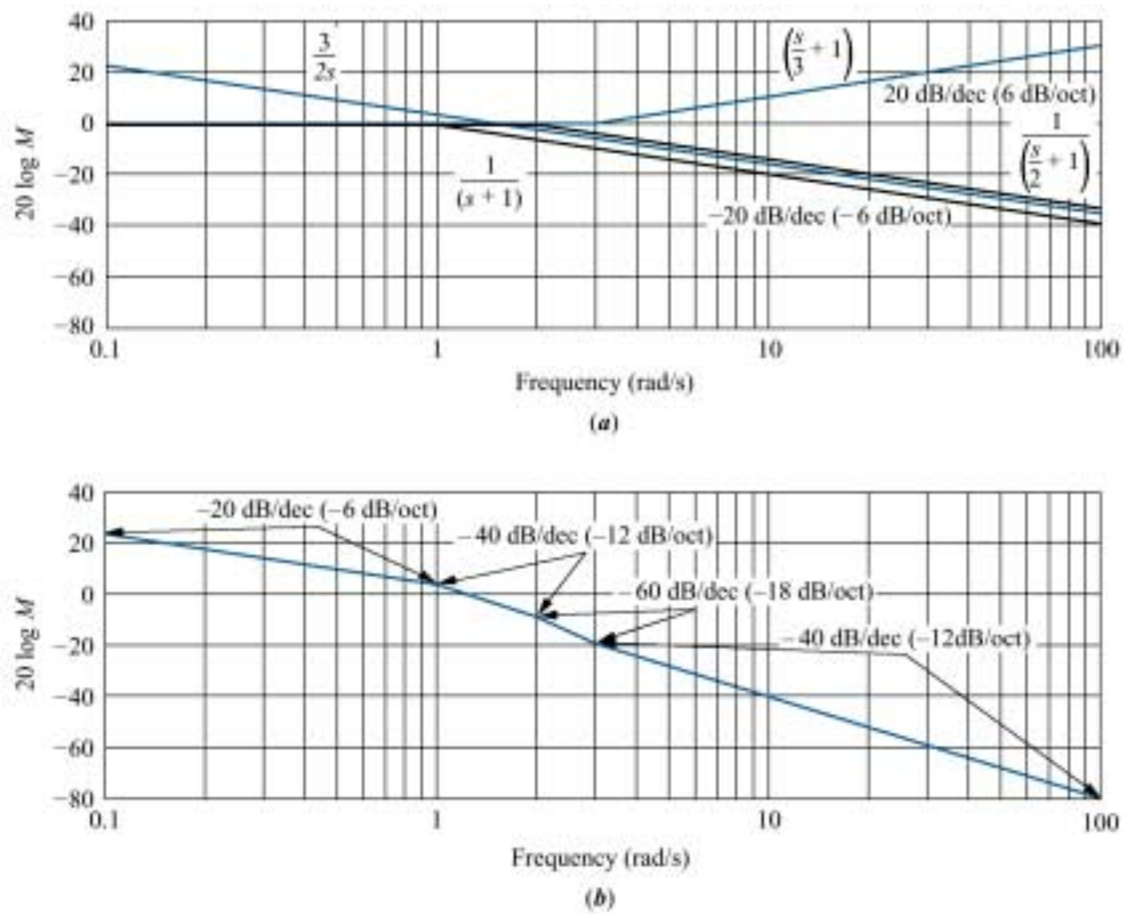

Figure 10.12
Bode phase plot for Example 10.2:
a. components;
b. composite

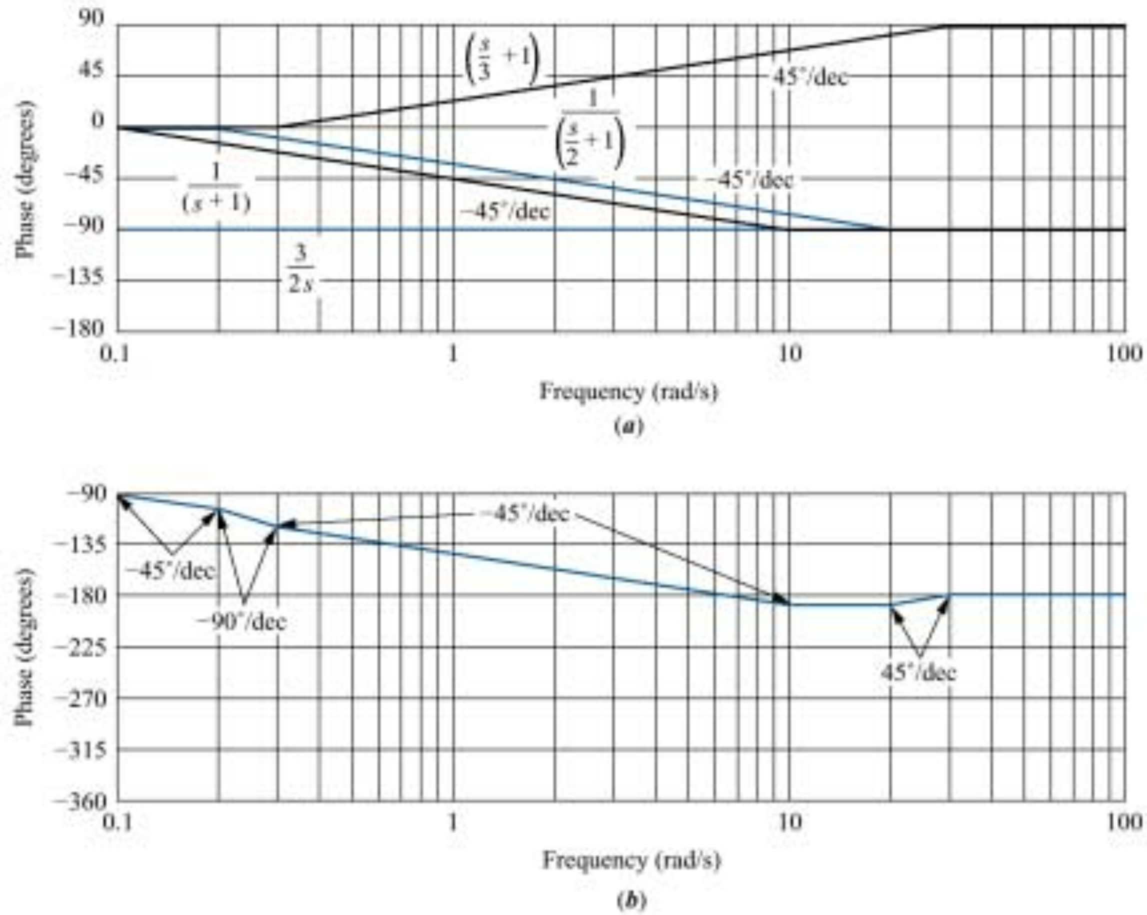

Figure 10.13 Bode asymptotes for normalized and scaled $G(s) = s^2 + 2\zeta\omega_n s + \omega_n^2$:
a. magnitude;
b. phase

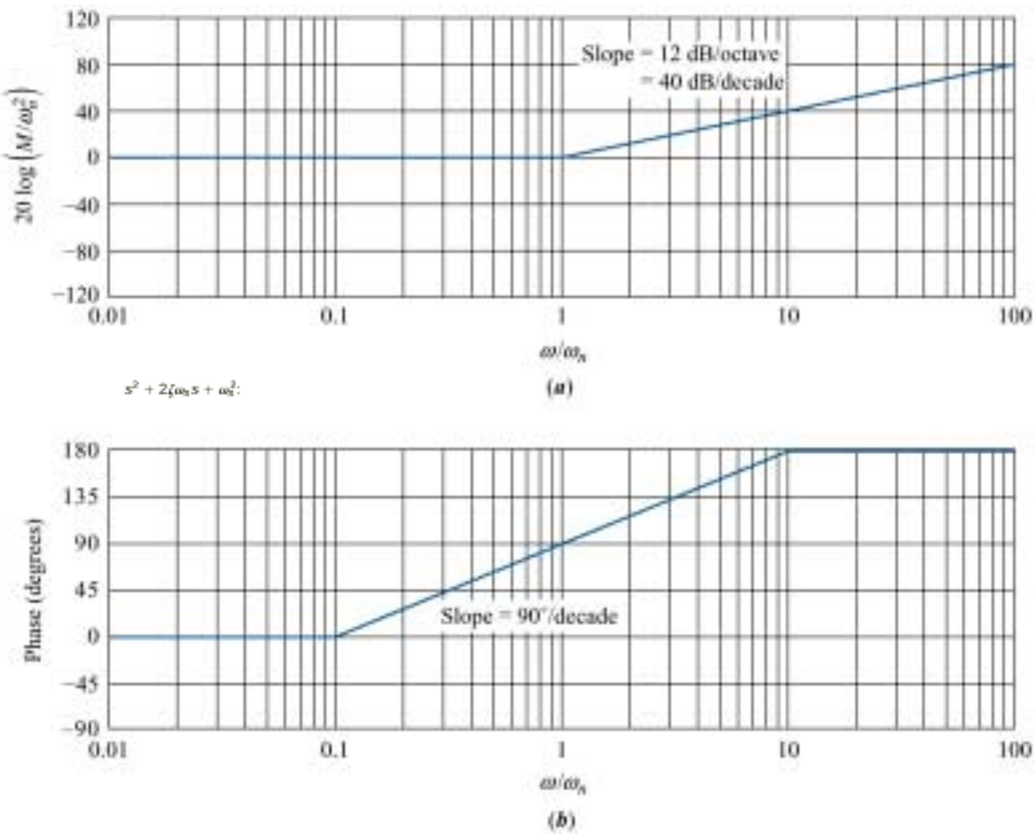

Figure 10.14
Normalized and scaled log-magnitude response for
$(s^2 + 2\zeta\omega_n s + \omega_n^2)$

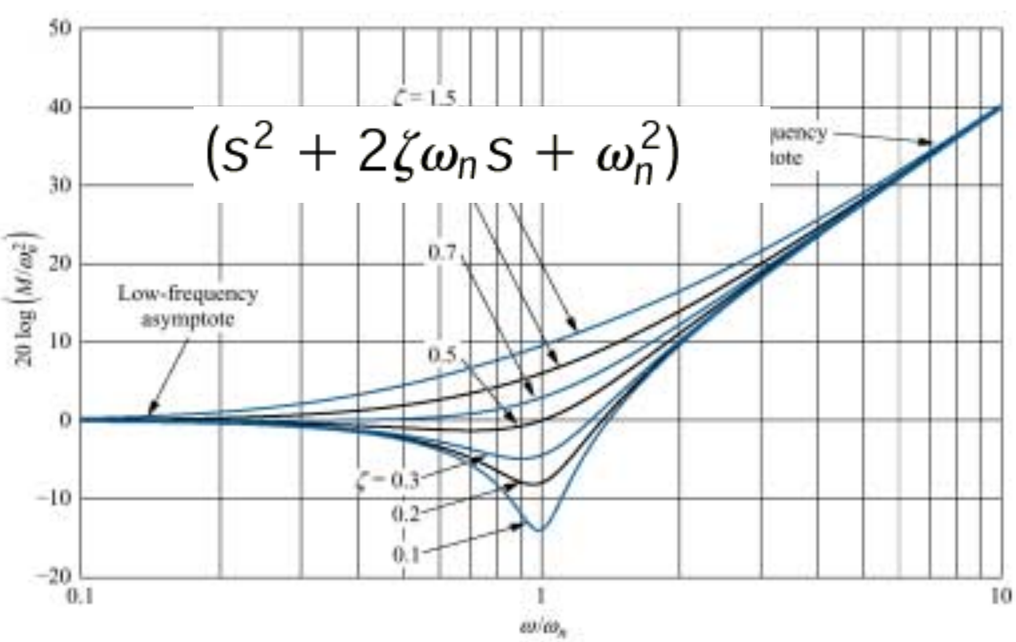

Figure 10.15
Scaled phase response for
$(s^2 + 2\zeta\omega_n s + \omega_n^2)$

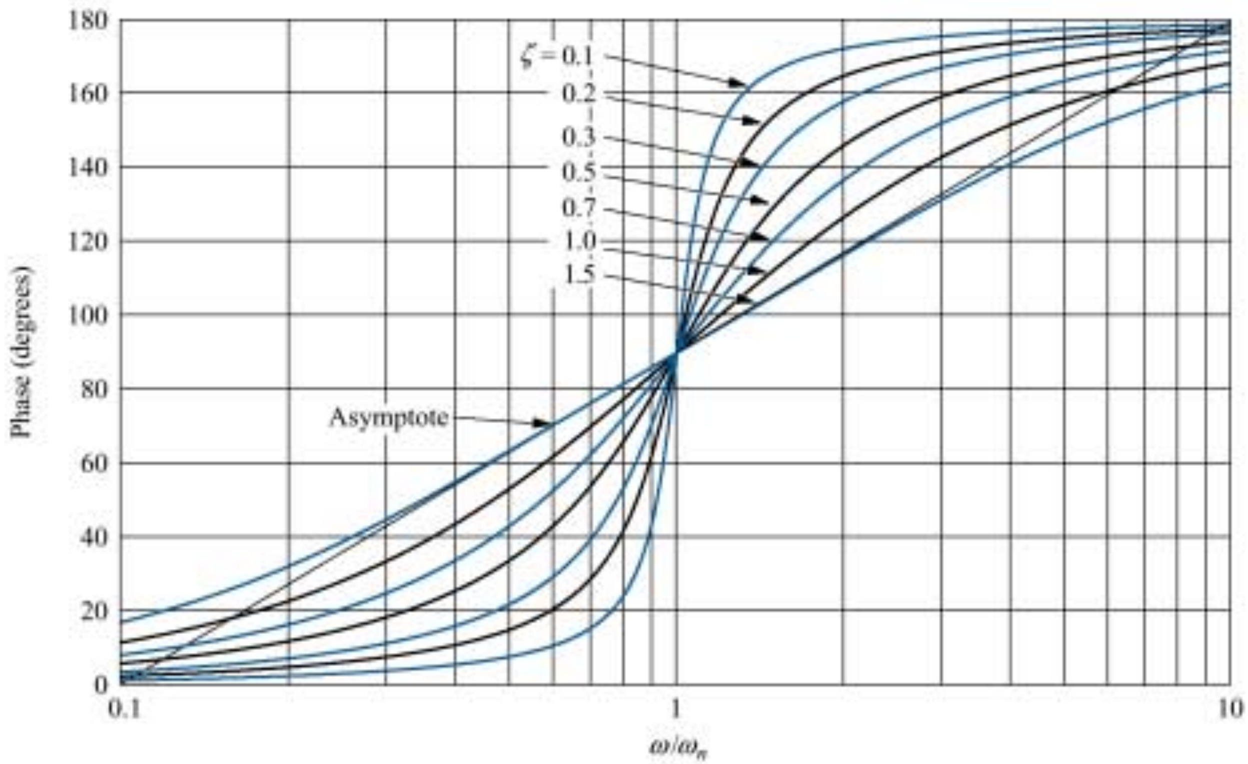

Figure 10.16

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

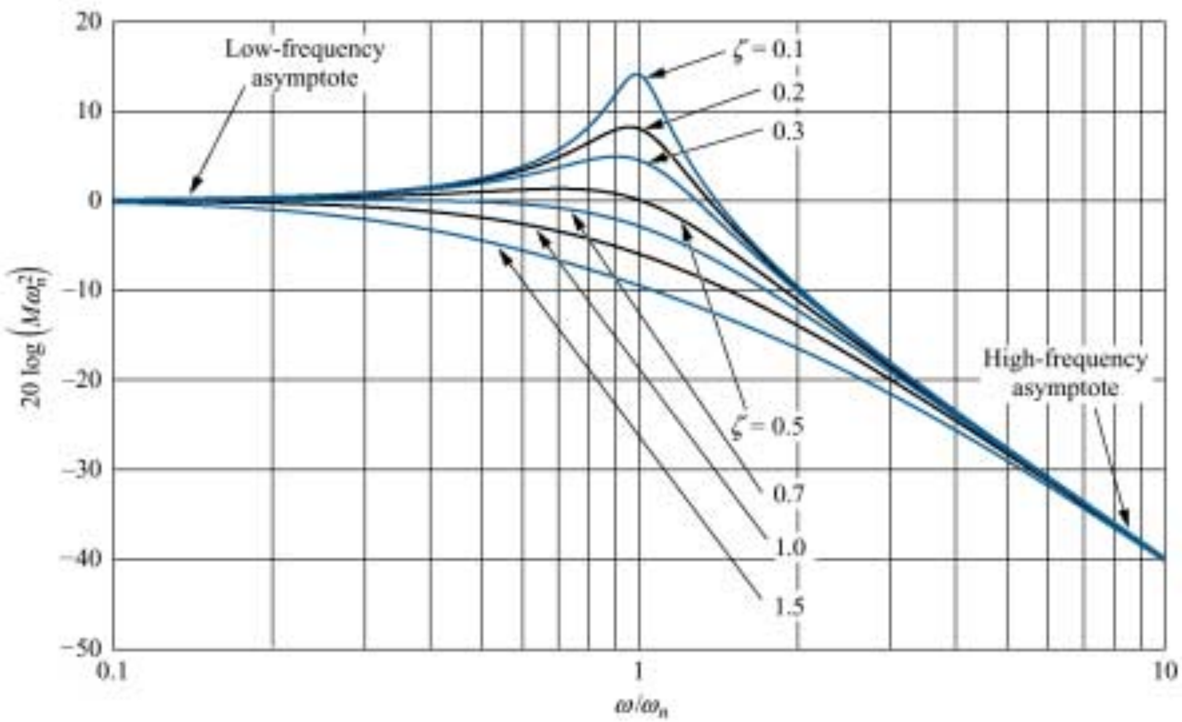

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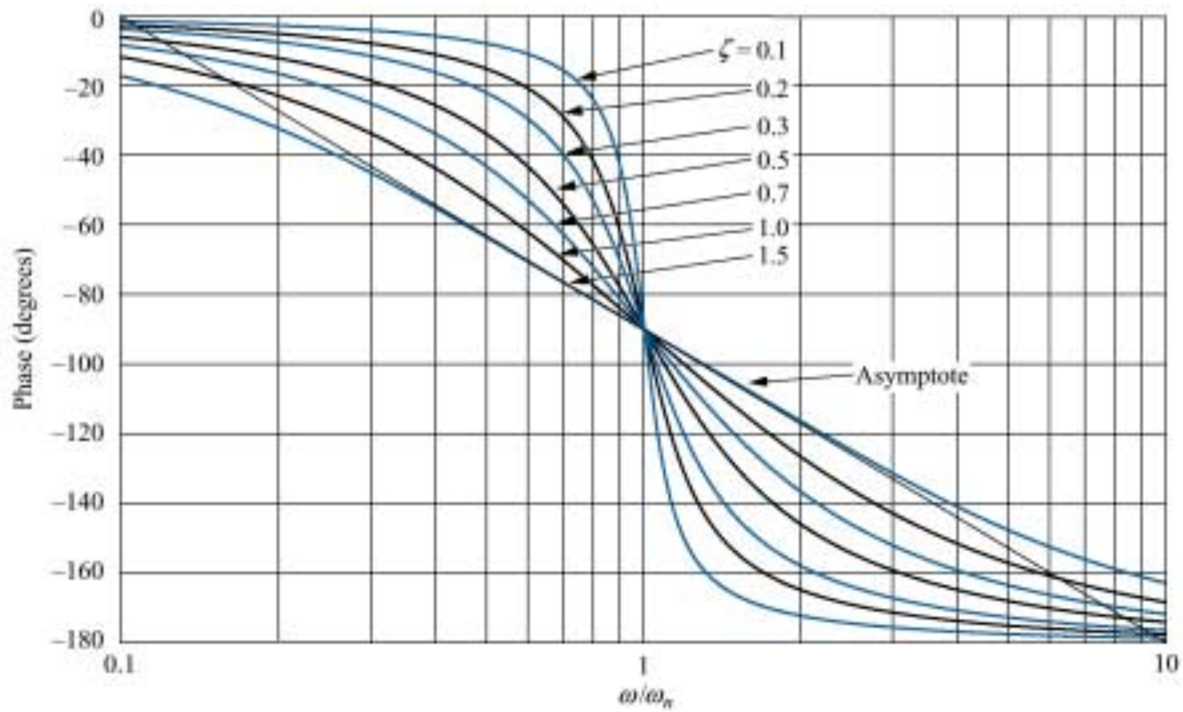
Figure 10.17
Scaled phase response for
$1/(s^2 + 2\zeta\omega_n s + \omega_n^2)$



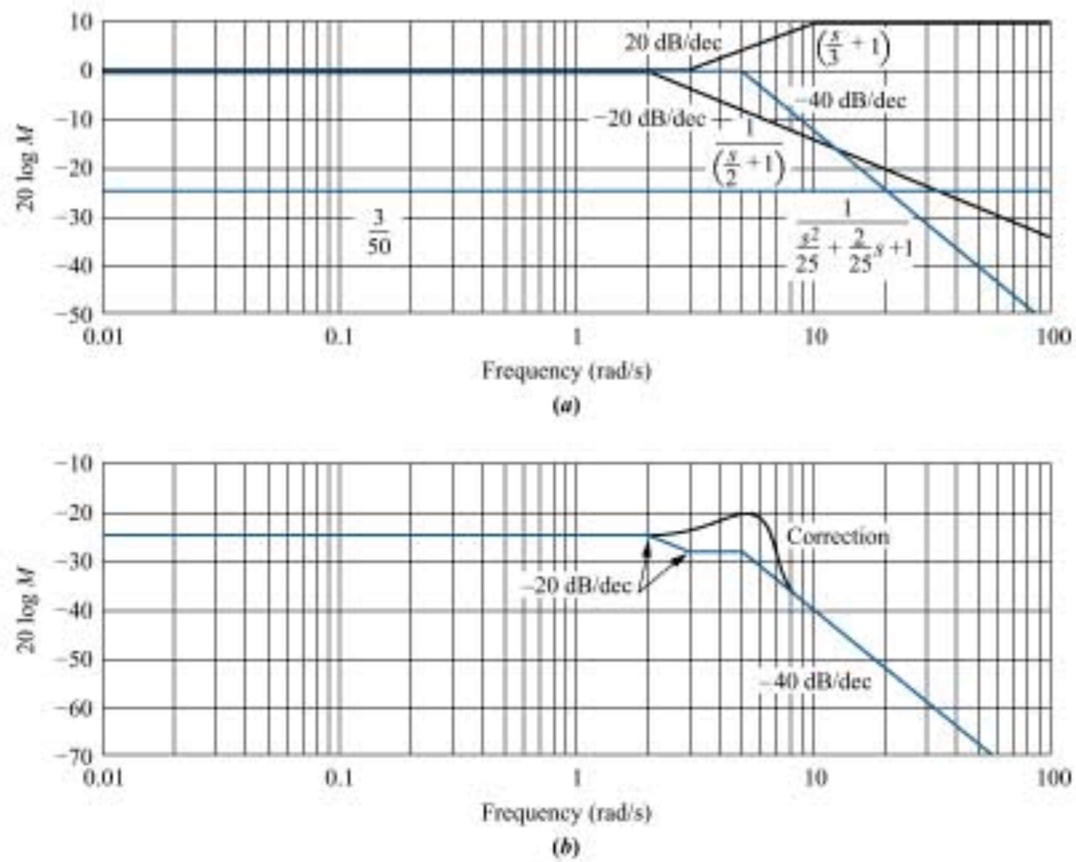


Figure 10.18 Bode magnitude plot for $G(s) = (s + 3)/[(s + 2)(s^2 + 2s + 25)]$: **a.** components; **b.** composite

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

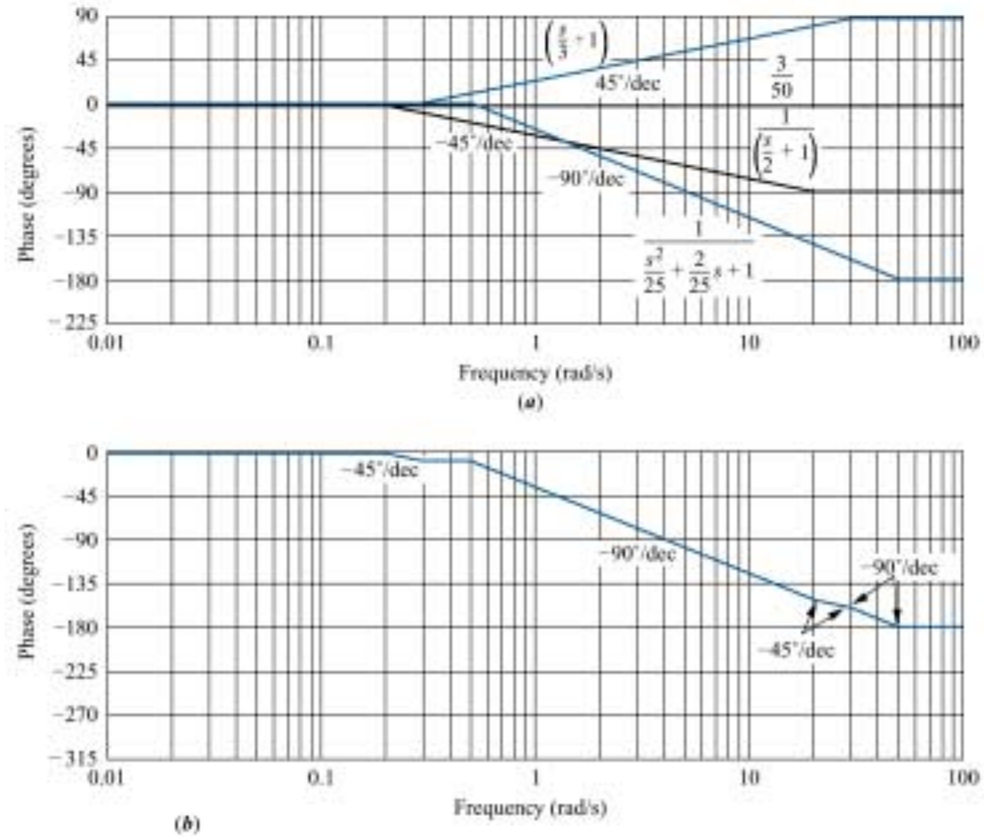


Figure 10.20
Closed- loop control system

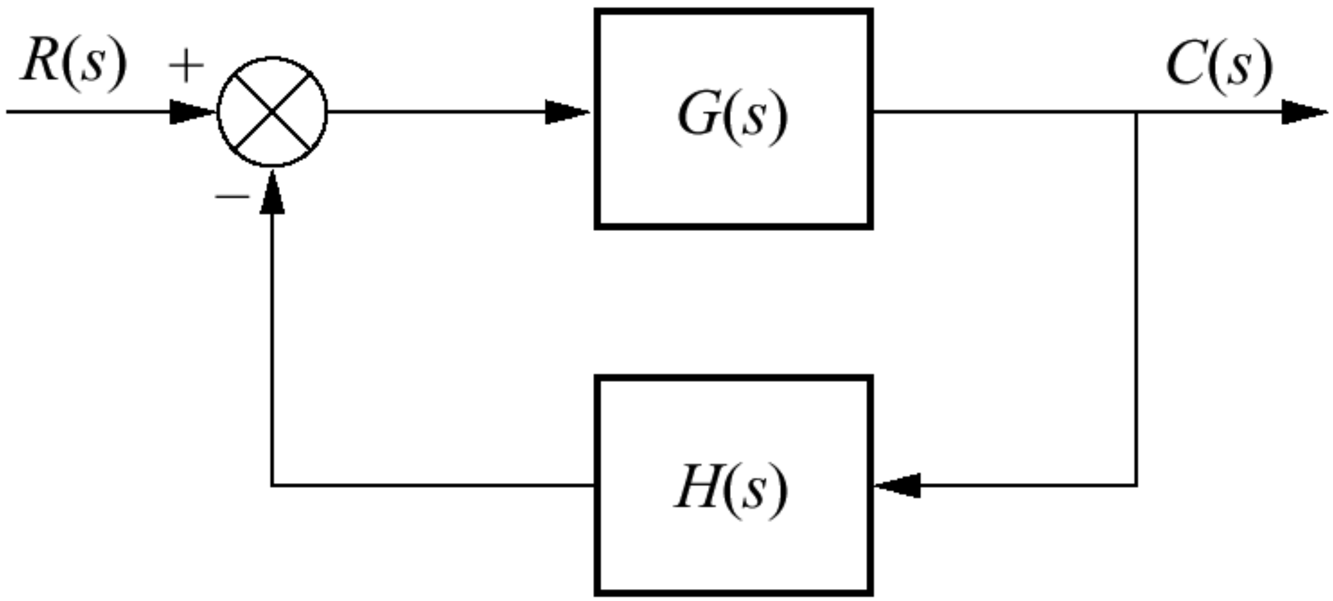


Figure 10.21
Mapping contour *A* through function *F*(*s*) to contour *B*

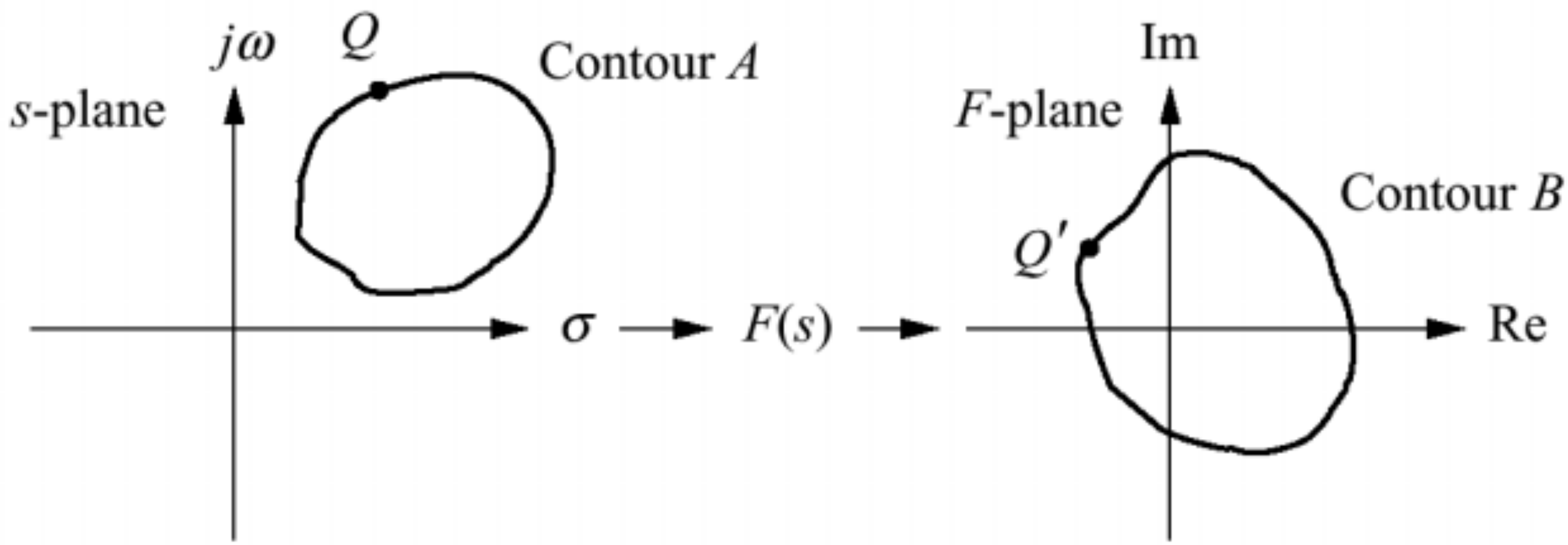


Figure 10.22
Examples of contour mapping

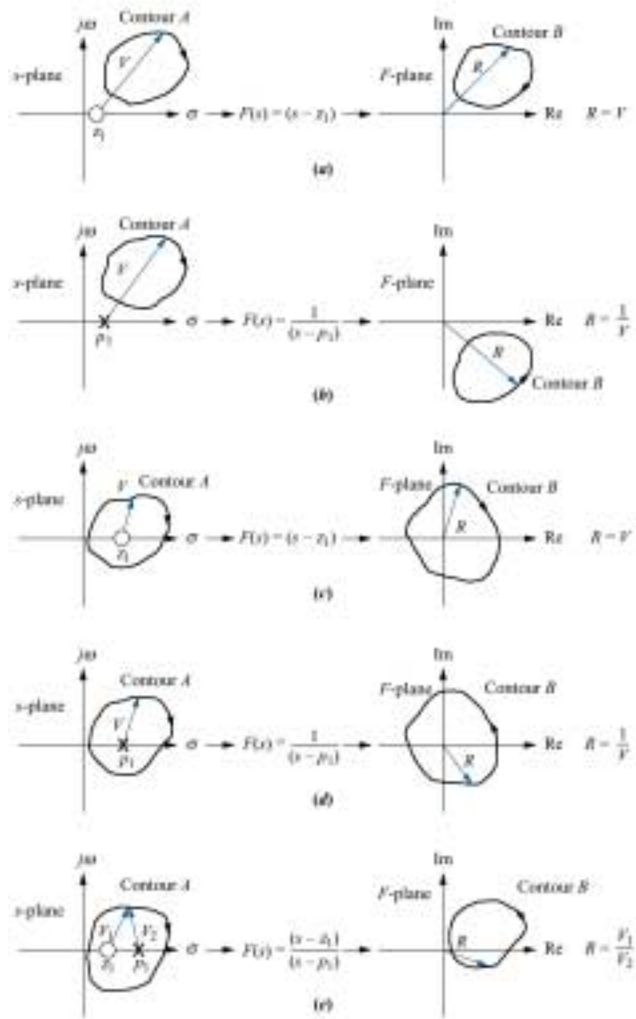


Figure 10.23
Vector representation of mapping

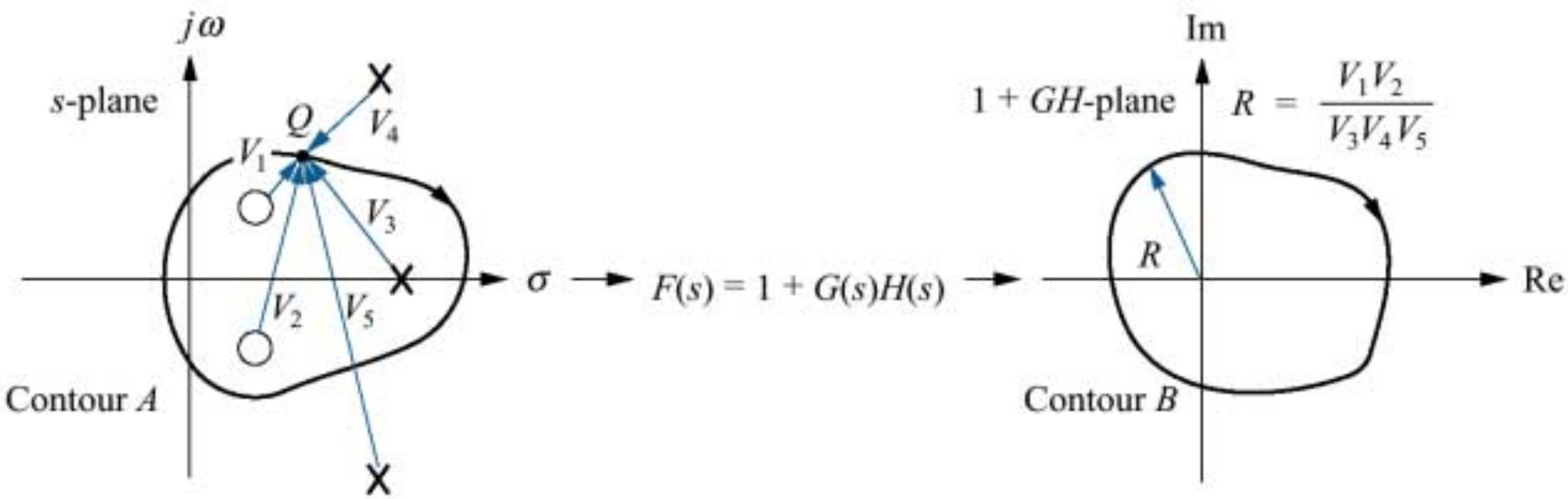


Figure 10.24
Contour enclosing right half-plane to determine stability

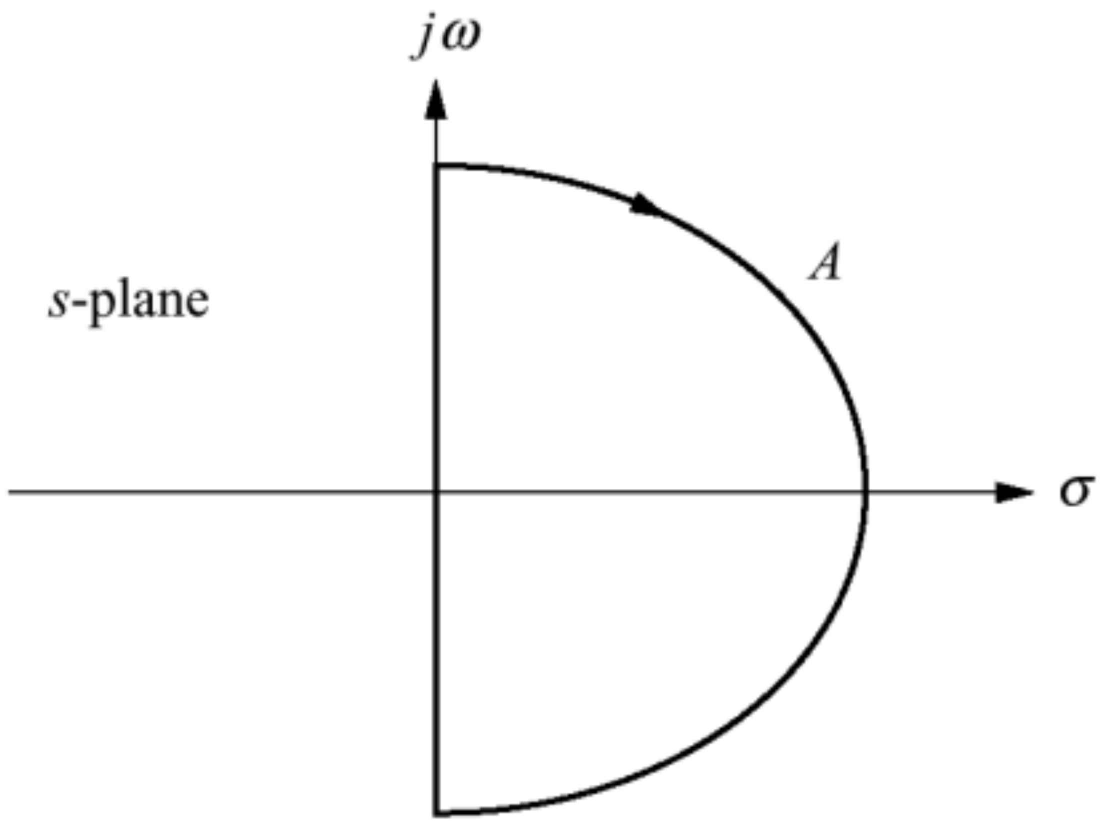


Figure 10.25
Mapping examples:
a. contour does not enclose closed- loop poles;
b. contour does enclose closed- loop poles

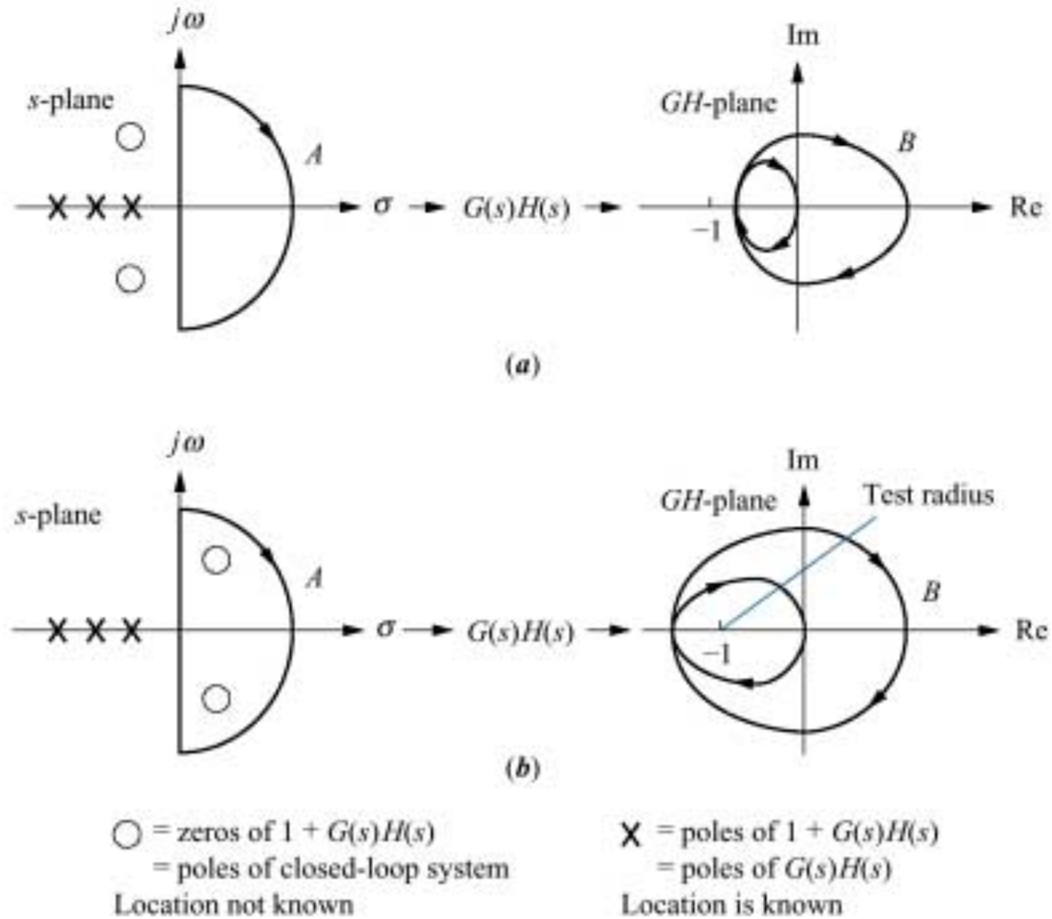


Figure 10.26
a. Turbine and generator;
b. block diagram of speed control system for Example 10.4

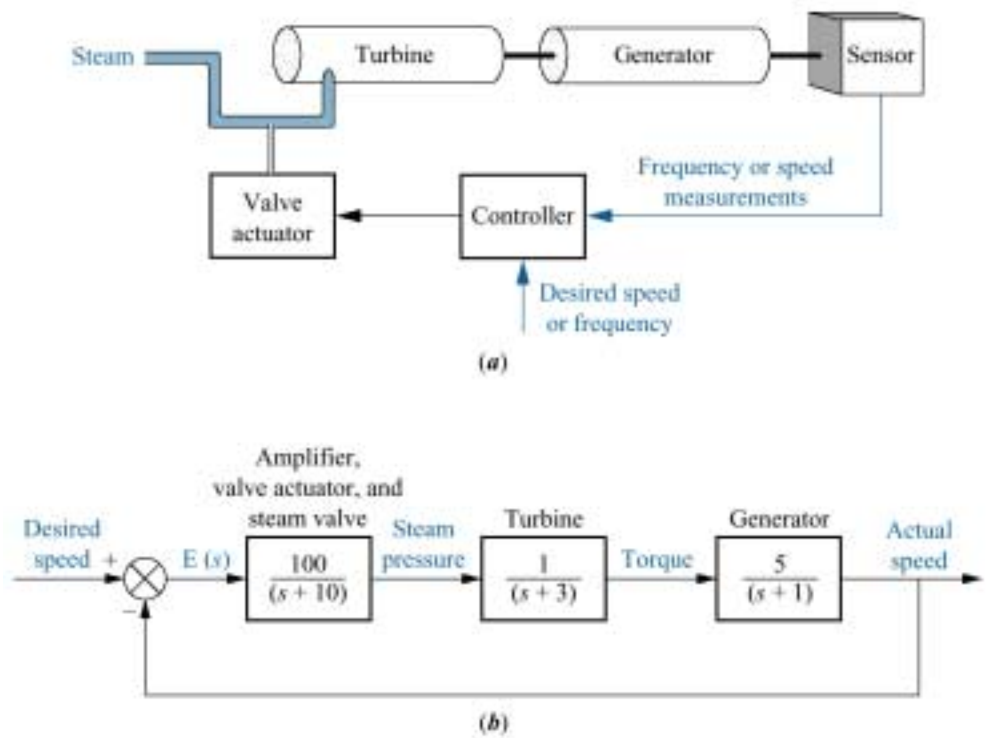


Figure 10.27
Vector evaluation of the Nyquist diagram for Example 10.4:
a. vectors on contour at low frequency;
b. vectors on contour around infinity;
c. Nyquist diagram

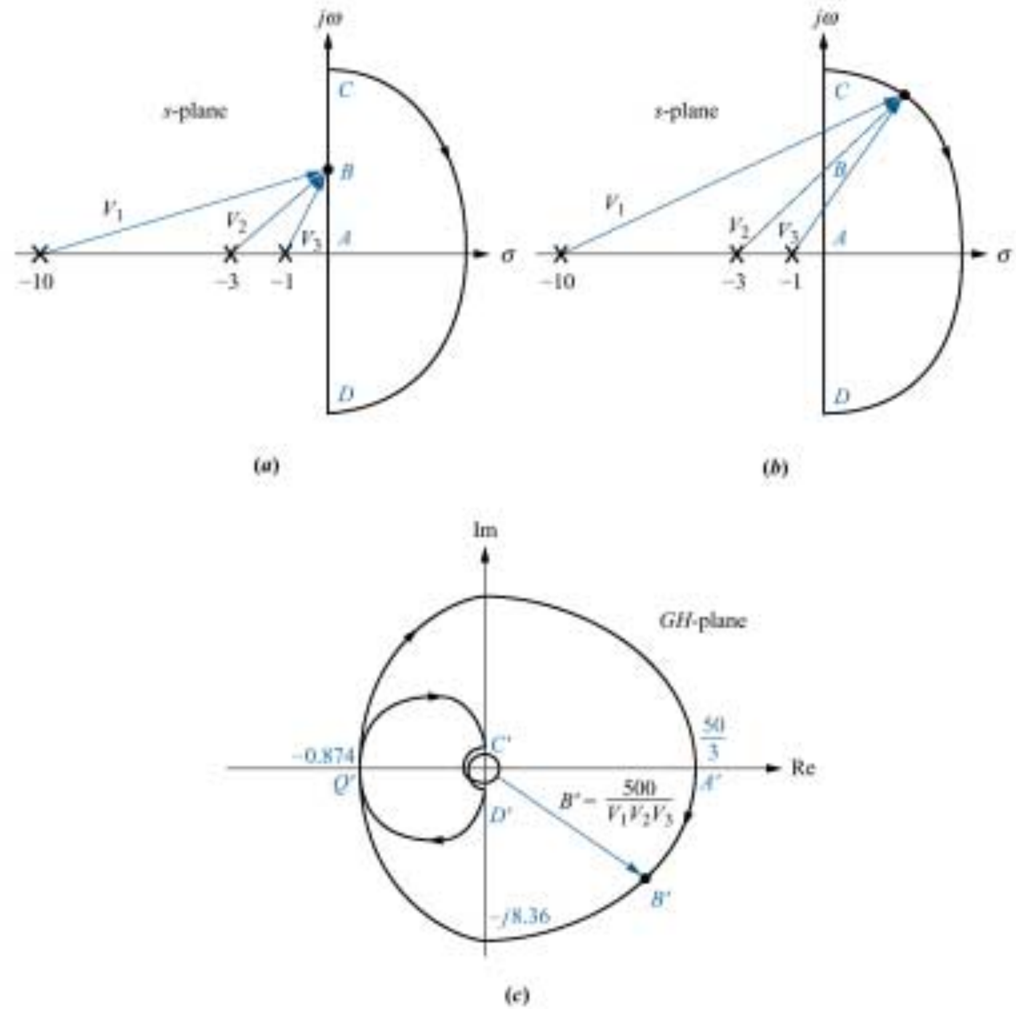


Figure 10.28
Detouring around open-loop poles:
a. poles on contour;
b. detour right;
c. detour left

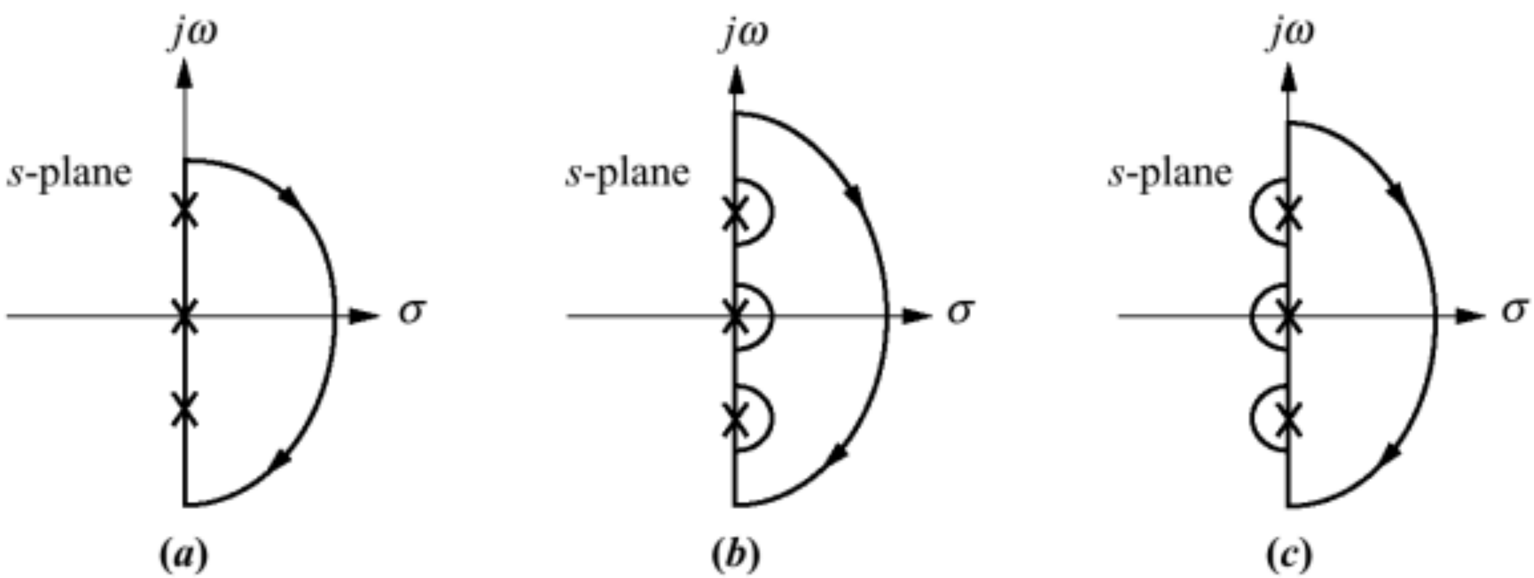


Figure 10.29
a. Contour for Example 10.5;
b. Nyquist diagram for Example 10.5

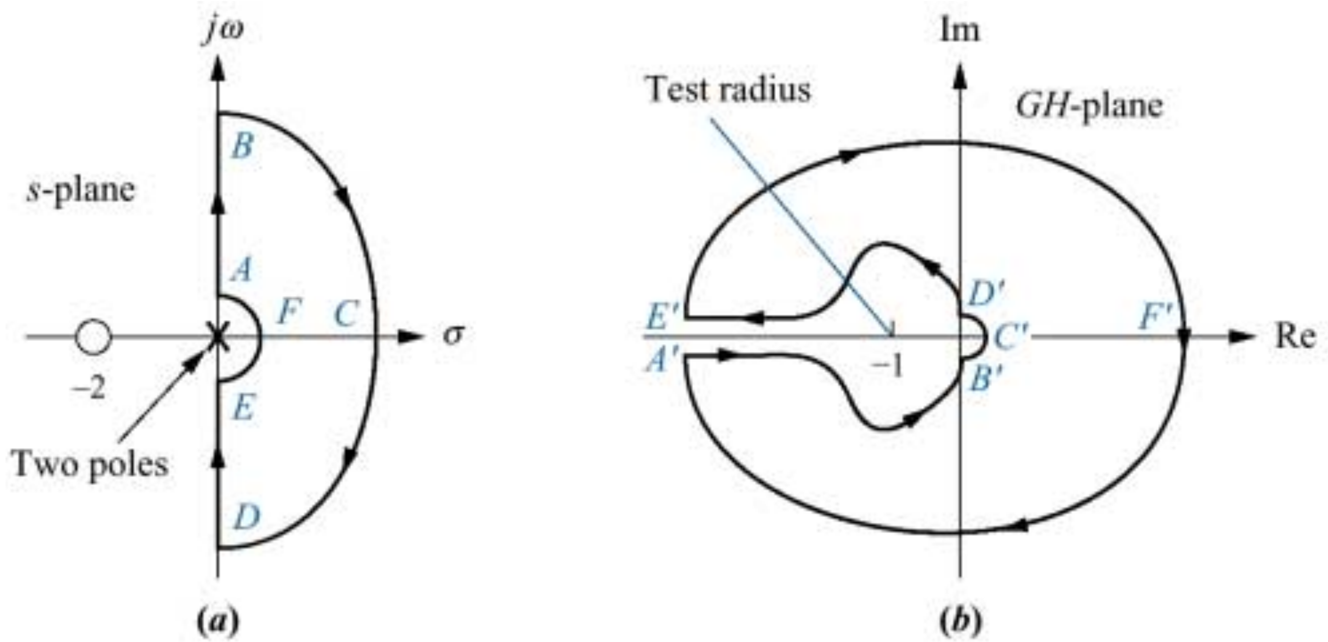


Figure 10.30
Demonstrating
Nyquist stability:
a. system;
b. contour;
c. Nyquist diagram

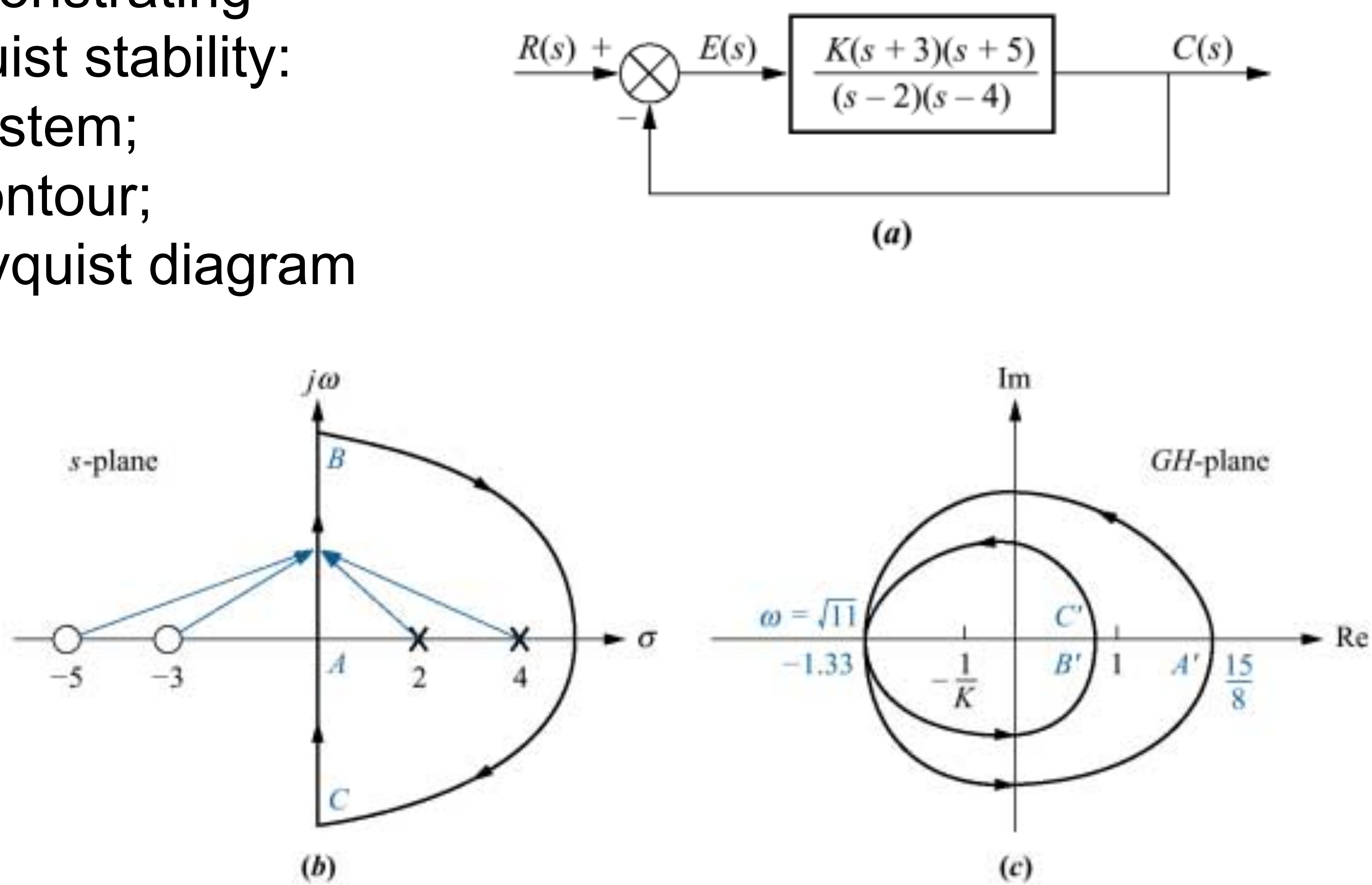


Figure 10.31
a. Contour for Example 10.6;
b. Nyquist diagram

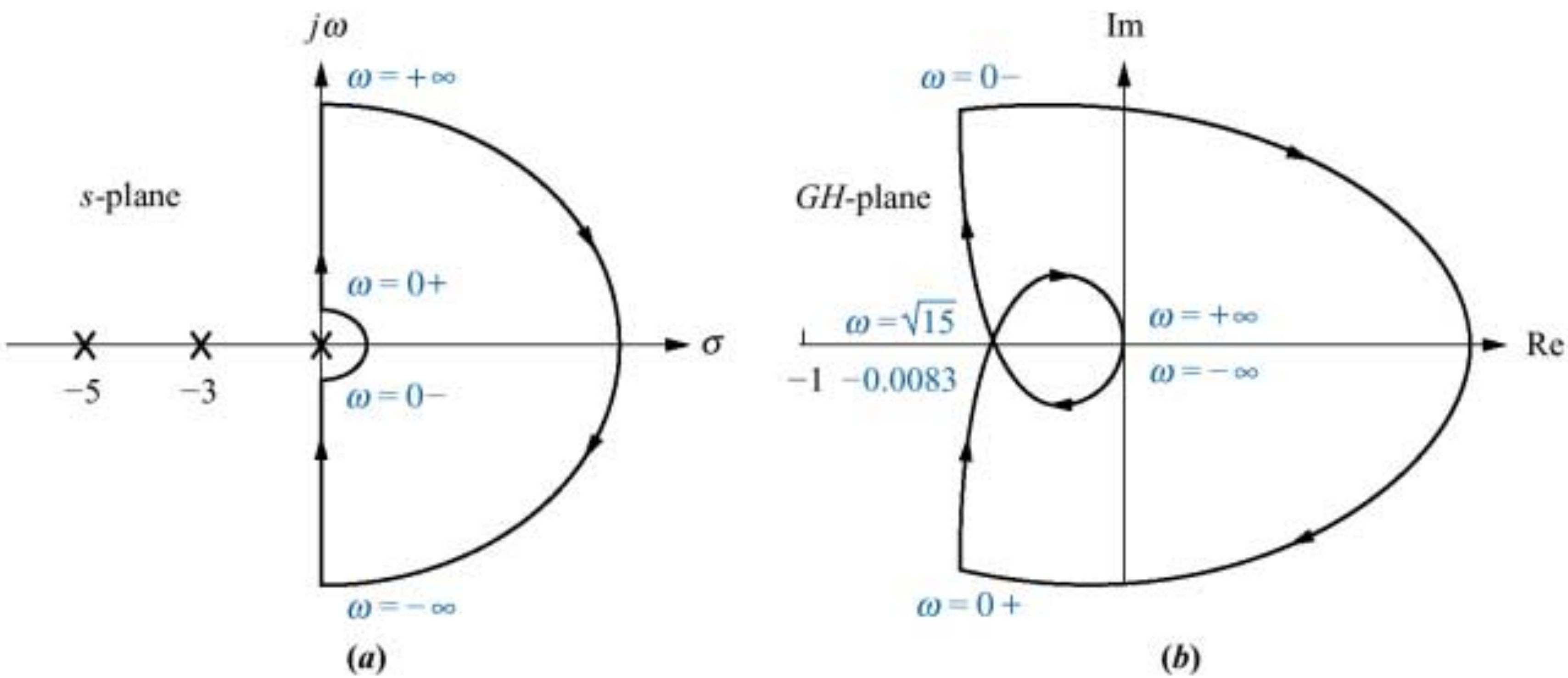


Figure 10.32
a. Contour and root locus of system that is stable for small gain and unstable for large gain;
b. Nyquist diagram

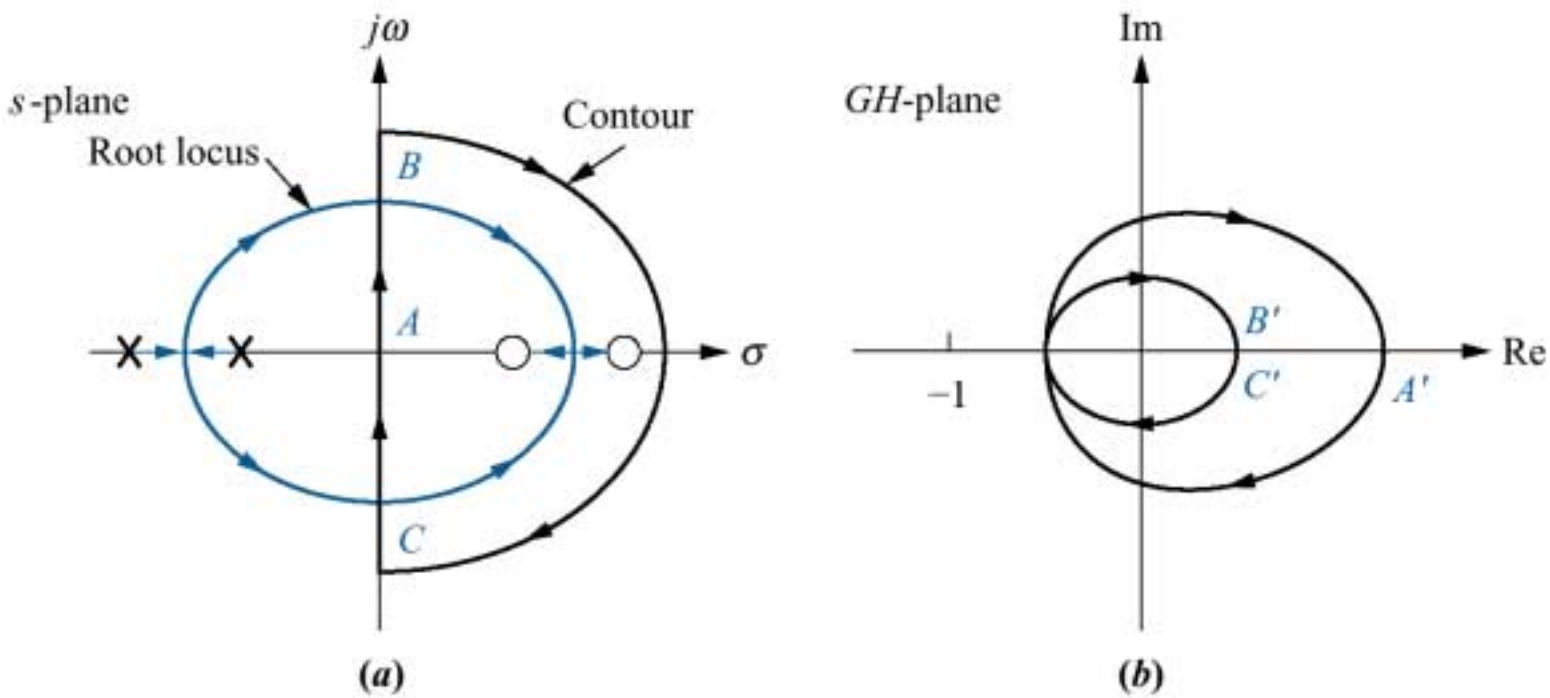


Figure 10.33
a. Contour and root locus of system that is unstable for small gain and stable for large gain;
b. Nyquist diagram

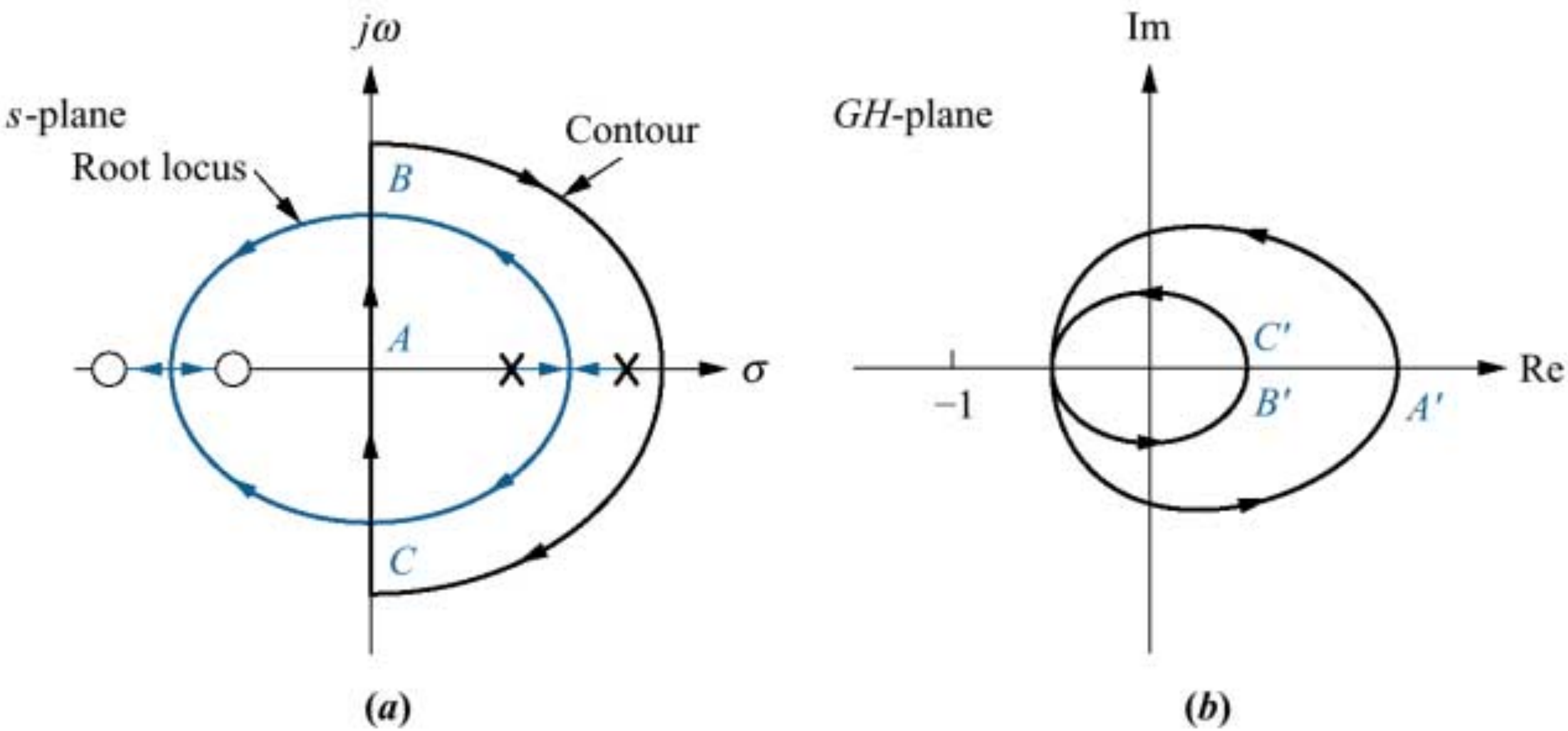


Figure 10.34
a. Portion of contour to be mapped for Example 10.7;
b. Nyquist diagram of mapping of positive imaginary axis

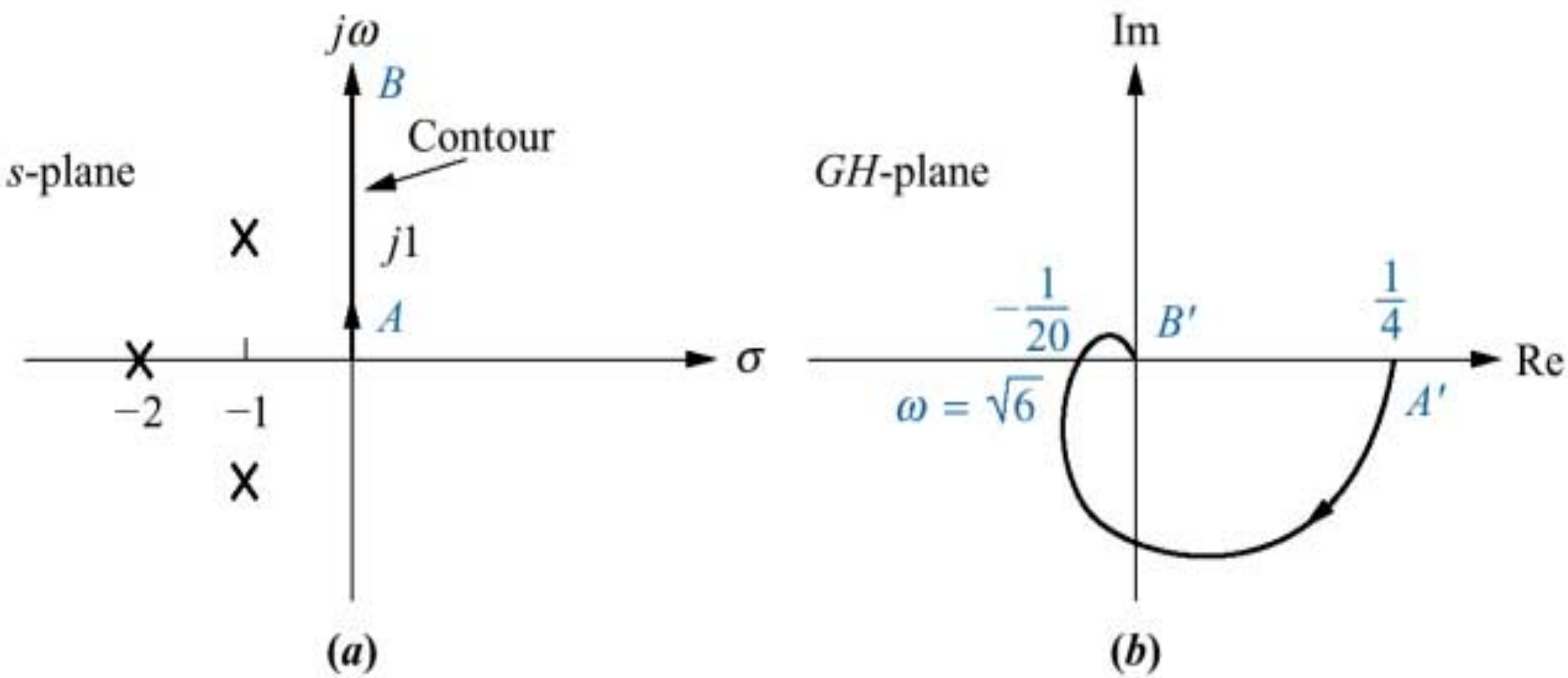


Figure 10.35
Nyquist diagram showing gain and phase margins

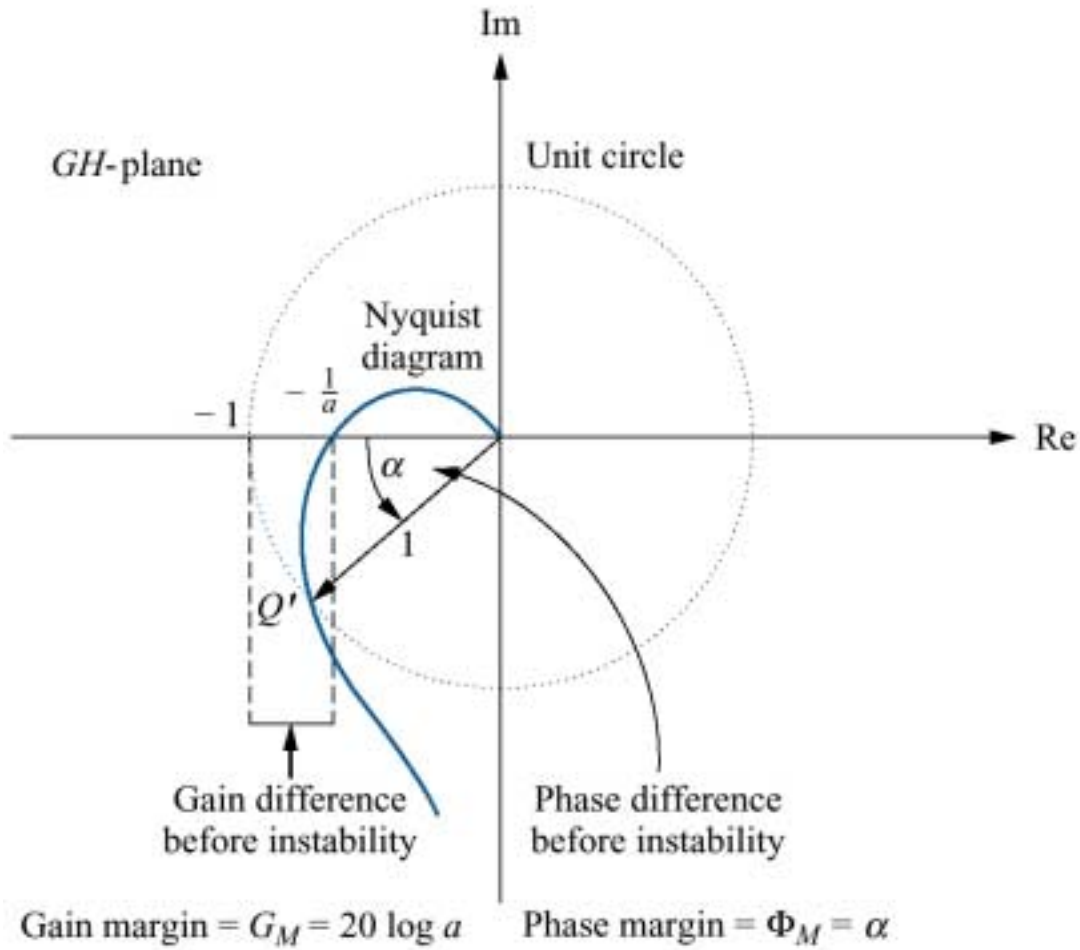


Figure 10.36
Bode log-magnitude and phase diagrams for the system of Example 10.9

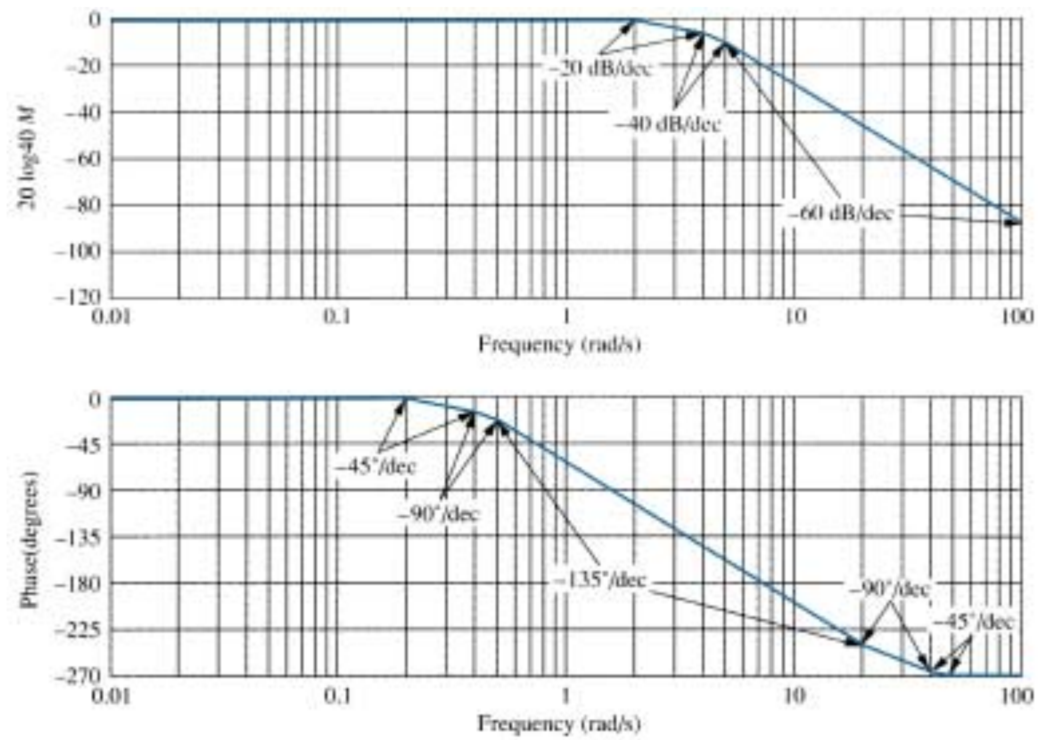


Figure 10.37
Gain and phase margins on the Bode diagrams

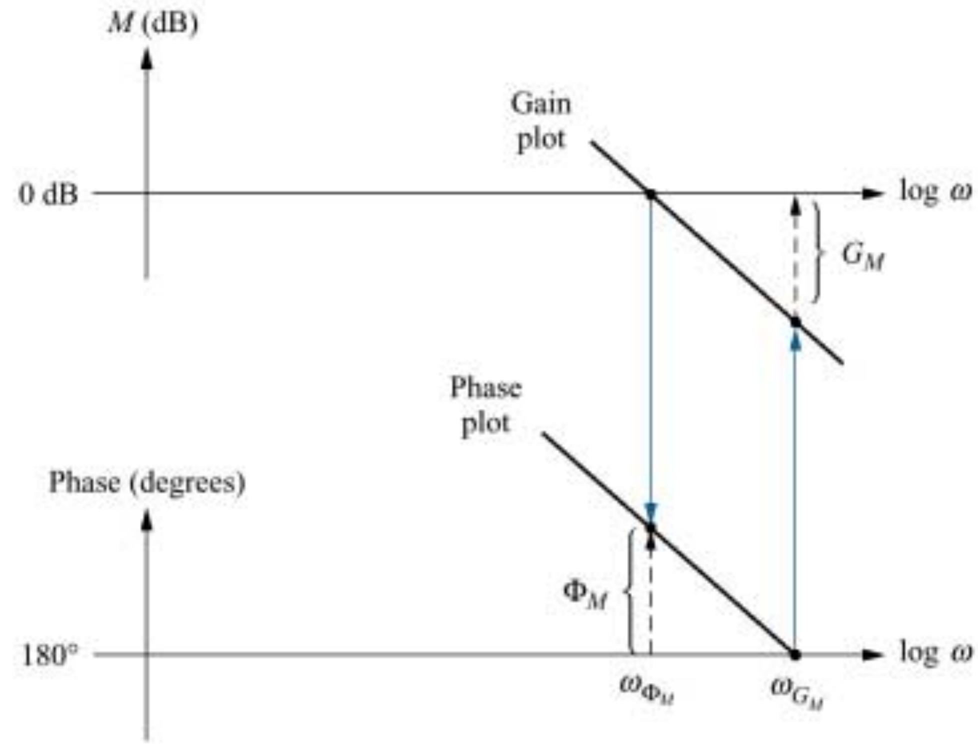


Figure 10.38
Second-order closed-loop system

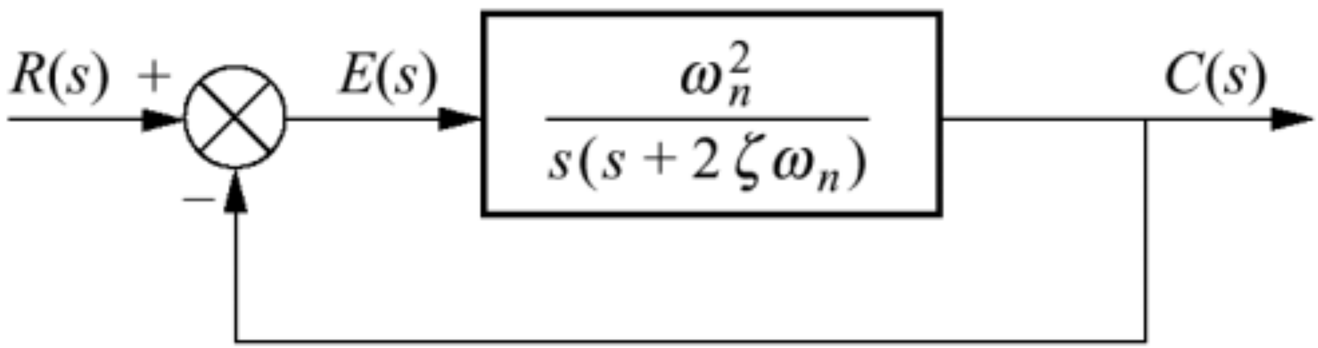


Figure 10.39
Representative log-magnitude plot of Eq. (10.51)

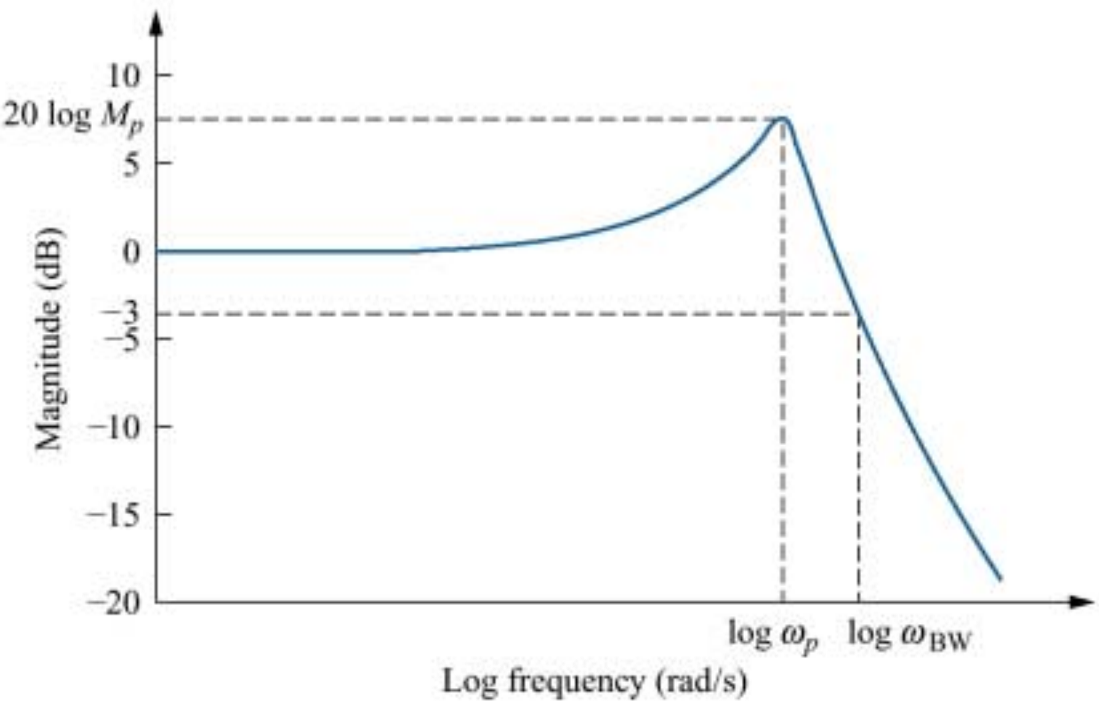


Figure 10.40
Closed-loop frequency percent overshoot for a two-pole system

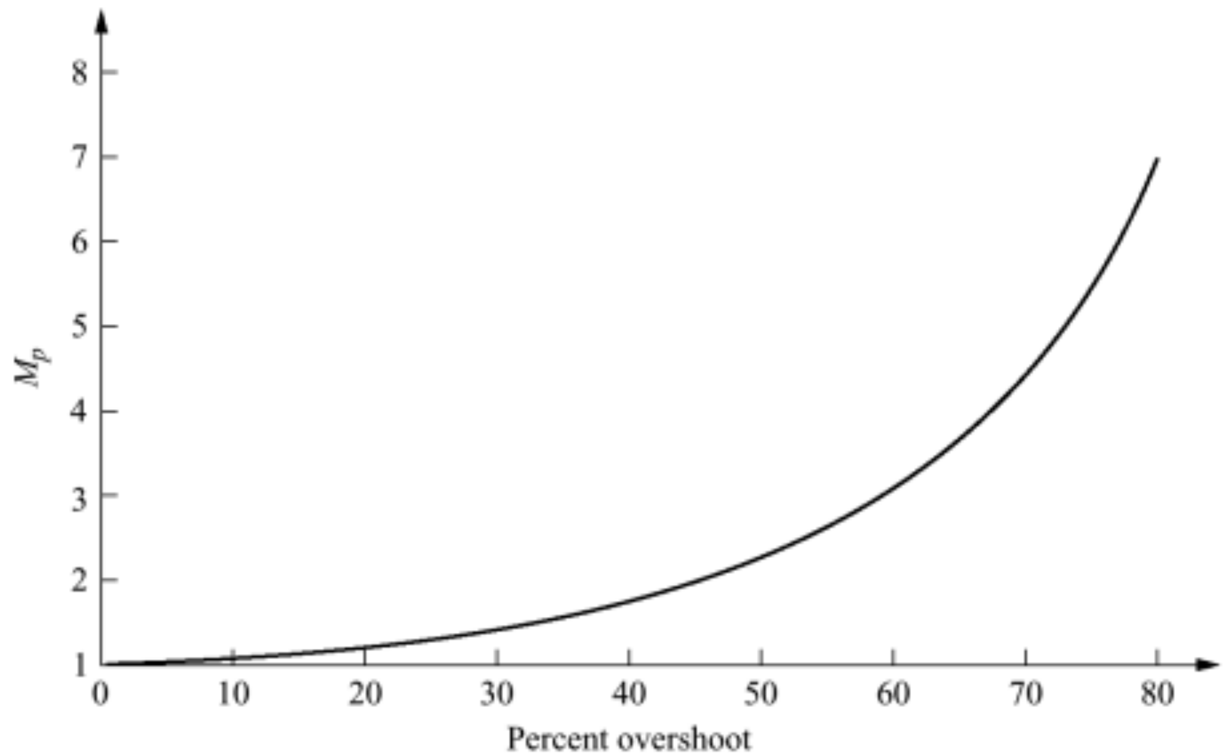


Figure 10.41
Normalized bandwidth vs. damping ratio for:
a. settling time;
b. peak time;
c. rise time

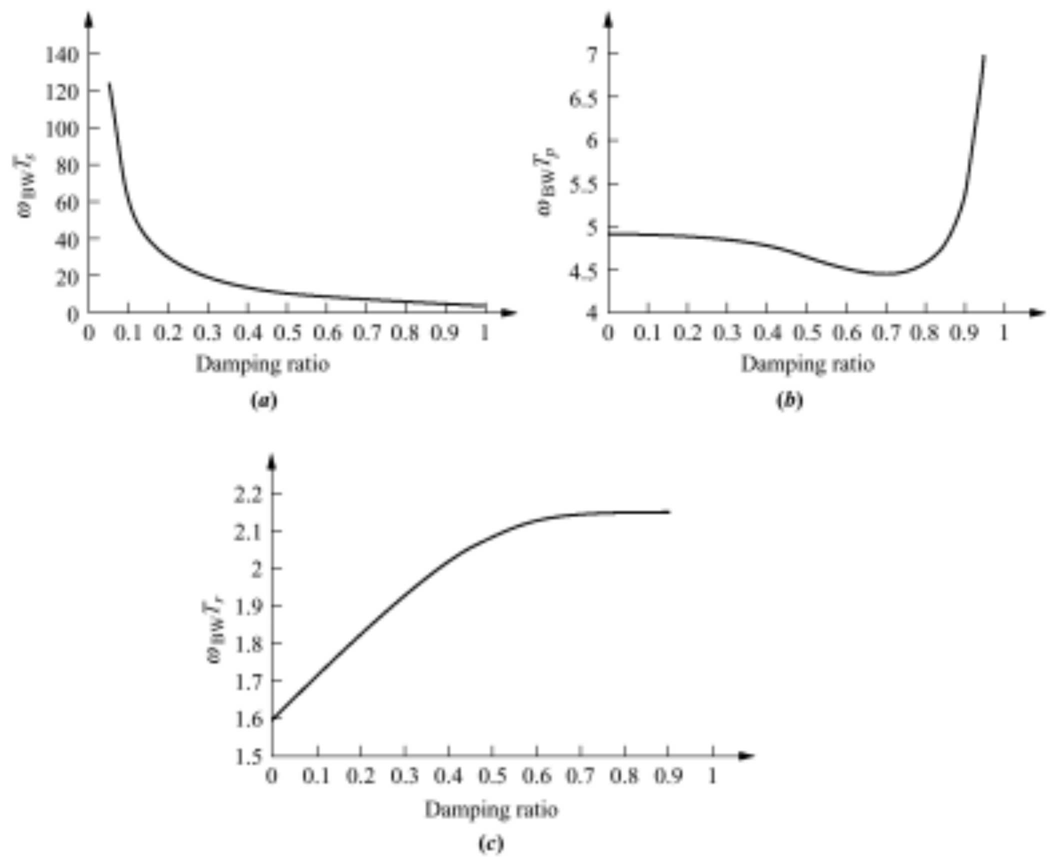


Figure 10.42
Constant *M* circles

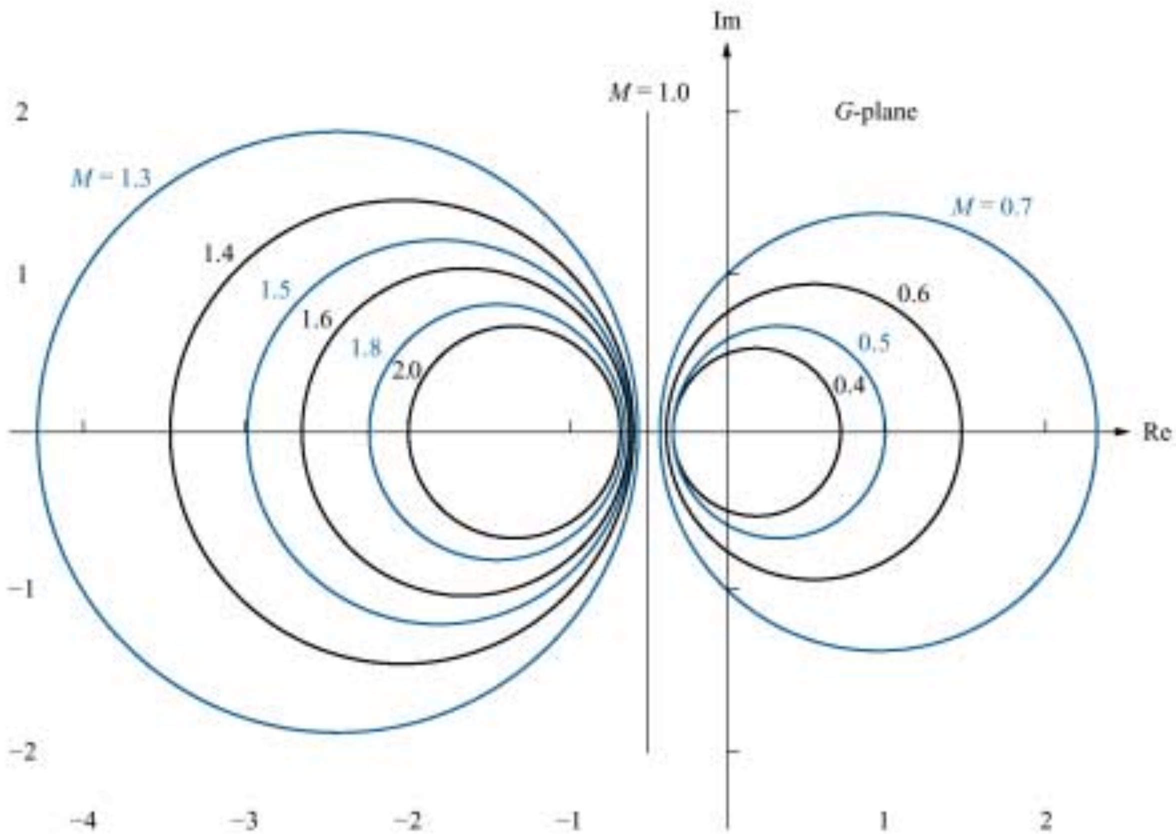


Figure 10.43
Constant *N* circles

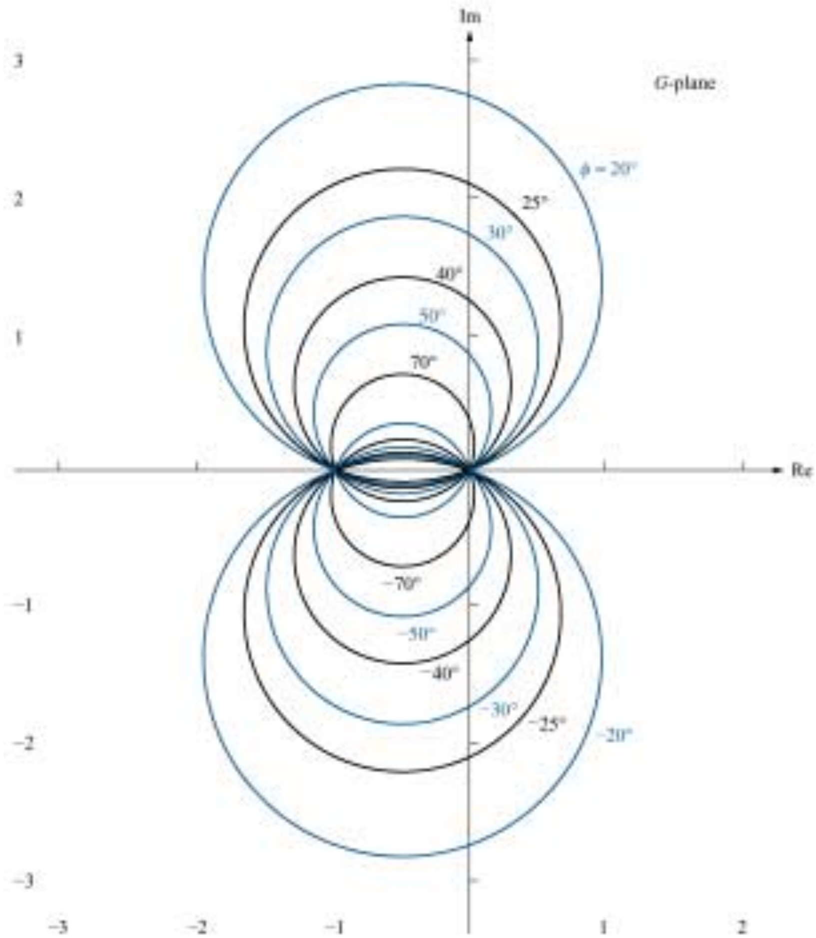


Figure 10.44
Nyquist diagram for Example 10.11 and constant *M* and *N* circles

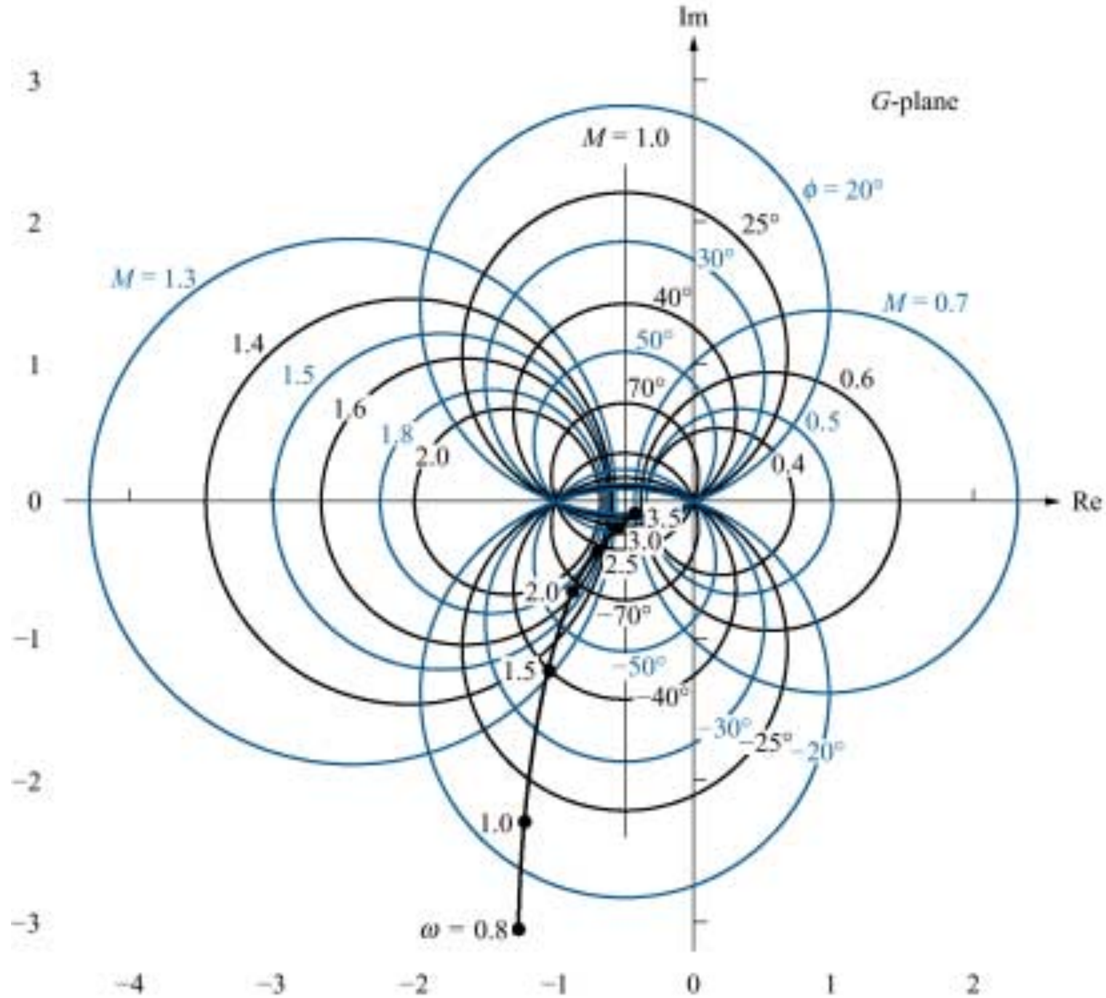


Figure 10.45
Closed-loop frequency response for Example 10.11

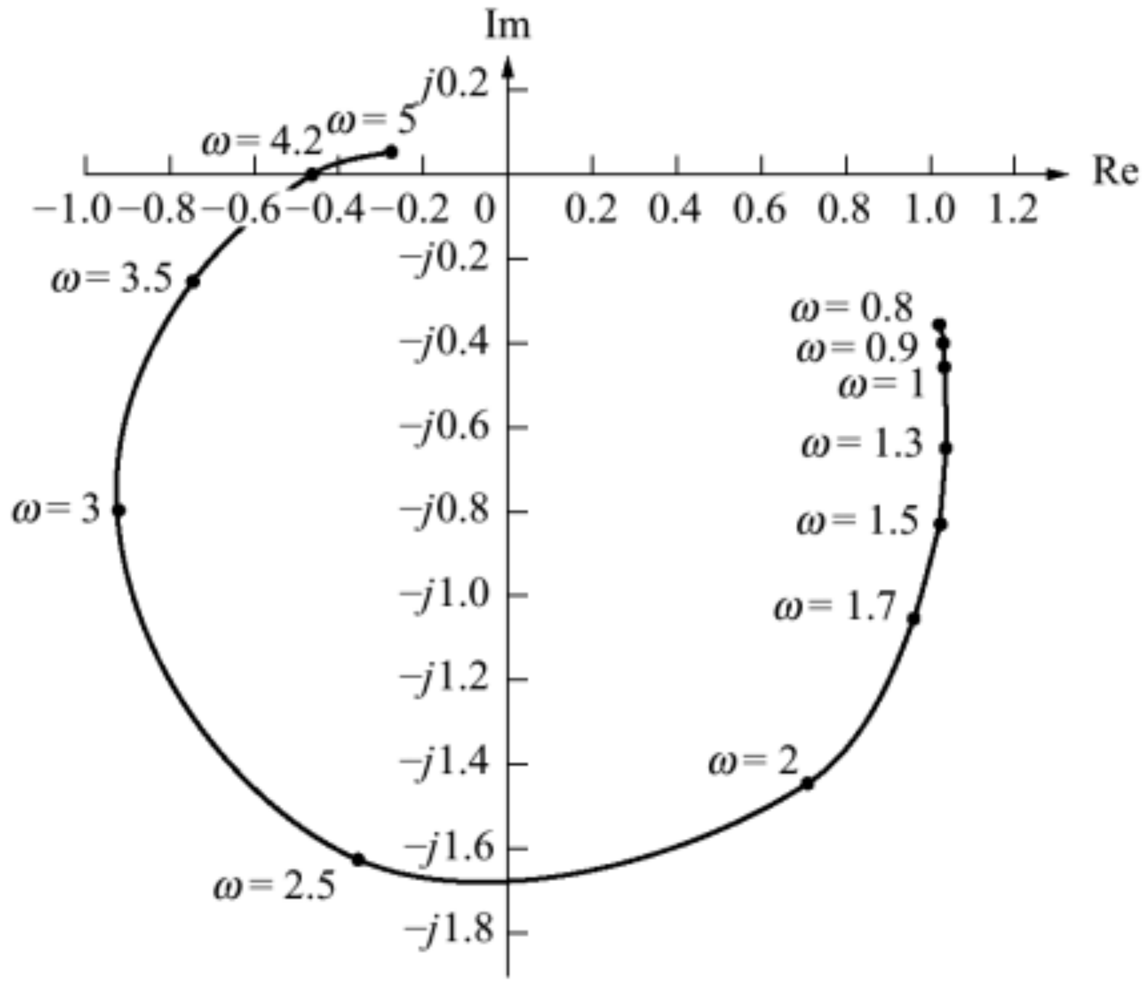


Figure 10.46
Nichols chart

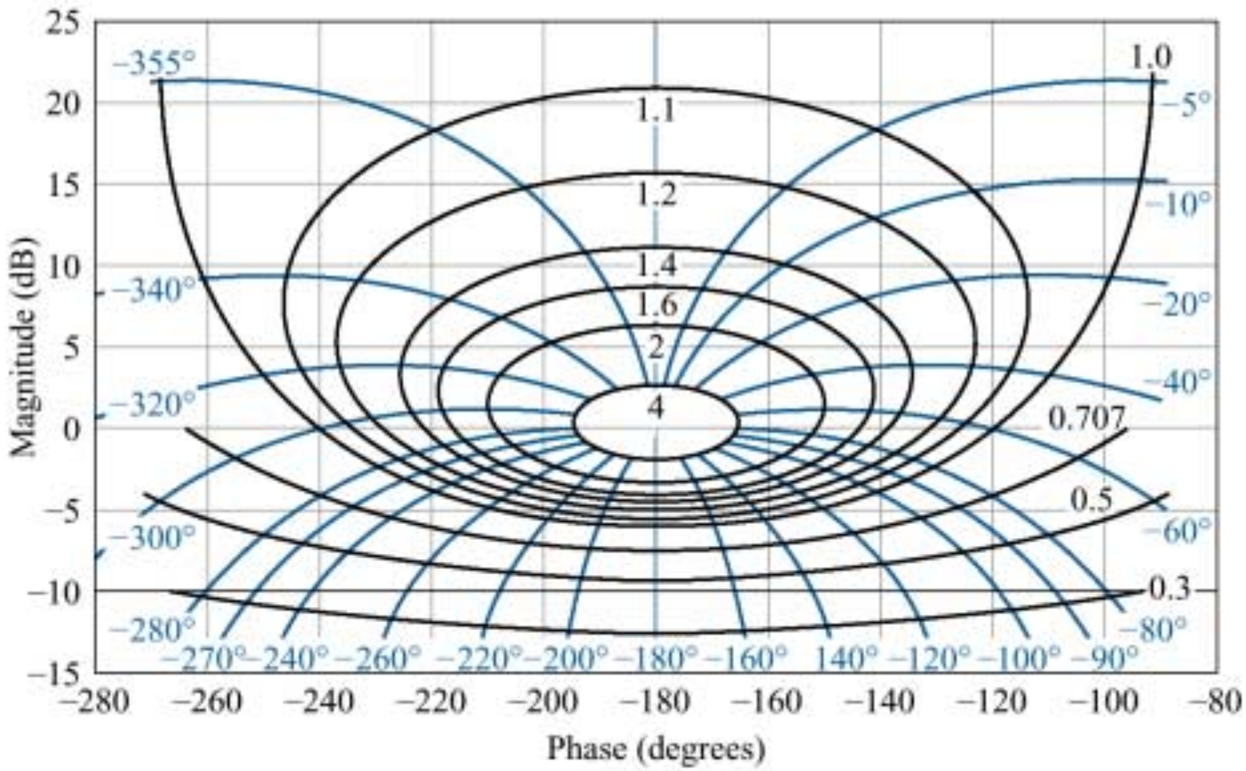


Figure 10.47

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.

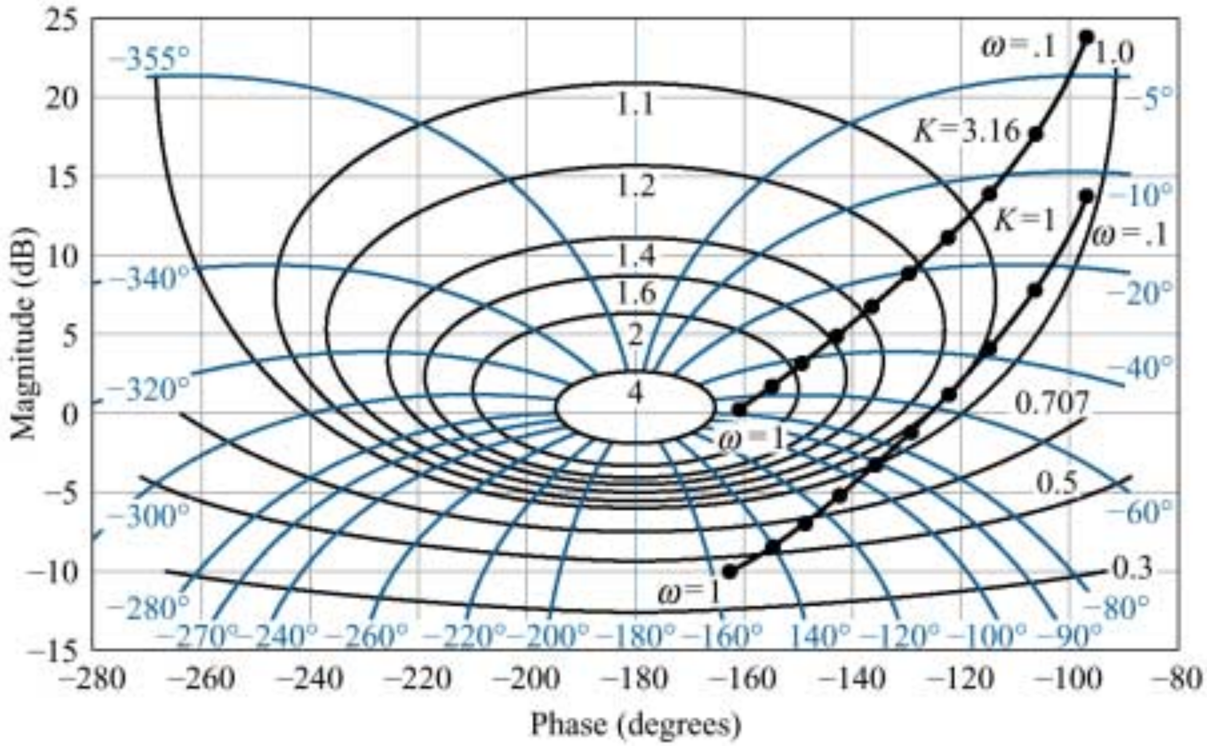


Figure 10.48
Phase margin vs. damping ratio

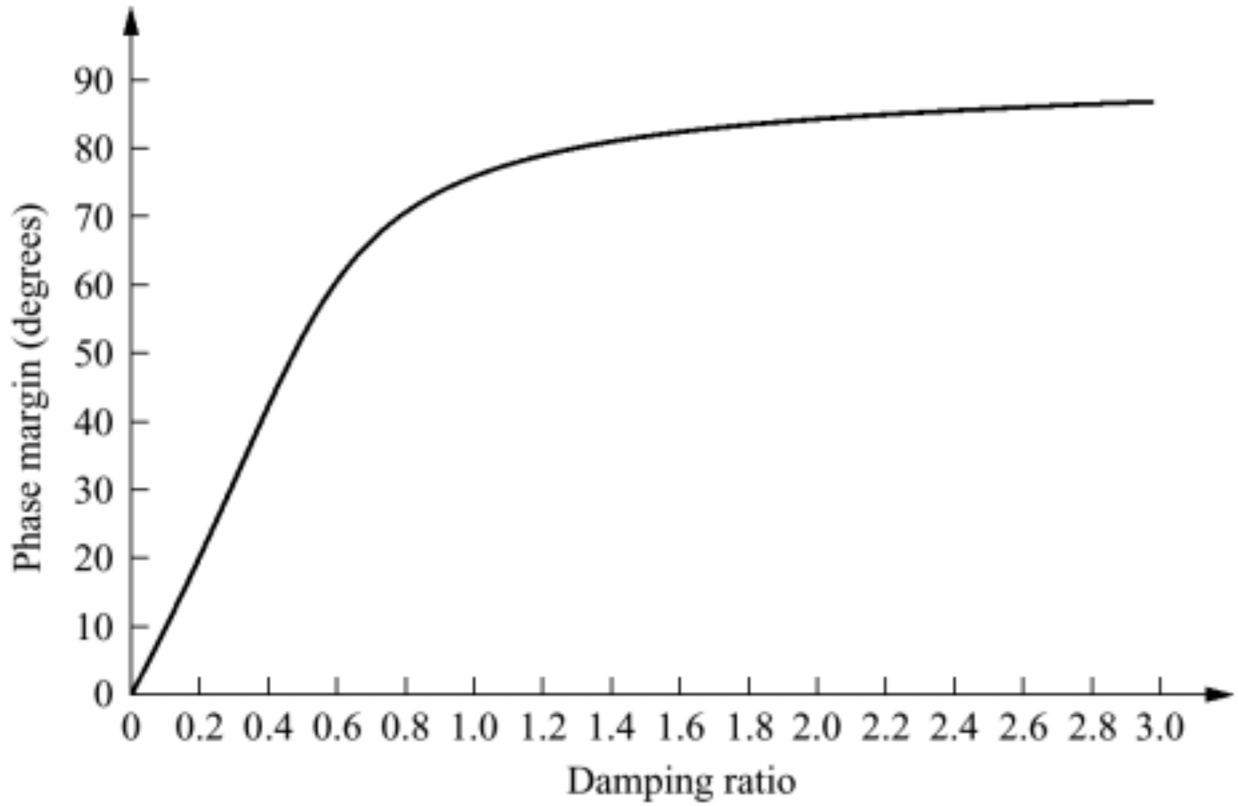


Figure 10.49
Open-loop gain vs. open-loop phase angle for –3 dB closed-loop gain

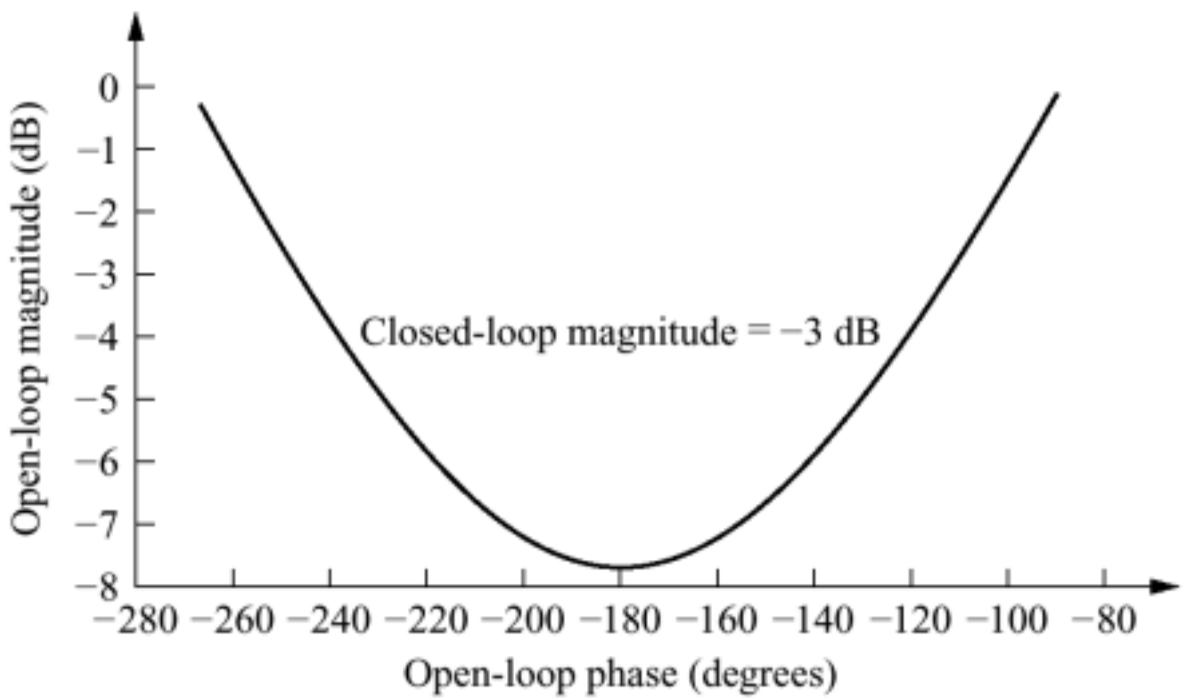
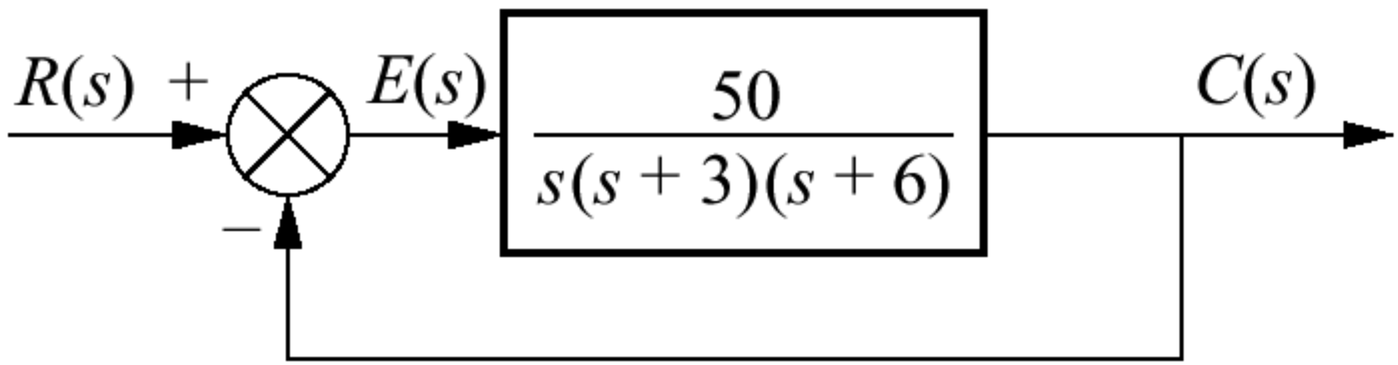


Figure 10.50
a. Block diagram
(figure continues)



(*a*)

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

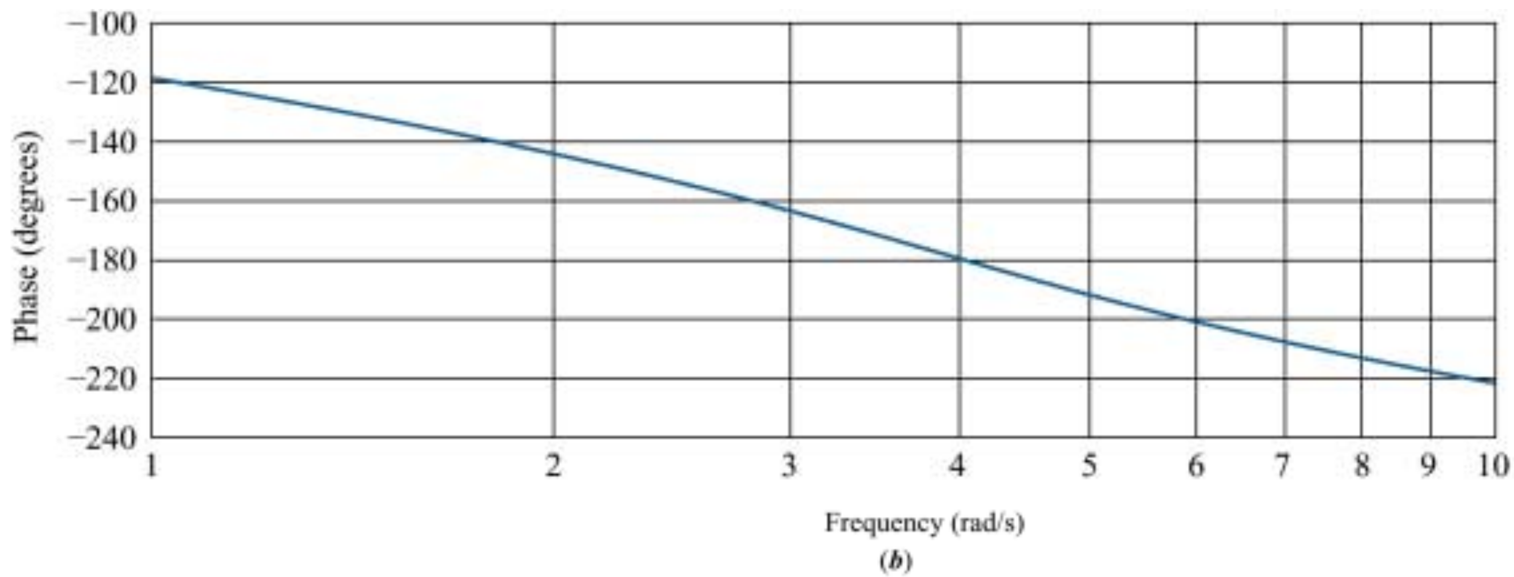


Figure 10.51
Typical unnormalized and unscaled Bode log-magnitude plots showing the value of static error constants:
a. Type 0;
b. Type 1;
c. Type 2

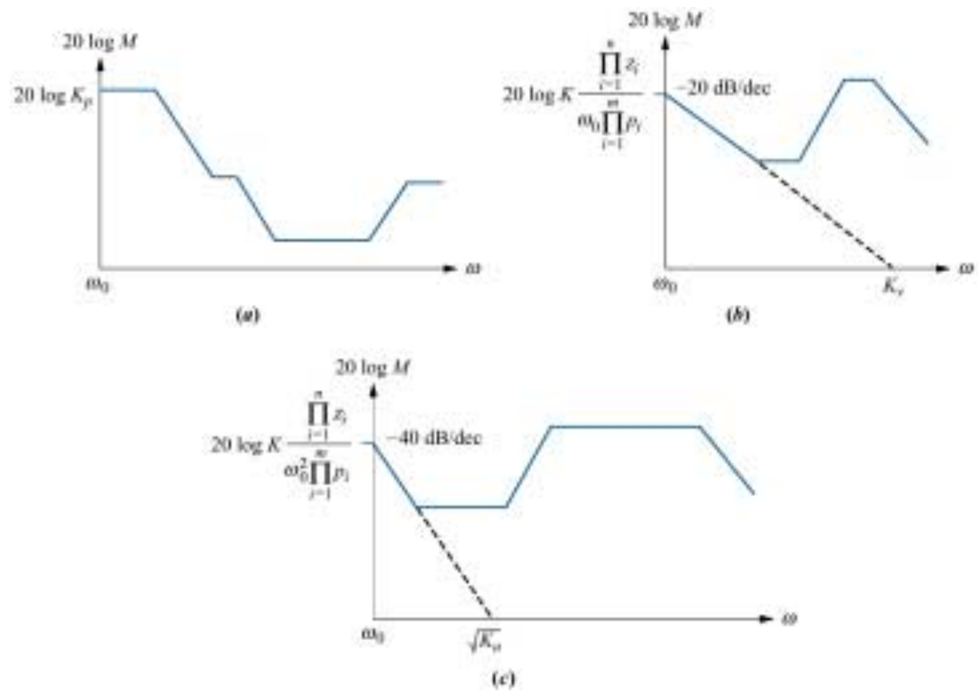


Figure 10.52
Bode log-magnitude plots for Example 10.14

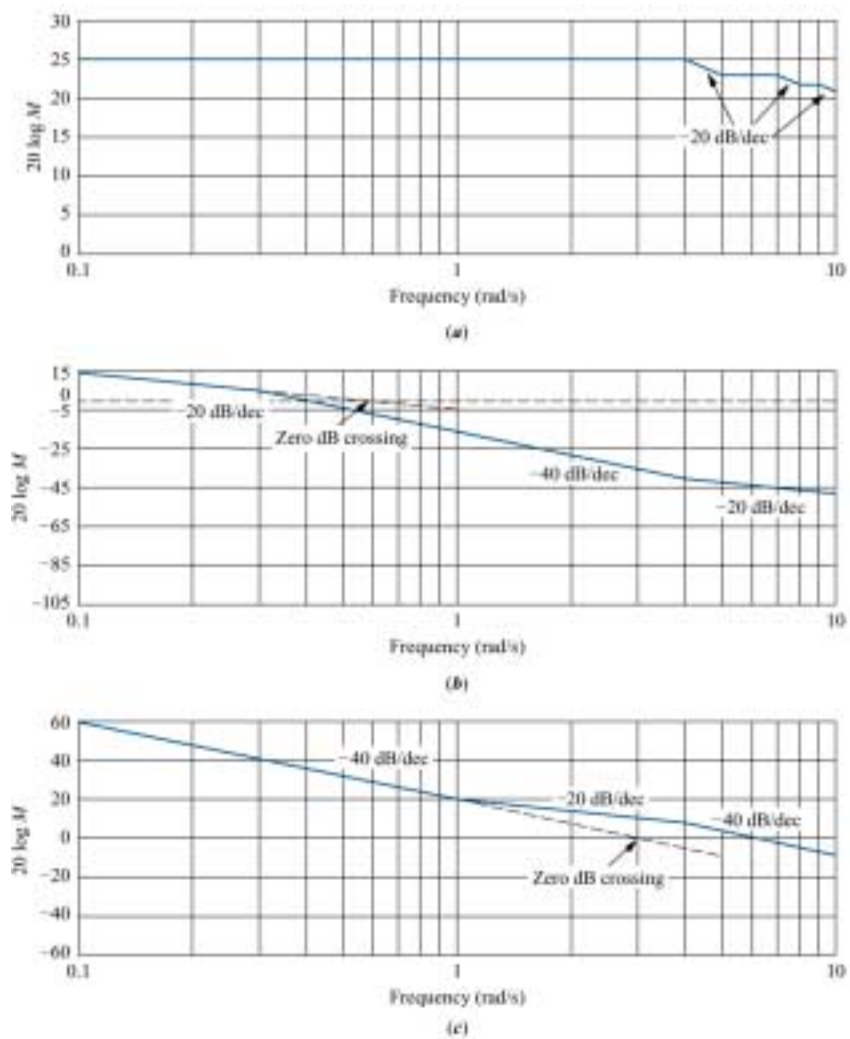


Figure 10.53
Bode log-magnitude plot for Skill-Assessment Exercise 10.10

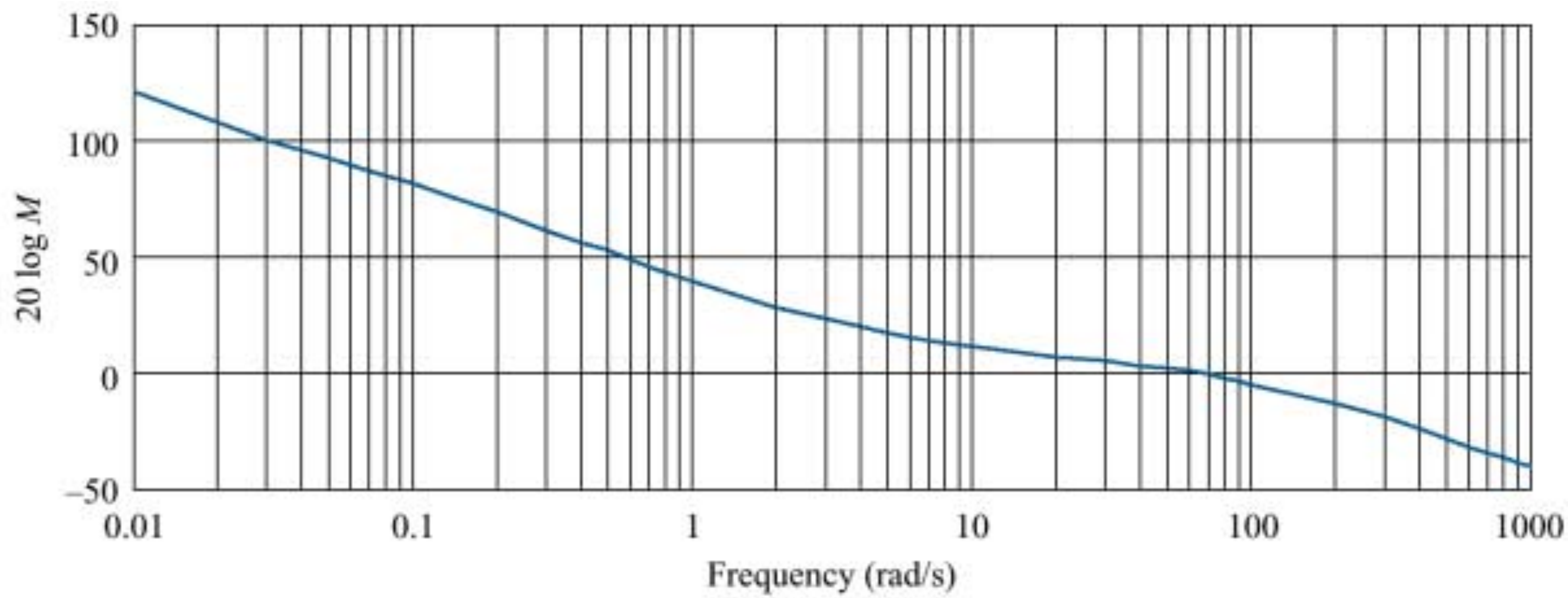


Figure 10.54
Effect of delay upon frequency response

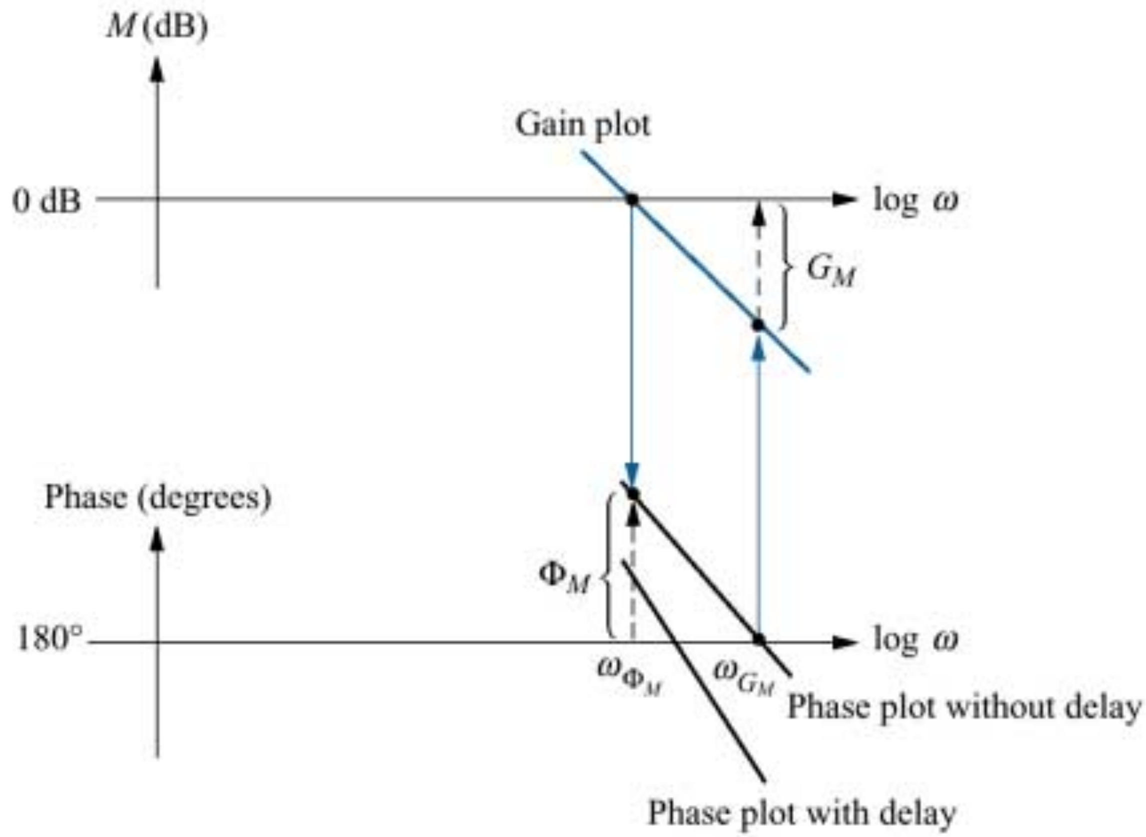


Figure 10.55
Frequency response plots for $G(s) = K/[s(s+1)(s+10)]$ with a delay of 1 second and $K = 1$:
a. magnitude plot;
b. phase plot

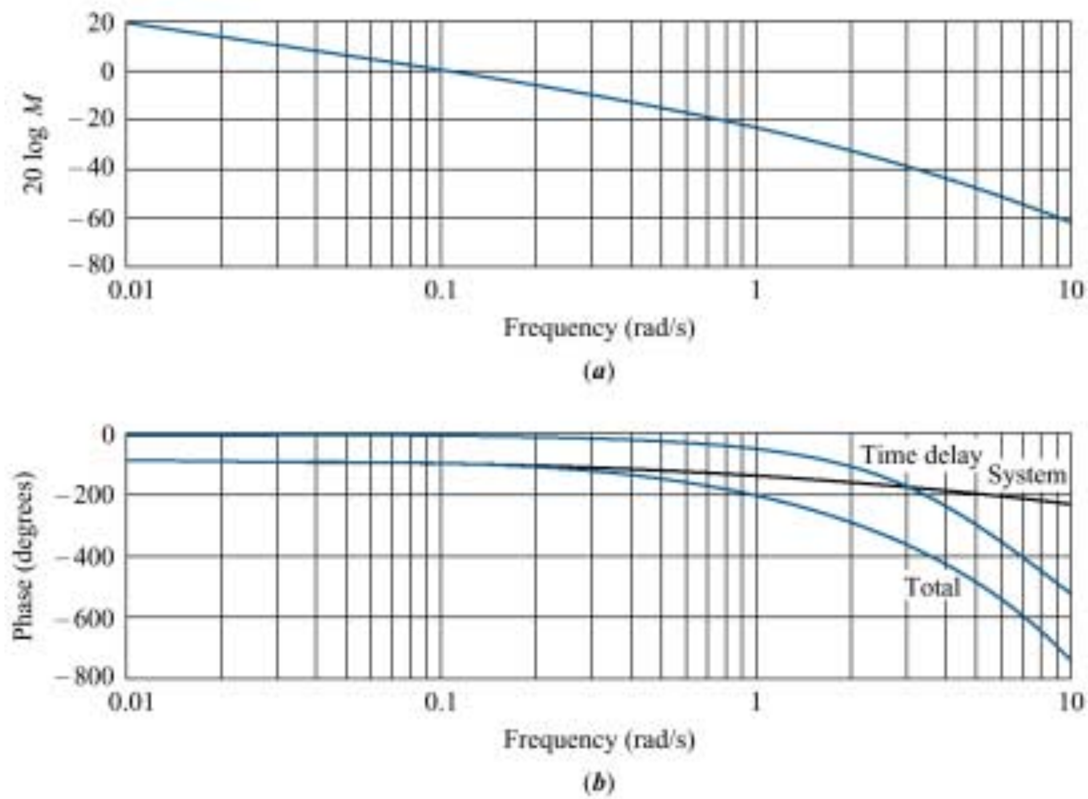


Figure 10.56
Step response for closed-loop system with $G(s) = 5/[s(s+1)(s+10)]$:
a. with a 1 second delay;
b. without delay

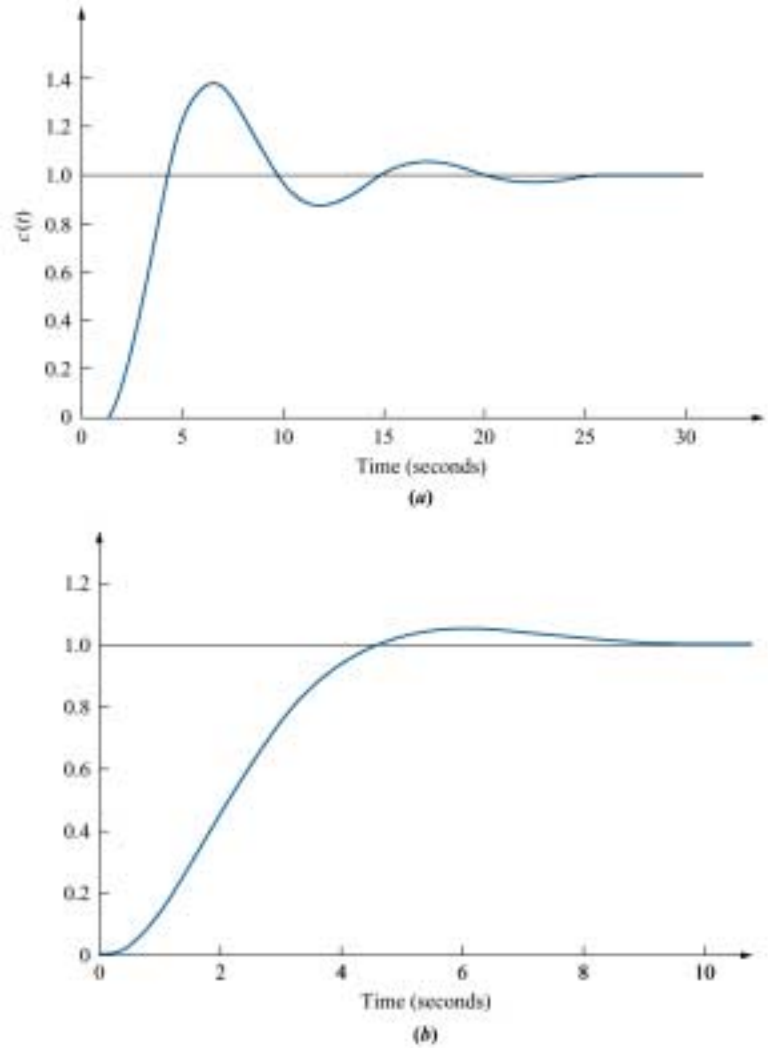


Figure 10.57
Bode plots for subsystem with undetermined transfer function

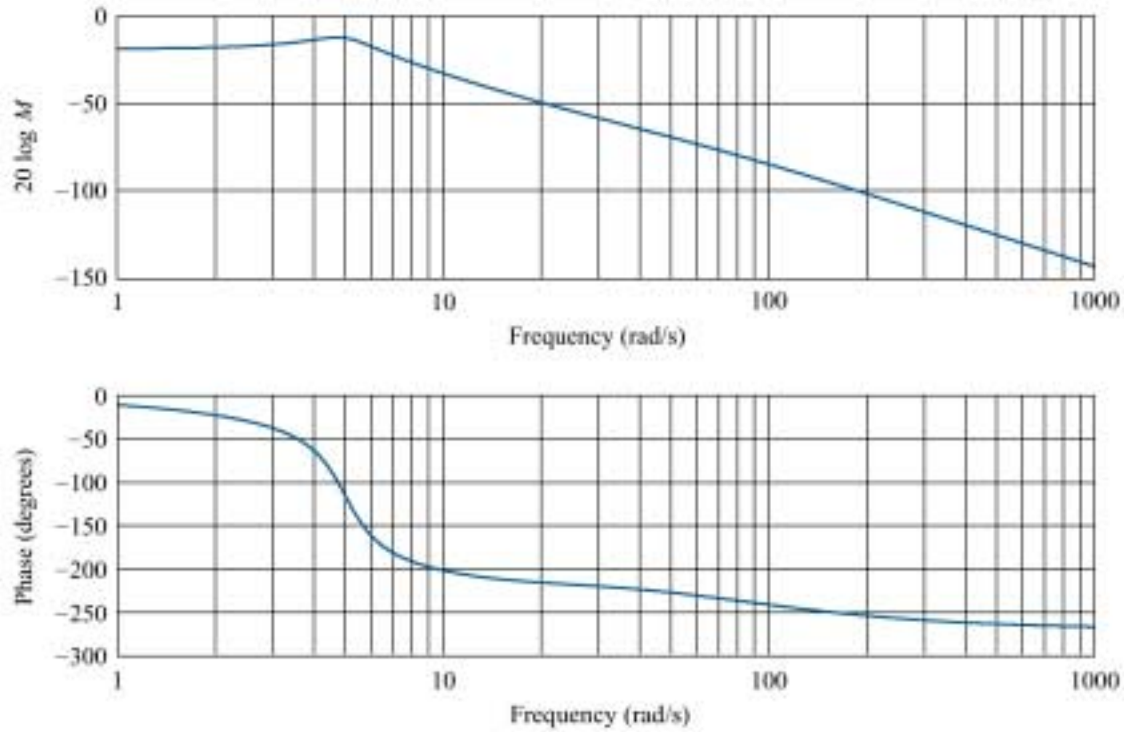


Figure 10.58
Original Bode plots minus response of $G_1(s) = 25/(s^2 + 2.4s + 25)$

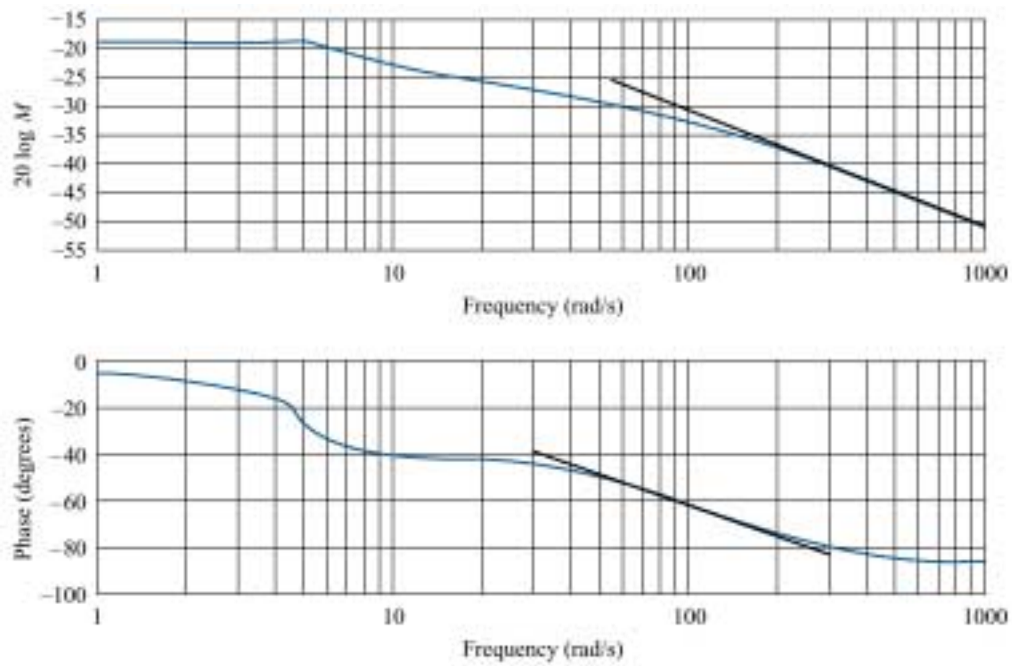


Figure 10.59
Original Bode plot minus response of $G1(s)G_2(s) = [25/(s^2 + 2.4s + 25)] \cdot [90/(s + 90)]$

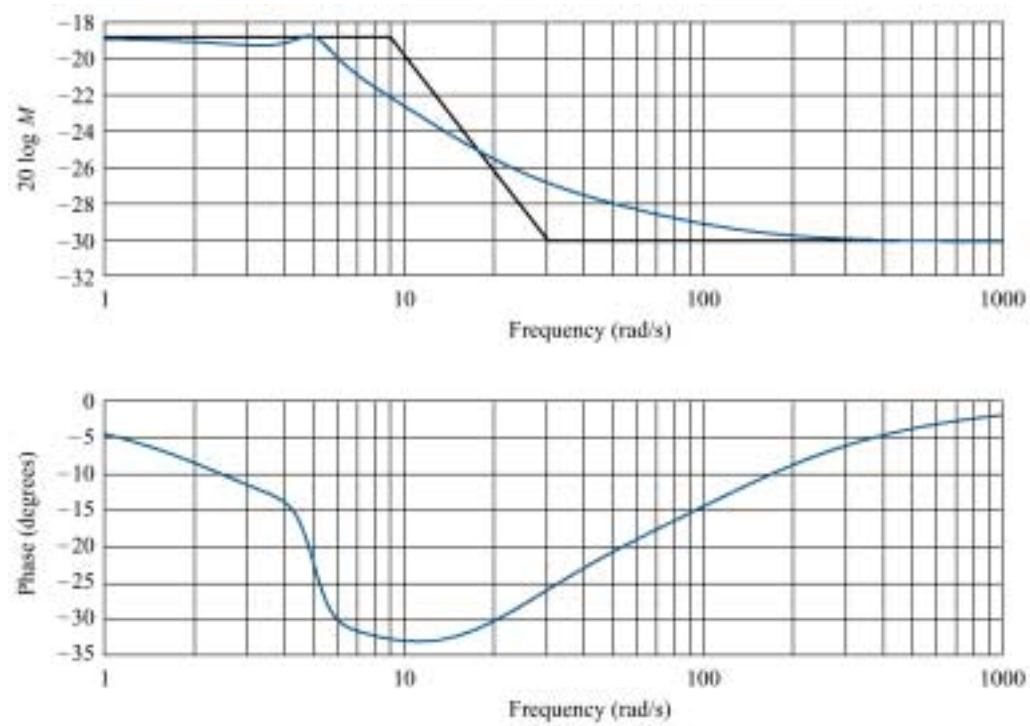


Figure 10.60
Bode plots for Skill-Assessment Exercise 10.12

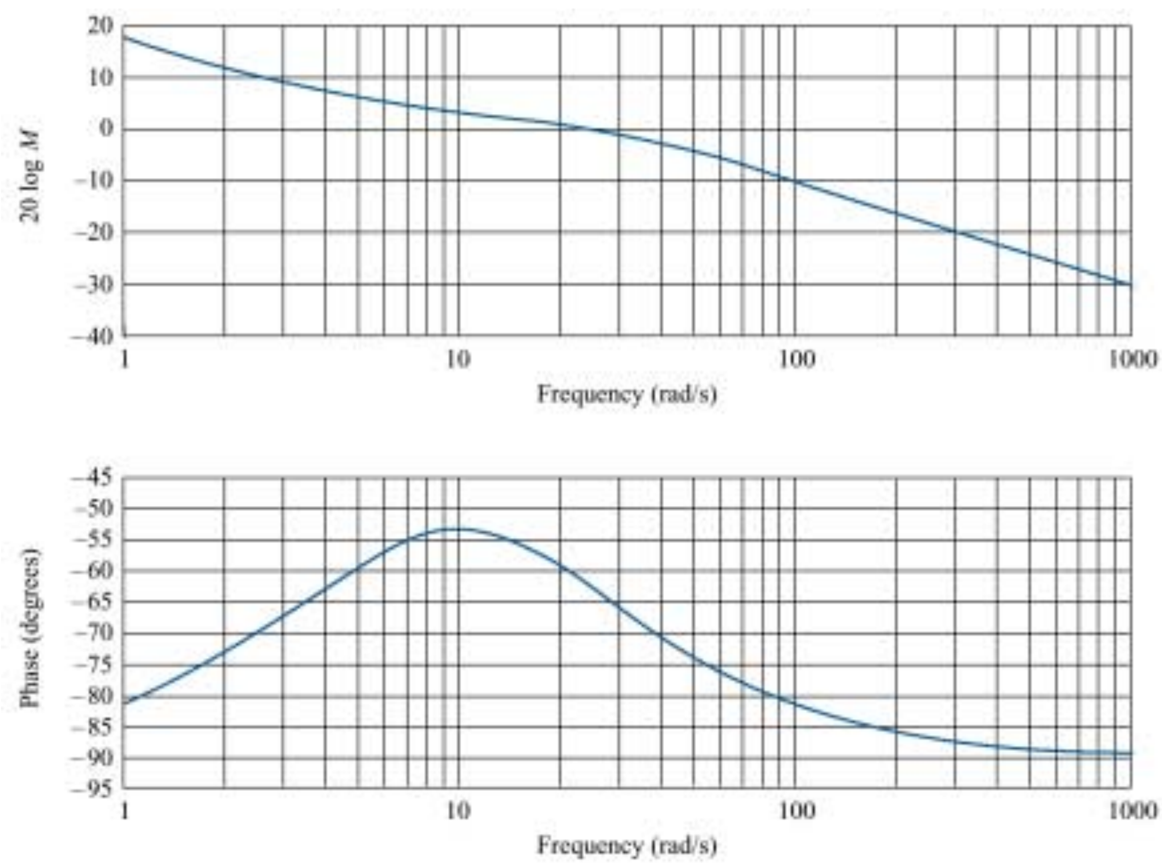


Figure 10.61
Open-loop frequency response plots for the antenna control system (K = 1)

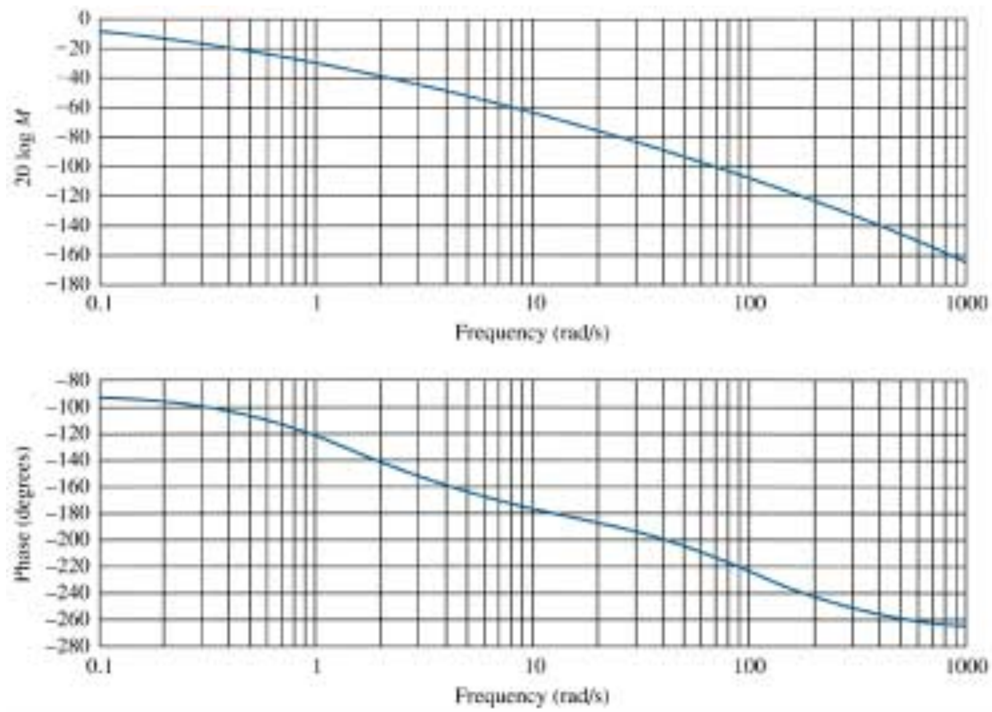


Figure P10.1

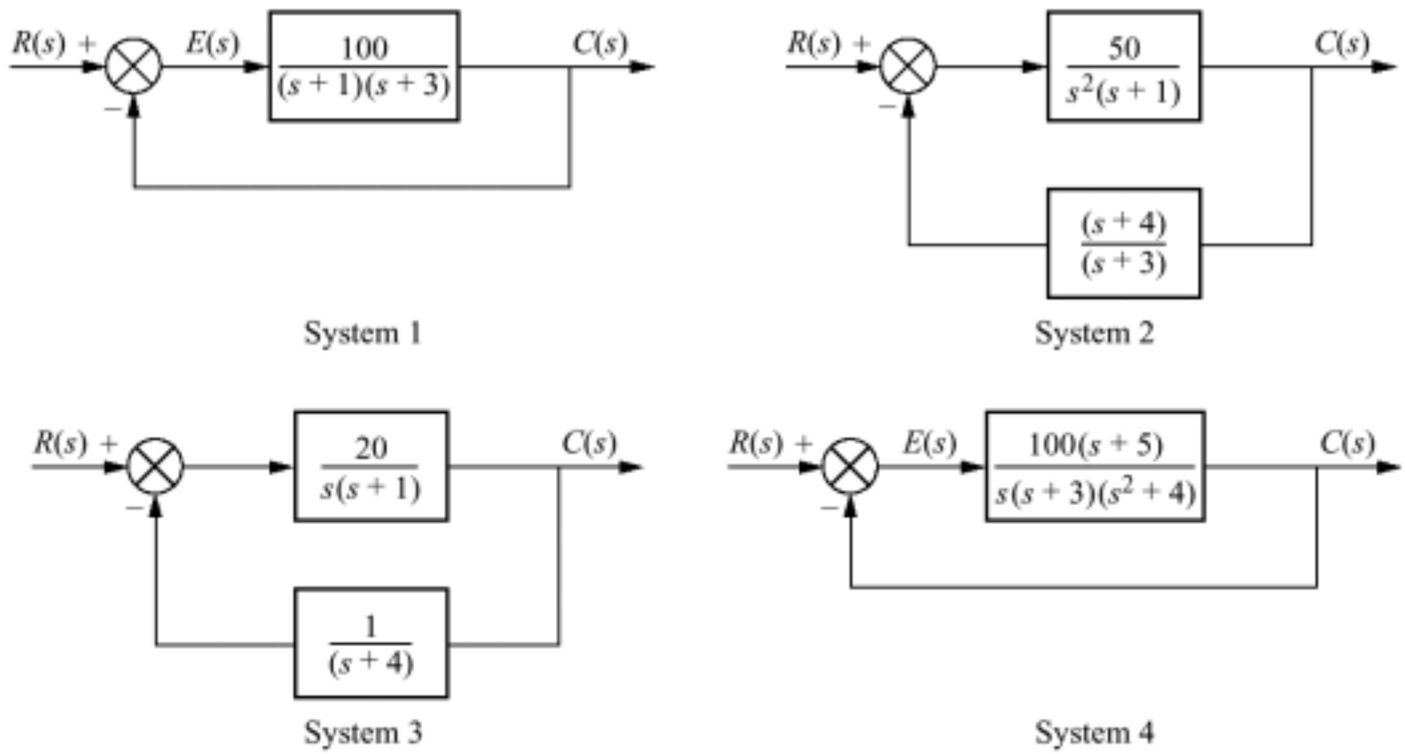

R(s)
+
−
E(s)
100
(s + 1)(s + 3)
C(s)
System 1
R(s)
+
−
50
s²(s + 1)
(s + 4)
(s + 3)
C(s)
System 2
R(s)
+
−
20
s(s + 1)
1
(s + 4)
C(s)
System 3
R(s)
+
−
E(s)
100(s + 5)
s(s + 3)(s² + 4)
C(s)
System 4

Figure P10.2

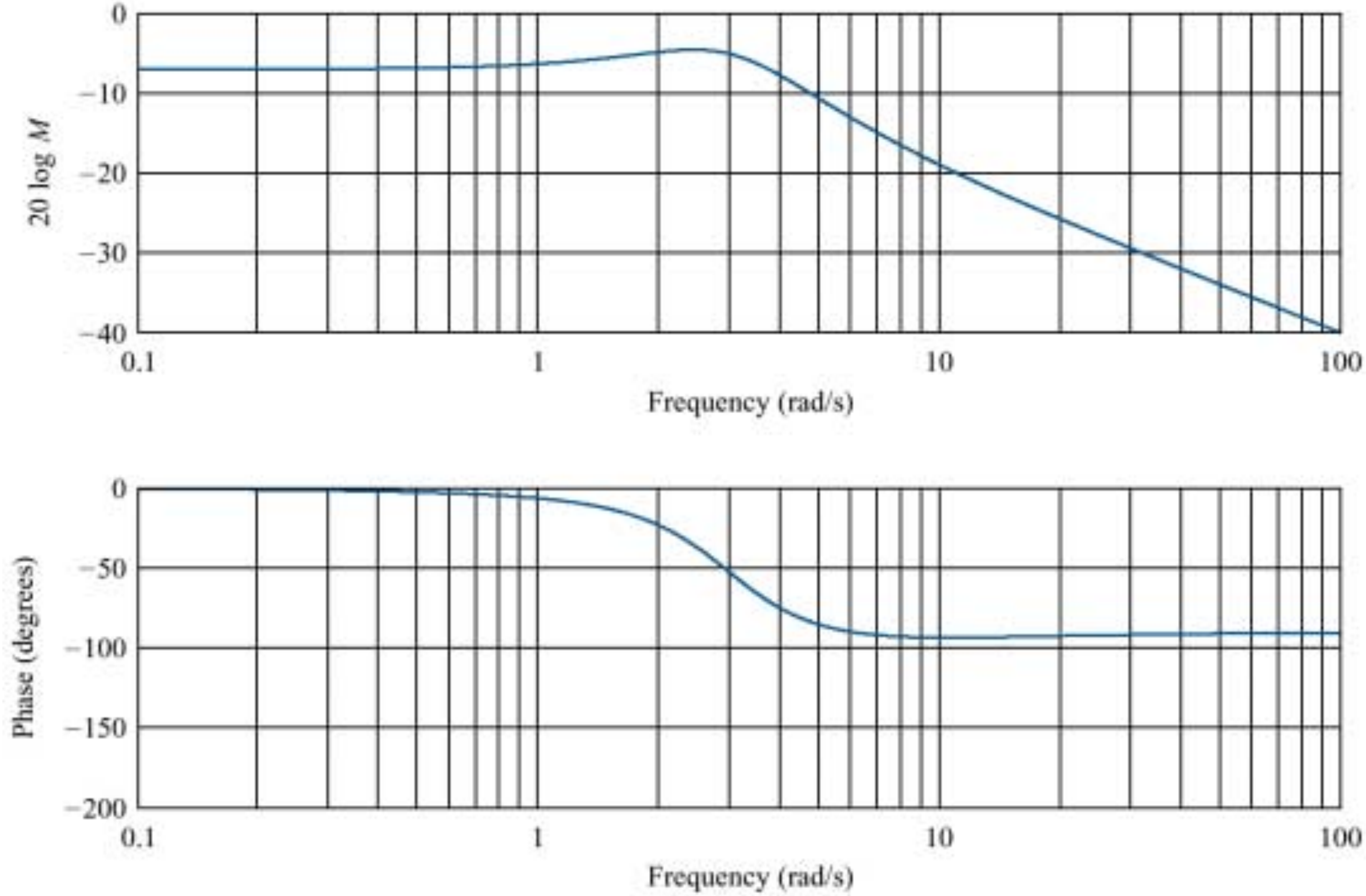

0
−10
−20
−30
−40
20 log M
0.1
1
10
100
Frequency (rad/s)
0
−50
−100
−150
−200
Phase (degrees)
0.1
1
10
100
Frequency (rad/s)

Figure P10.3

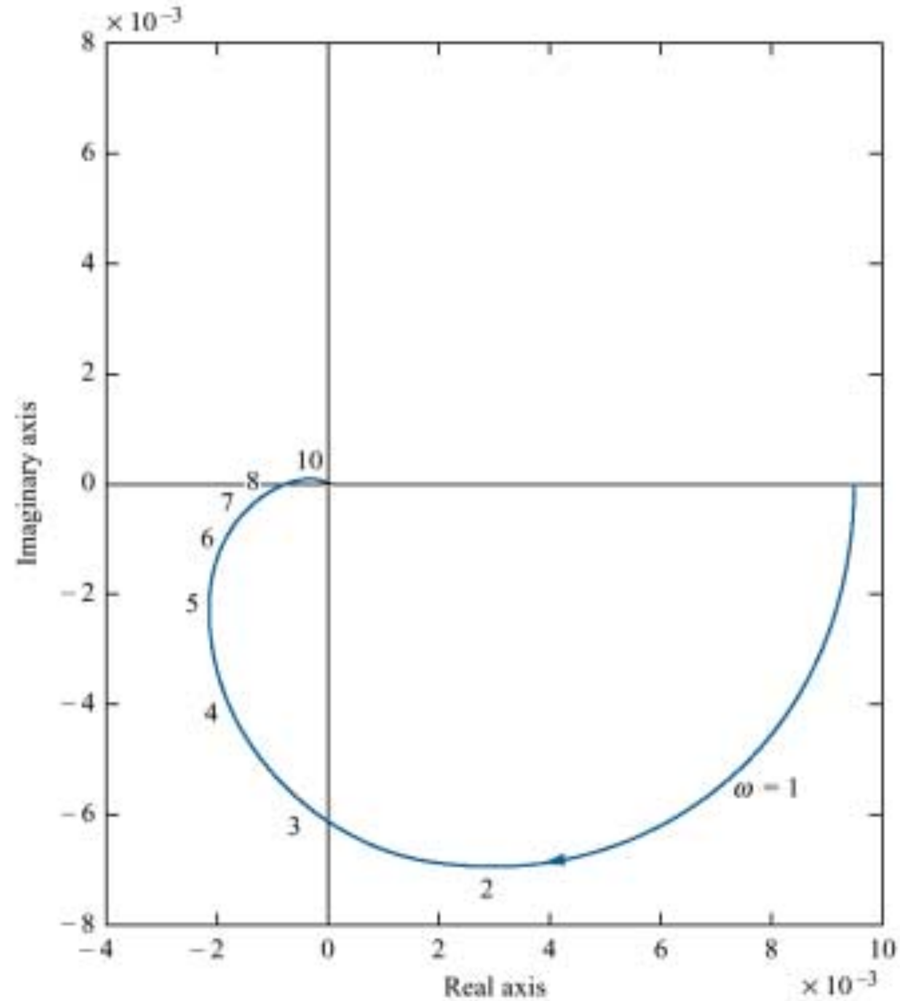

× 10⁻³
8
6
4
2
0
−2
−4
−6
−8
Imaginary axis
10
8
7
6
5
4
3
2
ω = 1
−4
−2
0
2
4
6
8
10
Real axis
× 10⁻³

Figure P10.4

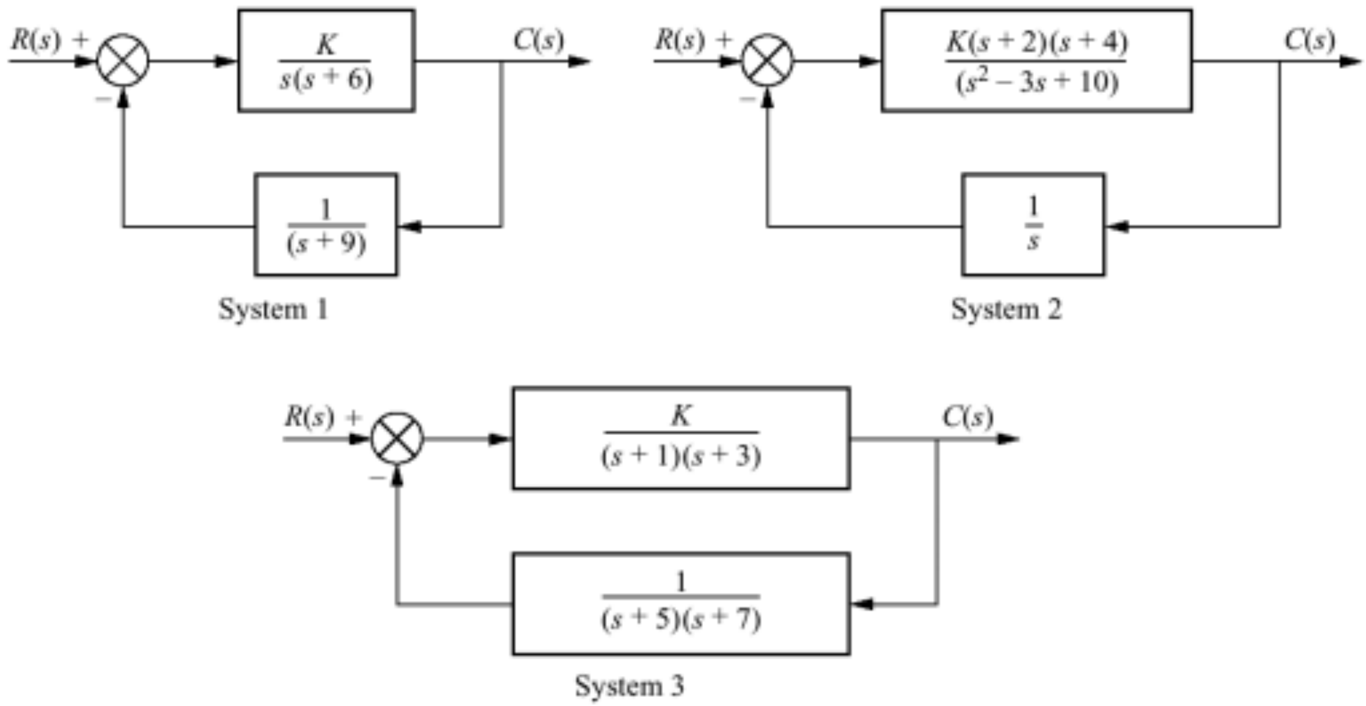

R(s)
+
−
K
s(s + 6)
C(s)
1
(s + 9)
System 1
R(s)
+
−
K(s + 2)(s + 4)
(s² − 3s + 10)
C(s)
1
s
System 2
R(s)
+
−
K
(s + 1)(s + 3)
C(s)
1
(s + 5)(s + 7)
System 3

Figure P10.5

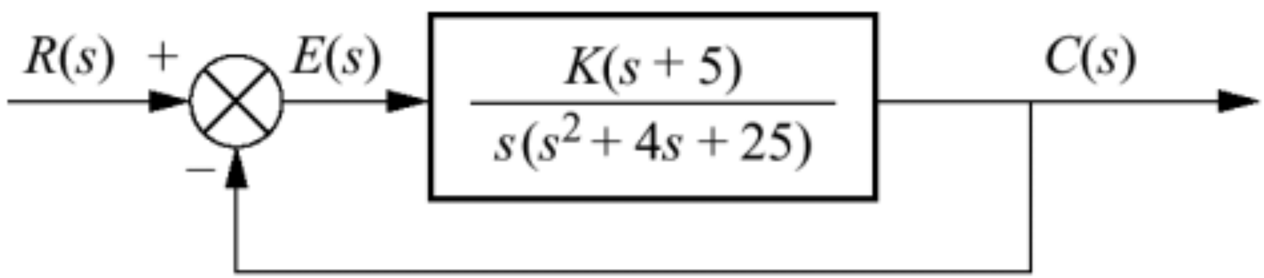


Figure P10.6

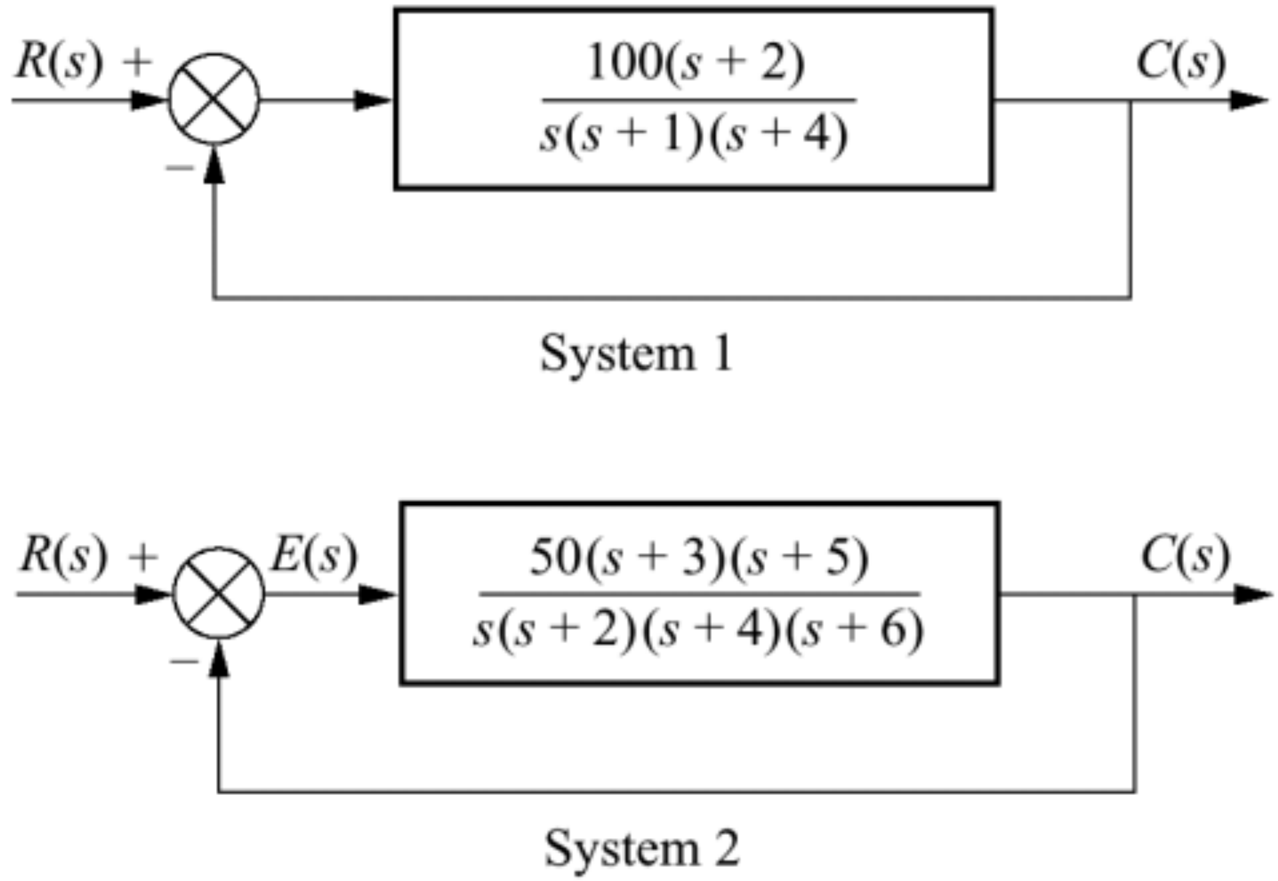


Figure P10.7

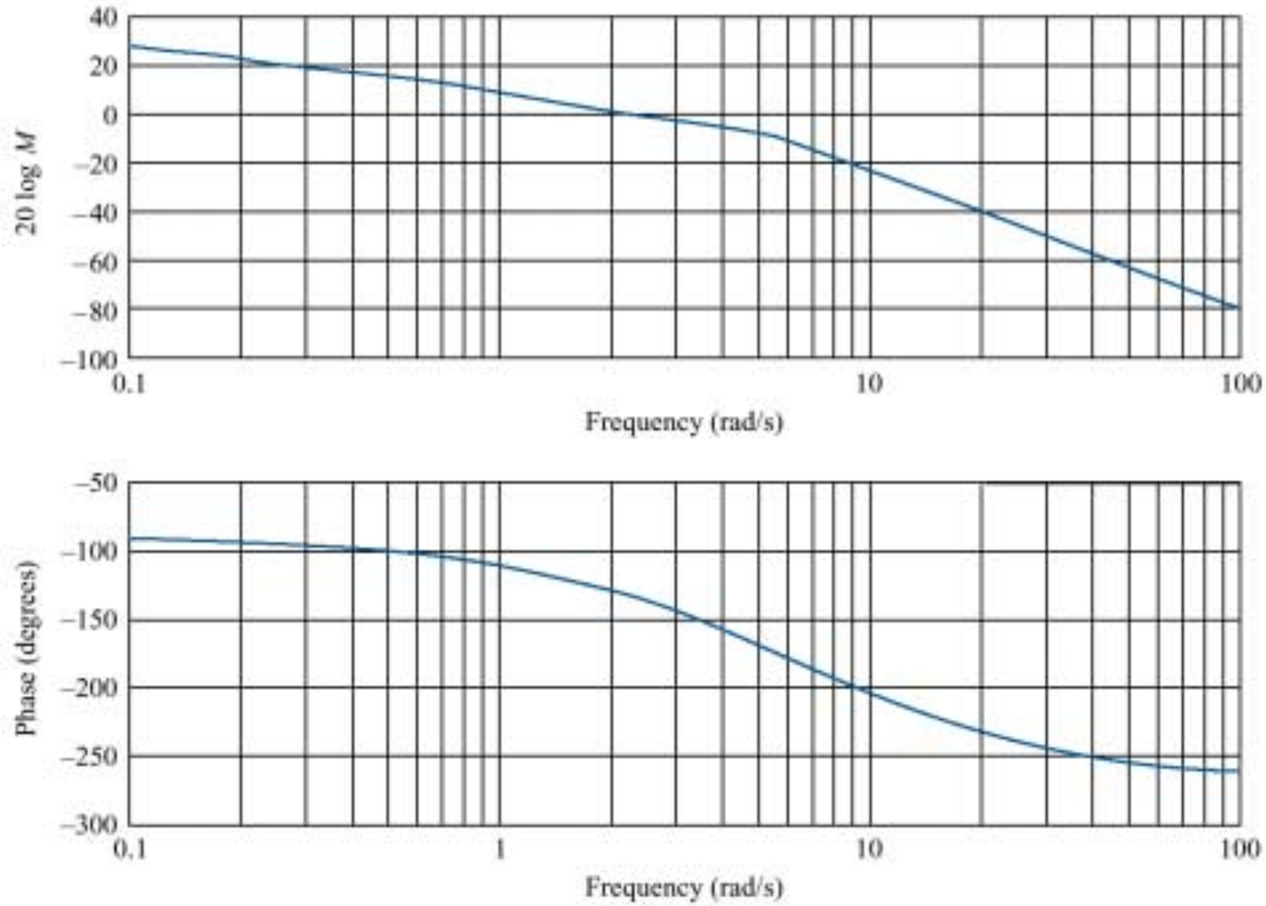

40
20
0
−20
−40
−60
−80
−100
20 log M
0.1
10
100
Frequency (rad/s)
−50
−100
−150
−200
−250
−300
Phase (degrees)
0.1
1
10
100
Frequency (rad/s)

Figure P10.8

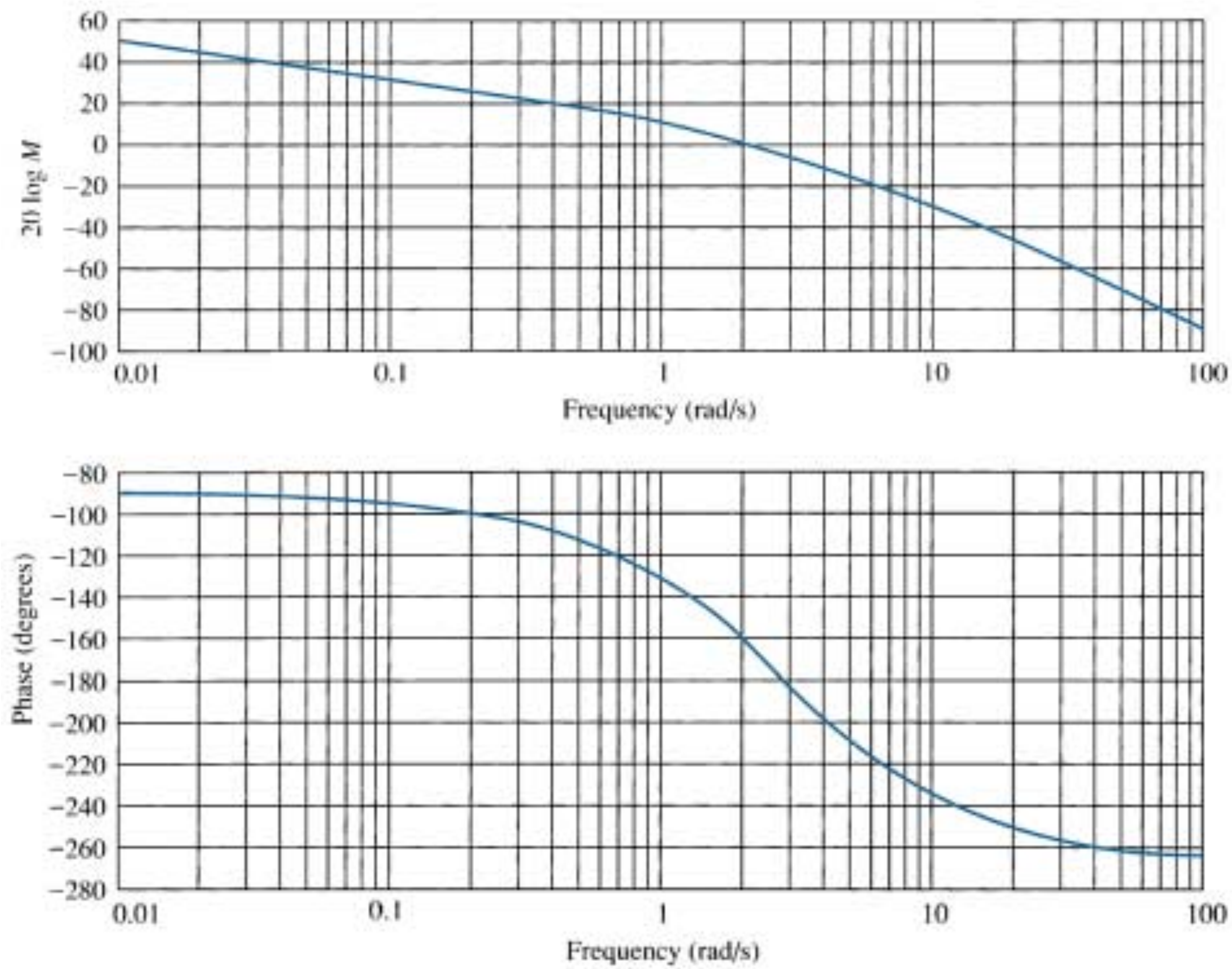

60
40
20
0
−20
−40
−60
−80
−100
20 log M
0.01
0.1
1
10
100
Frequency (rad/s)
−80
−100
−120
−140
−160
−180
−200
−220
−240
−260
−280
Phase (degrees)
0.01
0.1
1
10
100
Frequency (rad/s)

Figure P10.9

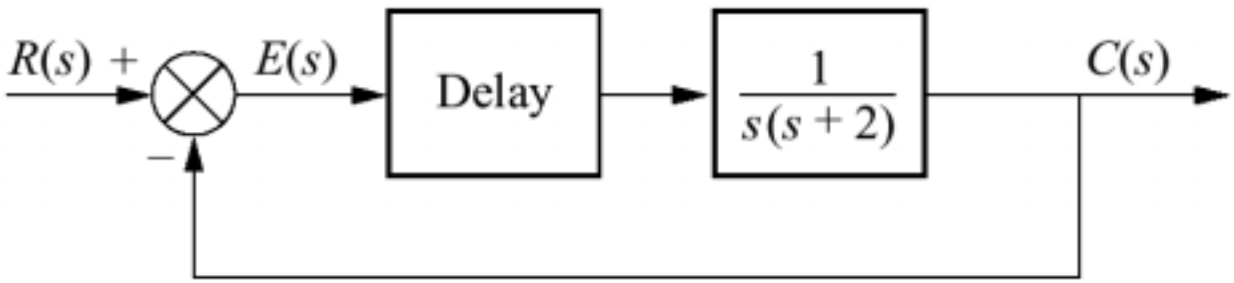


Figure P10.10

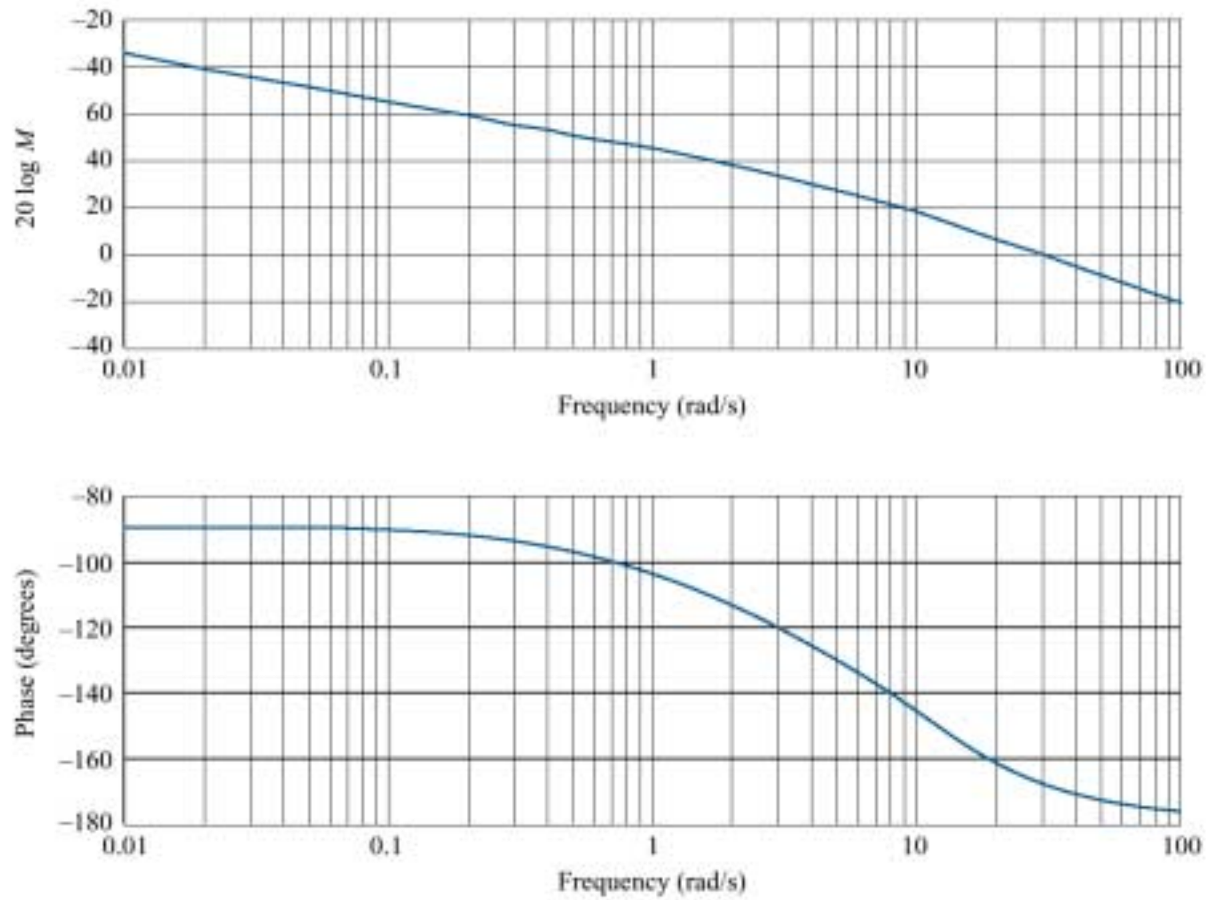


Figure P10.11

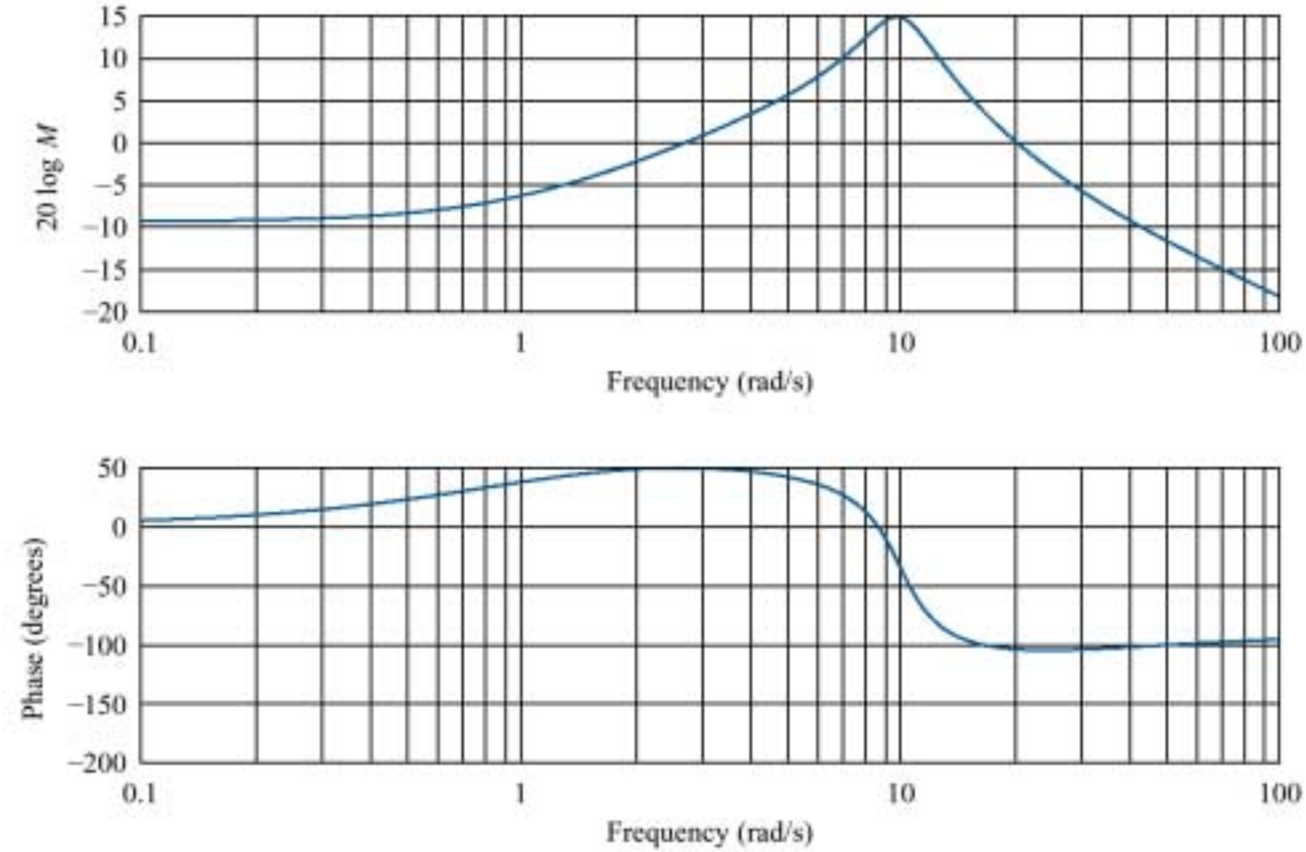


Figure P10.12
Soft Arm position control system block diagram

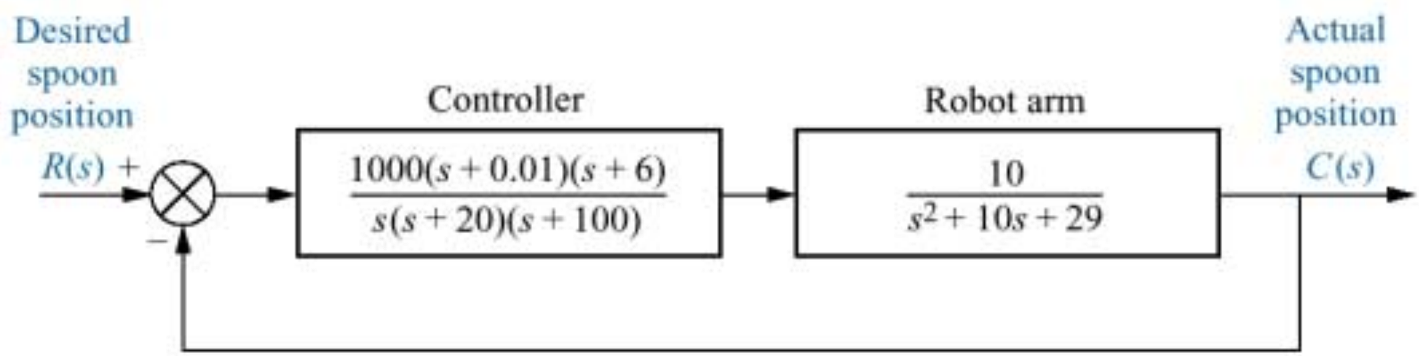


Figure P10.13
Floppy disk drive
block diagram

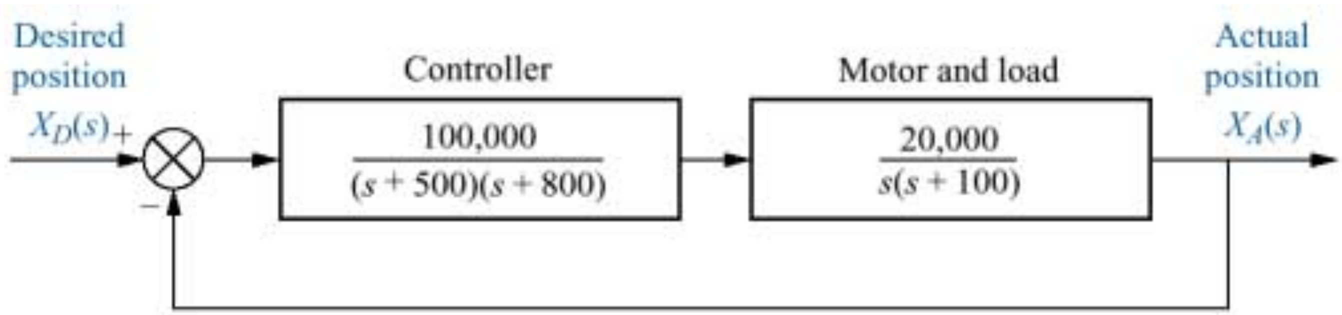


Figure P10.14
AdeptOne, a four- or five-axis industrial robot, is used for assembly, packaging, and other manufacturing tasks.

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

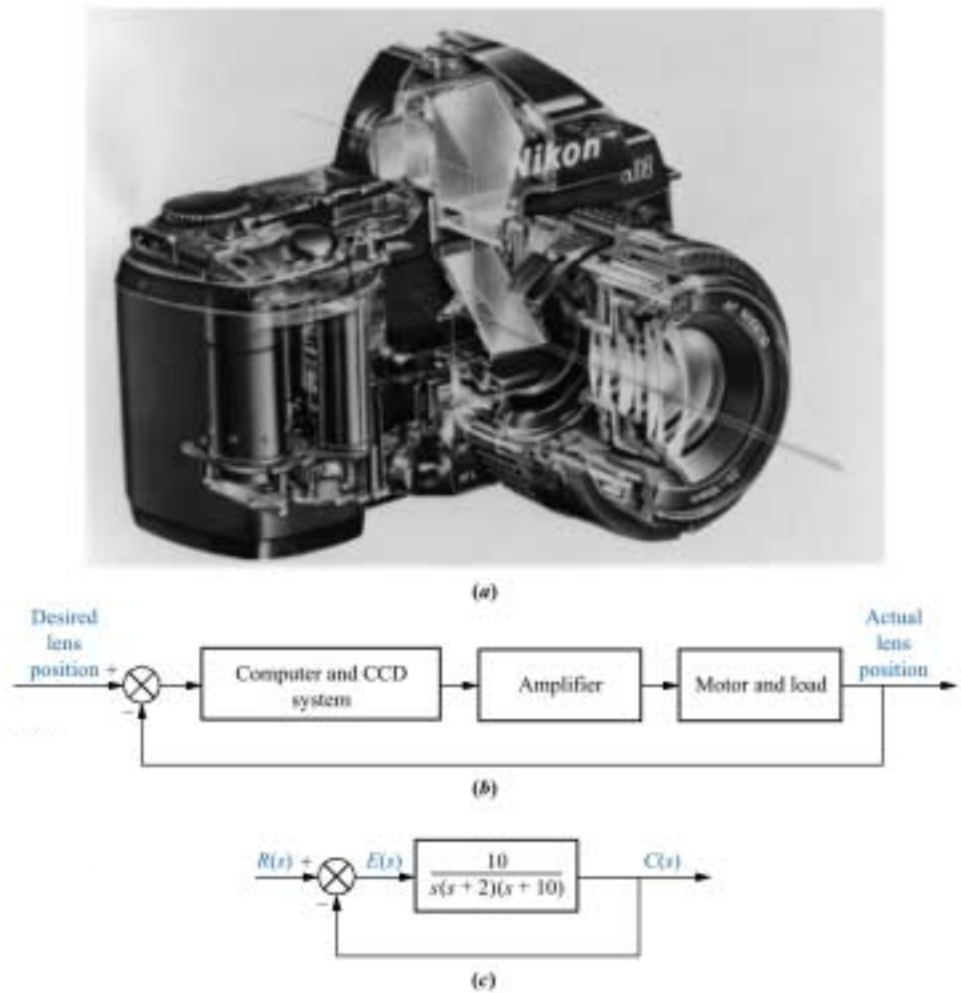


Figure P10.16
Block diagram of a ship's roll stabilizing system