Figure 9.1

a. Sample root locus, showing possible design point via gain adjustment (*A*) and desired design point that cannot be met via simple gain adjustment (*B*);
b. responses from poles at *A* and *B*

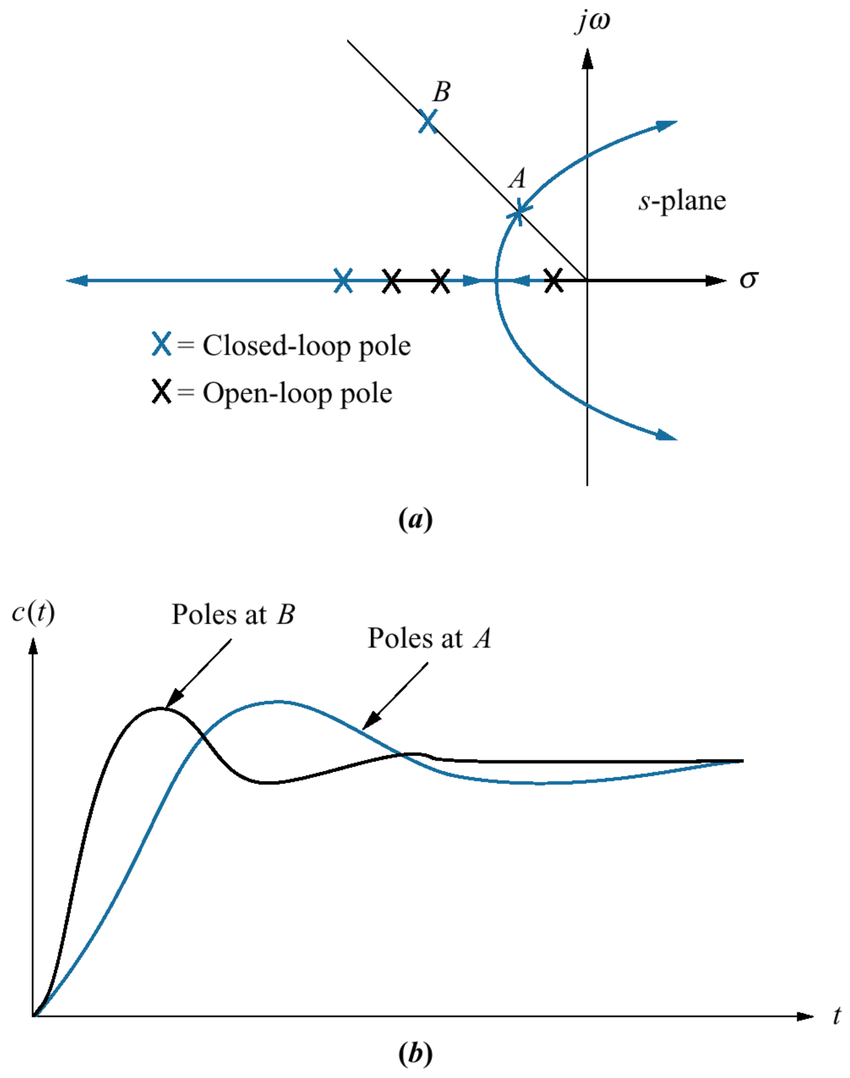

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Figure 9.2
Compensation techniques:
a. cascade;
b. feedback

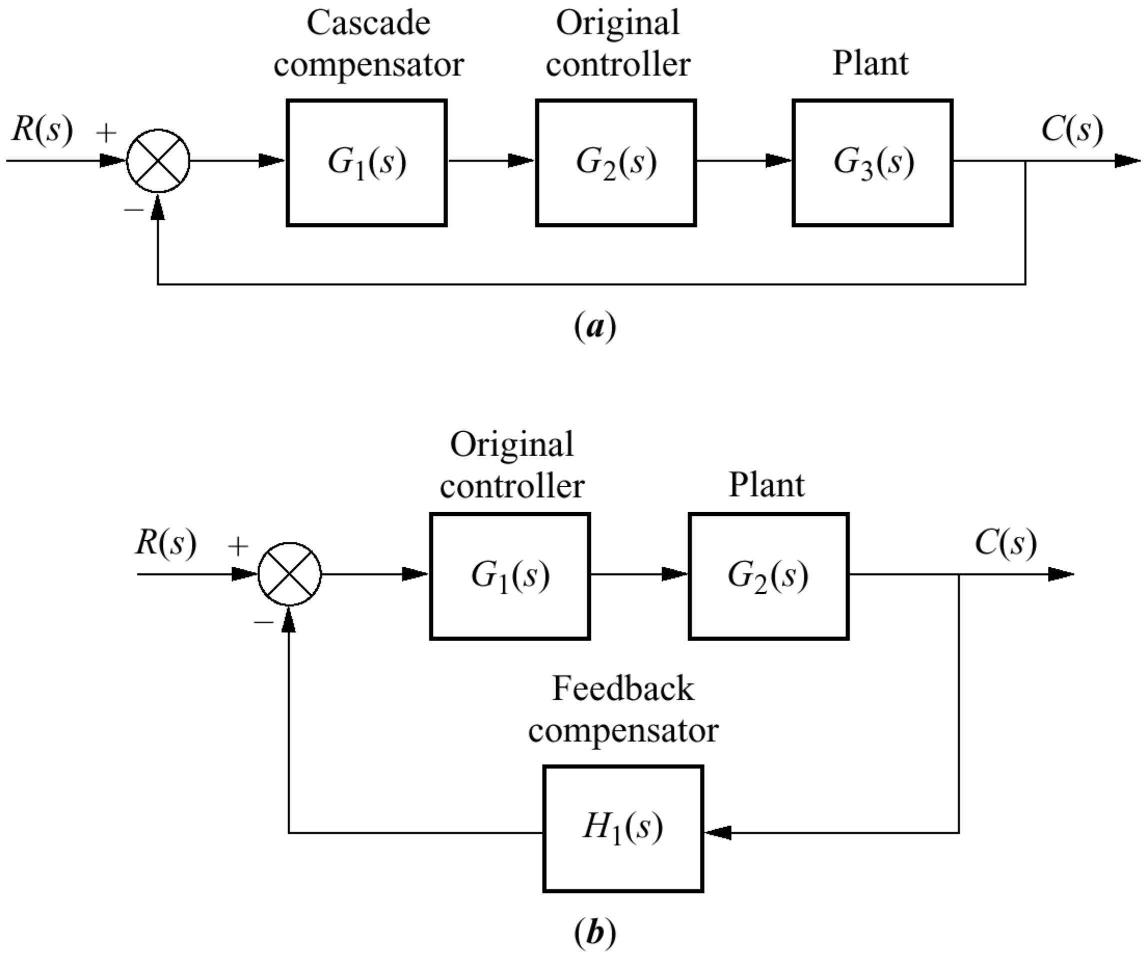

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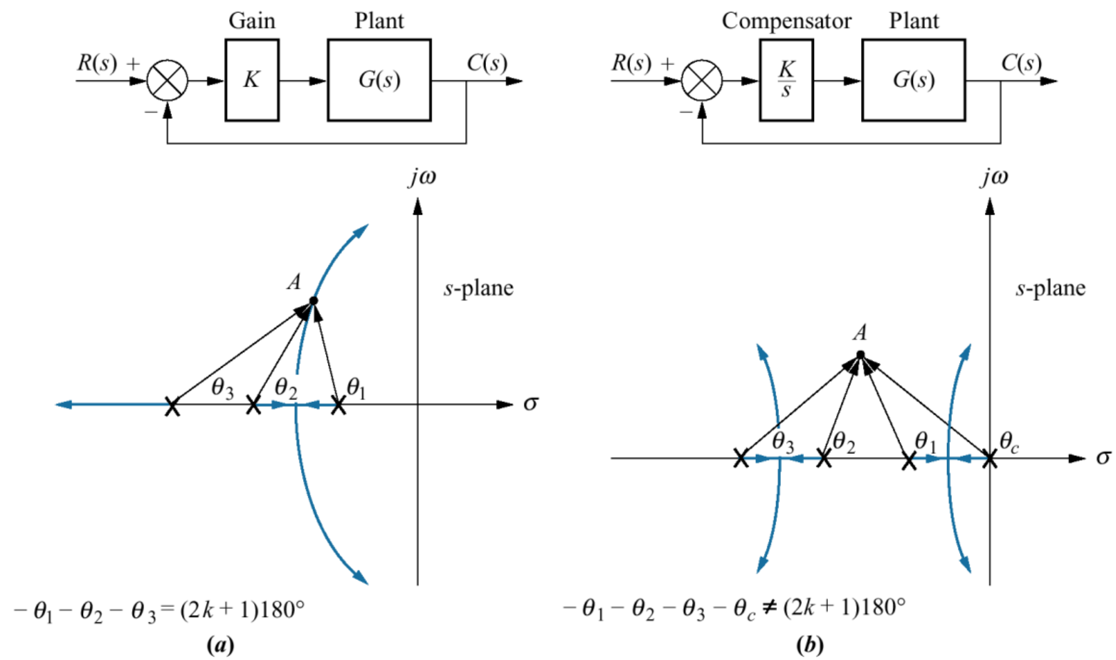
Figure 9.3
Pole at *A* is:
a. on the root locus without compensator;
b. not on the root locus with compensator pole added;
(figure continues)



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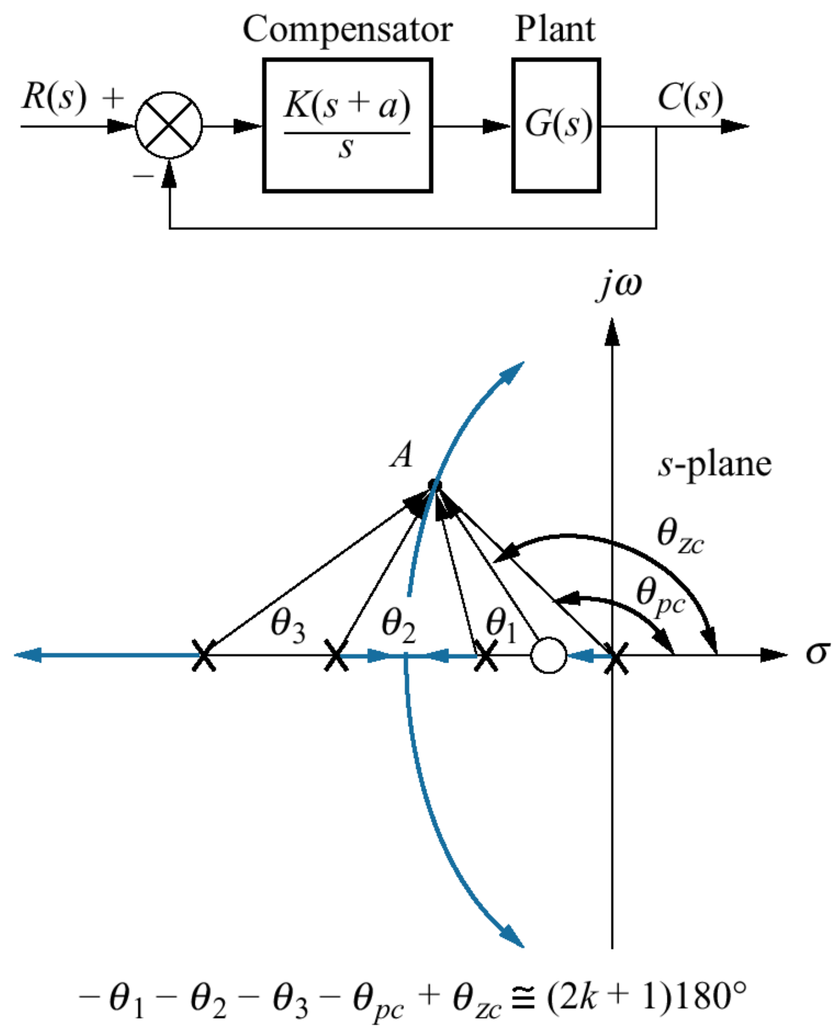

Figure 9.3
(continued)
c. approximately on the root locus with compensator pole and zero added

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Figure 9.4 Closed-loop system for Example 9.1: **a.** before compensation; **b.** after ideal integral compensation

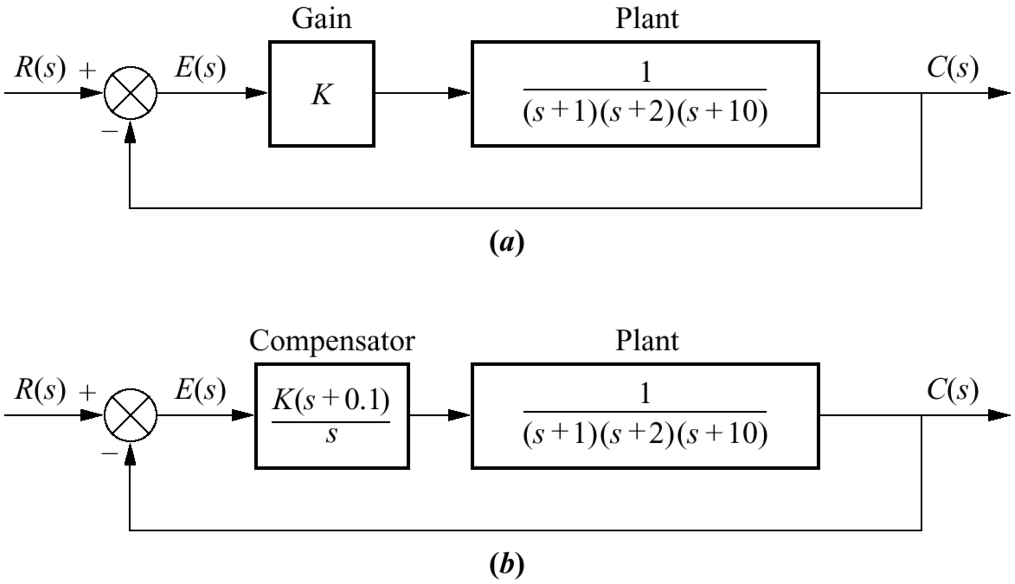

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Figure 9.5
Root locus for uncompensated system of Figure 9.4(*a*)

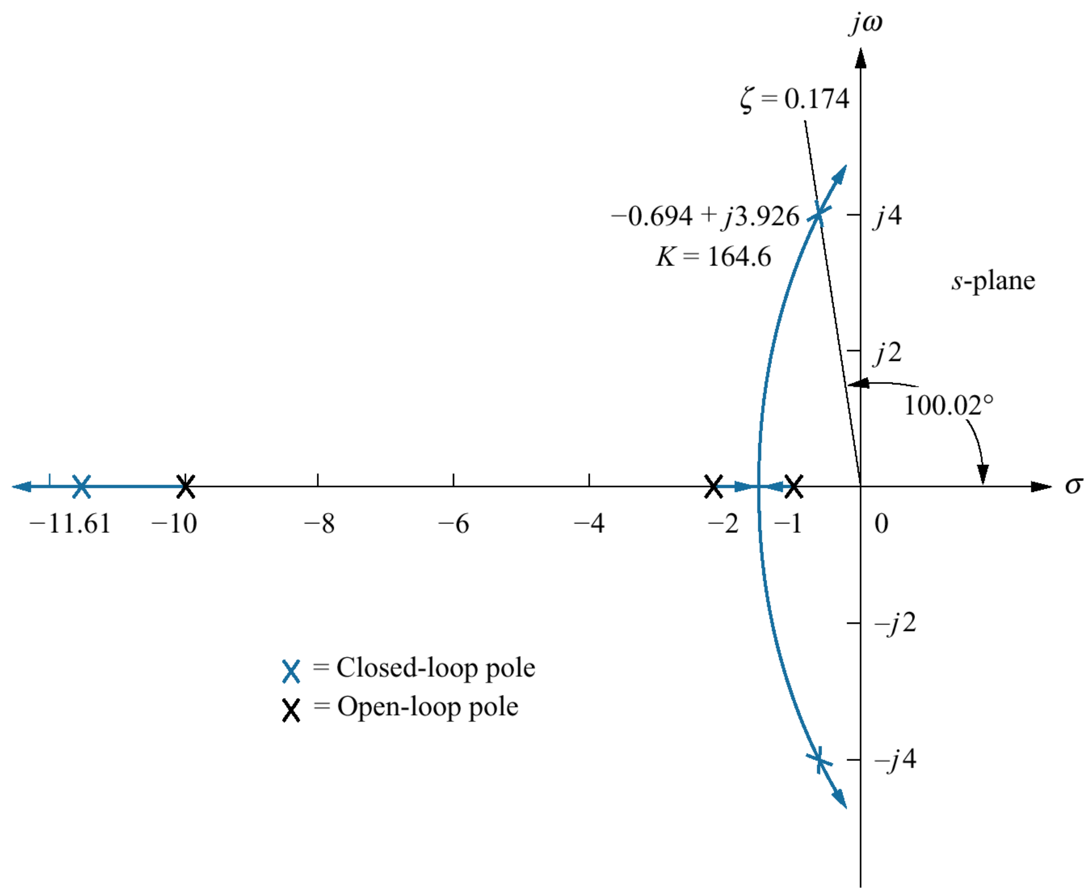

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Figure 9.6
Root locus for compensated system of Figure 9.4(b)

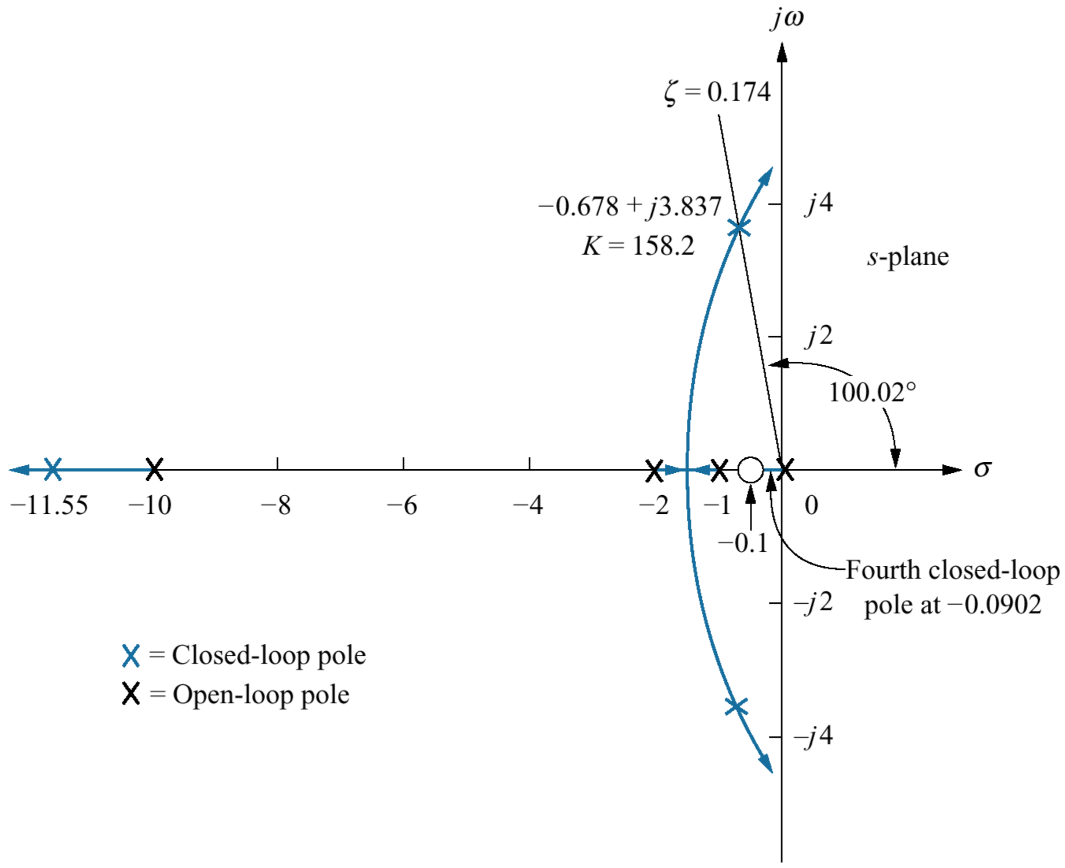

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Figure 9.7

Ideal integral compensated system response and the uncompensated system response of Example 9.1

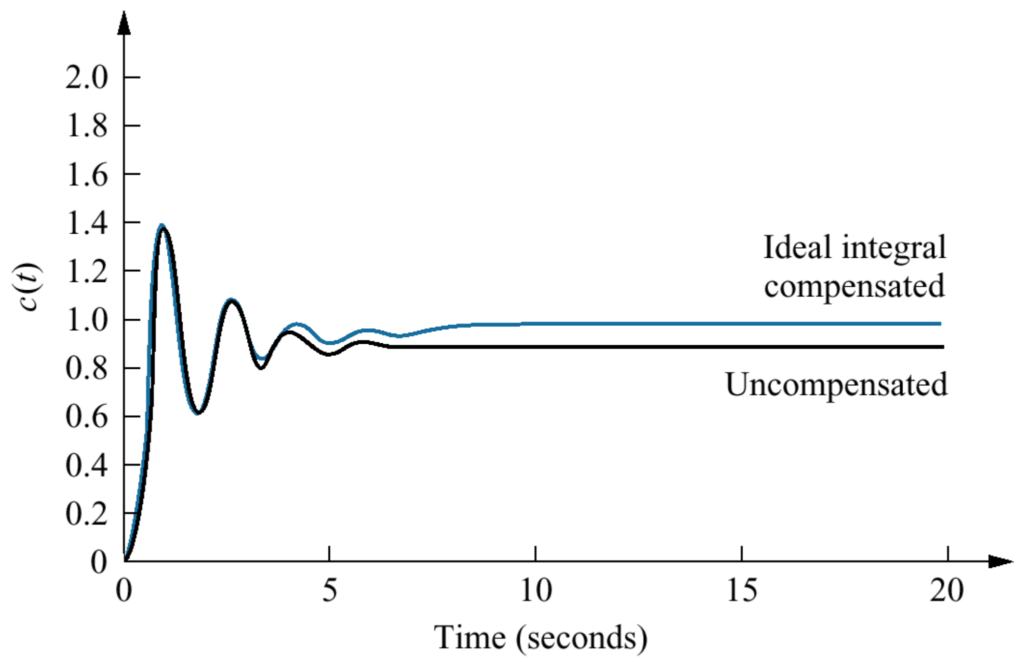

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Figure 9.8
PI controller

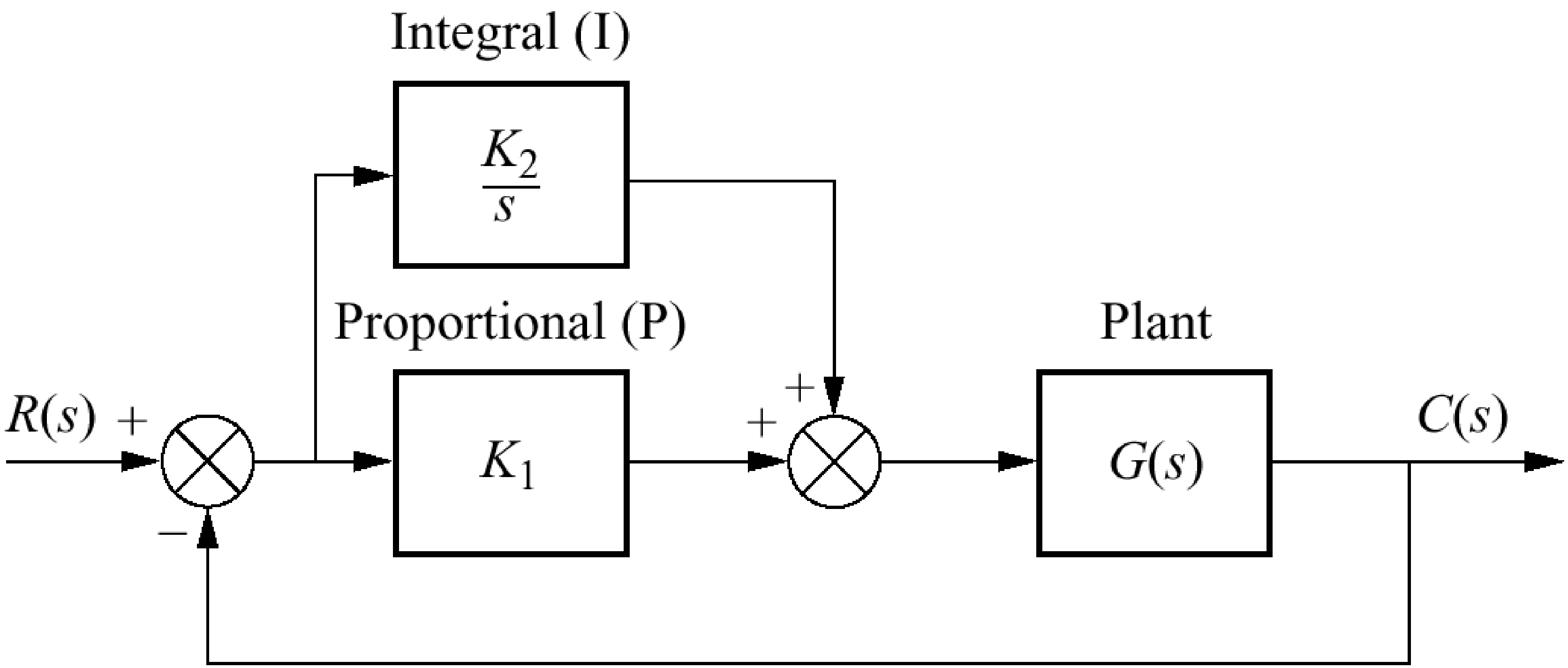

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Figure 9.9

a. Type 1 uncompensated system;
b. Type 1 compensated system;
c. compensator pole-zero plot

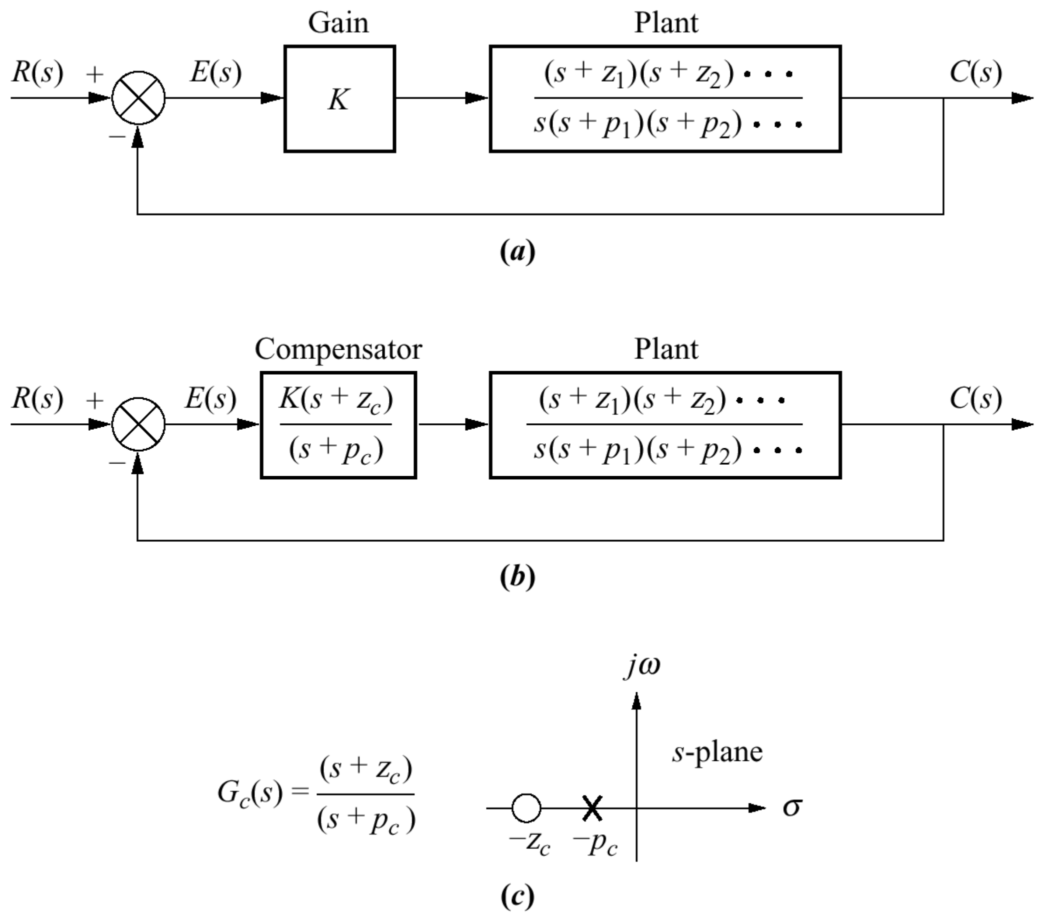

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Figure 9.10

Root locus:

a. before lag compensation;

b. after lag compensation

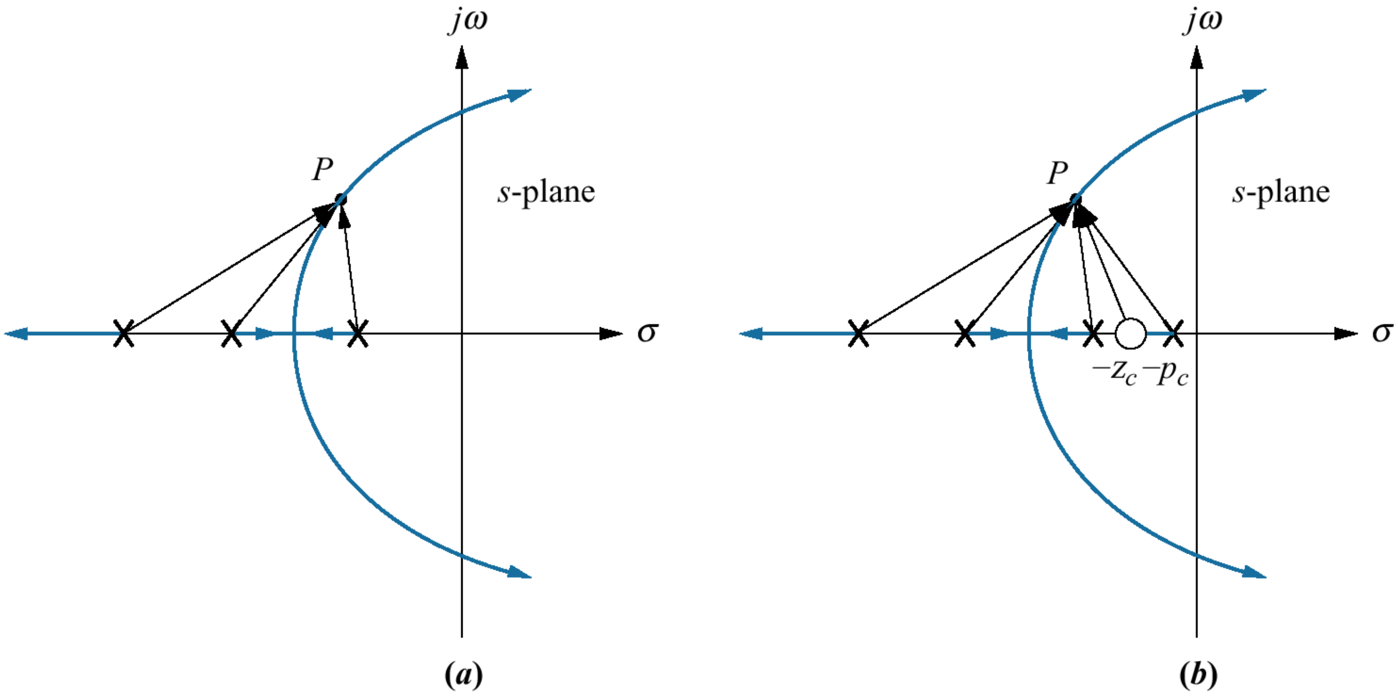

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Figure 9.11
Compensated system
for Example 9.2

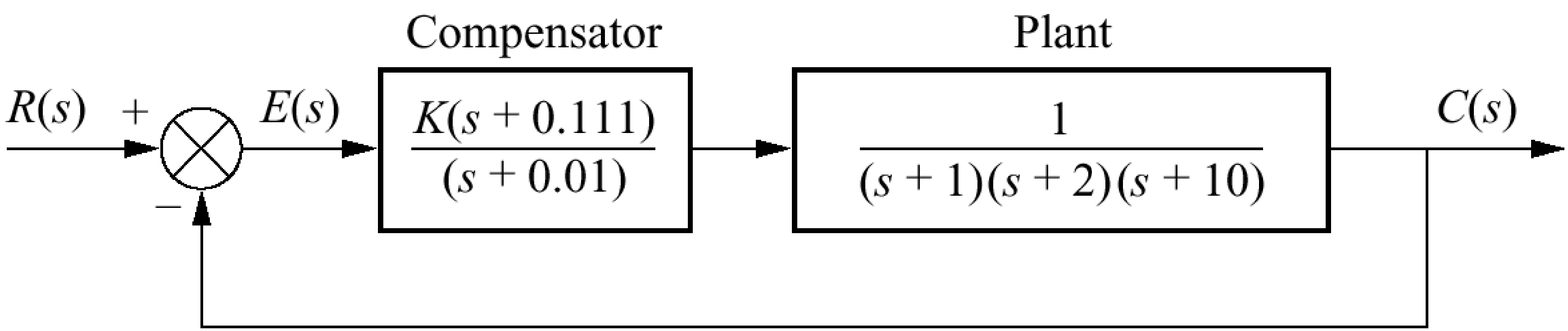

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Figure 9.12
Root locus for compensated system of Figure 9.11

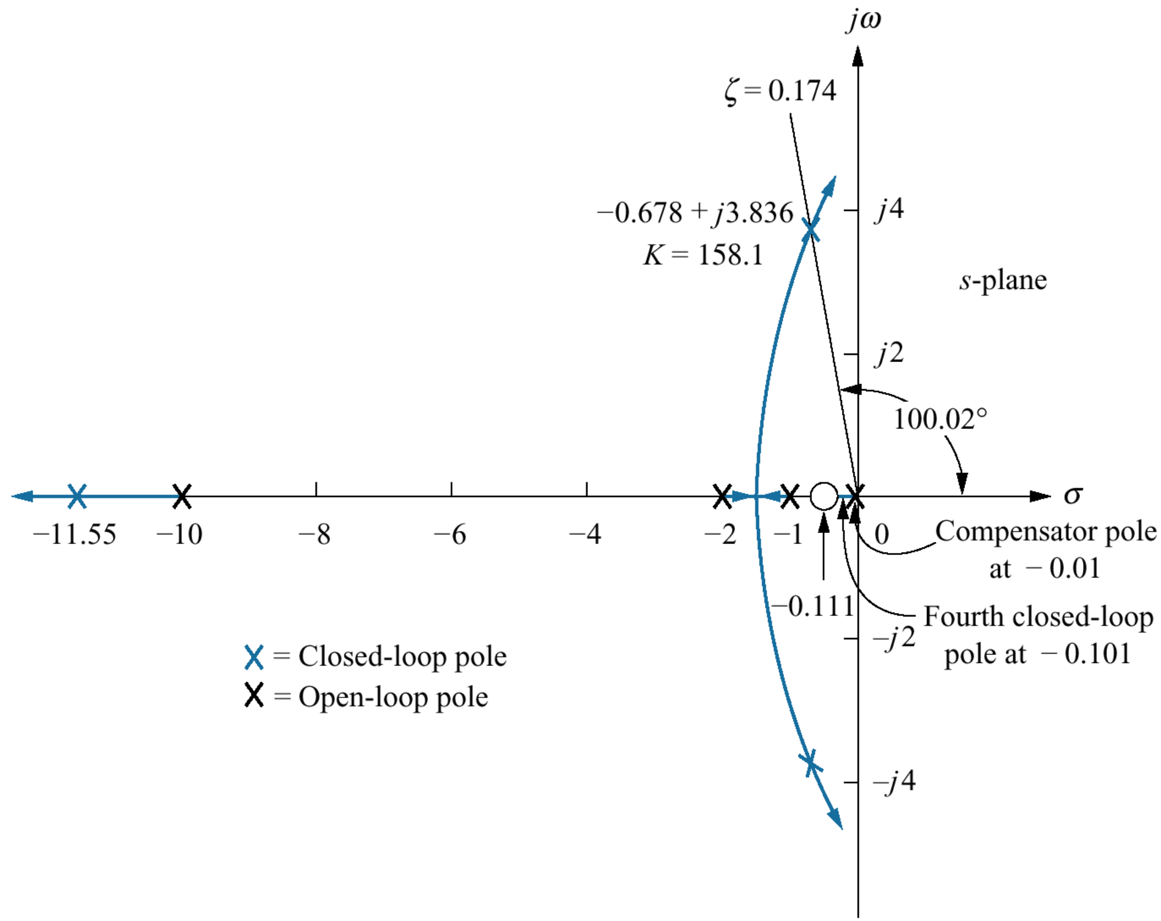

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Table 9.1

Predicted characteristics of uncompensated and lag-compensated systems for Example 9.2

Parameter	Uncompensated	Lag-compensated
Plant and compensator	$\dfrac{K}{(s+1)(s+2)(s+10)}$	$\dfrac{K(s+0.111)}{(s+1)(s+2)(s+10)(s+0.01)}$
K	164.6	158.1
K_p	8.23	87.75
$e(\infty)$	0.108	0.011
Dominant second-order poles	$-0.694 \pm j3.926$	$-0.678 \pm j3.836$
Third pole	-11.61	-11.55
Fourth pole	None	-0.101
Zero	None	-0.111

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Figure 9.13

Step responses of uncompensated and lag-compensated systems for Example 9.2

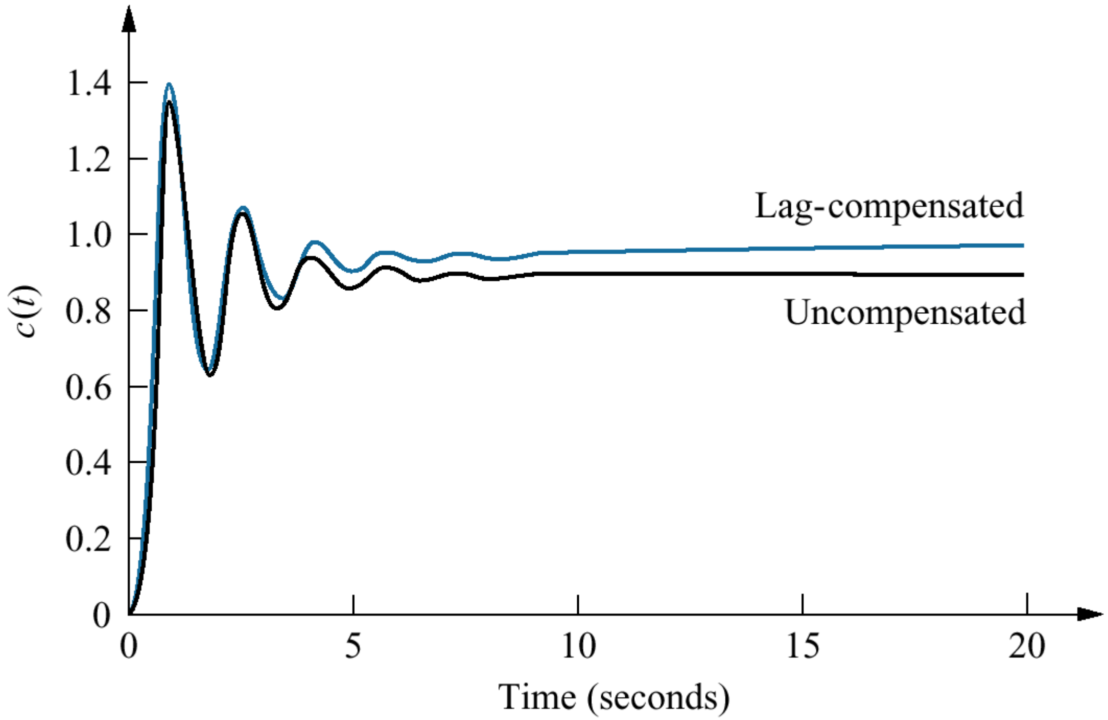

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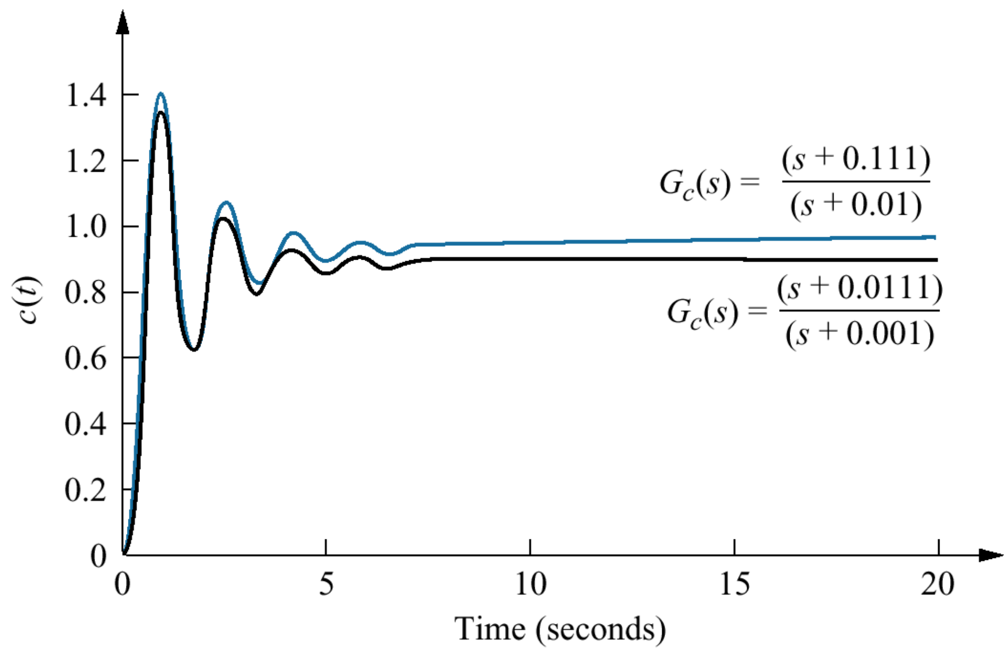
Figure 9.14

Step responses of the system for Example 9.2 using different lag compensators



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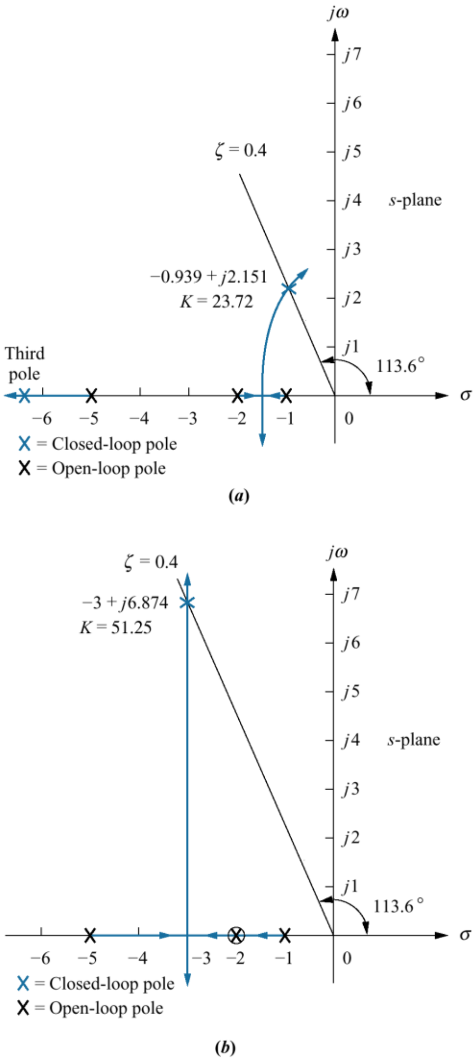

Figure 9.15

Using ideal derivative compensation:
a. uncompensated;
b. compensator zero at –2;
(figure continues)

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Figure 9.15
(*continued*)
c. compensator zero at –3;
d. compensator zero at – 4

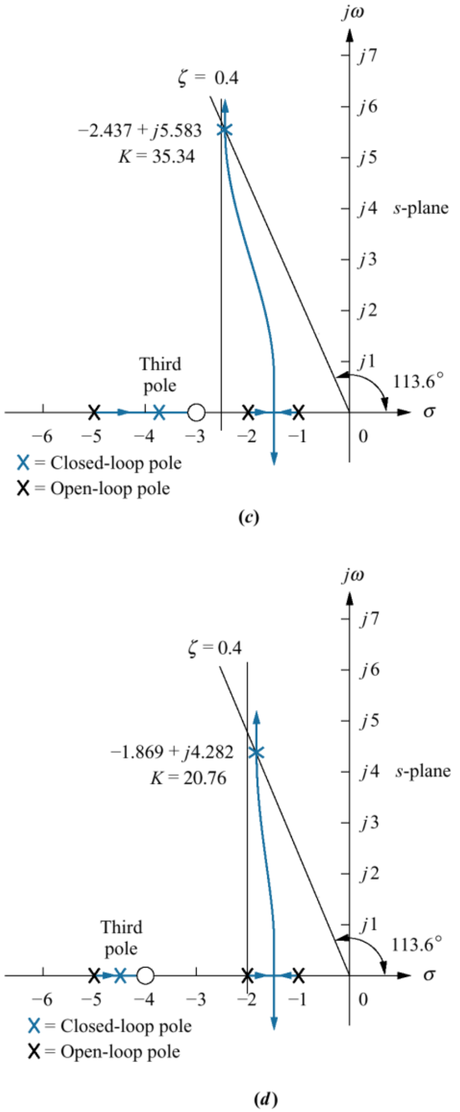

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Figure 9.16
Uncompensated system and ideal derivative compensation solutions from Table 9.2

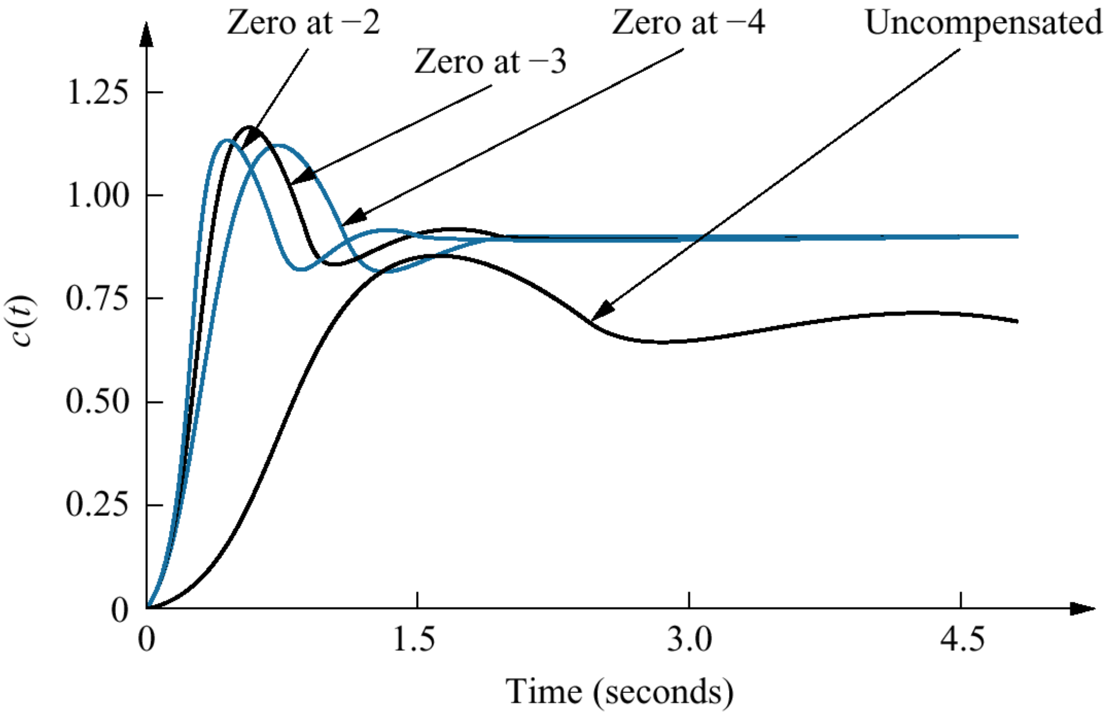

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Table 9.2
Predicted characteristics for the systems of Figure 9.15

	Uncompensated	Compensation b	Compensation c	Compensation d
Plant and compensator	$\frac{K}{(s+1)(s+2)(s+5)}$	$\frac{K(s+2)}{(s+1)(s+2)(s+5)}$	$\frac{K(s+3)}{(s+1)(s+2)(s+5)}$	$\frac{K(s+4)}{(s+1)(s+2)(s+5)}$
Dom. poles	$-0.939 \pm j2.151$	$-3 \pm j6.874$	$-2.437 \pm j5.583$	$-1.869 \pm j4.282$
K	23.72	51.25	35.34	20.76
ζ	0.4	0.4	0.4	0.4
ω_n	2.347	7.5	6.091	4.673
$\%OS$	25.38	25.38	25.38	25.38
T_s	4.26	1.33	1.64	2.14
T_p	1.46	0.46	0.56	0.733
K_p	2.372	10.25	10.6	8.304
$e(\infty)$	0.297	0.089	0.086	0.107
Third pole	−6.123	None	−3.127	−4.262
Zero	None	None	−3	−4
Comments	Second-order approx. OK	Pure second-order	Second-order approx. OK	Second-order approx. OK

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Figure 9.17
Feedback
control system
for Example 9.3

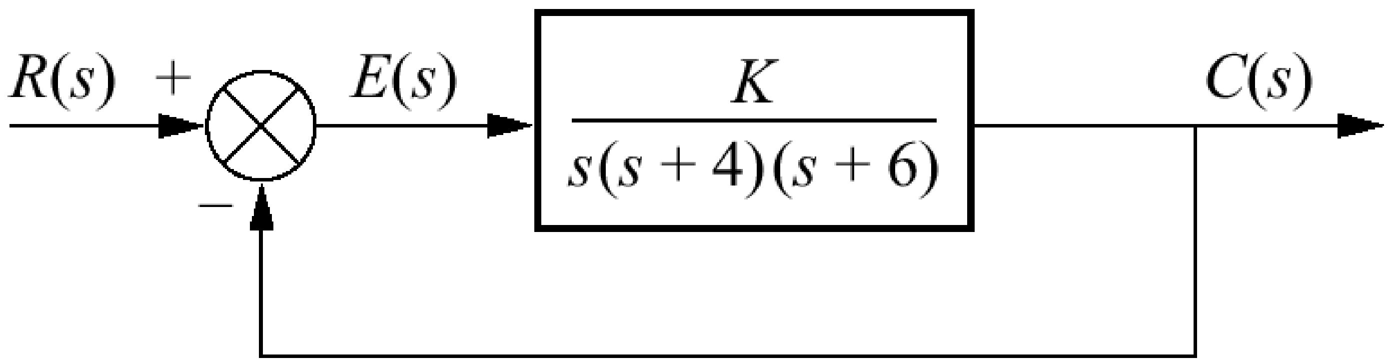

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Figure 9.18

Root locus for uncompensated system shown in Figure 9.17

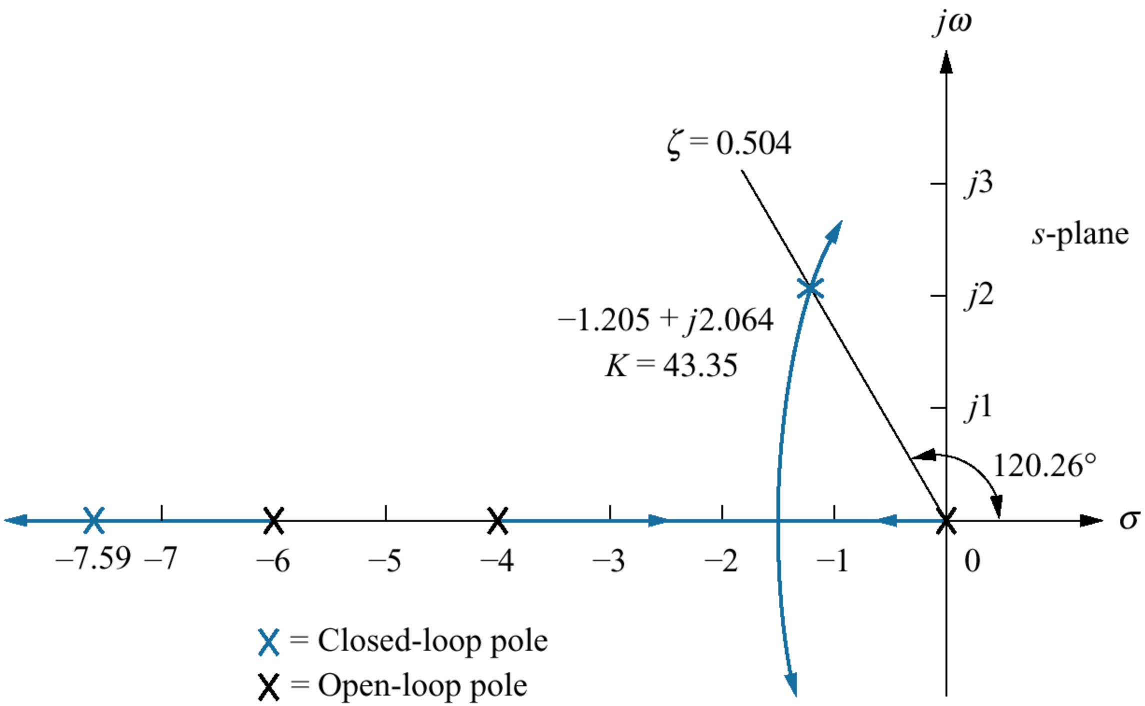

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Table 9.3

Uncompensated and compensated system characteristics for Example 9.3

	Uncompensated	Simulation	Compensated	Simulation
Plant and compensator	$\frac{K}{s(s+4)(s+6)}$		$\frac{K(s+3.006)}{s(s+4)(s+6)}$	
Dominant poles	$-1.205 \pm j2.064$		$-3.613 \pm j6.193$	
K	43.35		47.45	
ζ	0.504		0.504	
ω_n	2.39		7.17	
$\%OS$	16	14.8	16	11.8
T_s	3.320	3.6	1.107	1.2
T_p	1.522	1.7	0.507	0.5
K_v	1.806		5.94	
$e(\infty)$	0.554		0.168	
Third pole	−7.591		−2.775	
Zero	None		−3.006	
Comments	Second-order approx. OK		Pole-zero not canceling	

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Figure 9.19
Compensated dominant pole superimposed over the uncompensated root locus for Example 9.3

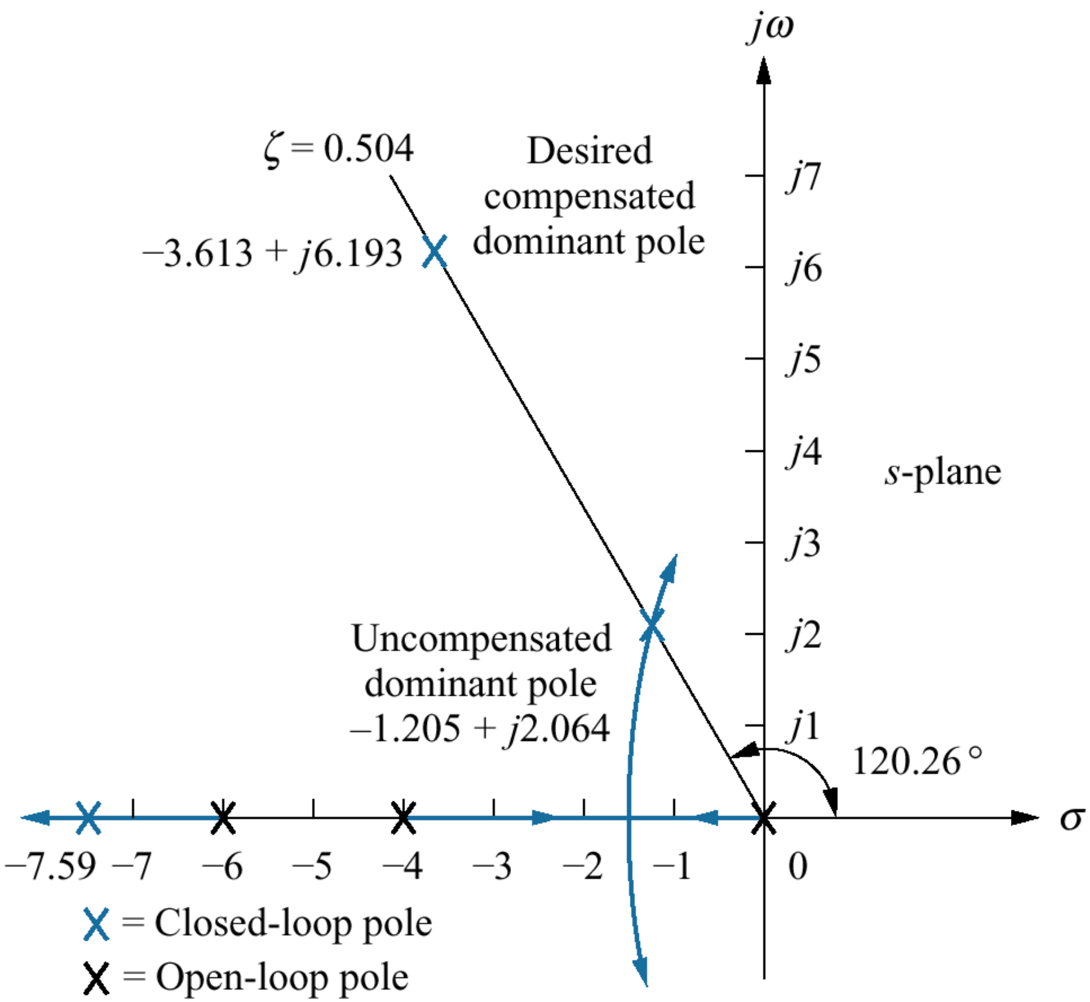

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Figure 9.20 Evaluating the location of the compensating zero for Example 9.3

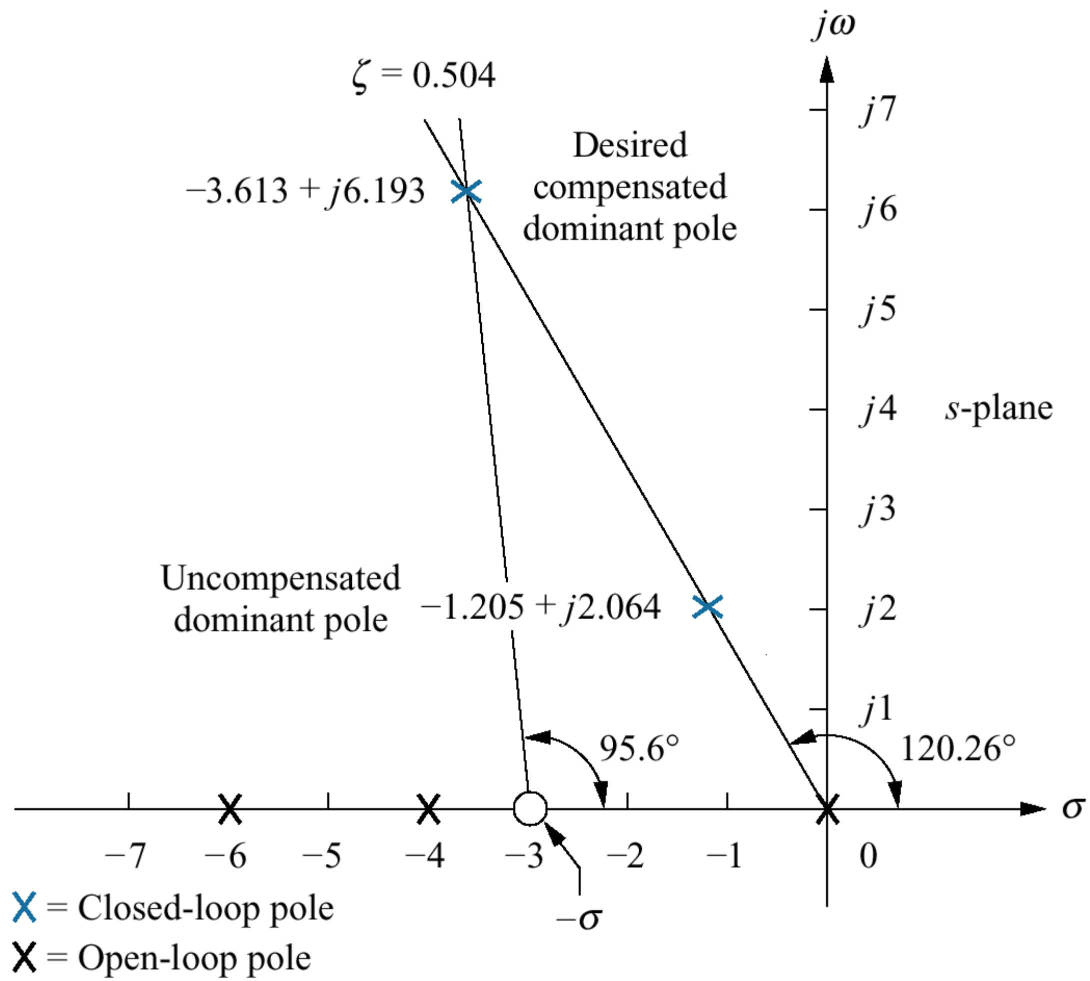

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Figure 9.21
Root locus for the compensated system of Example 9.3

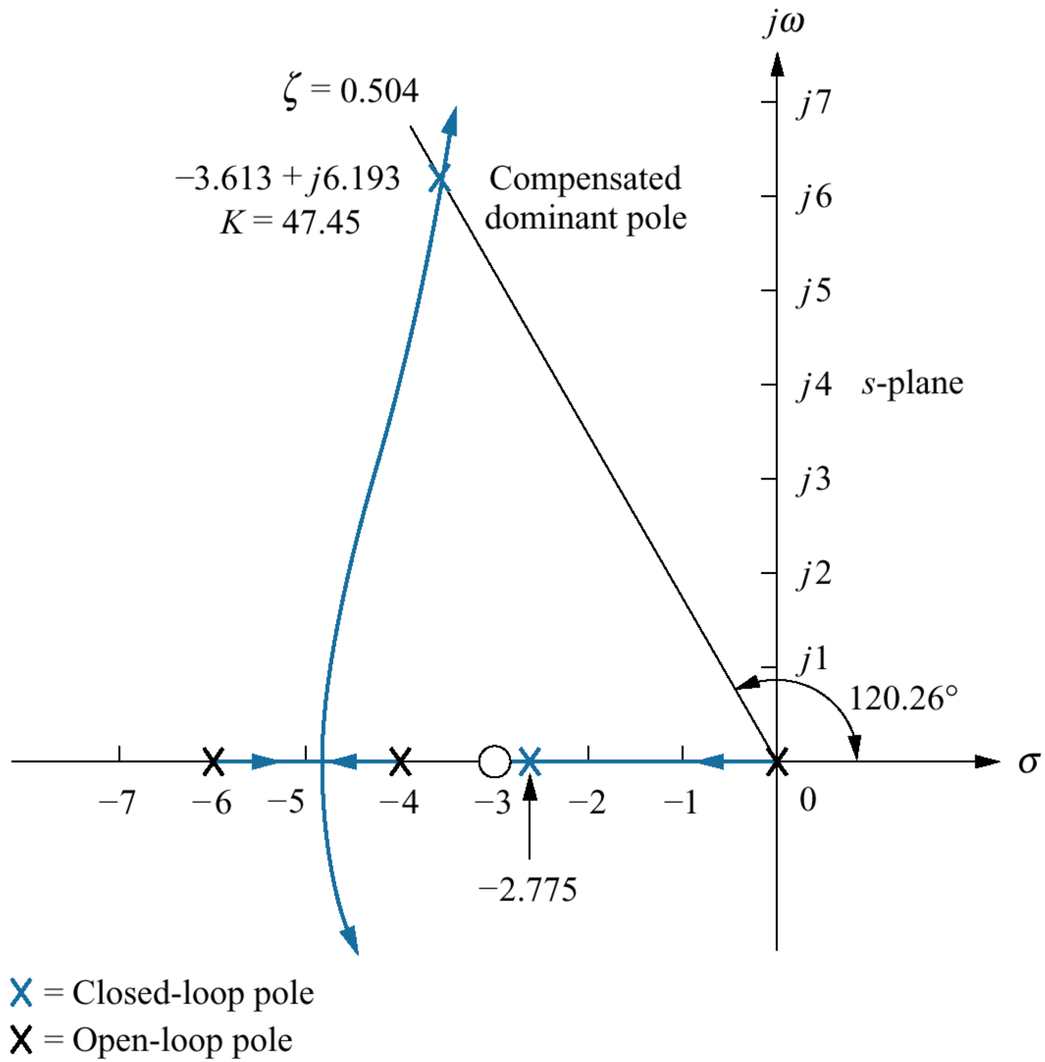

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Figure 9.22
Uncompensated and compensated system step responses of Example 9.3

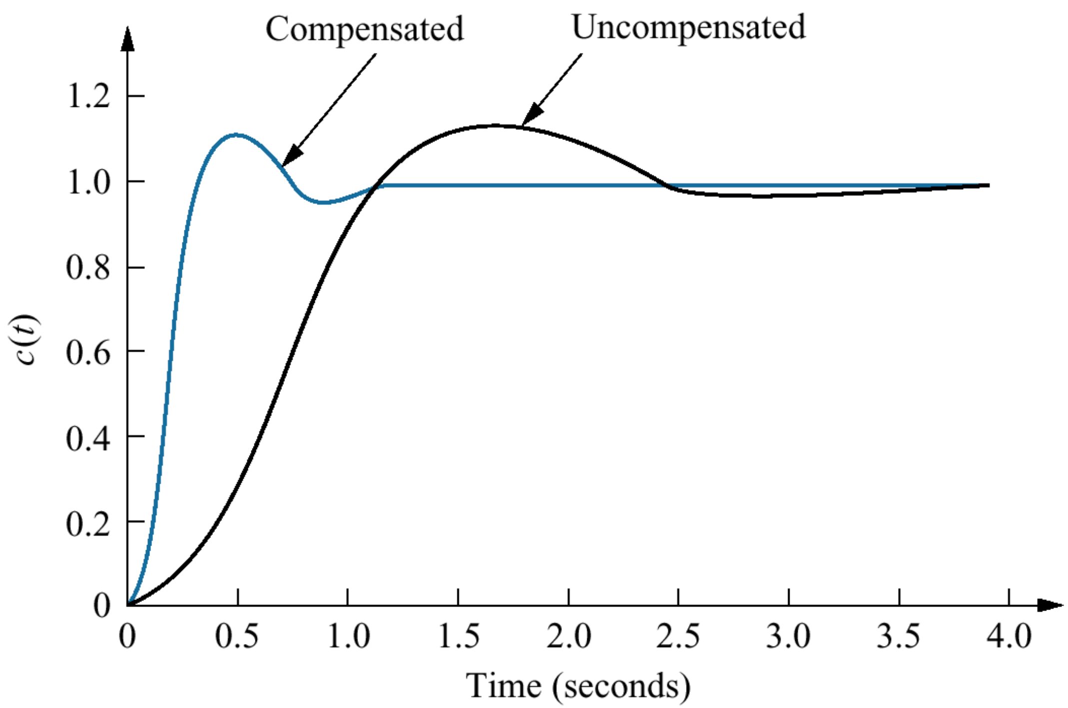

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Figure 9.23
PD controller

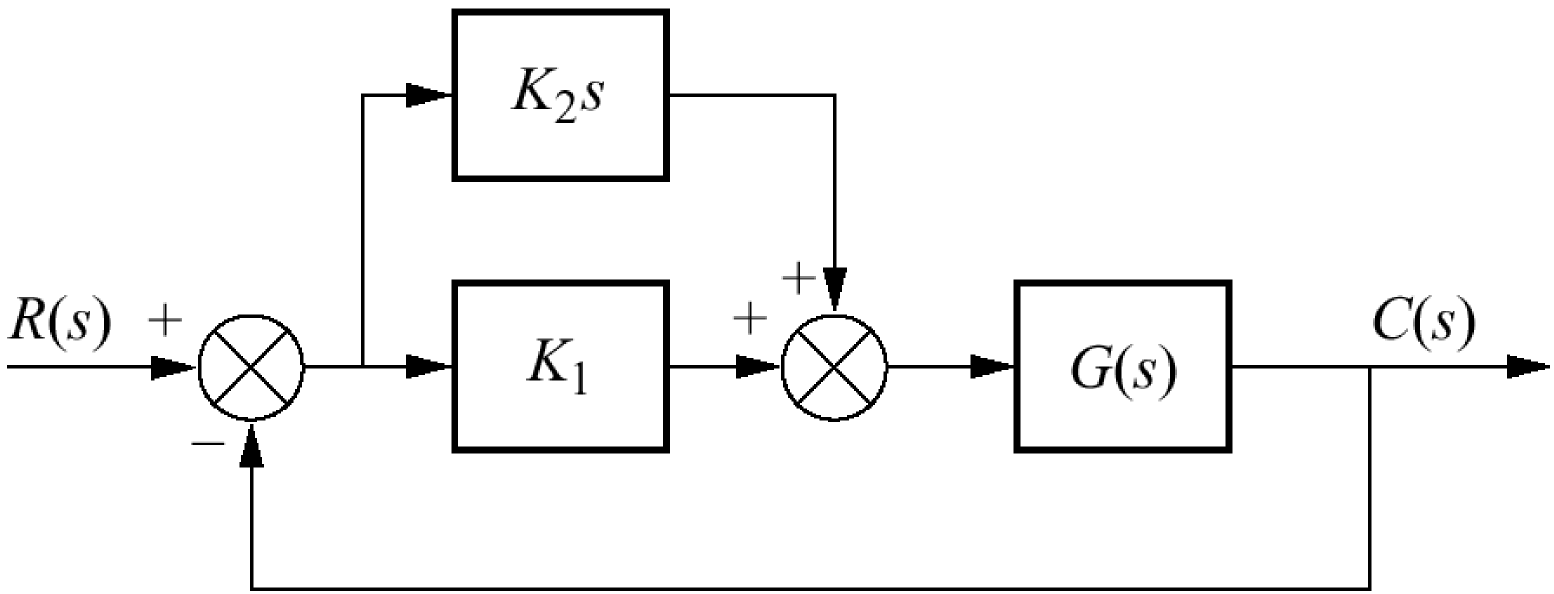

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Figure 9.24
Geometry of lead compensation

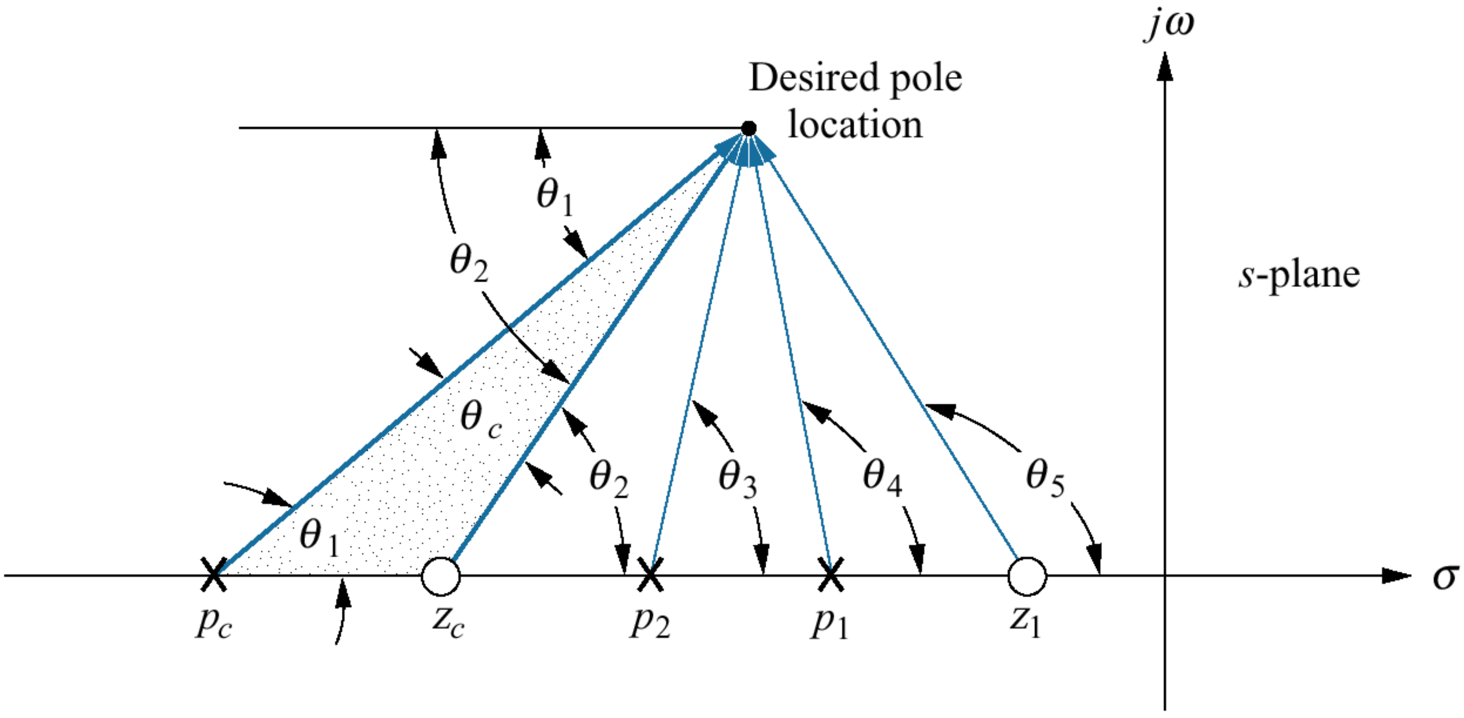

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Figure 9.25
Three of the infinite possible lead compensator solutions

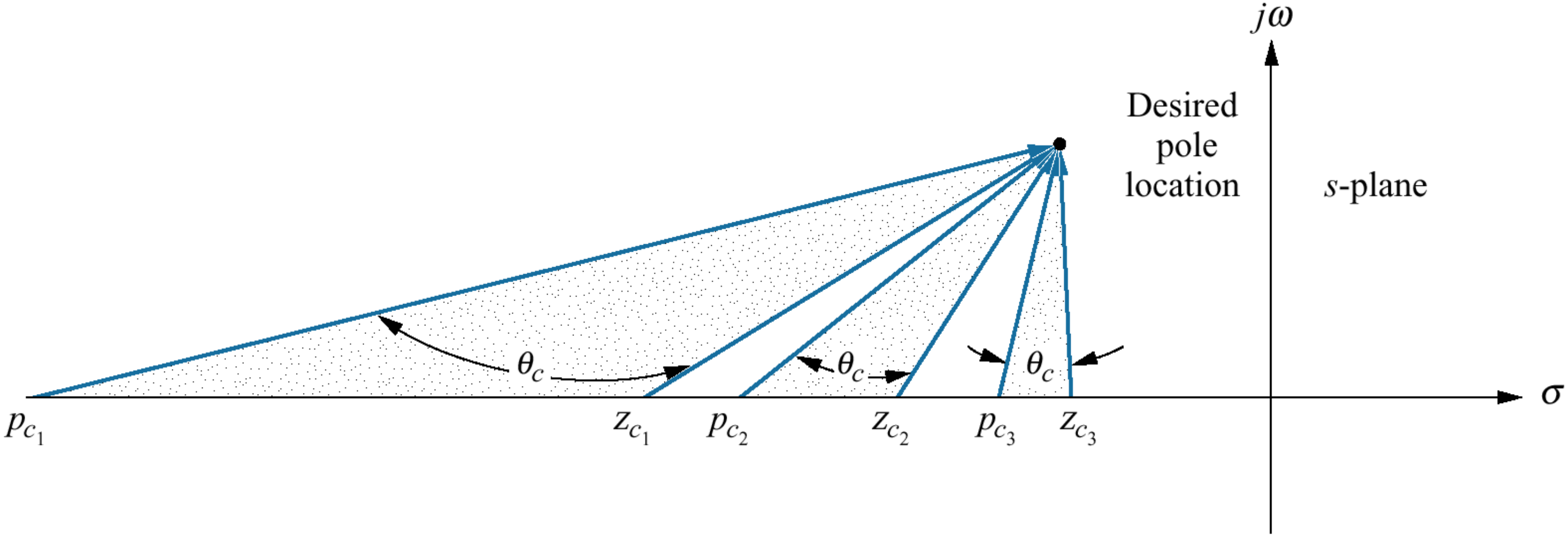

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Figure 9.26
Lead compensator design, showing evaluation of uncompensated and compensated dominant poles for Example 9.4

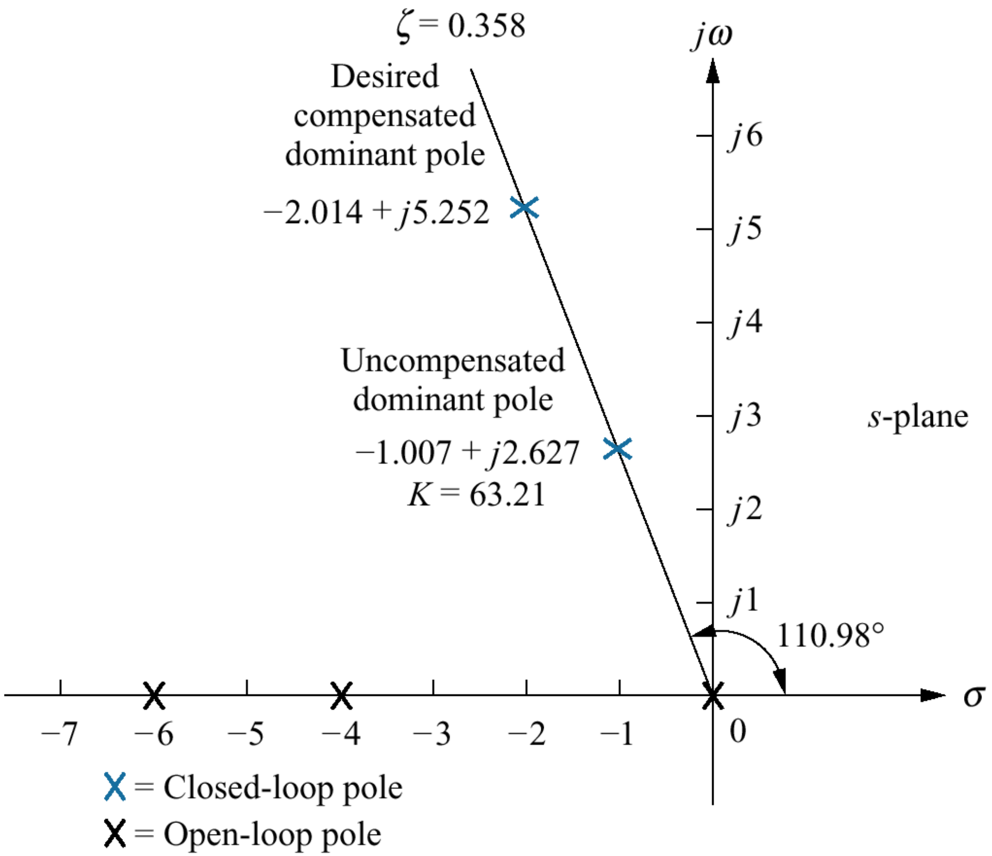

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Table 9.4 Comparison of lead compensation designs for Example 9.4

	Uncompensated	Compensation a	Compensation b	Compensation c
Plant and compensator	$\frac{K}{s(s+4)(s+6)}$	$\frac{K(s+5)}{s(s+4)(s+6)(s+42.96)}$	$\frac{K(s+4)}{s(s+4)(s+6)(s+20.09)}$	$\frac{K(s+2)}{s(s+4)(s+6)(s+8.971)}$
Dominant poles	$-1.007 \pm j2.627$	$-2.014 \pm j5.252$	$-2.014 \pm j5.252$	$-2.014 \pm j5.252$
K	63.21	1423	698.1	345.6
ζ	0.358	0.358	0.358	0.358
ω_n	2.813	5.625	5.625	5.625
$\%OS^*$	30 (28)	30 (30.7)	30 (28.2)	30 (14.5)
T_s^*	3.972 (4)	1.986 (2)	1.986 (2)	1.986 (1.7)
T_p^*	1.196 (1.3)	0.598 (0.6)	0.598 (0.6)	0.598 (0.7)
K_v	2.634	6.9	5.791	3.21
$e(\infty)$	0.380	0.145	0.173	0.312
Other poles	−7.986	−43.8, −5.134	−22.06	−13.3, −1.642
Zero	None	−5	None	−2
Comments	Second-order approx. OK	Second-order approx. OK	Second-order approx. OK	No pole-zero cancellation

* Simulation results are shown in parentheses.

Table 9.4

Comparison of lead compensation designs for Example 9.4

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Figure 9.27
s-plane picture used to calculate the location of the compensator pole for Example 9.4

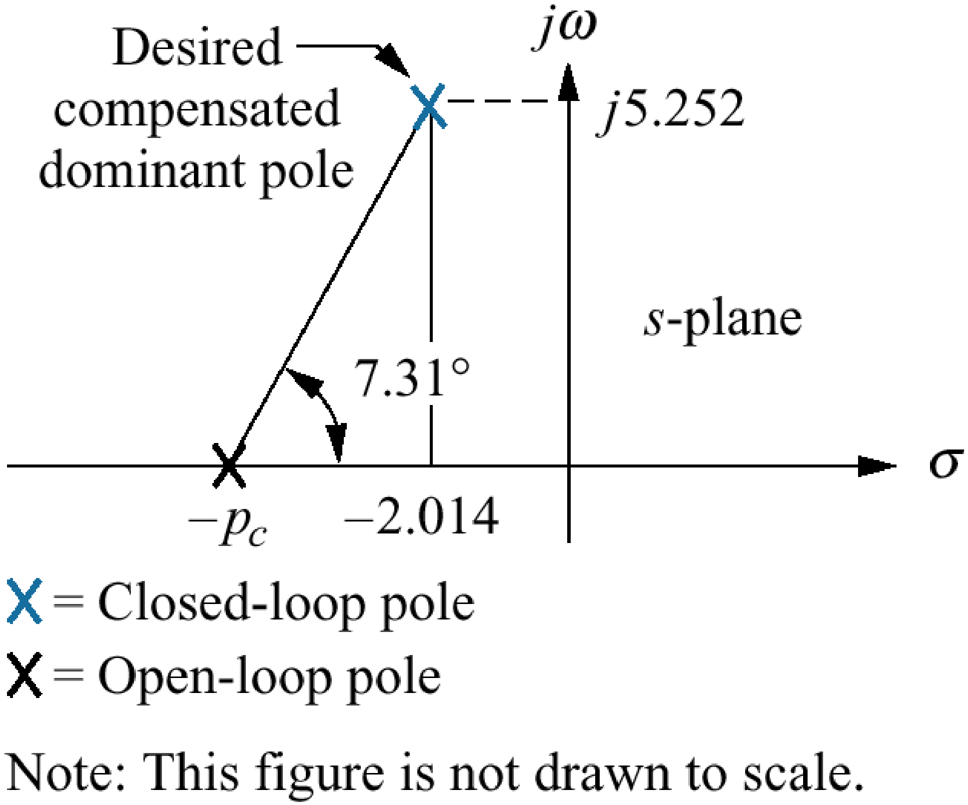

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Figure 9.28
Compensated system root locus

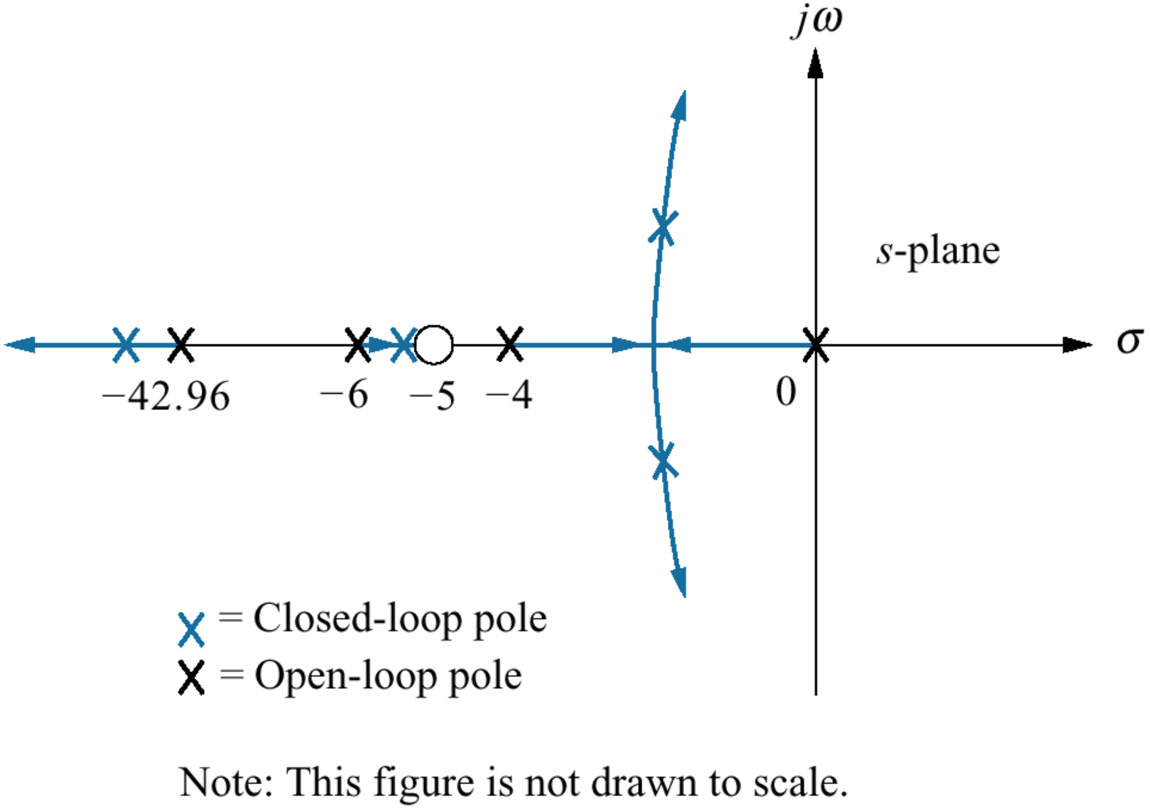

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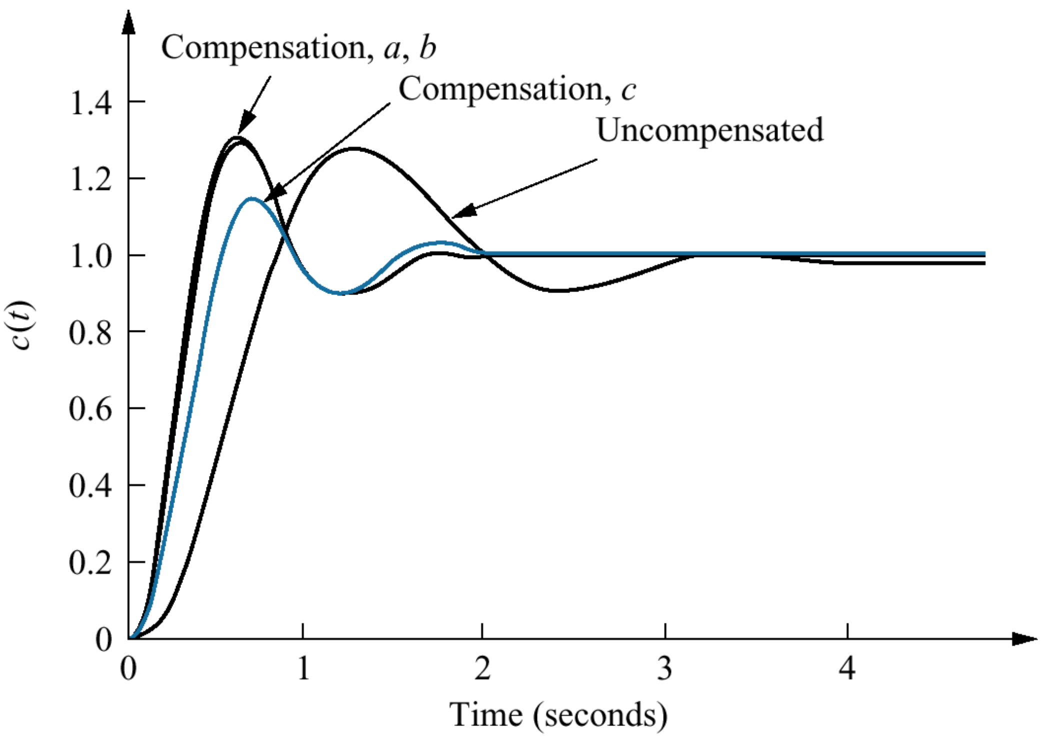
Figure 9.29 Uncompensated system and lead compensation responses for Example 9.4



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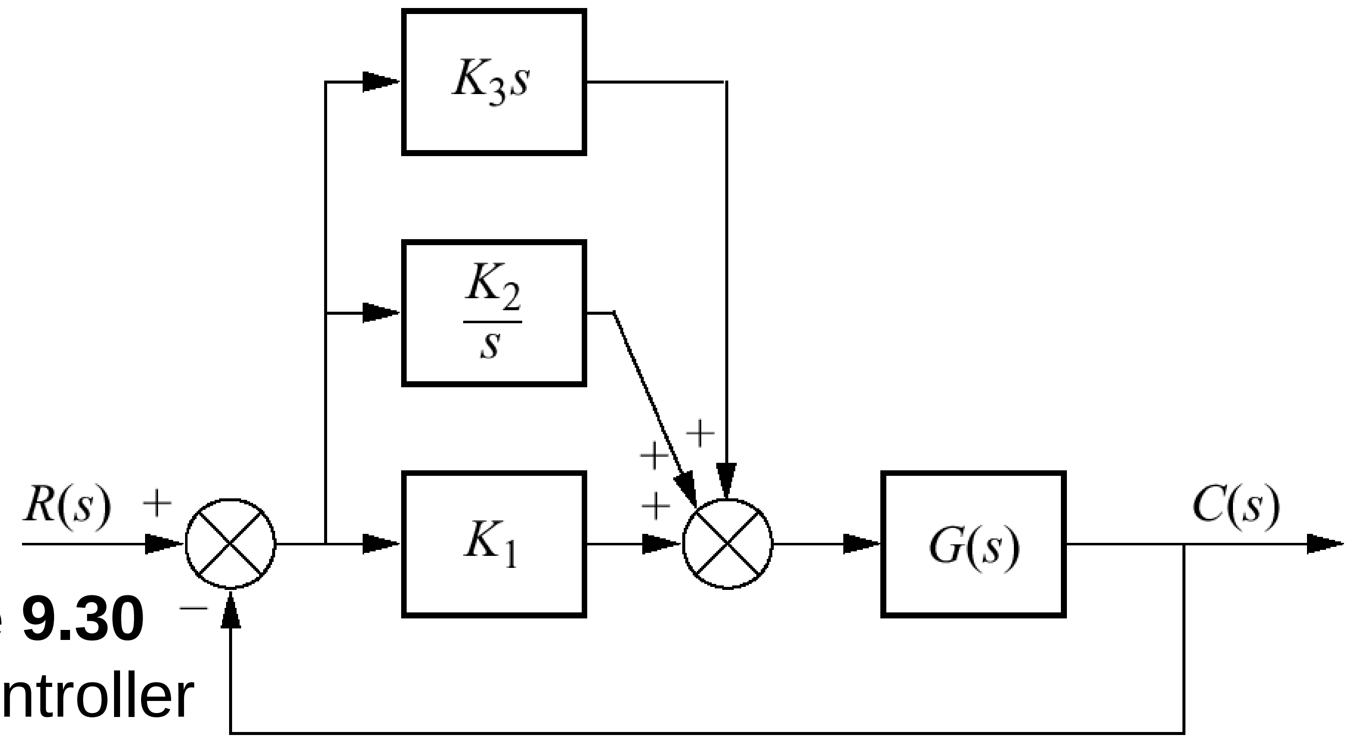

Figure 9.30
PID controller

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Figure 9.31

Uncompensated feedback control system for Example 9.5

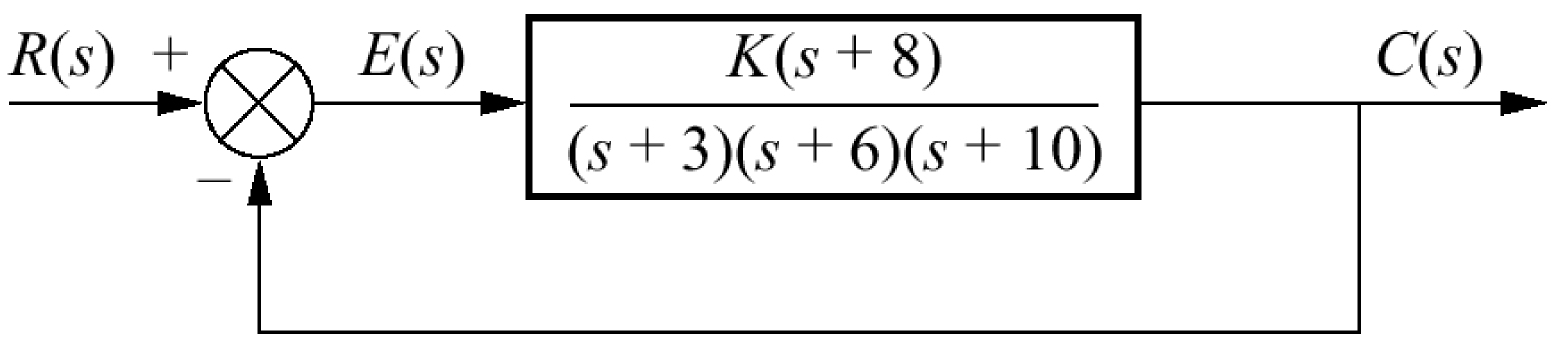

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Figure 9.32
Root locus for the uncompensated system of Example 9.5

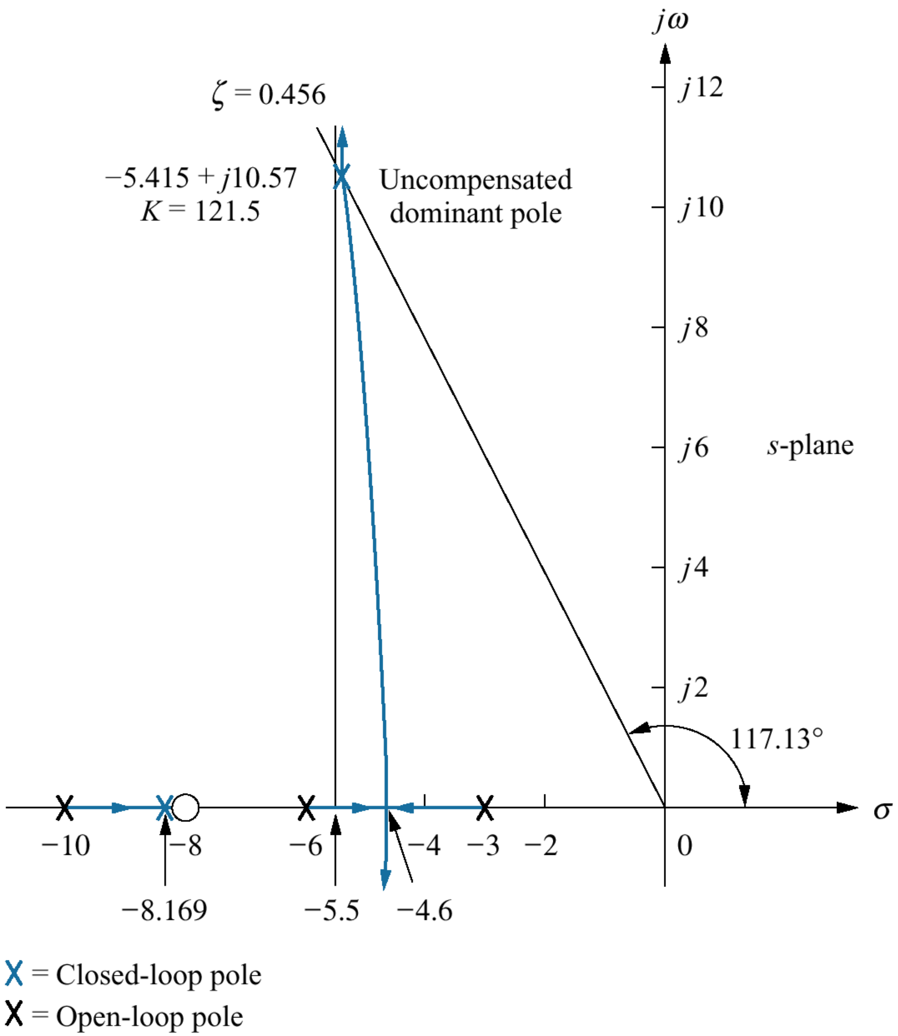

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Table 9.5

Predicted characteristics of uncompensated, PD- , and PID-compensated systems of Example 9.5

	Uncompensated	PD-compensated	PID-compensated
Plant and compensator	$\frac{K(s+8)}{(s+3)(s+6)(s+10)}$	$\frac{K(s+8)(s+55.92)}{(s+3)(s+6)(s+10)}$	$\frac{K(s+8)(s+55.92)(s+0.5)}{(s+3)(s+6)(s+10)s}$
Dominant poles	$-5.415 \pm j10.57$	$-8.13 \pm j15.87$	$-7.516 \pm j14.67$
K	121.5	5.34	4.6
ζ	0.456	0.456	0.456
ω_n	11.88	17.83	16.49
$\%OS$	20	20	20
T_s	0.739	0.492	0.532
T_p	0.297	0.198	0.214
K_p	5.4	13.27	∞
$e(\infty)$	0.156	0.070	0
Other poles	-8.169	-8.079	$-8.099, -0.468$
Zeros	-8	$-8, -55.92$	$-8, -55.92, -0.5$
Comments	Second-order approx. OK	Second-order approx. OK	Zero at -55.92 and -0.5 not canceled

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Figure 9.33
Calculating the
PD compensator zero
for Example 9.5

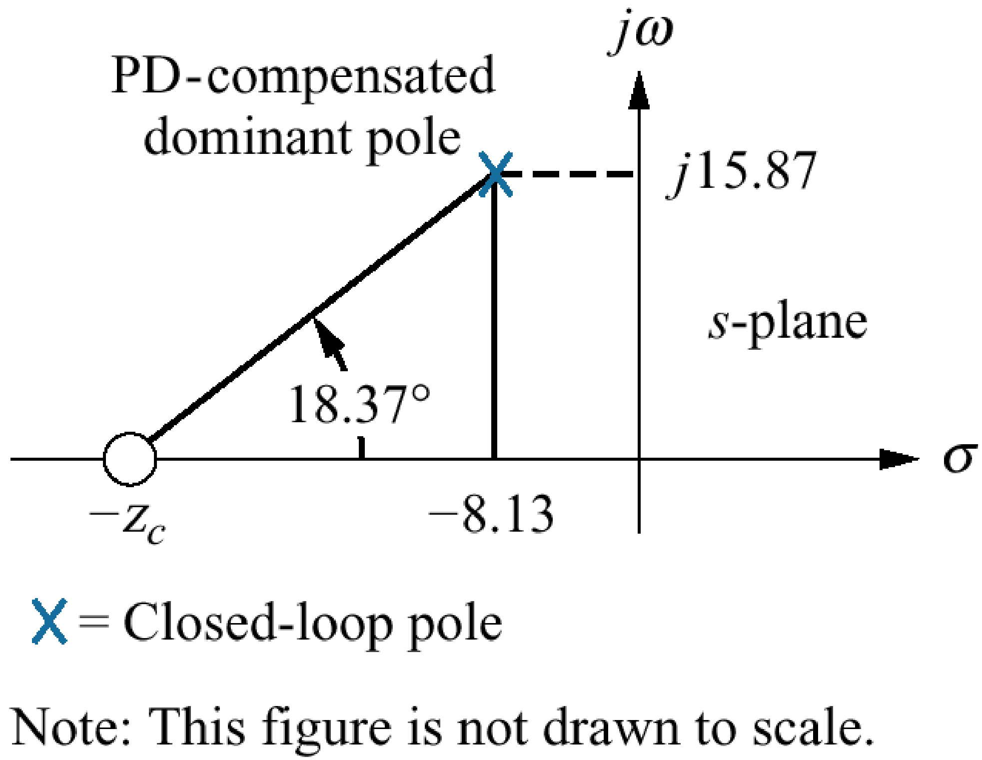

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Figure 9.34

Root locus for PD-compensated system of Example 9.5

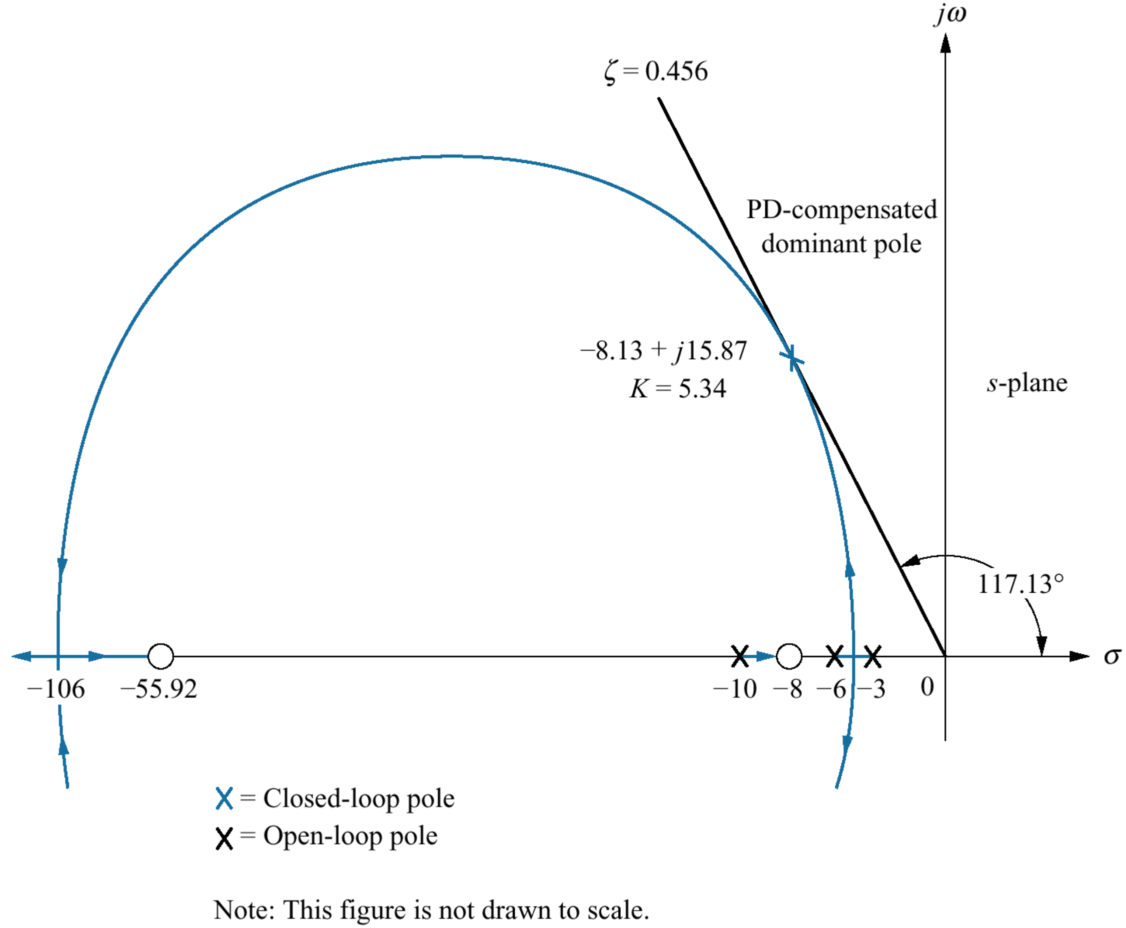

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Figure 9.35
Step responses for uncompensated, PD-compensated, and PID-compensated systems of Example 9.5

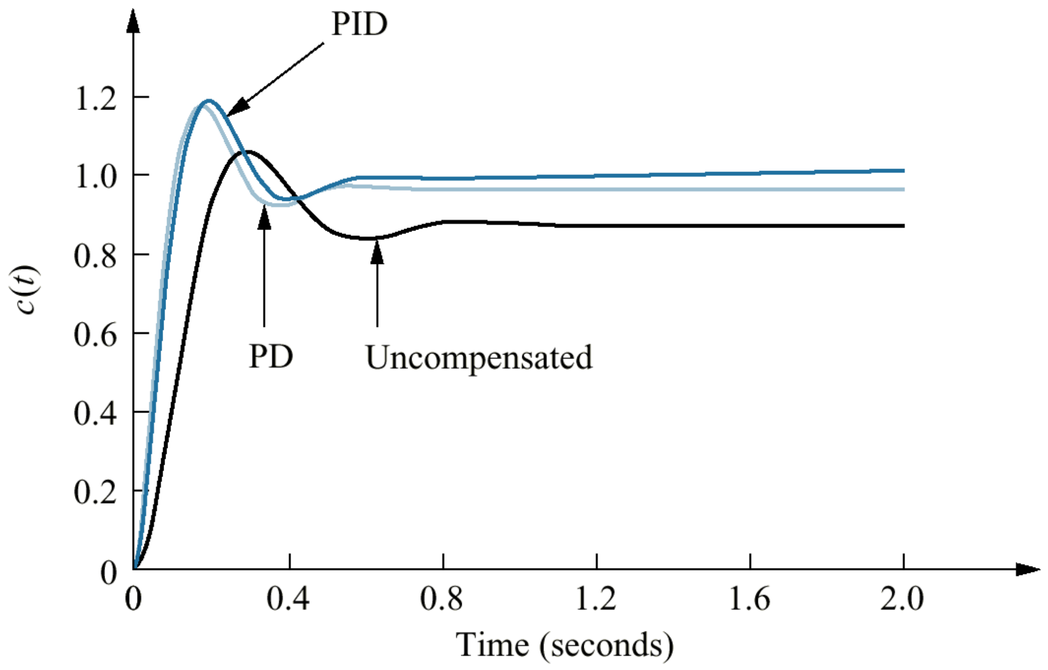

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Figure 9.36
Root locus for PID-compensated system
of Example 9.5

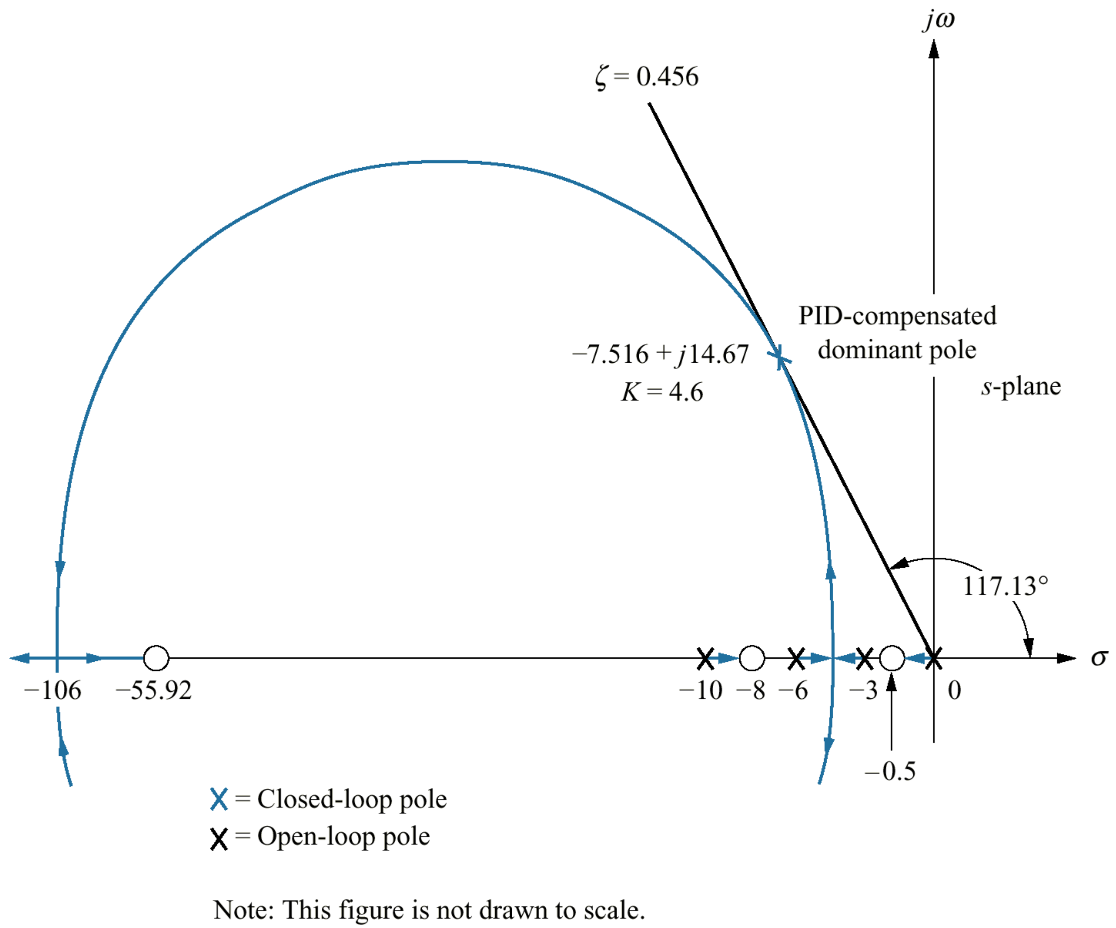

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Figure 9.37
Uncompensated system for Example 9.6

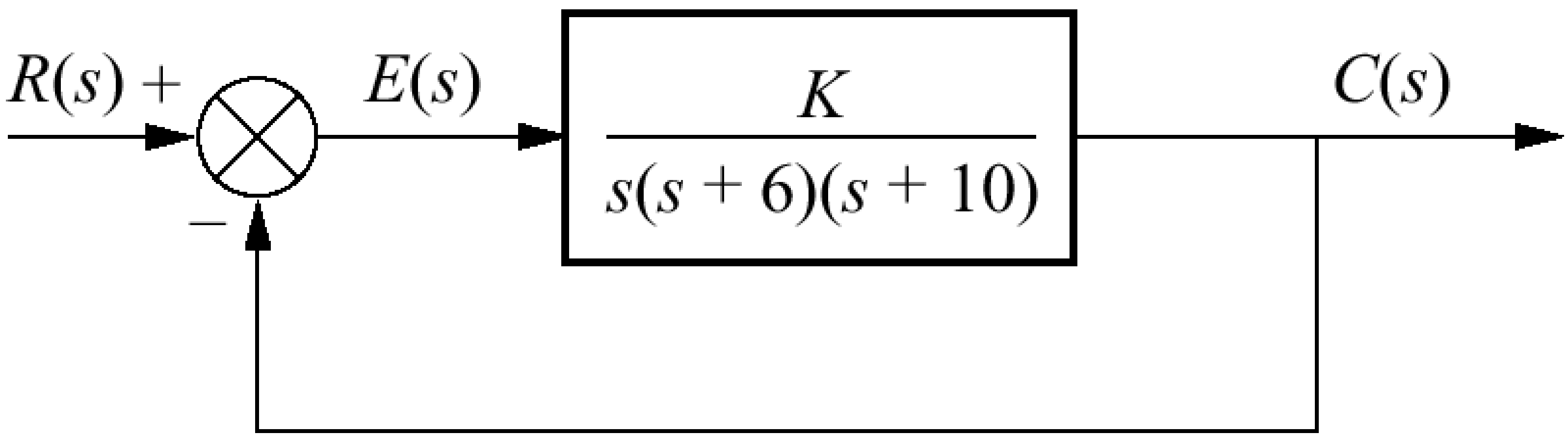

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Figure 9.38

Root locus for uncompensated system of Example 9.6

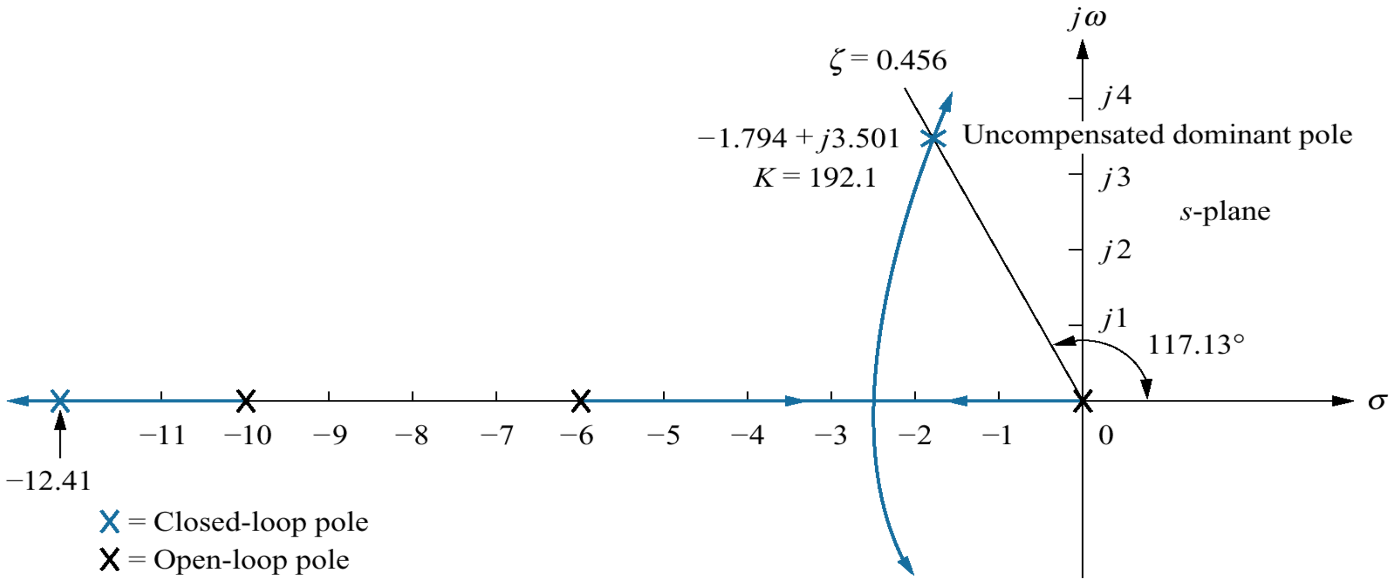

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Table 9.6
Predicted characteristics of uncompensated, lead-compensated, and lag-lead- compensated systems of Example 9.6

	Uncompensated	Lead-compensated	Lag-lead-compensated
Plant and compensator	$\frac{K}{s(s+6)(s+10)}$	$\frac{K}{s(s+10)(s+29.1)}$	$\frac{K(s+0.04713)}{s(s+10)(s+29.1)(s+0.01)}$
Dominant poles	$-1.794 \pm j3.501$	$-3.588 \pm j7.003$	$-3.574 \pm j6.976$
K	192.1	1977	1971
ζ	0.456	0.456	0.456
ω_n	3.934	7.869	7.838
$\%OS$	20	20	20
T_s	2.230	1.115	1.119
T_p	0.897	0.449	0.450
K_v	3.202	6.794	31.92
$e(\infty)$	0.312	0.147	0.0313
Third pole	−12.41	−31.92	−31.91, −0.0474
Zero	None	None	−0.04713
Comments	Second-order approx. OK	Second-order approx. OK	Second-order approx. OK

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Figure 9.39

Evaluating the compensator pole for Example 9.6

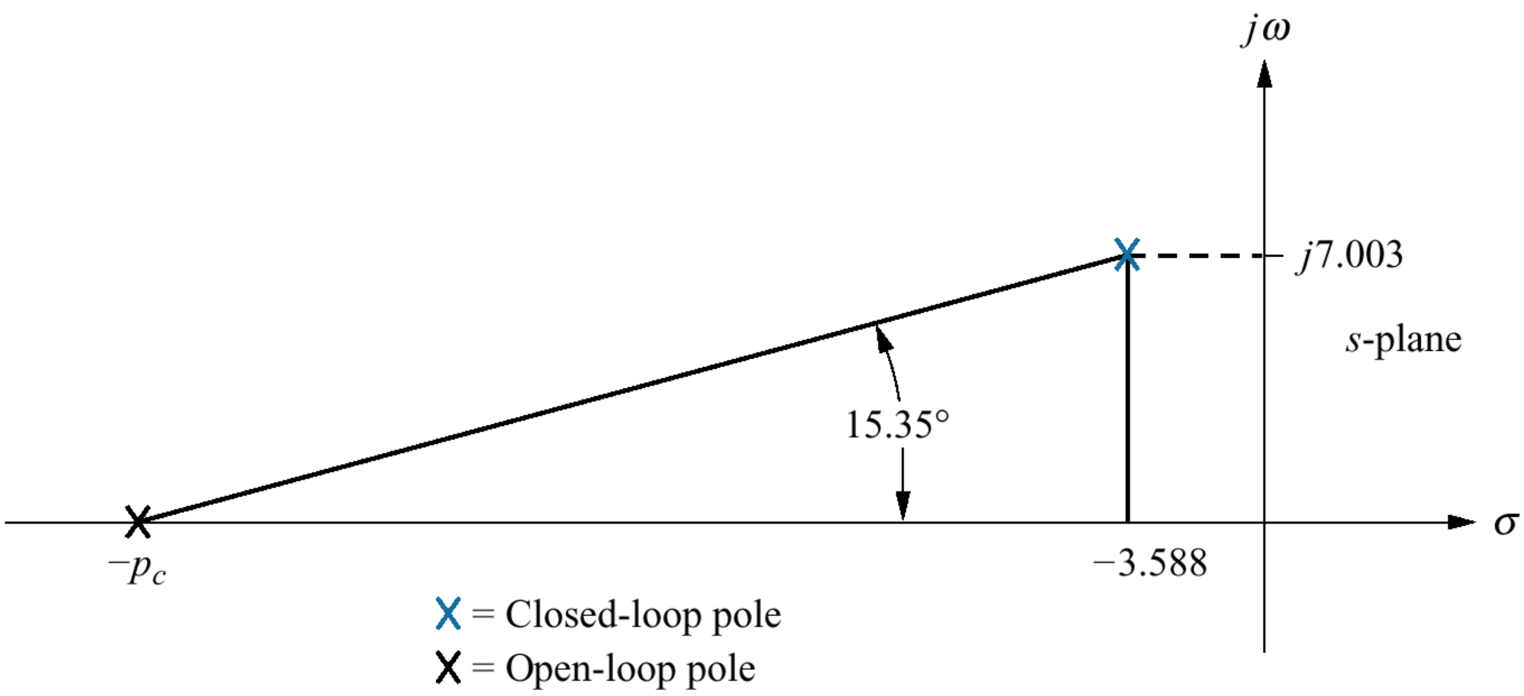

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Figure 9.40
Root locus for lead-compensated system of Example 9.6

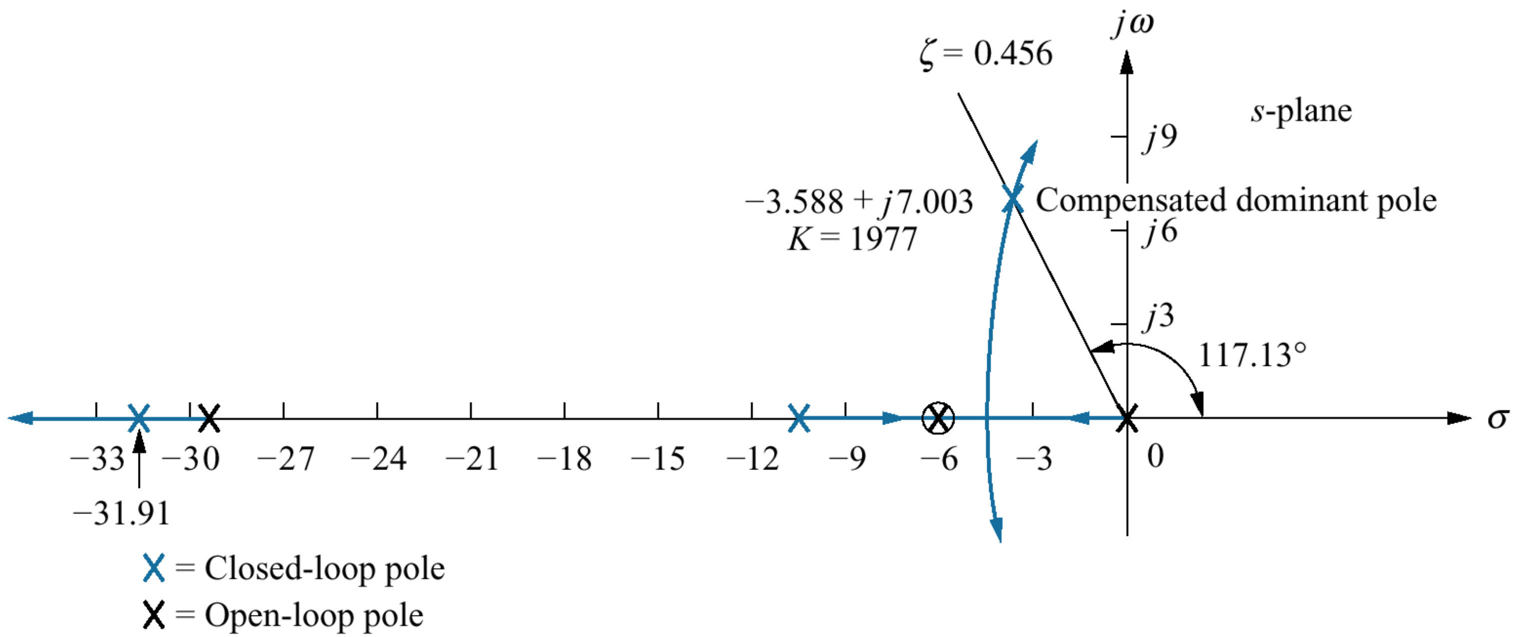

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Figure 9.41
Root locus for lag-lead-compensated system of Example 9.6

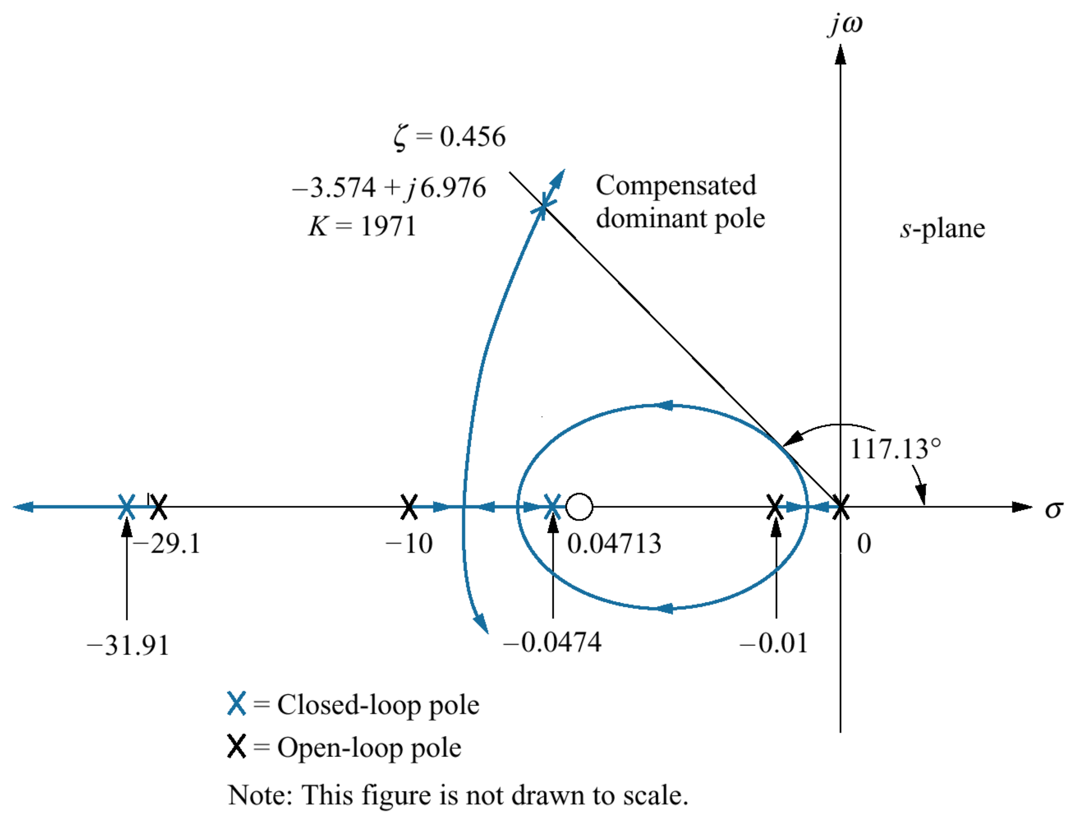

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Figure 9.42 Improvement in step response for lag-lead-compensated system of Example 9.6

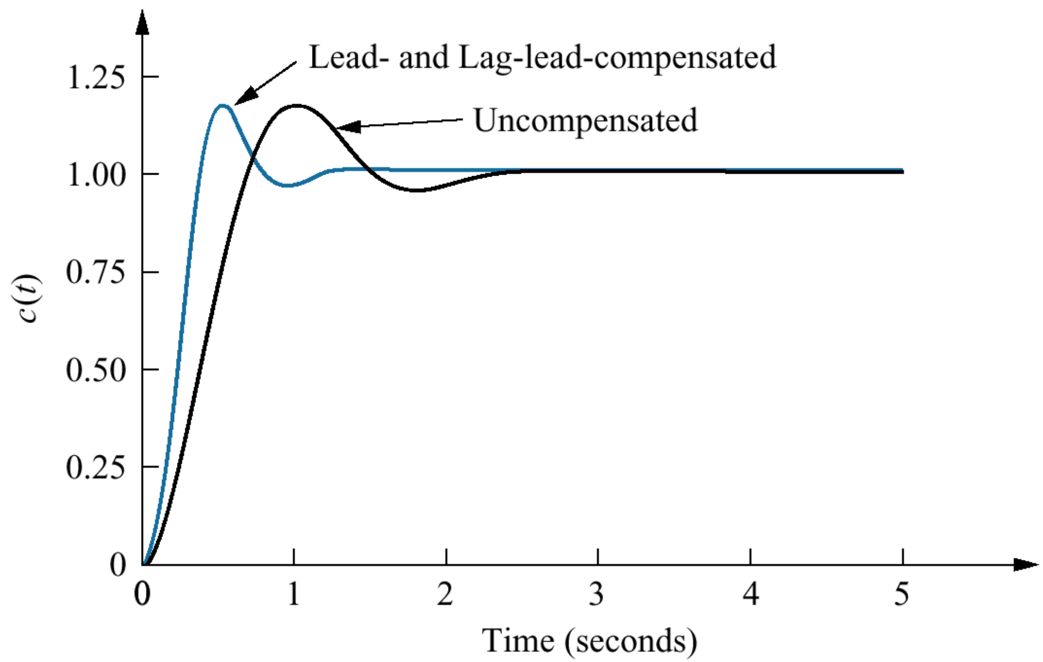

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Figure 9.43 Improvement in ramp response error for the system of Example 9.6:
a. lead-compensated;
b. lag-lead-compensated

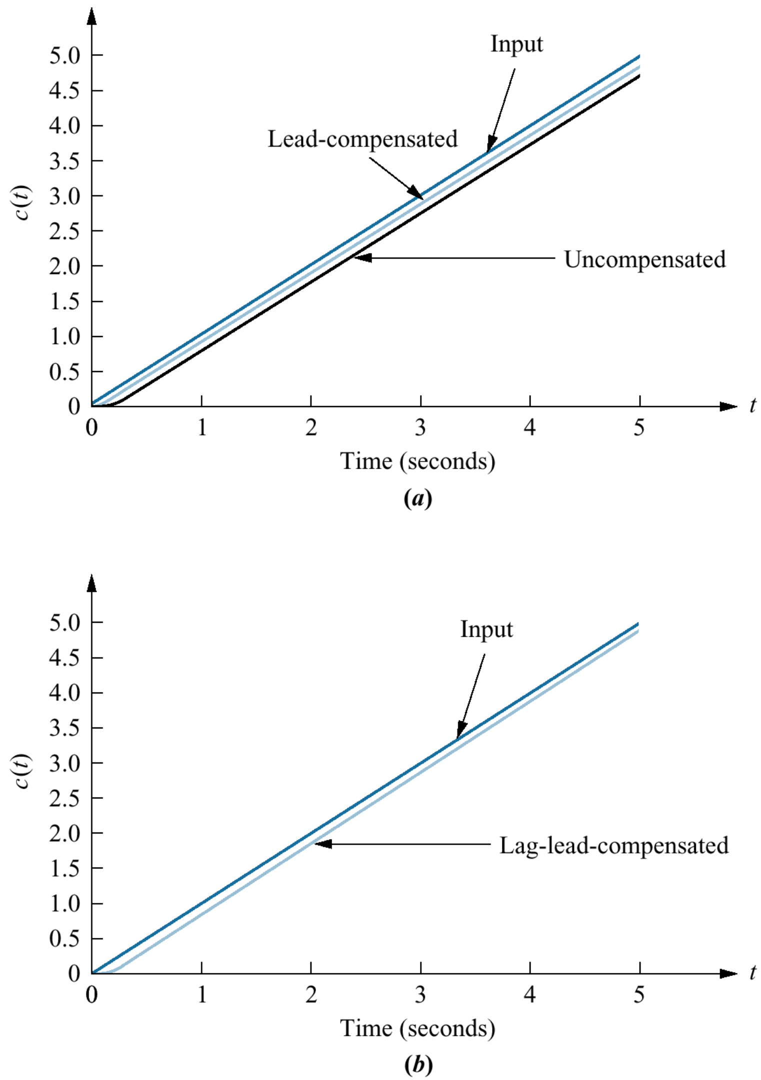

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Figure 9.44

a. Root locus
before cascading notch filter;
b. typical
closed-loop
step response
before cascading notch filter;

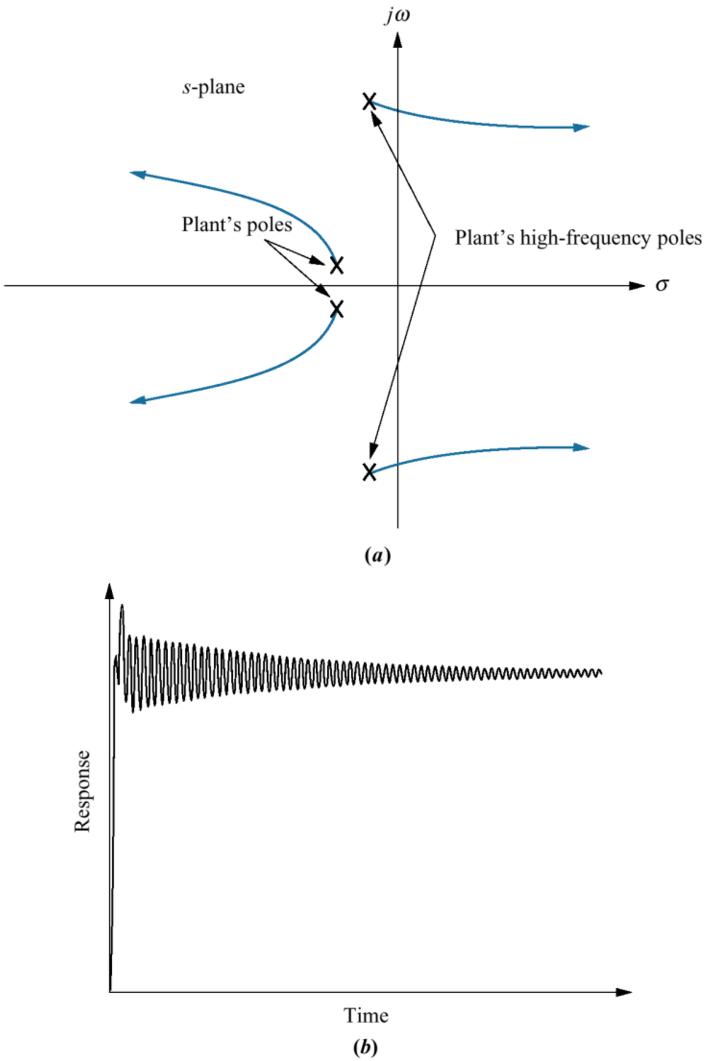

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Figure 9.44 (*continued)*

c. pole-zero plot of a notch filter;

d. root locus after cascading notch filter;

e. closed-loop step response after cascading notch filter.

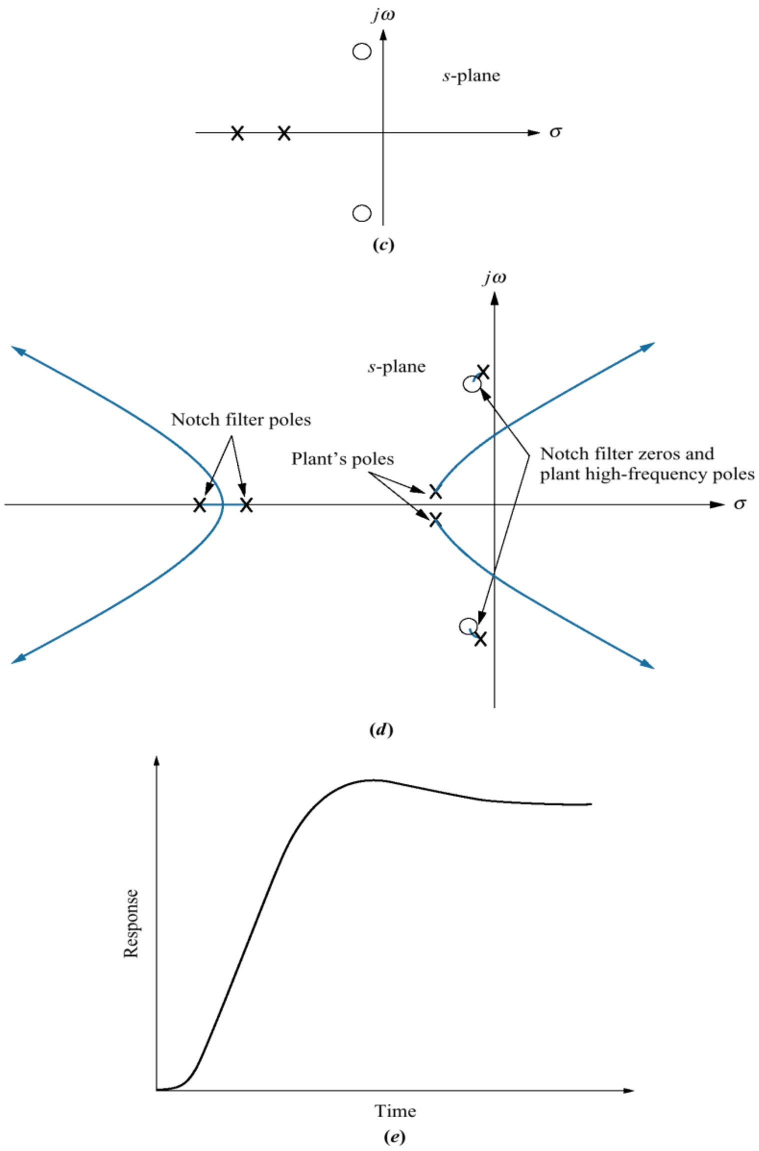

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Table 9.7 Types of cascade compensators

Function	Compensator	Transfer function	Characteristics
Improve steady-state error	PI	$K\frac{s+z_c}{s}$	1. Increases system type. 2. Error becomes zero. 3. Zero at $-z_c$ is small and negative. 4. Active circuits are required to implement.
Improve steady-state error	Lag	$K\frac{s+z_c}{s+p_c}$	1. Error is improved but not driven to zero. 2. Pole at $-p_c$ is small and negative. 3. Zero at $-z_c$ is close to, and to the left of, the pole at $-p_c$. 4. Active circuits are not required to implement.
Improve transient response	PD	$K(s+z_c)$	1. Zero at $-z_c$ is selected to put design point on root locus. 2. Active circuits are required to implement. 3. Can cause noise and saturation; implement with rate feedback or with a pole (lead).
Improve transient response	Lead	$K\frac{s+z_c}{s+p_c}$	1. Zero at $-z_c$ and pole at $-p_c$ are selected to put design point on root locus. 2. Pole at $-p_c$ is more negative than zero at $-z_c$. 3. Active circuits are not required to implement.

Table 9.7

Types of cascade compensators (continued on next slide)

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Table 9.7 Types of cascade compensators

Function	Compensator	Transfer function	Characteristics
Improve steady-state error and transient response	PID	$K\frac{(s+z_{lag})(s+z_{lead})}{s}$	1. Lag zero at $-z_{lag}$ and pole at origin improve steady-state error. 2. Lead zero at $-z_{lead}$ improves transient response. 3. Lag zero at $-z_{lag}$ is close to, and to the left of, the origin. 4. Lead zero at $-z_{lead}$ is selected to put design point on root locus. 5. Active circuits required to implement. 6. Can cause noise and saturation; implement with rate feedback or with an additional pole.
Improve steady-state error and transient response	Lag-lead	$K\frac{(s+z_{lag})(s+z_{lead})}{(s+p_{lag})(s+p_{lead})}$	1. Lag pole at $-p_{lag}$ and lag zero at $-z_{lag}$ are used to improve steady-state error. 2. Lead pole at $-p_{lead}$ and lead zero at $-z_{lead}$ are used to improve transient response. 3. Lag pole at $-p_{lag}$ is small and negative. 4. Lag zero at $-z_{lag}$ is close to, and to the left of, lag pole at $-p_{lag}$. 5. Lead zero at $-z_{lead}$ and lead pole at $-p_{lead}$ are selected to put design point on root locus. 6. Lead pole at $-p_{lead}$ is more negative than lead zero at $-z_{lead}$. 7. Active circuits are not required to implement.

Table 9.7

Types of cascade compensators (continued)

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Figure 9.45
Generic control system with feedback compensation

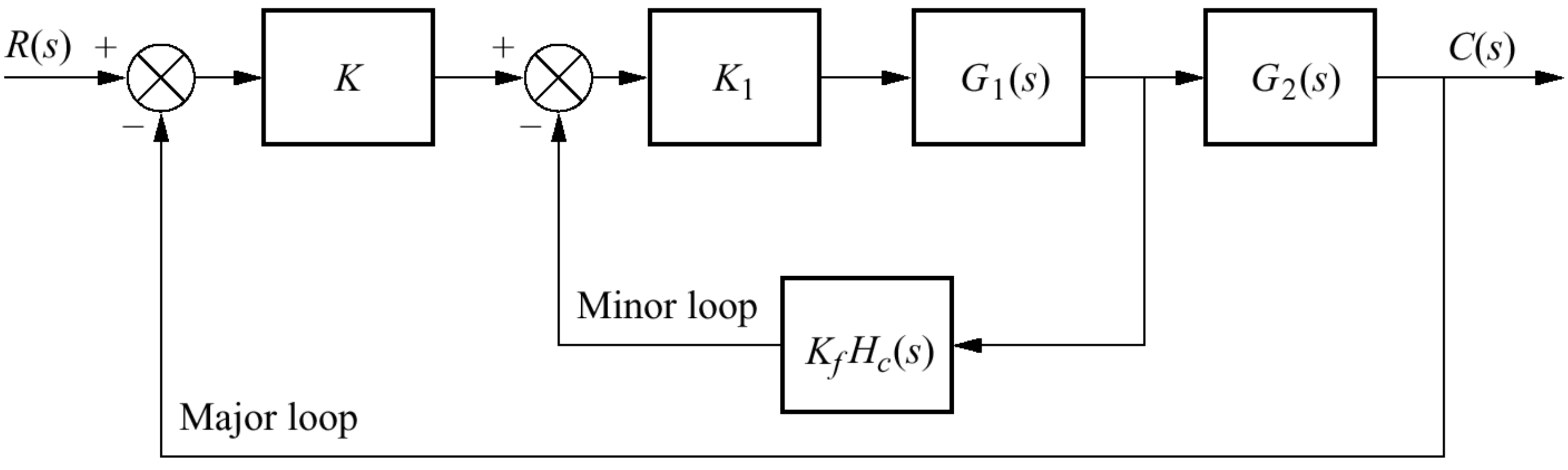

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Figure 9.46

A position control system that uses a tachometer as a differentiator in the feedback path. Can you see the similarity between this system and the schematic on
the front end papers?

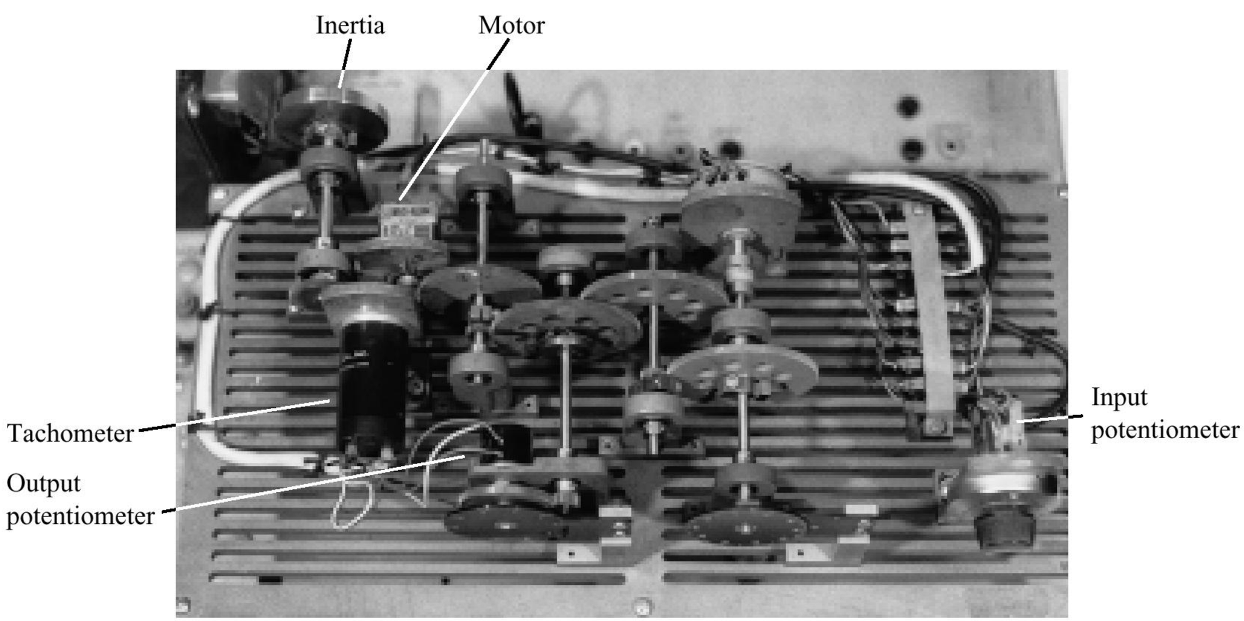

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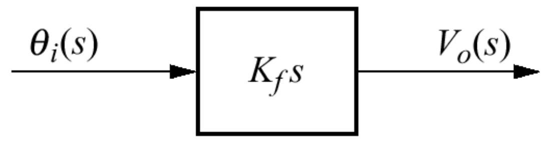
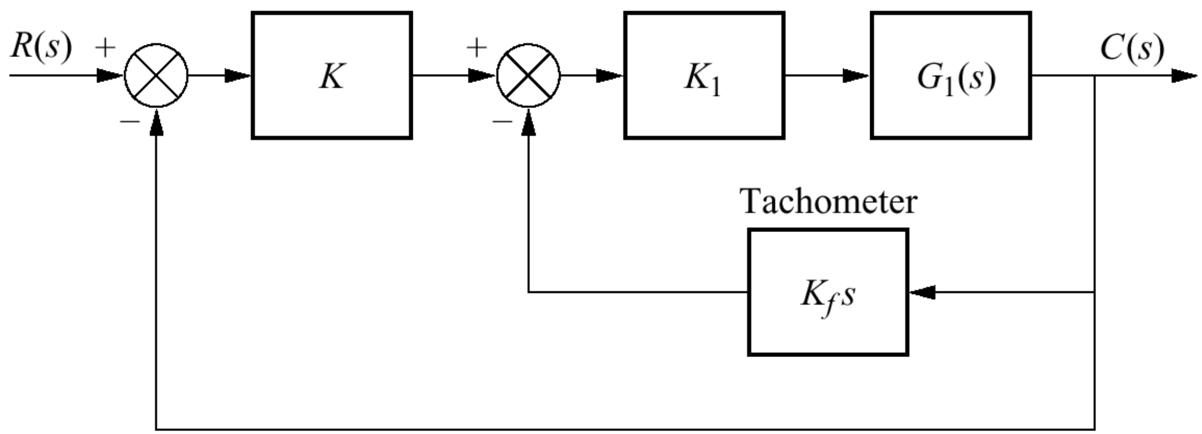
Figure 9.47

a. Transfer function of a tachometer;
b. tachometer feedback compensation



(*a*)



(*b*)

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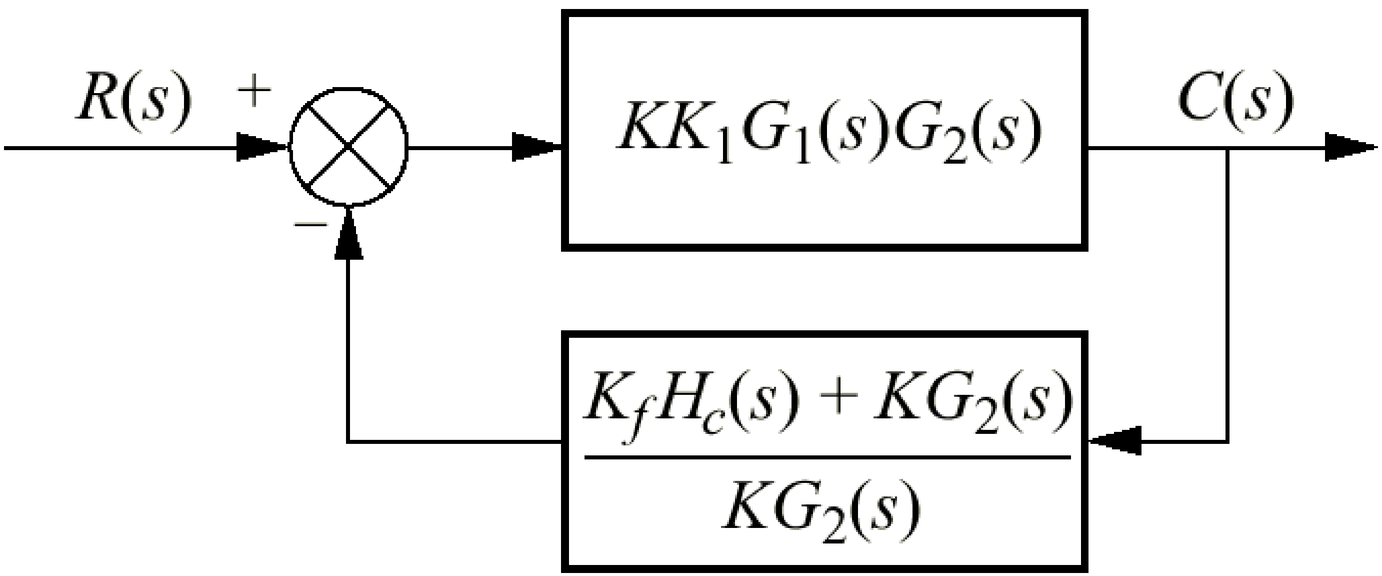
Figure 9.48
Equivalent block diagram of Figure 9.45



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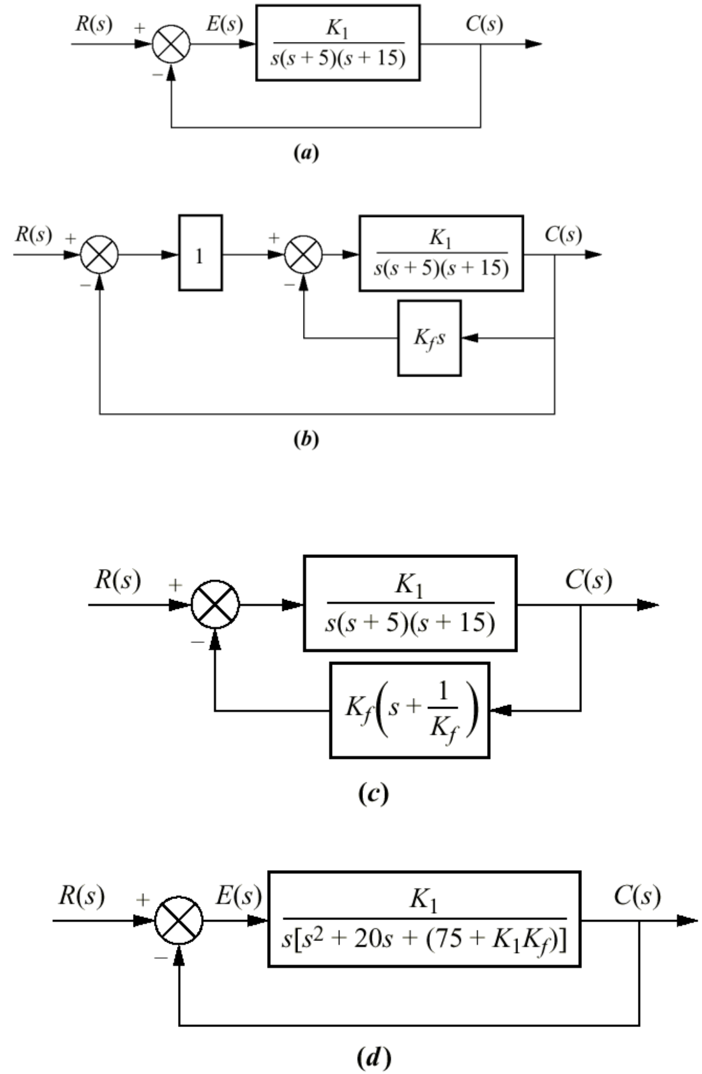

Figure 9.49

a. System for Example 9.7;
b. system with rate feedback compensation;
c. equivalent compensated system;
d. equivalent compensated system, showing unity feedback

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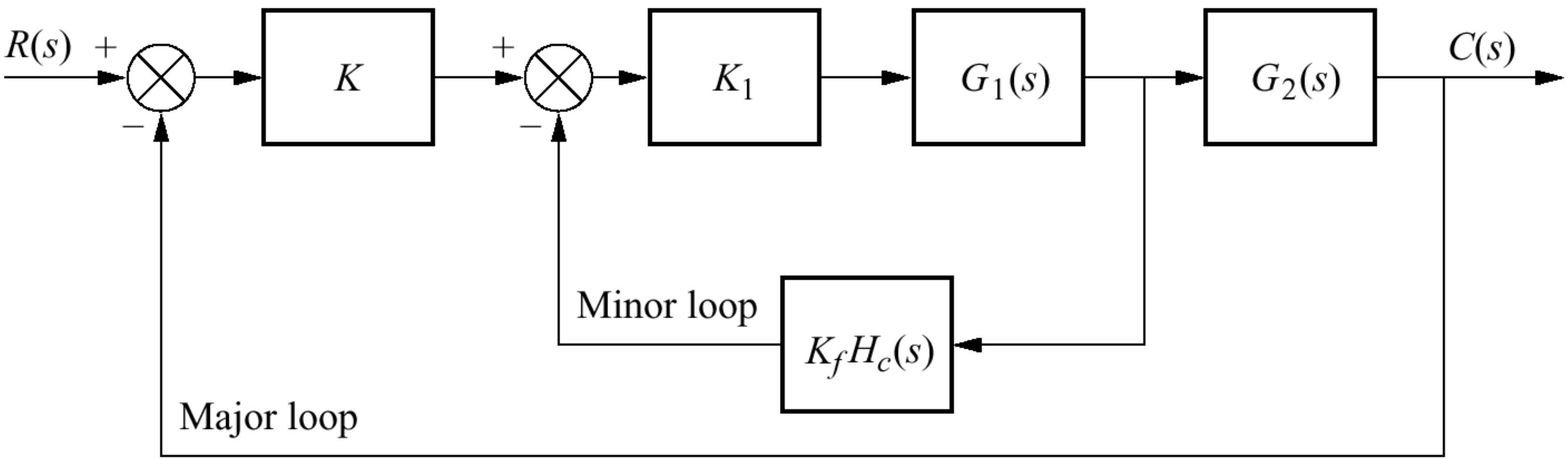
Figure 9.45
Generic control system with feedback compensation



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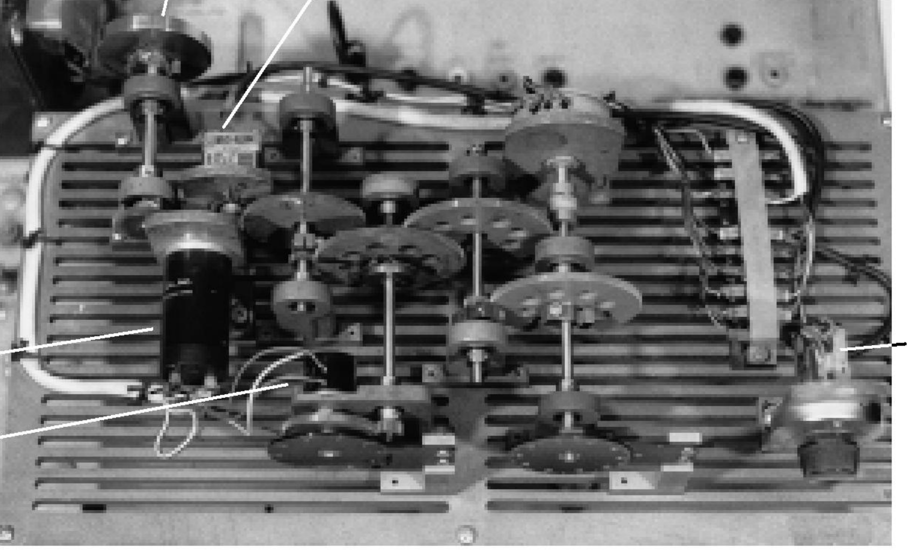

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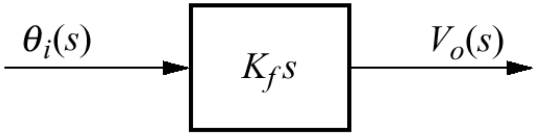
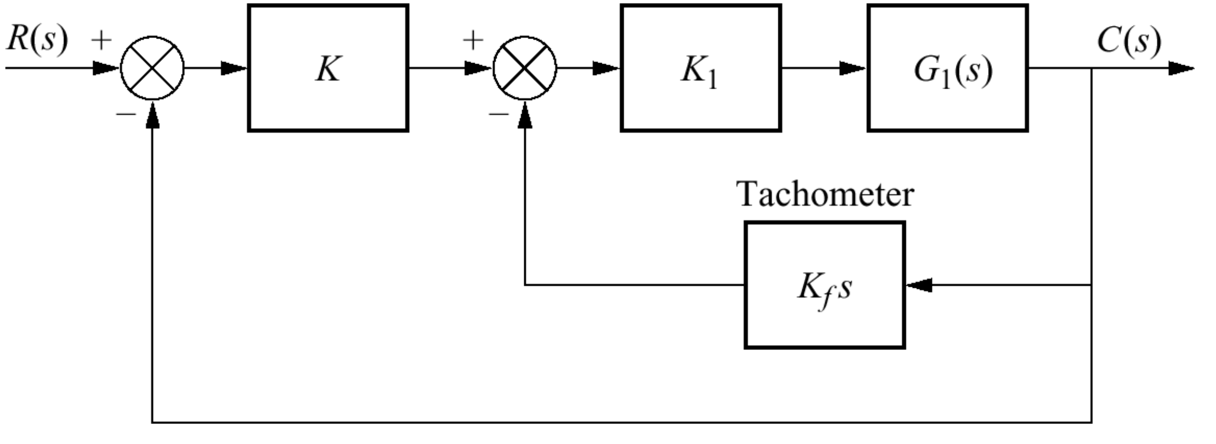
b. tachometer feedback compensation



(*a*)



(*b*)

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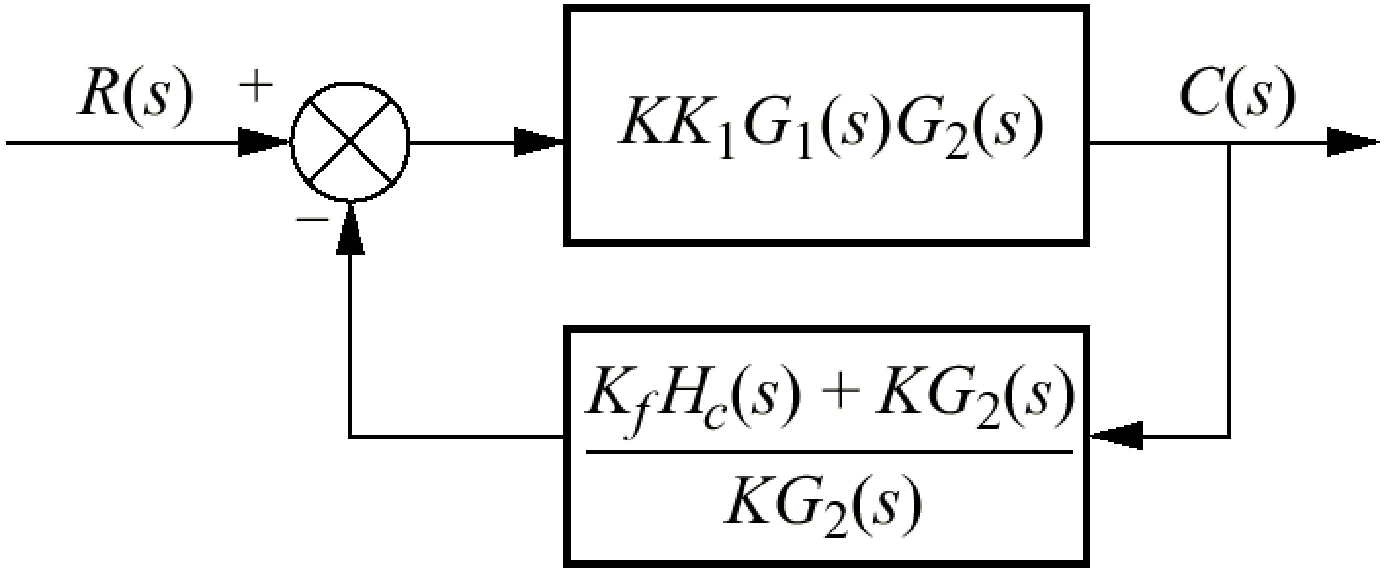
Figure 9.48
Equivalent block diagram of Figure 9.45



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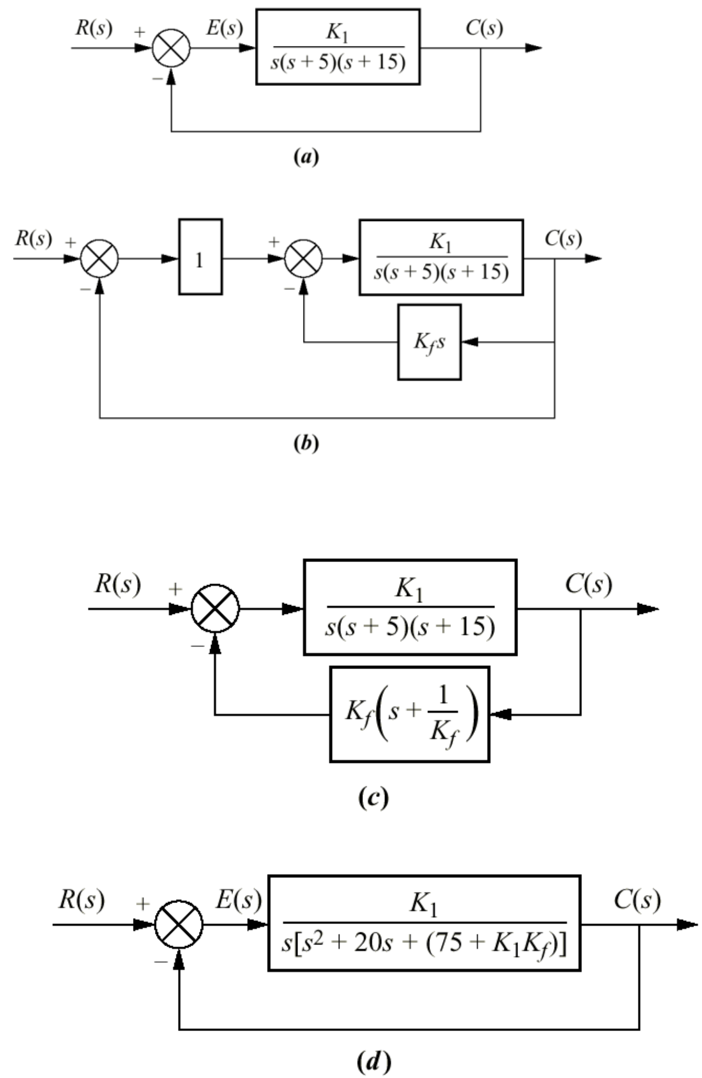

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d. equivalent compensated system, showing unity feedback

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