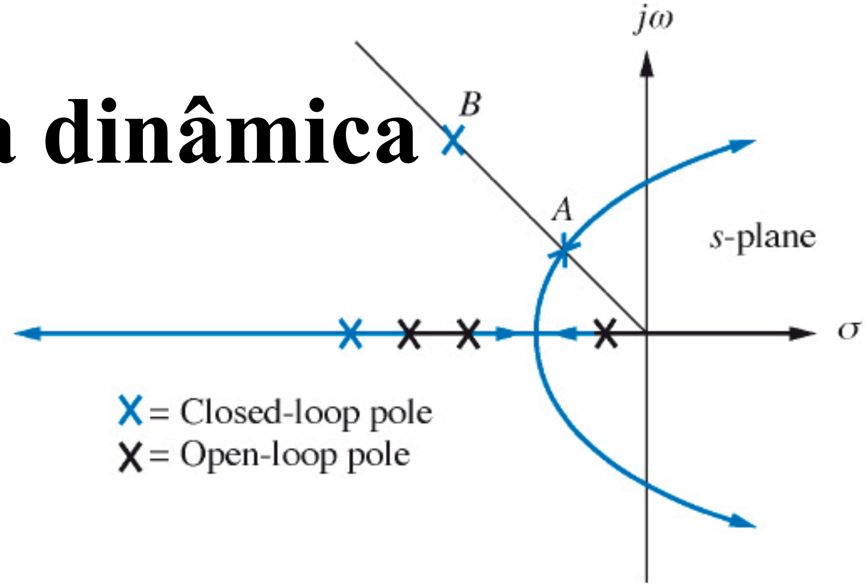
Projeto no LGR (Nise - Cap. 9)

Controladores Dinâmicos

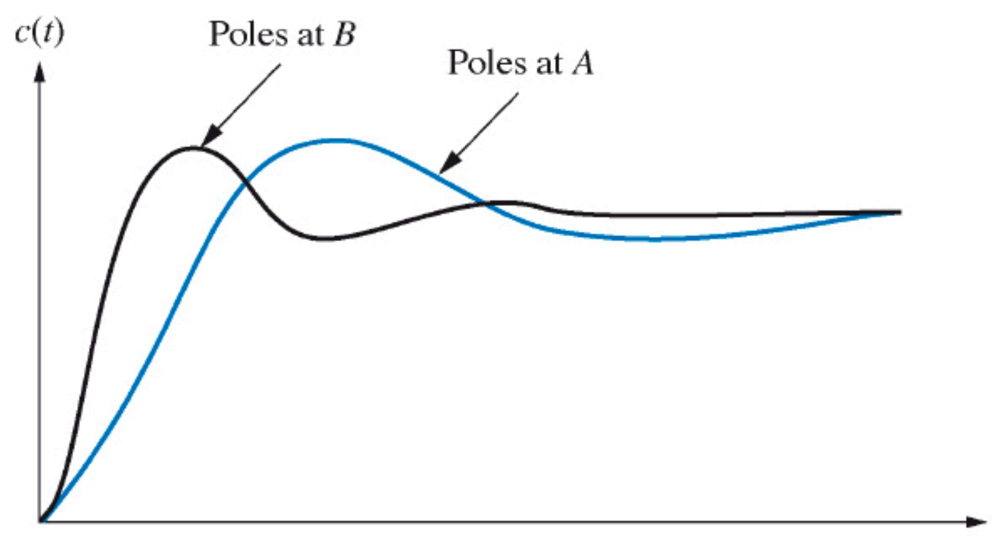
-I
-PI
-PD
-Atraso
-Avanço
-PID
-Avanço-Atraso

Melhoria da resposta dinâmica



(a)

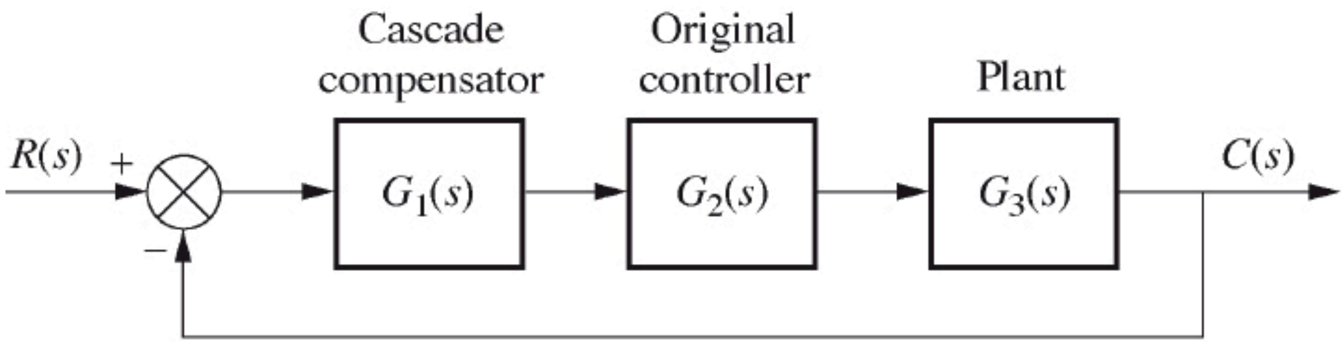
Ajuste do ganho no LGR
→ A



(b)

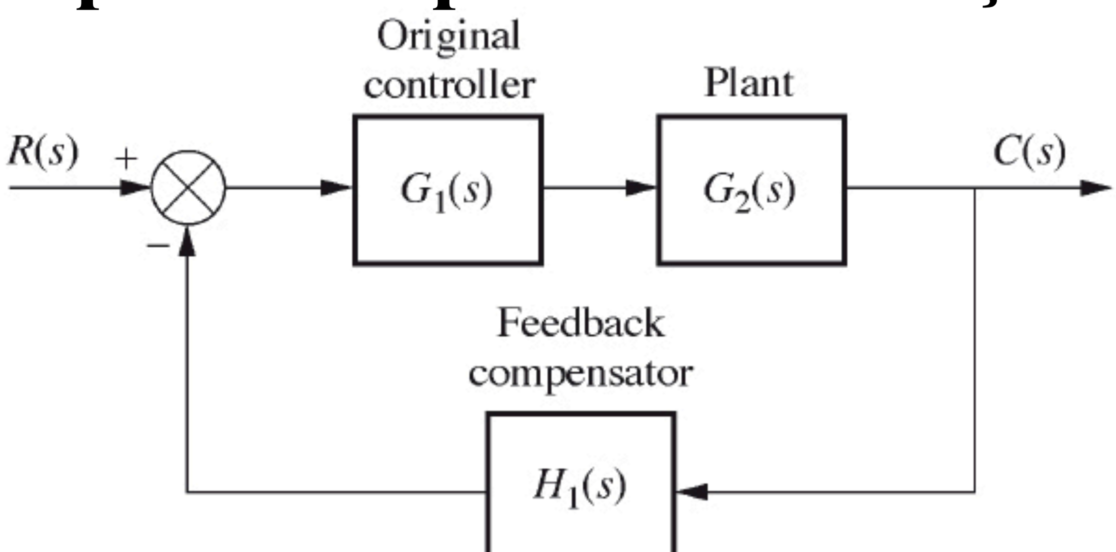
Compensador Dinâmico
> Posicionamento dos pólos dominantes
→ B

Compensador em cascata



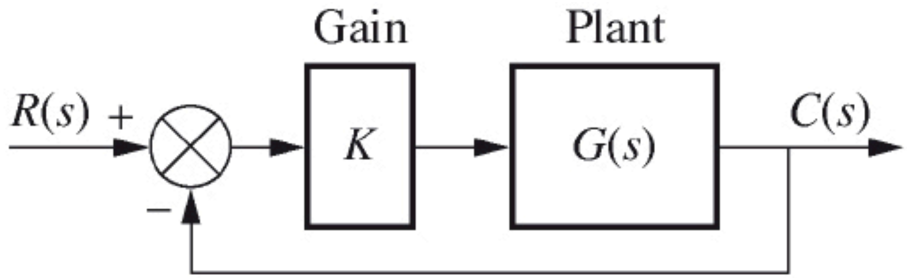
(*a*)

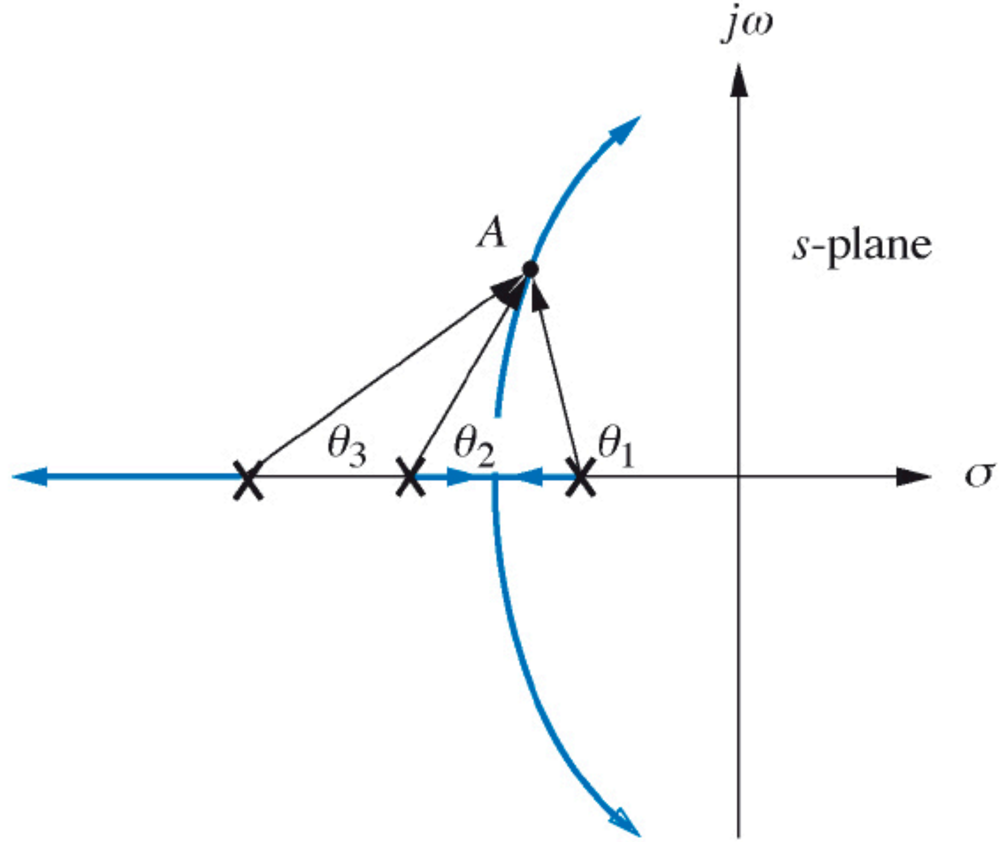
Compensador por realimentação



(*b*)

Compensador Proporcional



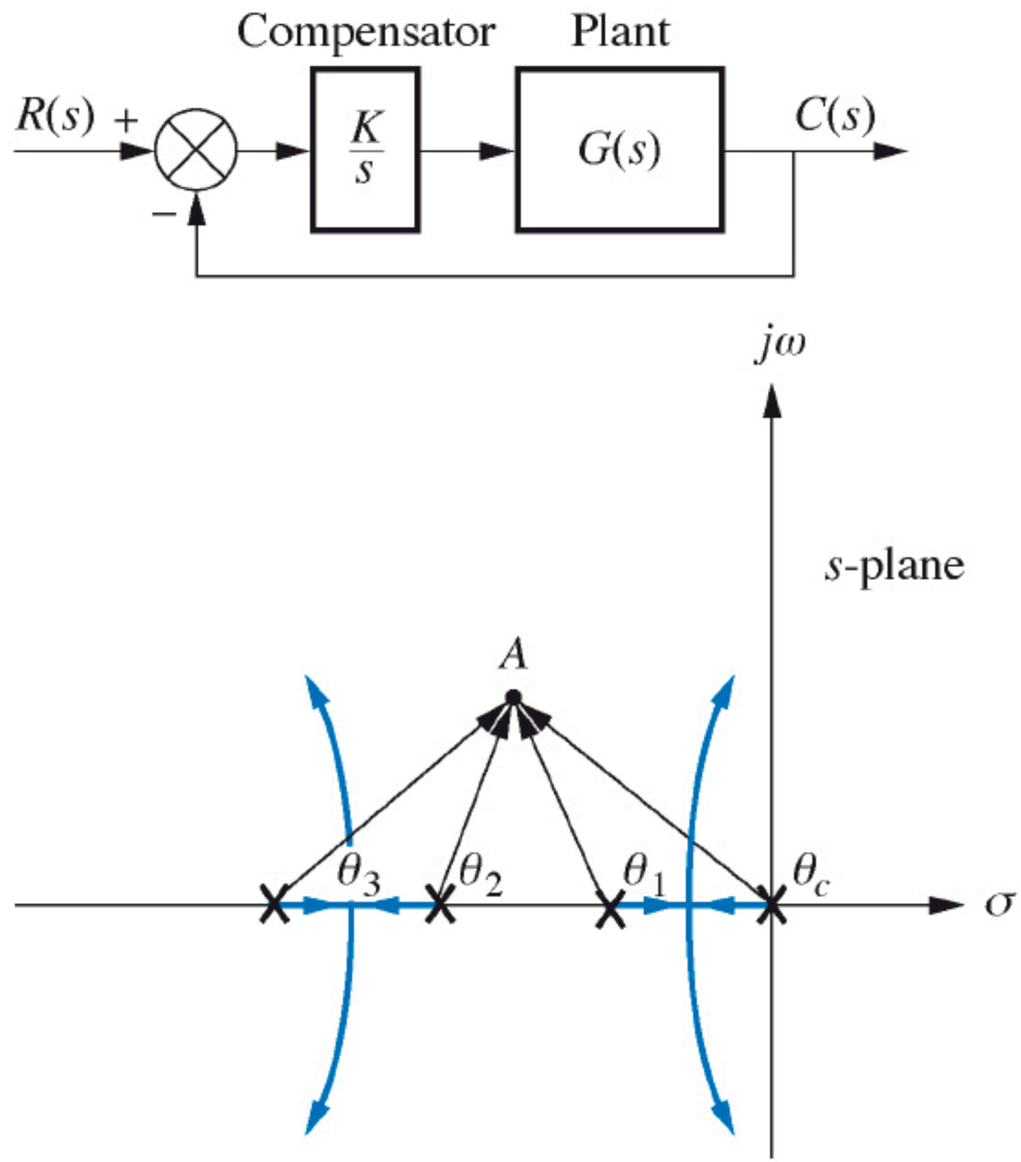


$-\theta_1 - \theta_2 - \theta_3 = (2k + 1)180$Υ

(*a*)

Posições possíveis dos pólos estão no LGR

Compensador Integral

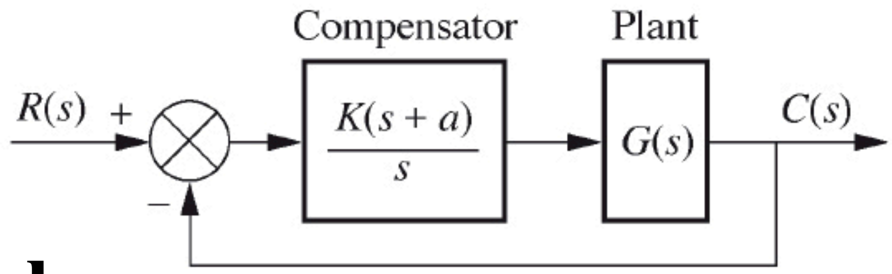


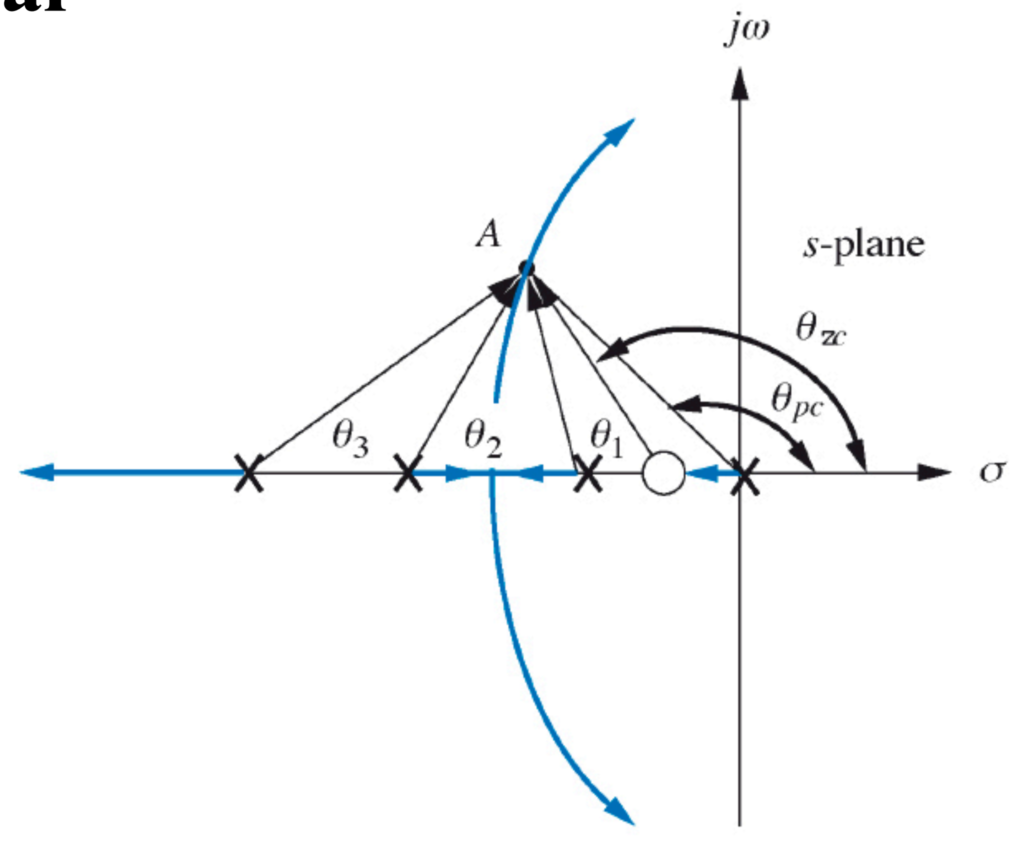
$$-\theta_1 - \theta_2 - \theta_3 - \theta_c \neq (2k+1)180Υ$$

(*b*)

- Tipo 0 → 1
- Sistema mais lento (ramos se deslocam p/ direita)

Compensador Proporcional-Integral



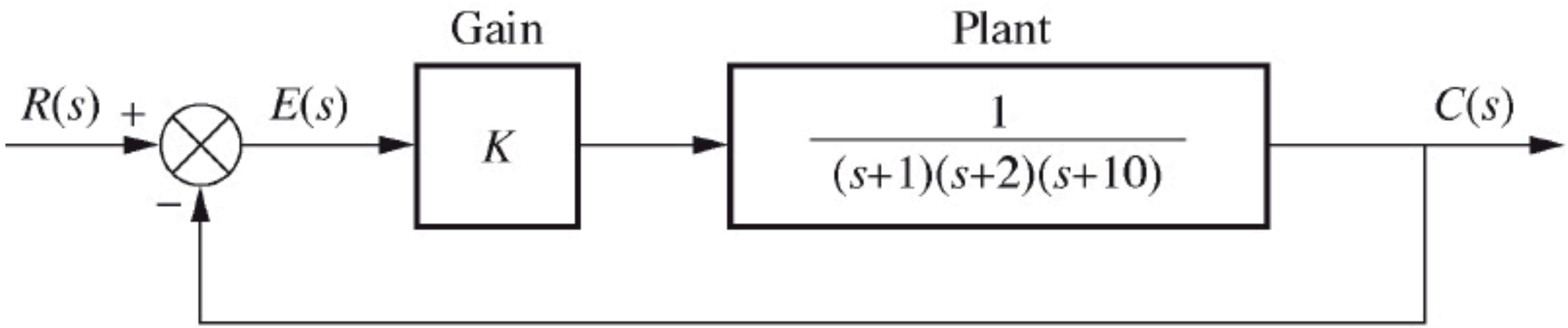


$$-\theta_1 - \theta_2 - \theta_3 - \theta_{pc} + \theta_{zc} \cong (2k+1)180Υ$$

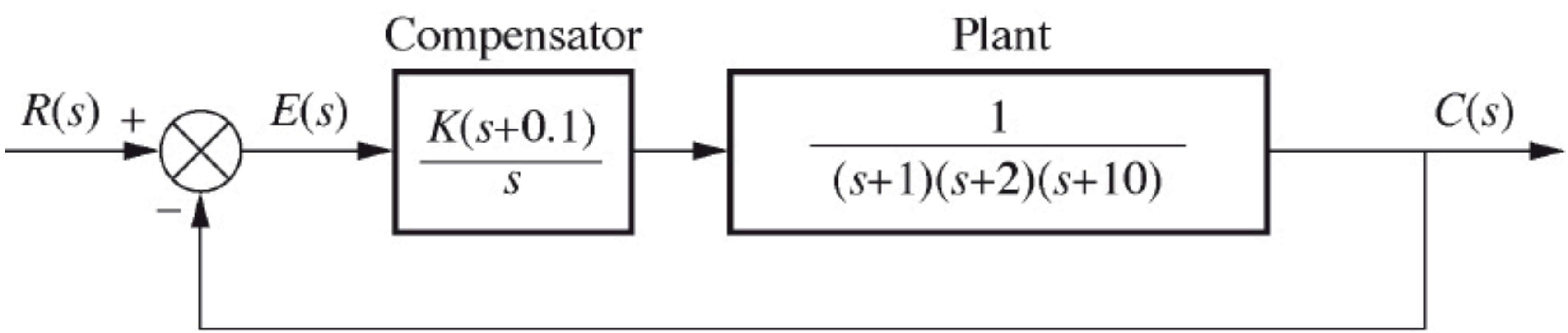
(c)

- Tipo 0 → 1
-Zero permite dinâmica mais rápida

Exemplo: P x PI



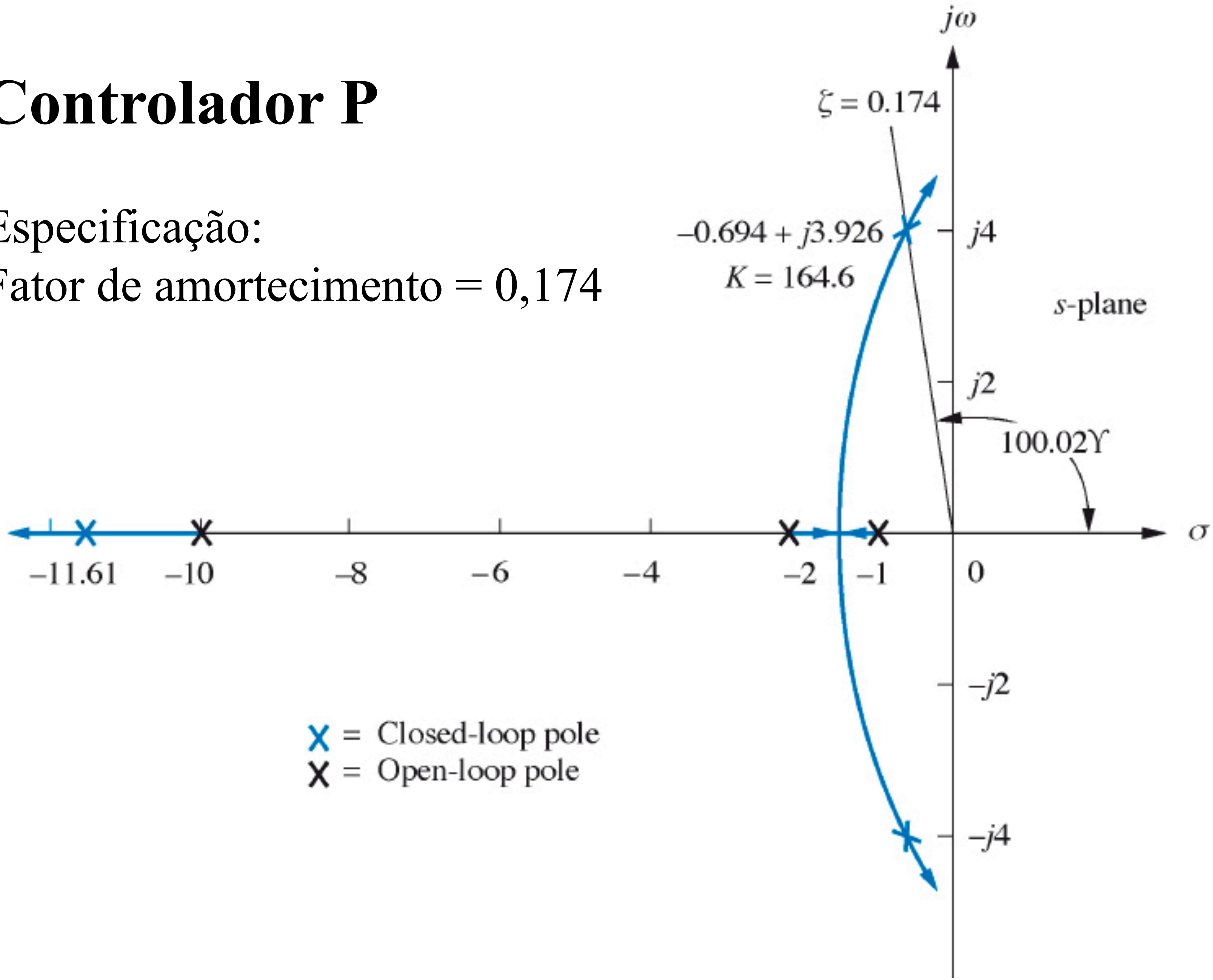
(a)



(b)

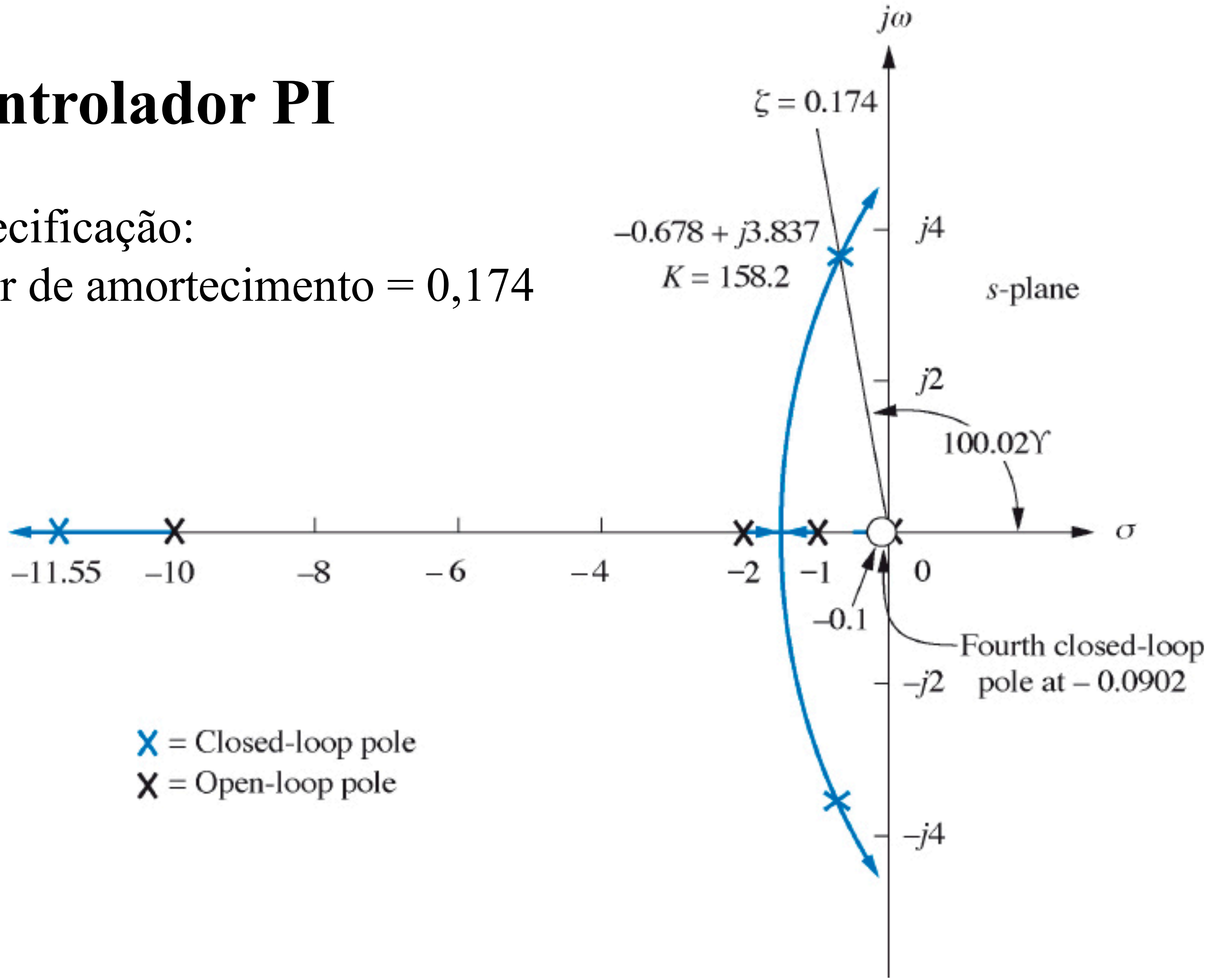
Controlador P

Especificação:
Fator de amortecimento = 0,174



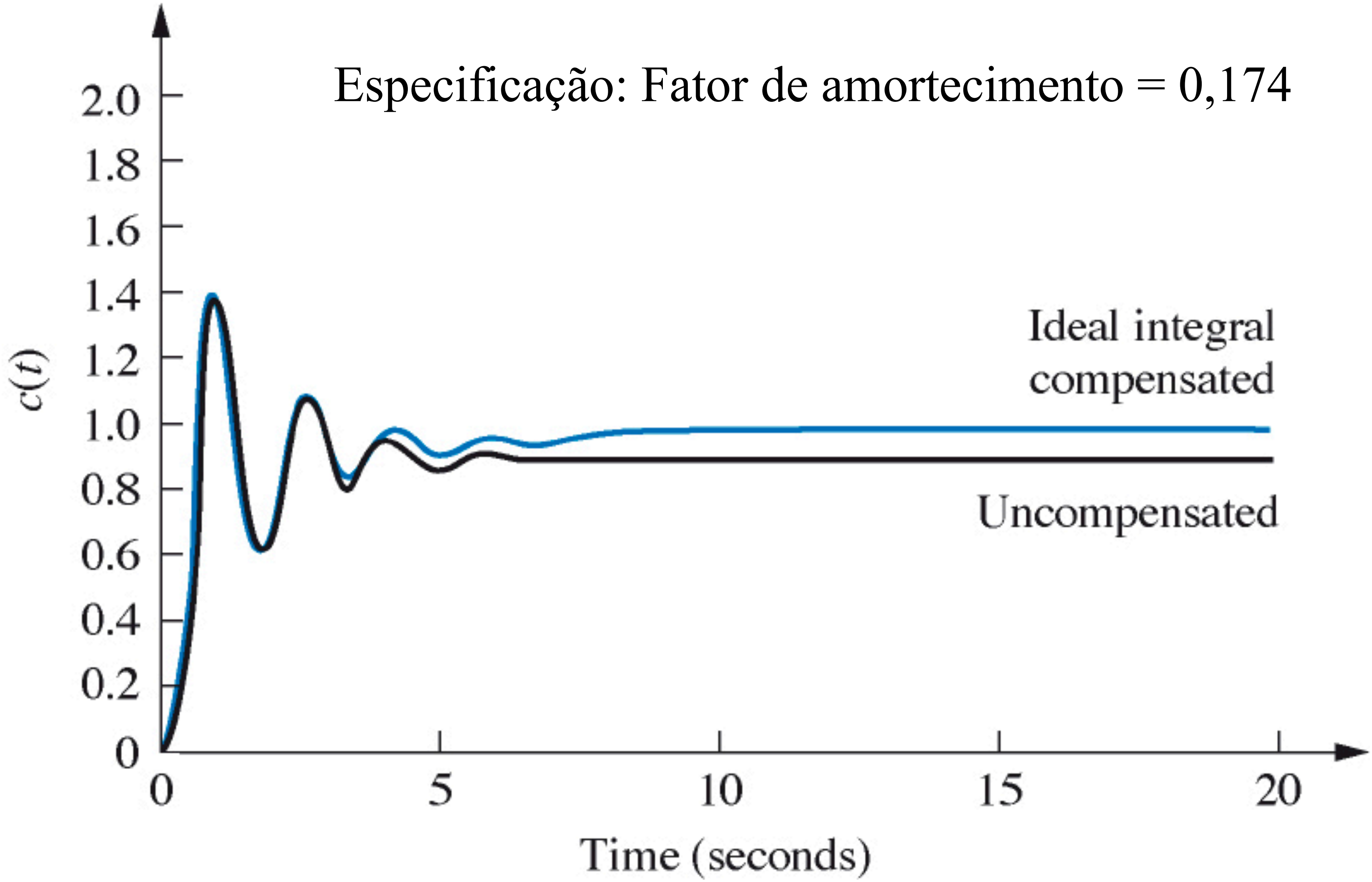
Controlador PI

Especificação:
Fator de amortecimento = 0,174



Controlador P x Compensador PI

Especificação: Fator de amortecimento = 0,174

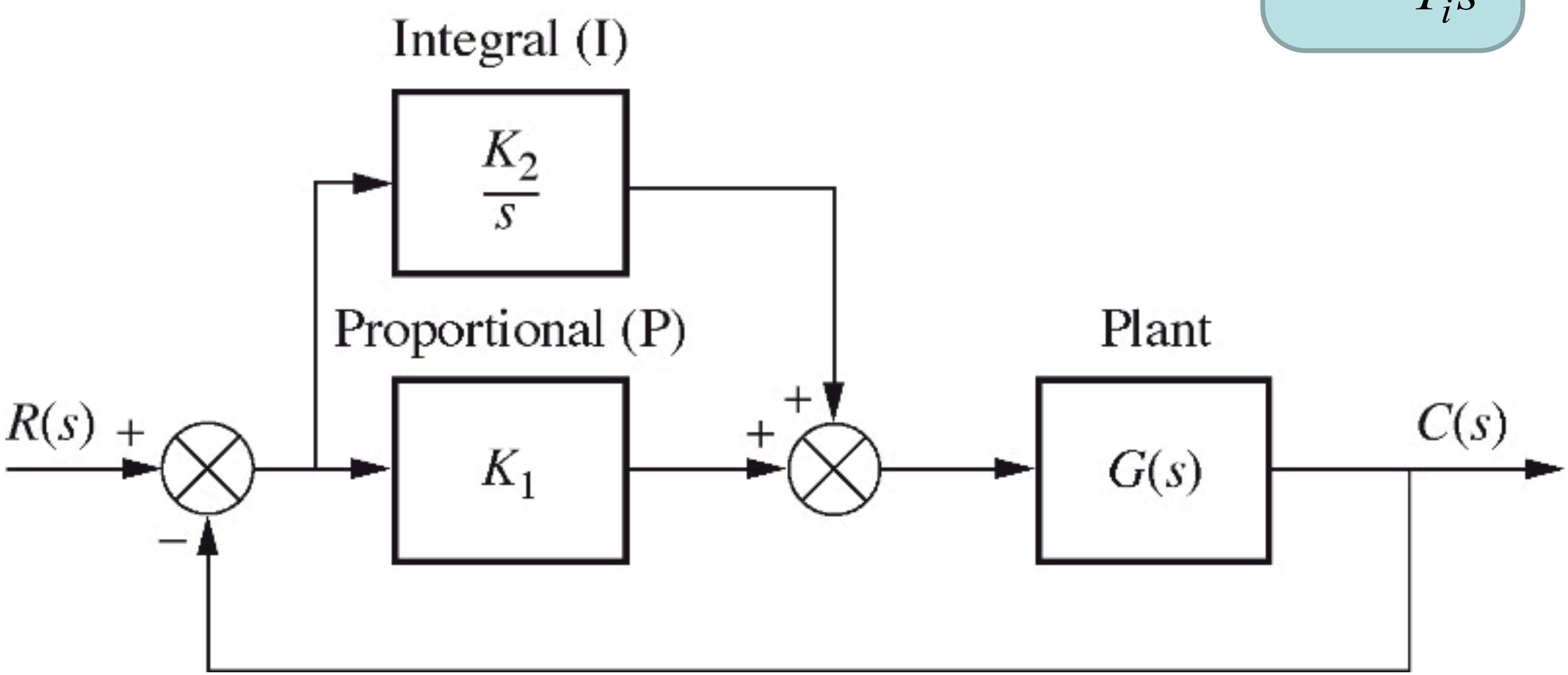


Controlador PI

Canal Integral + Canal Proporcional $K_p + \frac{K_i}{s}$

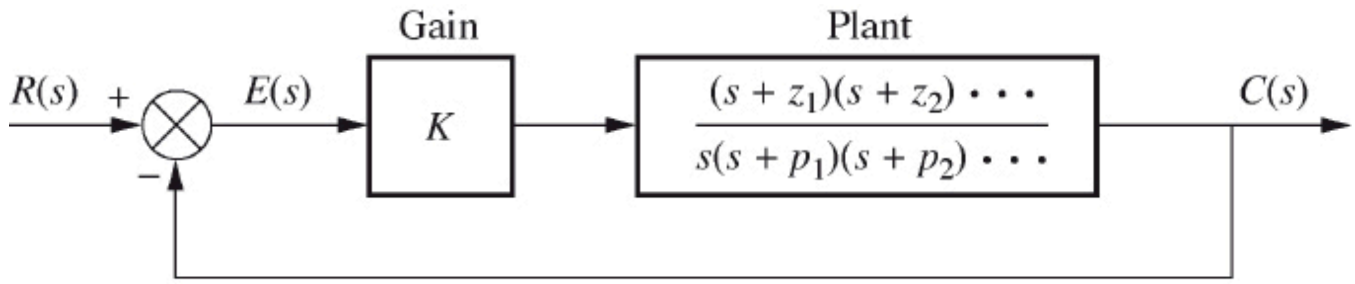
Ganho + Zero $K\frac{(s+z)}{s}$

Forma ISA (Indústria) $K(1+\frac{1}{T_i s})$

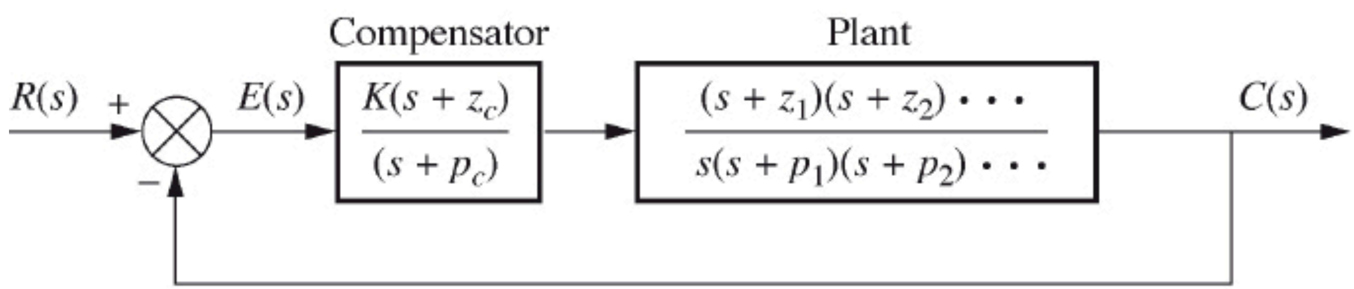


Controlador em Atraso

→ ganho em baixas frequências → redução do erro.

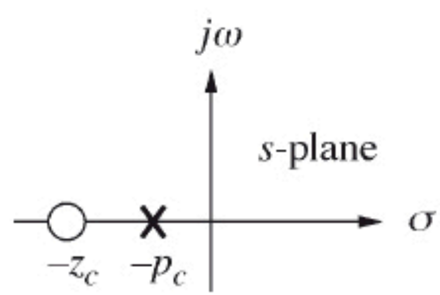


(*a*)



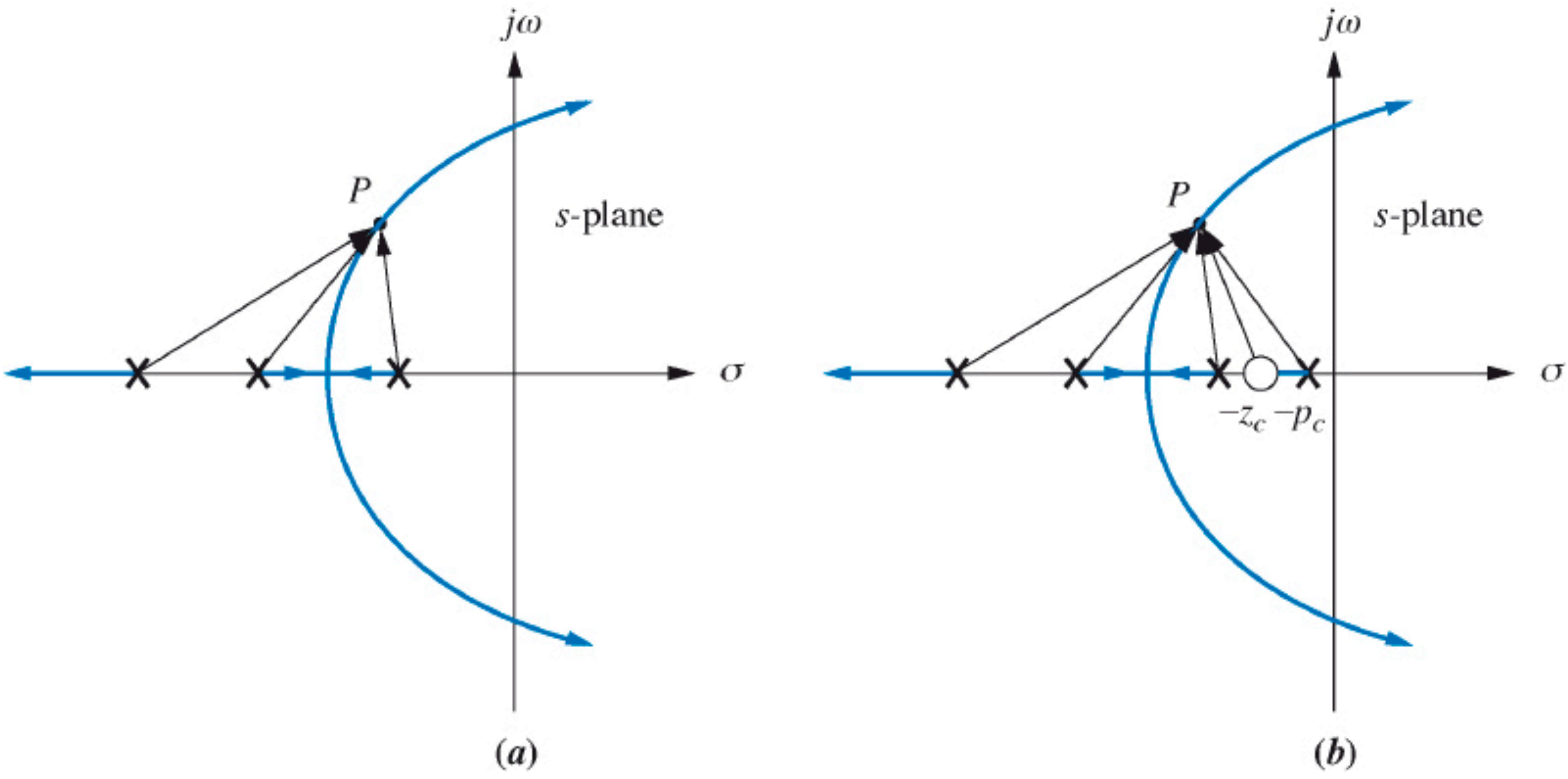
(*b*)

$$G_c(s) = \frac{(s + z_c)}{(s + p_c)}$$



Controlador em Atraso

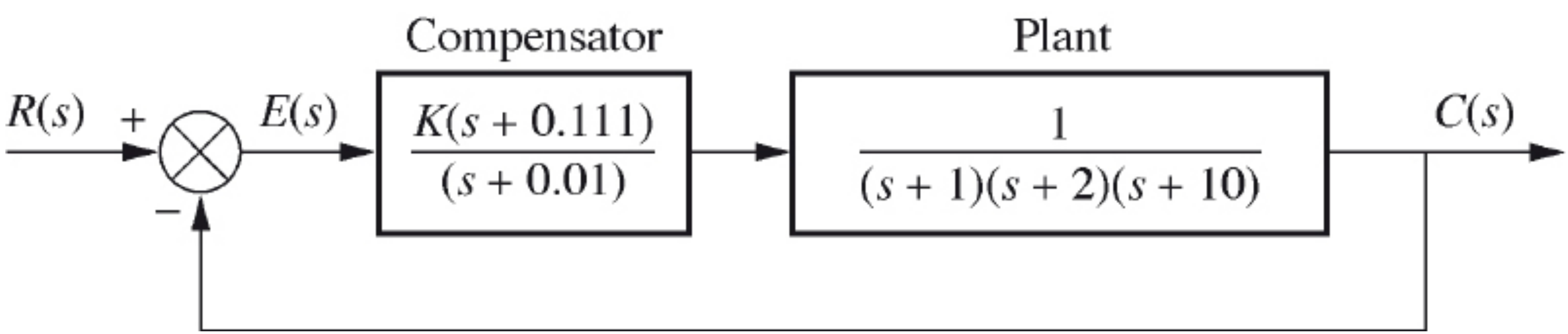
→ ganho em baixas frequências → redução do erro.

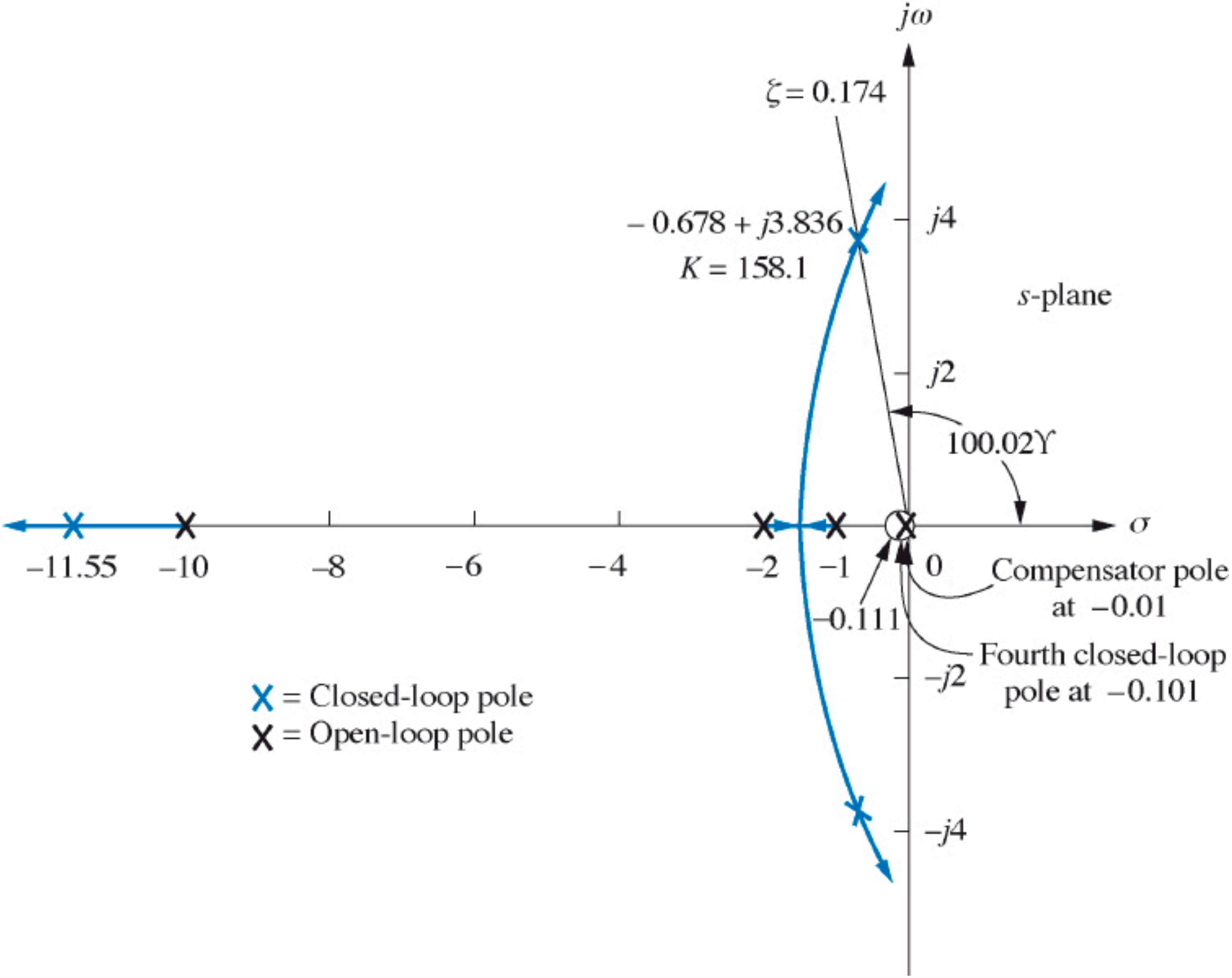


Exemplo: Controlador em Atraso

→ ganho em baixas frequências = 0,111/0,01 ($s \to 0$)

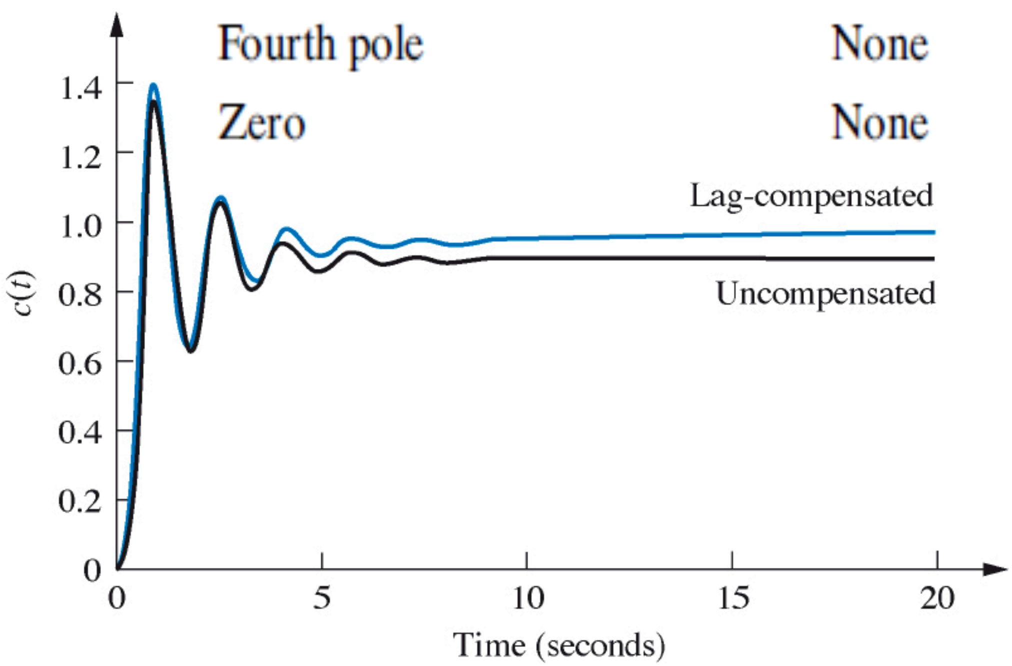
$$K_{v_N} = K_{v_O} \frac{z_c}{p_c} > K_{v_O}$$





jω
ζ = 0.174
– 0.678 + j3.836
K = 158.1
j4
j2
s-plane
100.02Υ
σ
–11.55
–10
–8
–6
–4
–2
–1
0
–0.111
Compensator pole
at –0.01
Fourth closed-loop
pole at –0.101
–j2
–j4
= Closed-loop pole
= Open-loop pole

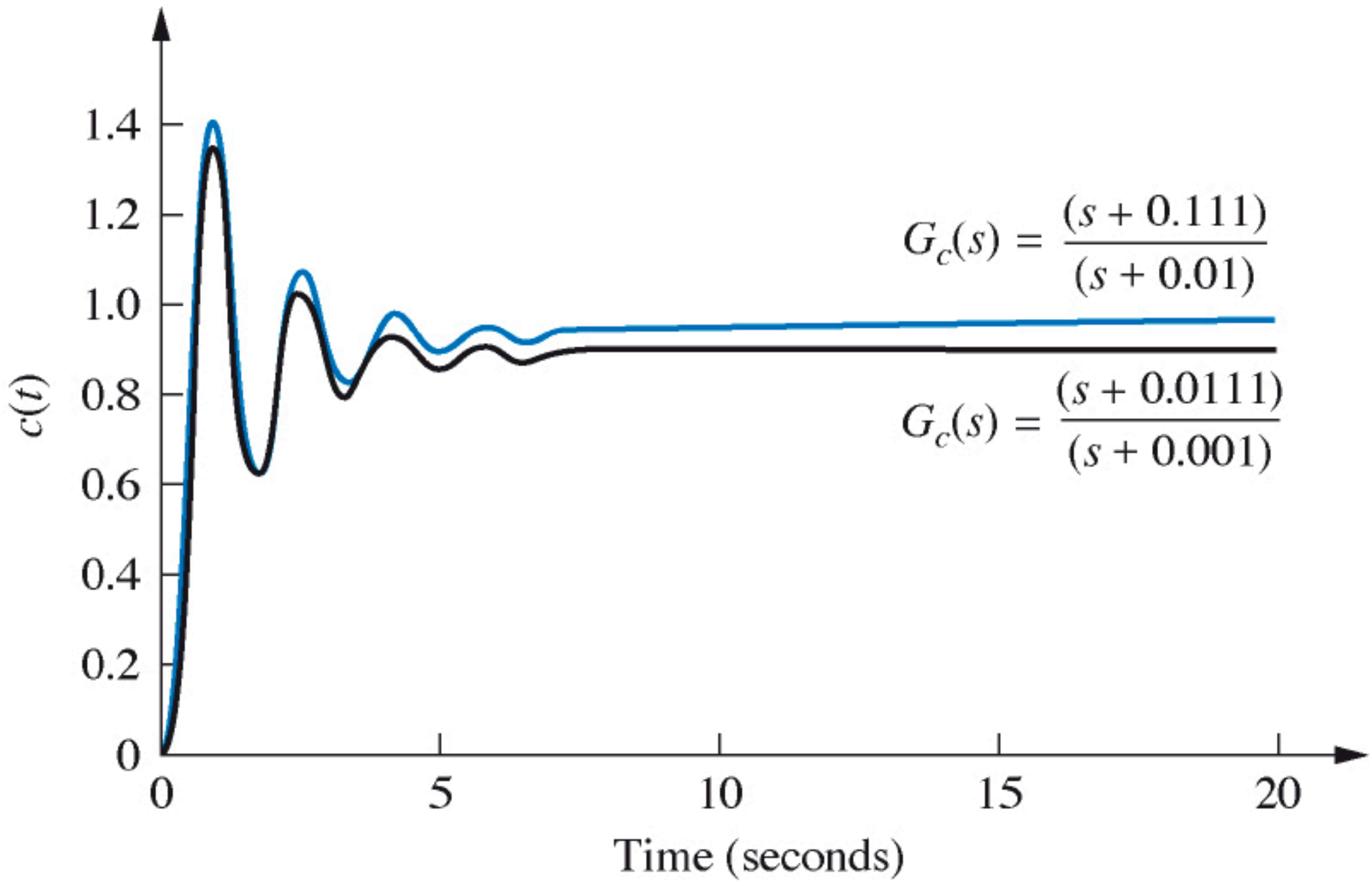
Parameter	Uncompensated	Lag-compensated
Plant and compensator	$\frac{K}{(s+1)(s+2)(s+10)}$	$\frac{K(s+0.111)}{(s+1)(s+2)(s+10)(s+0.01)}$
K	164.6	158.1
K_p	8.23	87.75
$e(\infty)$	0.108	0.011
Dominant second-order poles	$-0.694 \pm j3.926$	$-0.678 \pm j3.836$
Third pole	-11.61	-11.55
Fourth pole	None	-0.101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



Comparação de Compensadores em Atraso

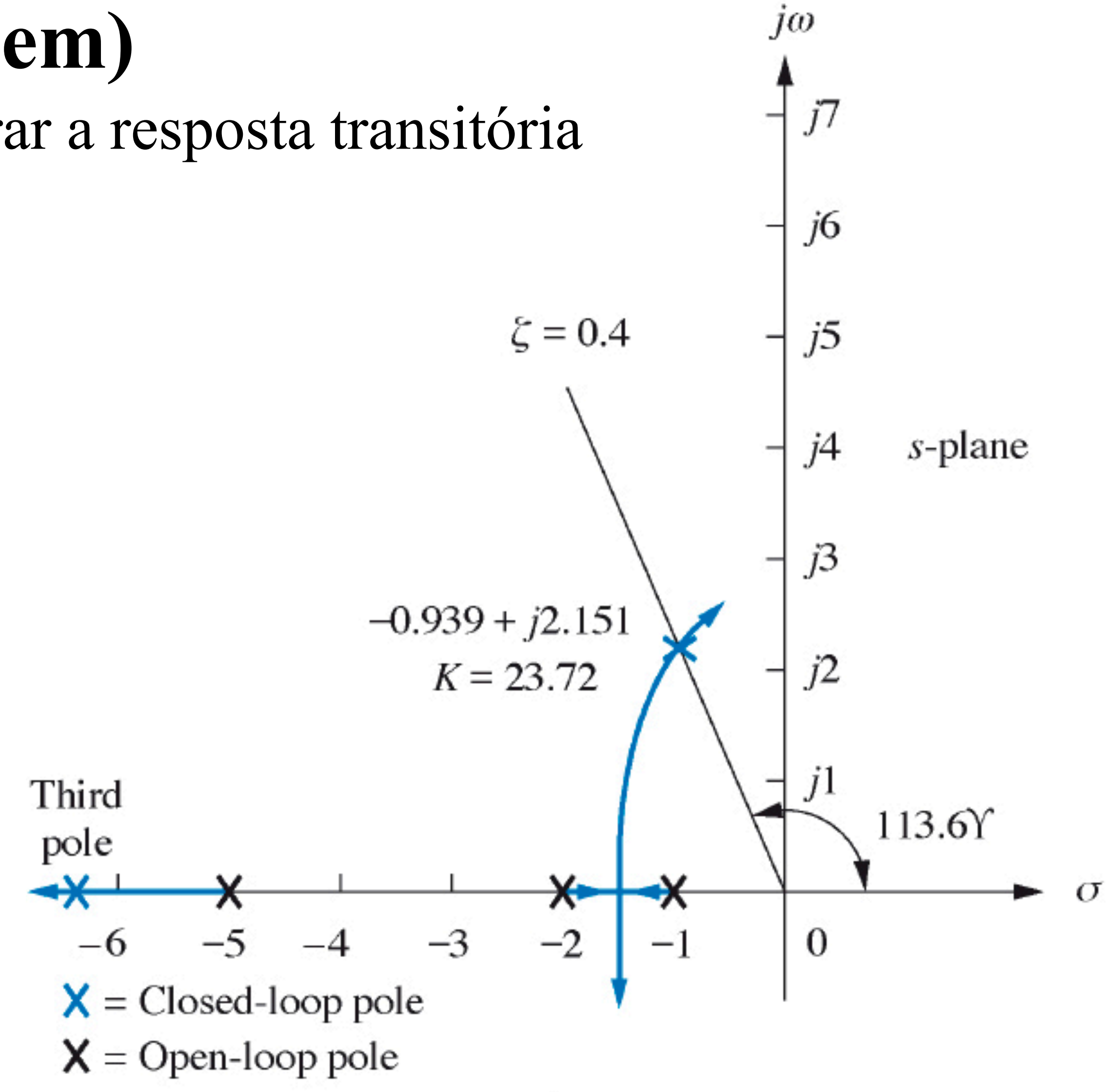
→ pouca influência na resp. dinâmica

realizável ?



Controlador Proporcional é lento (prox. à origem)

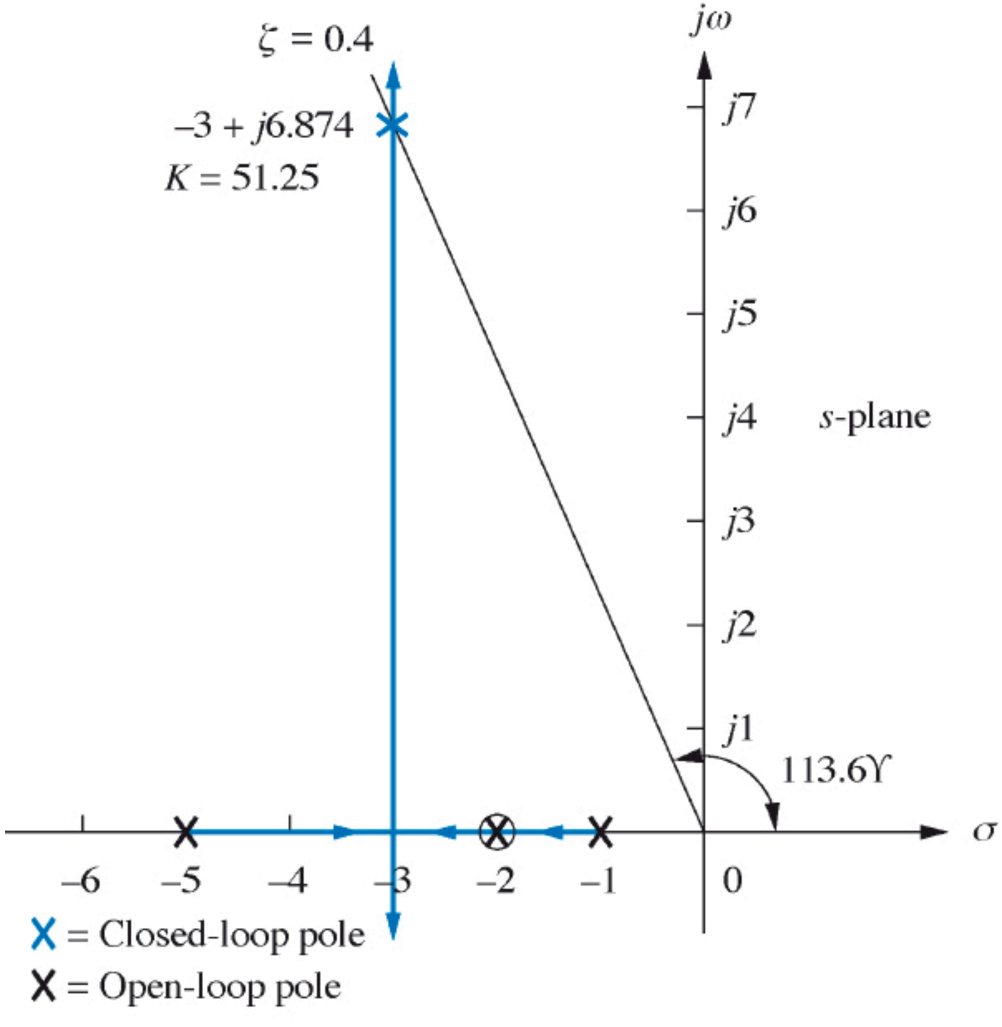
→ melhorar a resposta transitória



(a)

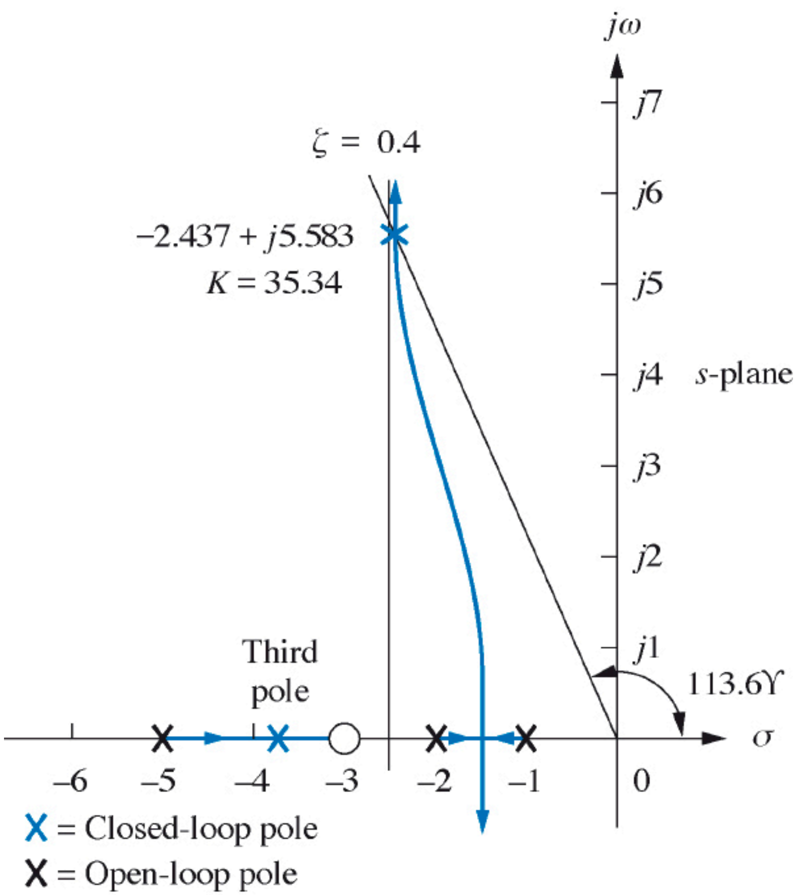
Controlador Proporcional Derivativo

→ "zero" melhora a resposta transitória

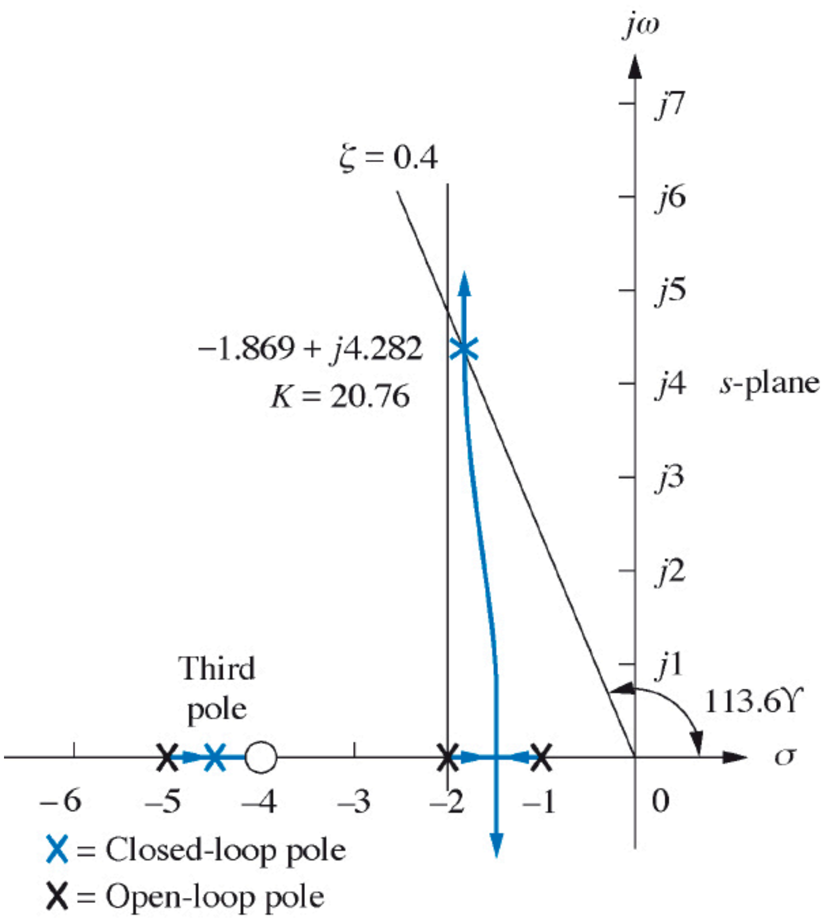


(b)

Contr. Proporcional Derivativo - alternativas



(c)

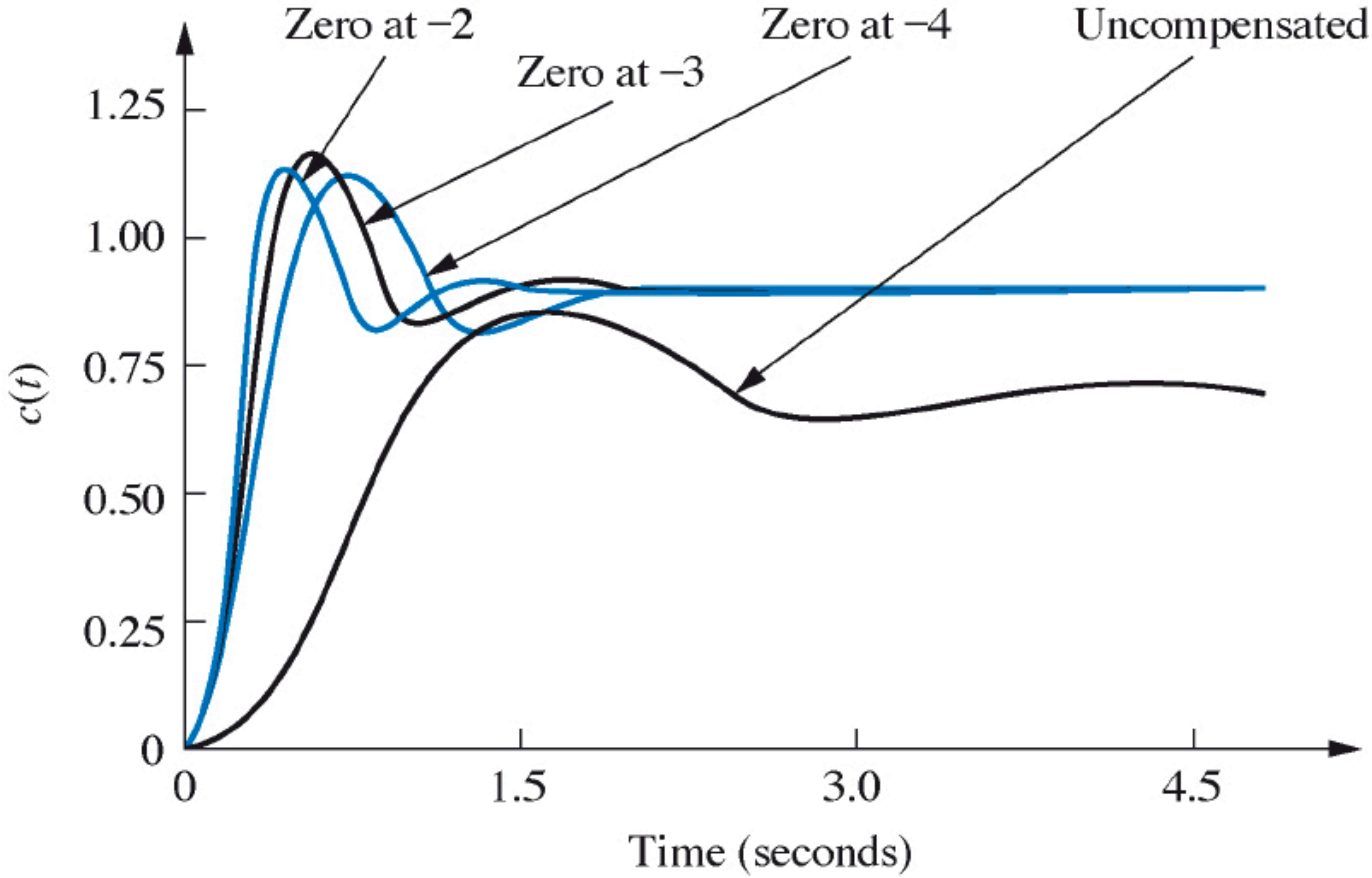


(d)

Ex. Alternativas Controlador PD

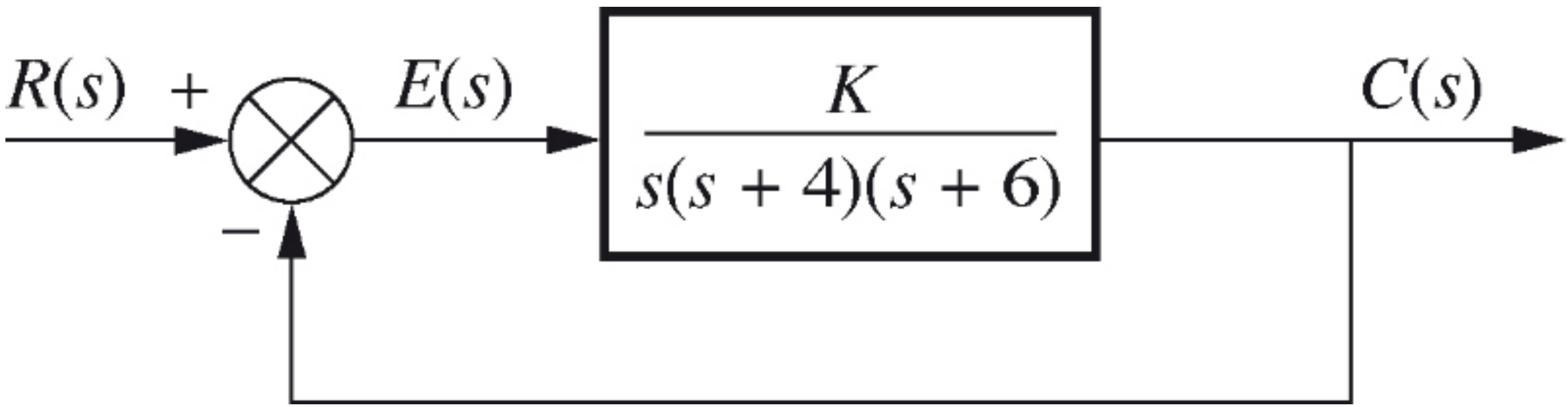
	Uncompensated	Compensation b	Compensation c	Compensation d
Plant and compensator	$\frac{K}{(s+1)(s+2)(s+5)}$	$\frac{K(s+2)}{(s+1)(s+2)(s+5)}$	$\frac{K(s+3)}{(s+1)(s+2)(s+5)}$	$\frac{K(s+4)}{(s+1)(s+2)(s+5)}$
Dom, poles	$-0.939 \pm j2.151$	$-3 \pm j6.874$	$-2.437 \pm j5.583$	$-1.869 \pm j4.282$
K	23.72	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

Contr. Proporcional Derivativo - alternativas



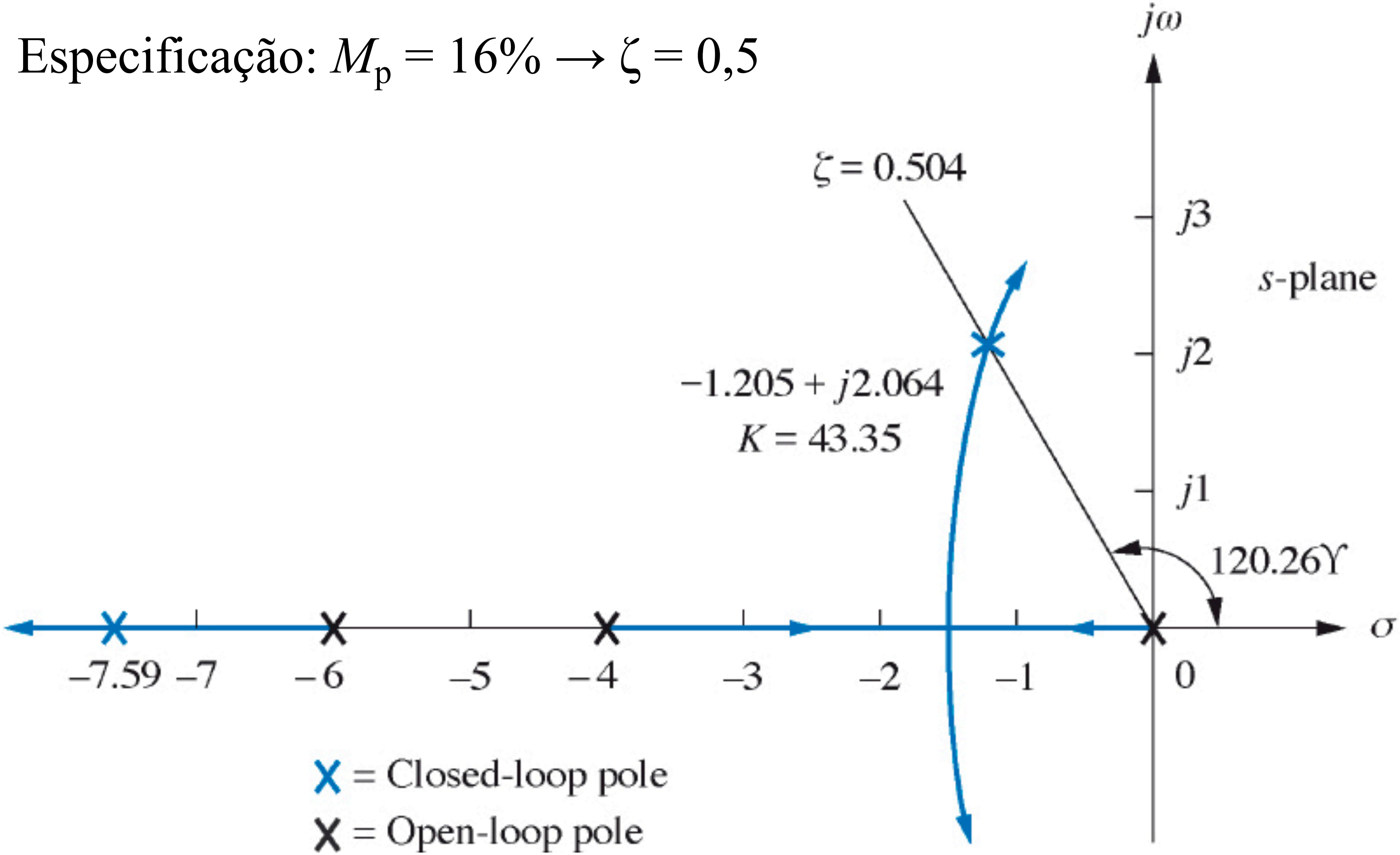
Exemplo: Controle Proporcional Derivativo

Especificação: $M_p = 16\% \rightarrow \zeta = 0{,}5$

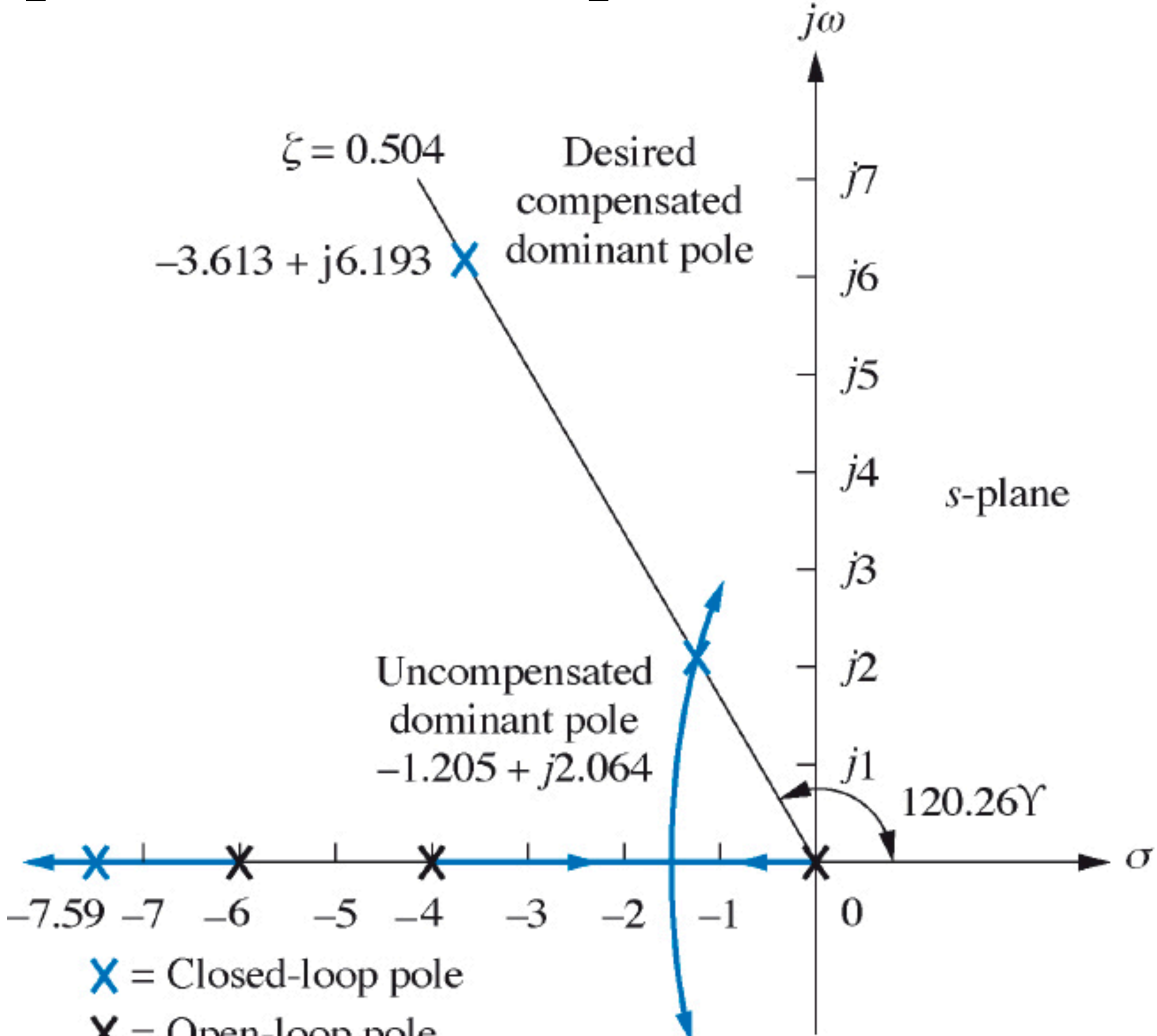


Exemplo: Controle Proporcional Derivativo

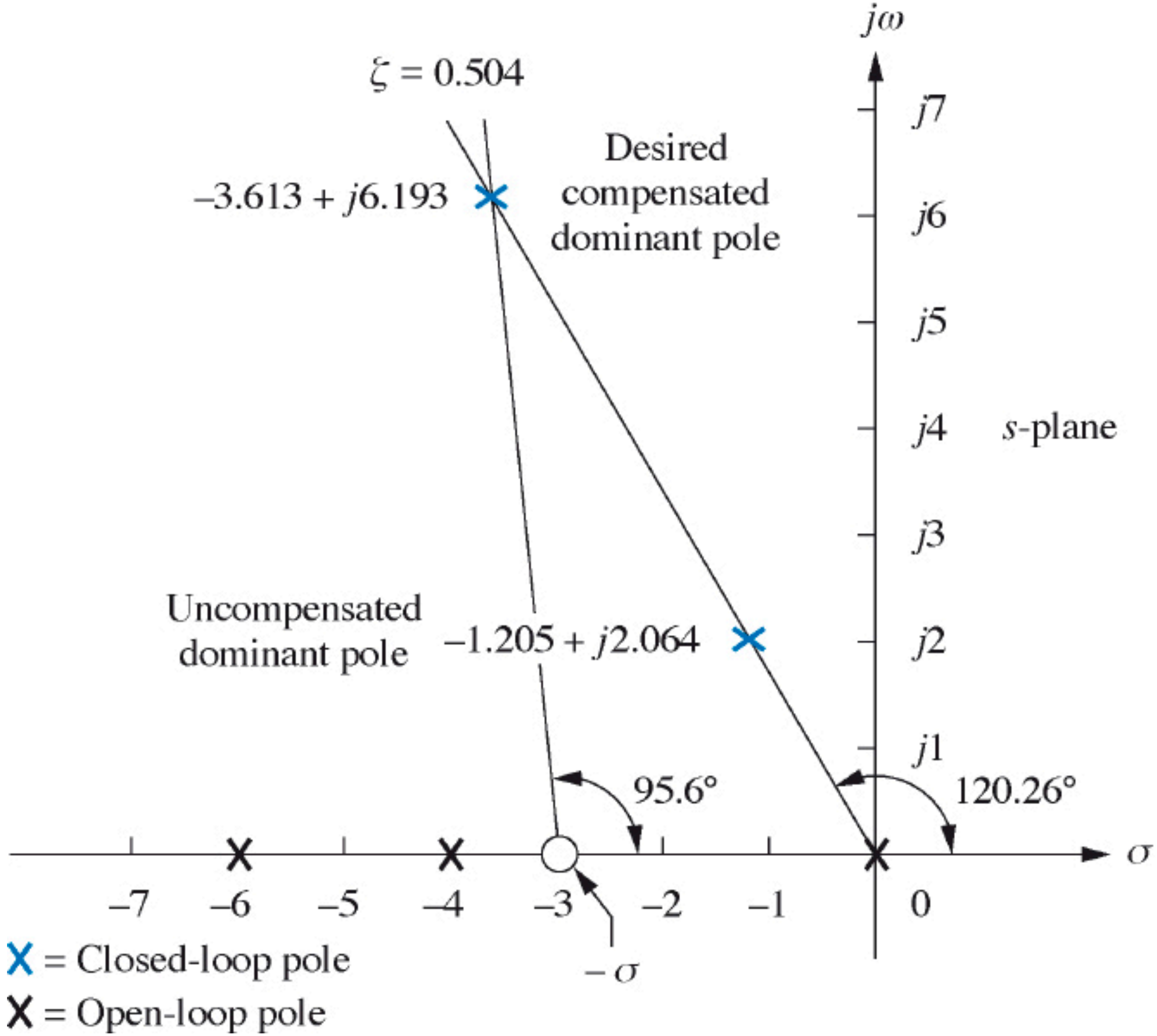
Especificação: $M_p = 16\% \rightarrow \zeta = 0{,}5$



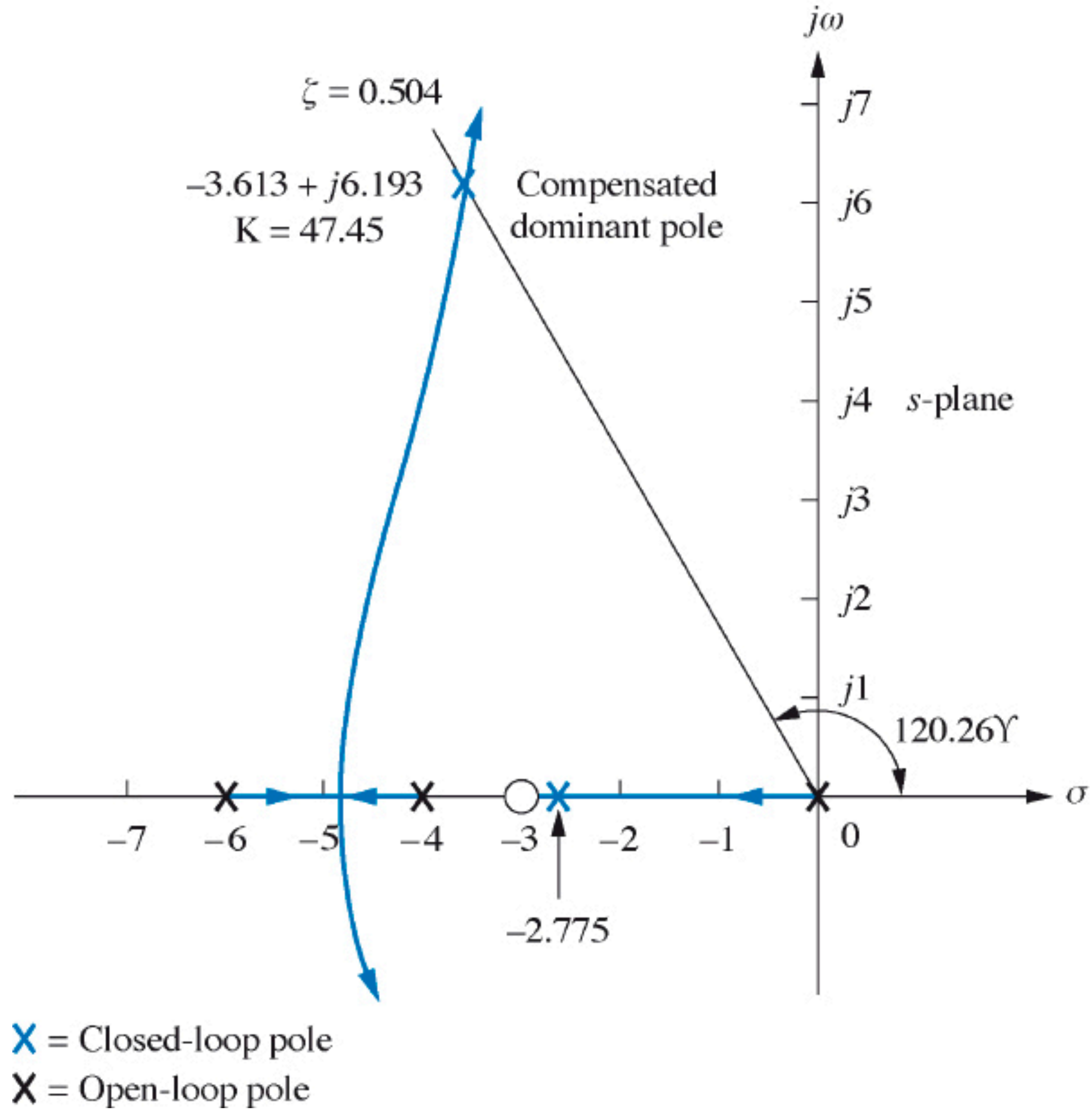
Exemplo: Controle Proporcional Derivativo



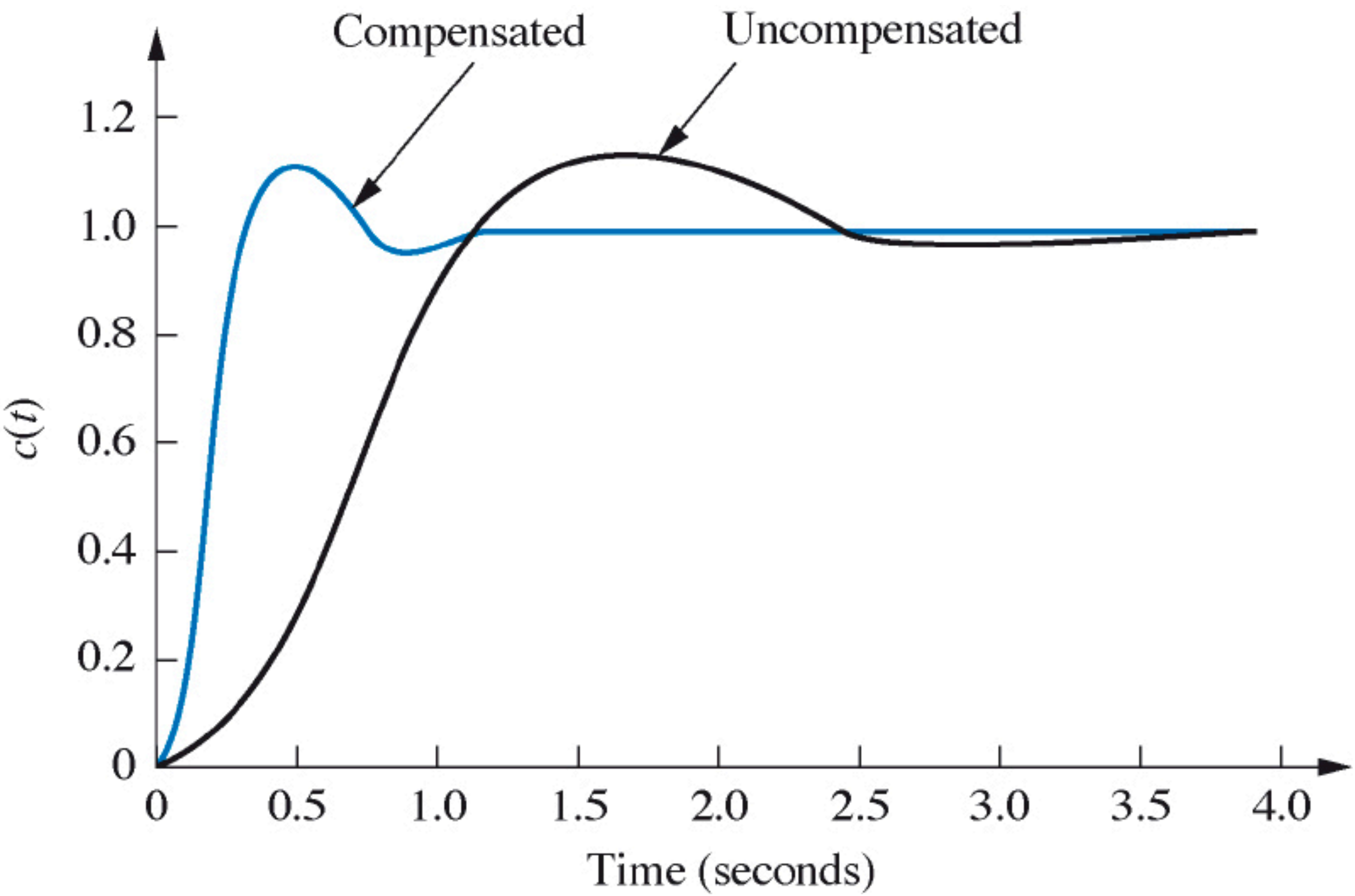
Exemplo: Controle Proporcional Derivativo



Exemplo: Controle Proporcional Derivativo



Exemplo: Controle Proporcional Derivativo

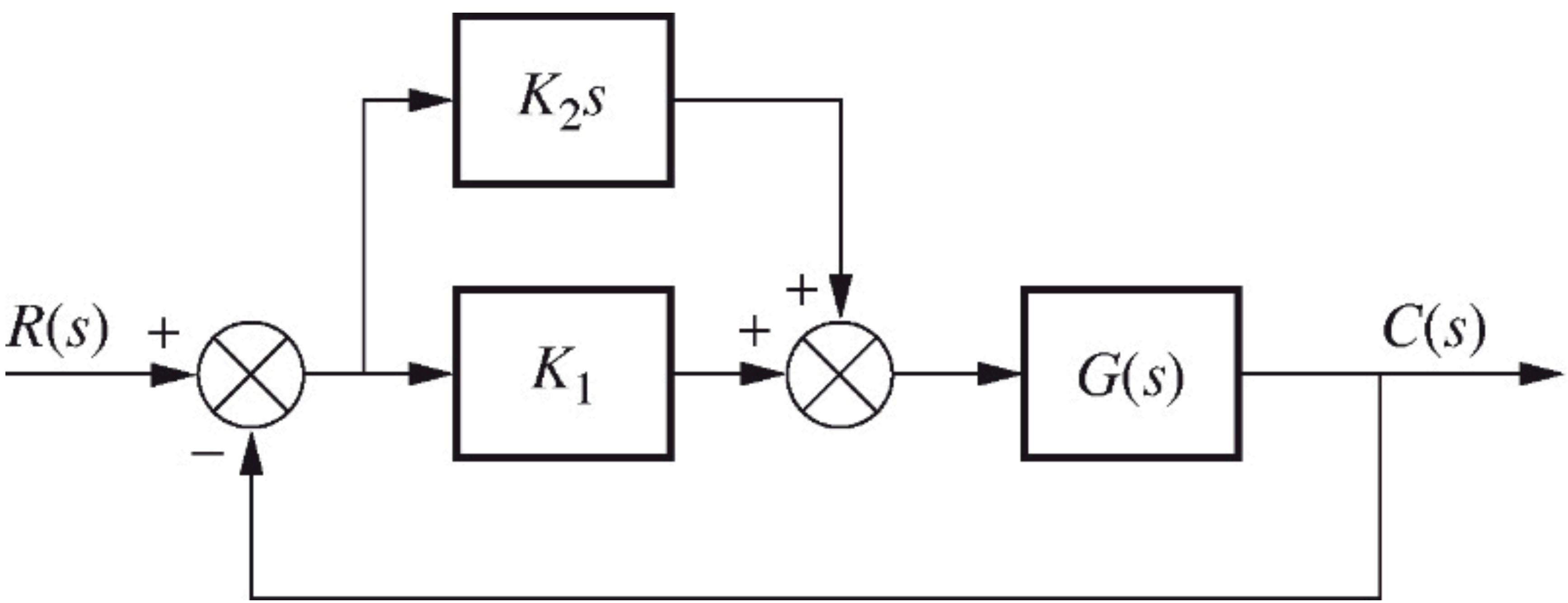


Exemplo: Controle Proporcional Derivativo

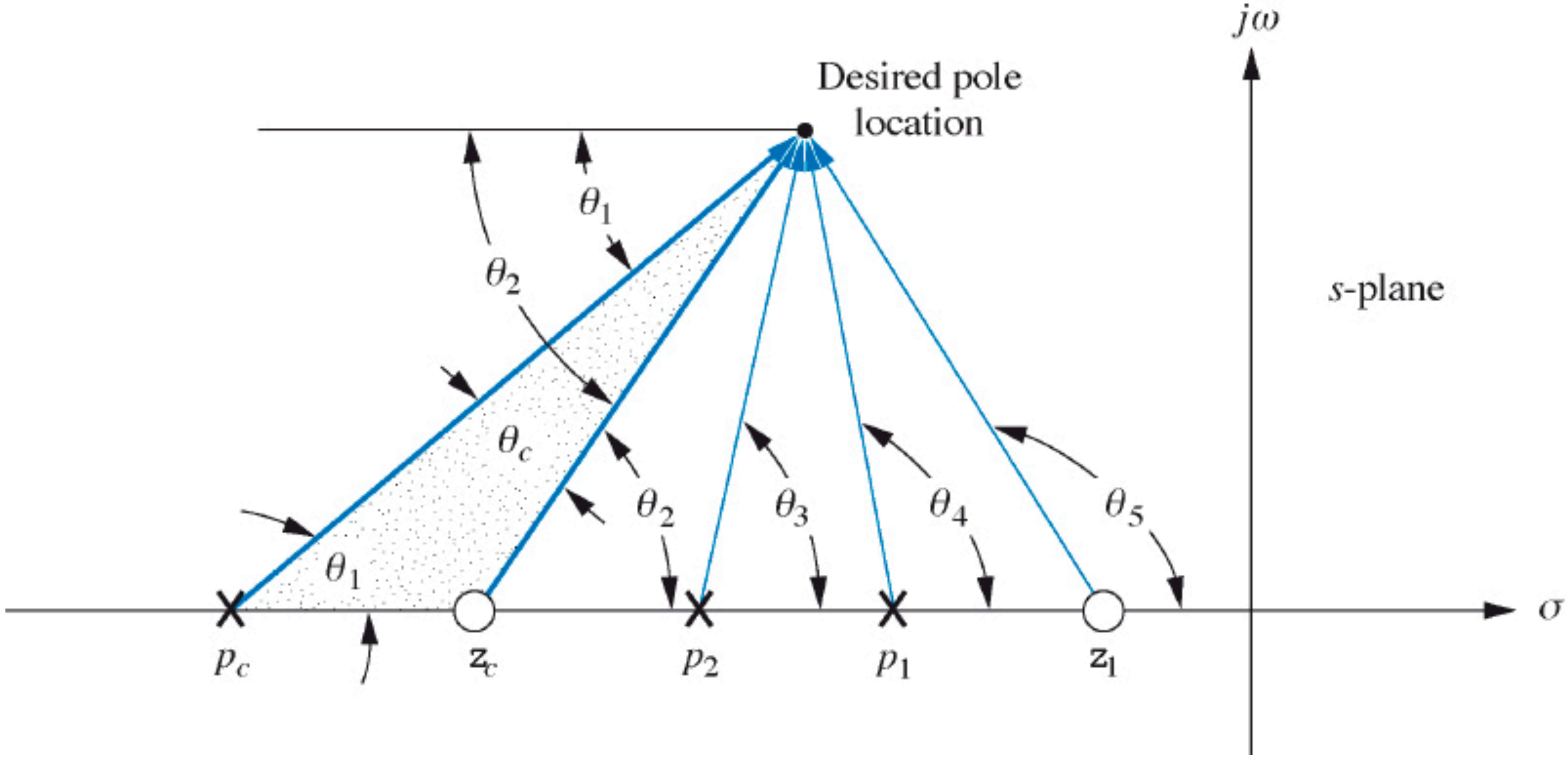
	Uncompensated	Simulation	Compensated	Simulation
Plant and compensator	$\frac{K}{s(s+4)(s+6)}$		$\frac{K(s+3.006)}{s(s+4)(s+6)}$	
Dominant poles	$-1.205 \pm j2.064$		$-3.613 \pm j6.193$	
K	43.35		47.45	
ζ	0.504		0.504	
ω_n	2.39		7.17	
$\%OS$	16	14.8	16	11.8
T_s	3.320	3.6	1.107	1.2
T_p	1.522	1.7	0.507	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	

Controle Proporcional Derivativo

Canal Proporcional + Canal Derivativo	$K_p + K_d s$
Ganho + Zero	$K(s+z)$
Forma ISA (Indústria)	$K(1+T_d s)$

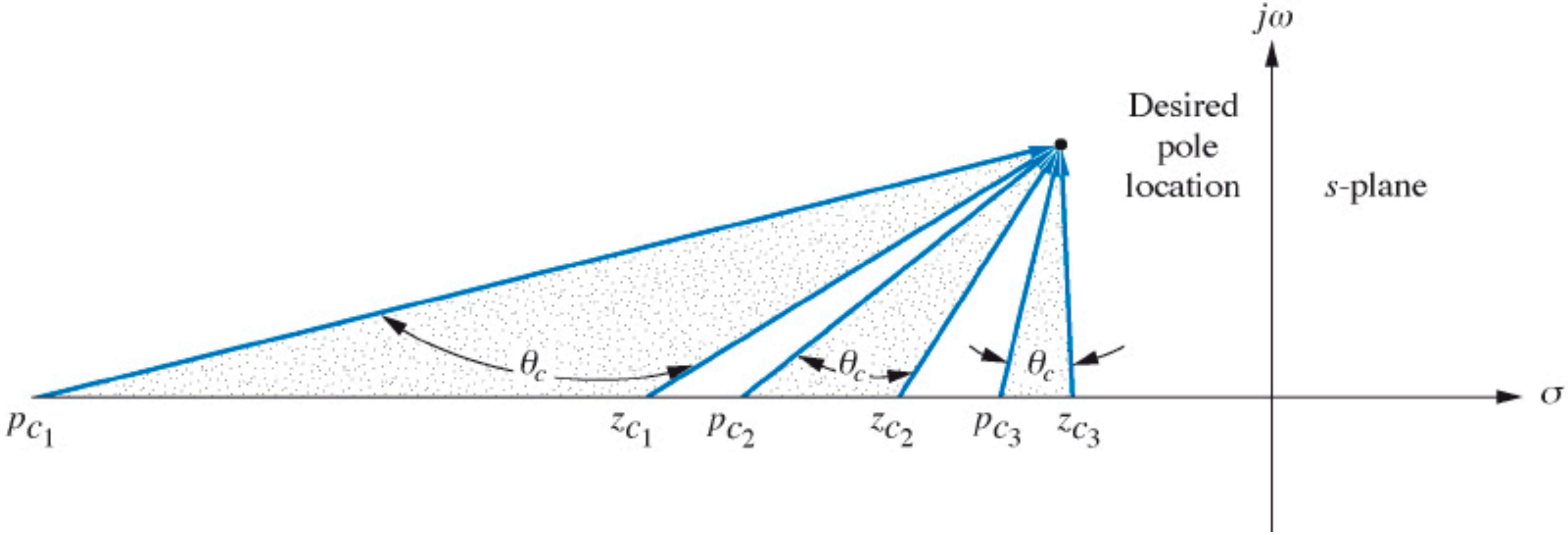


Compensador em Avanço

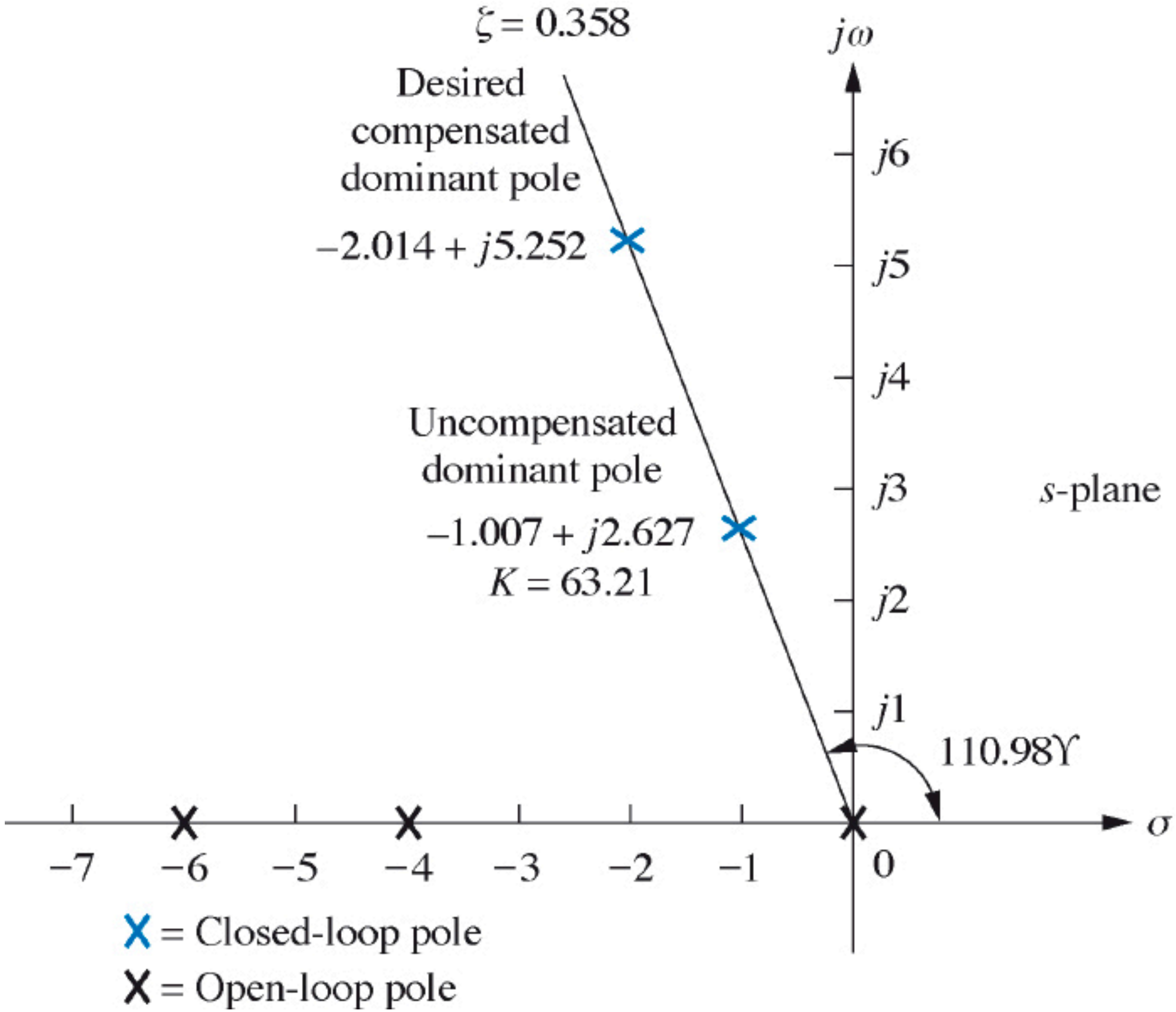


Compensador em Avanço

- Várias opções -

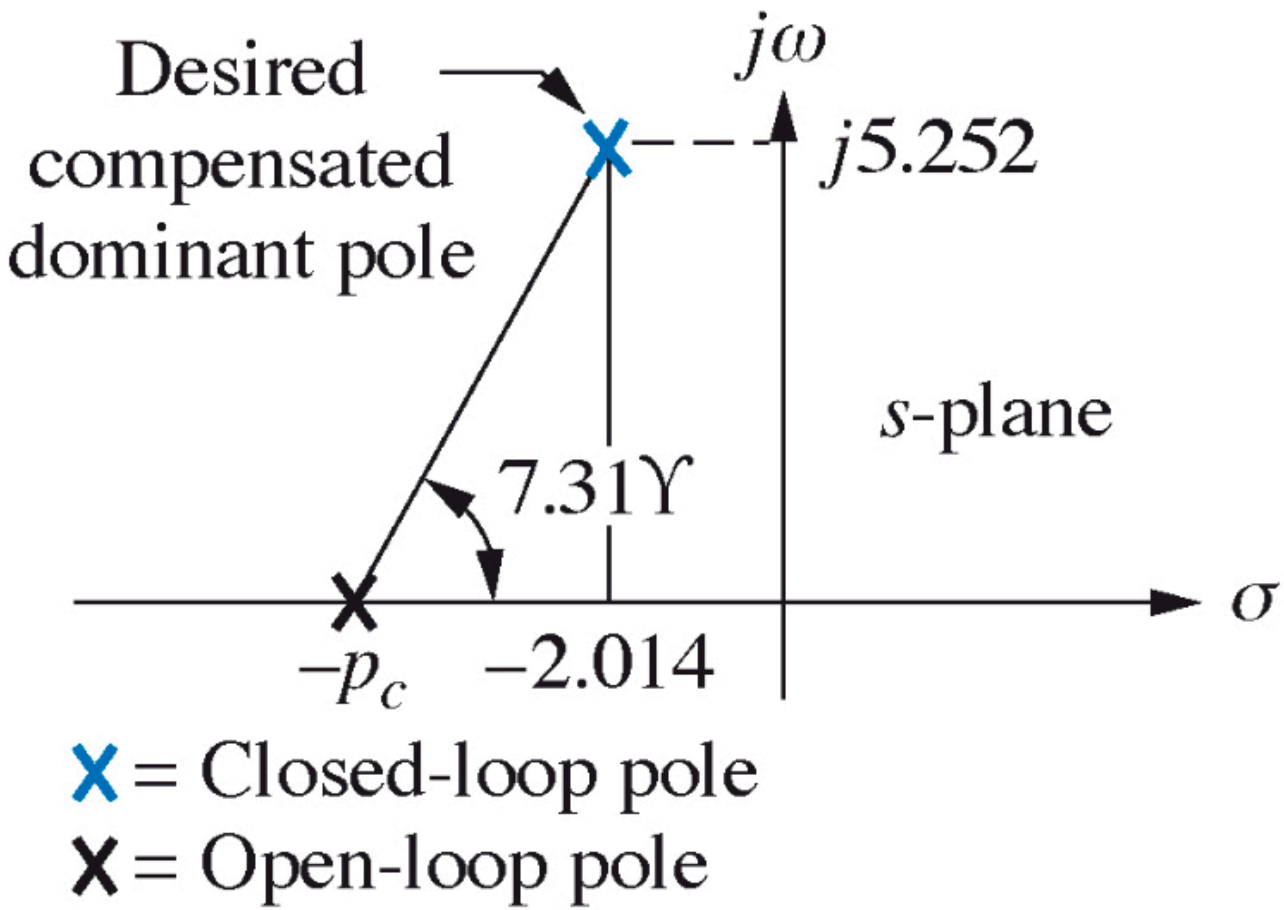


Exemplo 9.4:



ζ = 0.358
jω
Desired
compensated
dominant pole
−2.014 + j5.252
j6
j5
j4
Uncompensated
dominant pole
−1.007 + j2.627
K = 63.21
j3
s-plane
j2
j1
110.98Υ
σ
−7
−6
−5
−4
−3
−2
−1
0
X = Closed-loop pole
X = Open-loop pole

Exemplo 9.4:



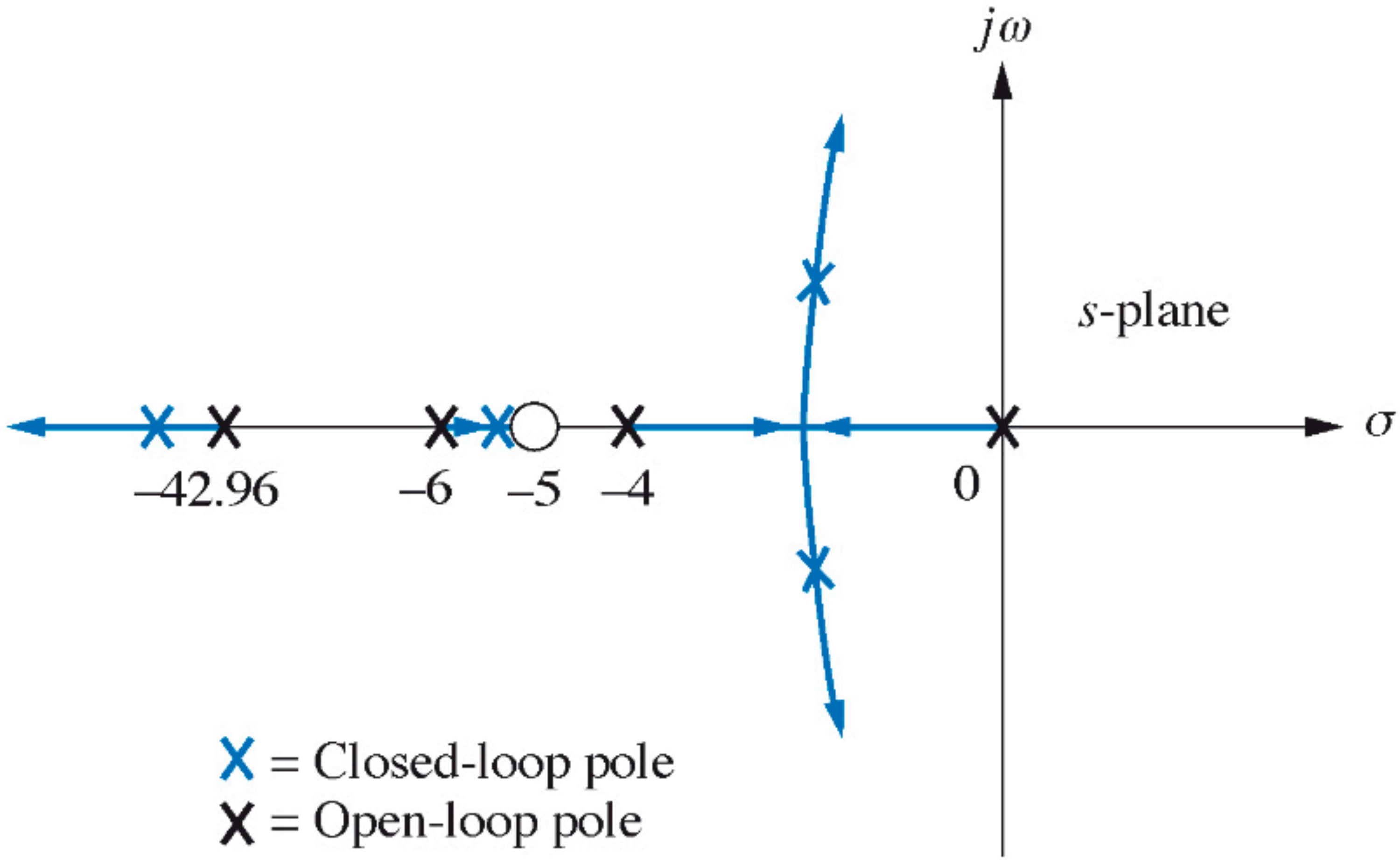
Note: This figure is not drawn to scale.

Ex. 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

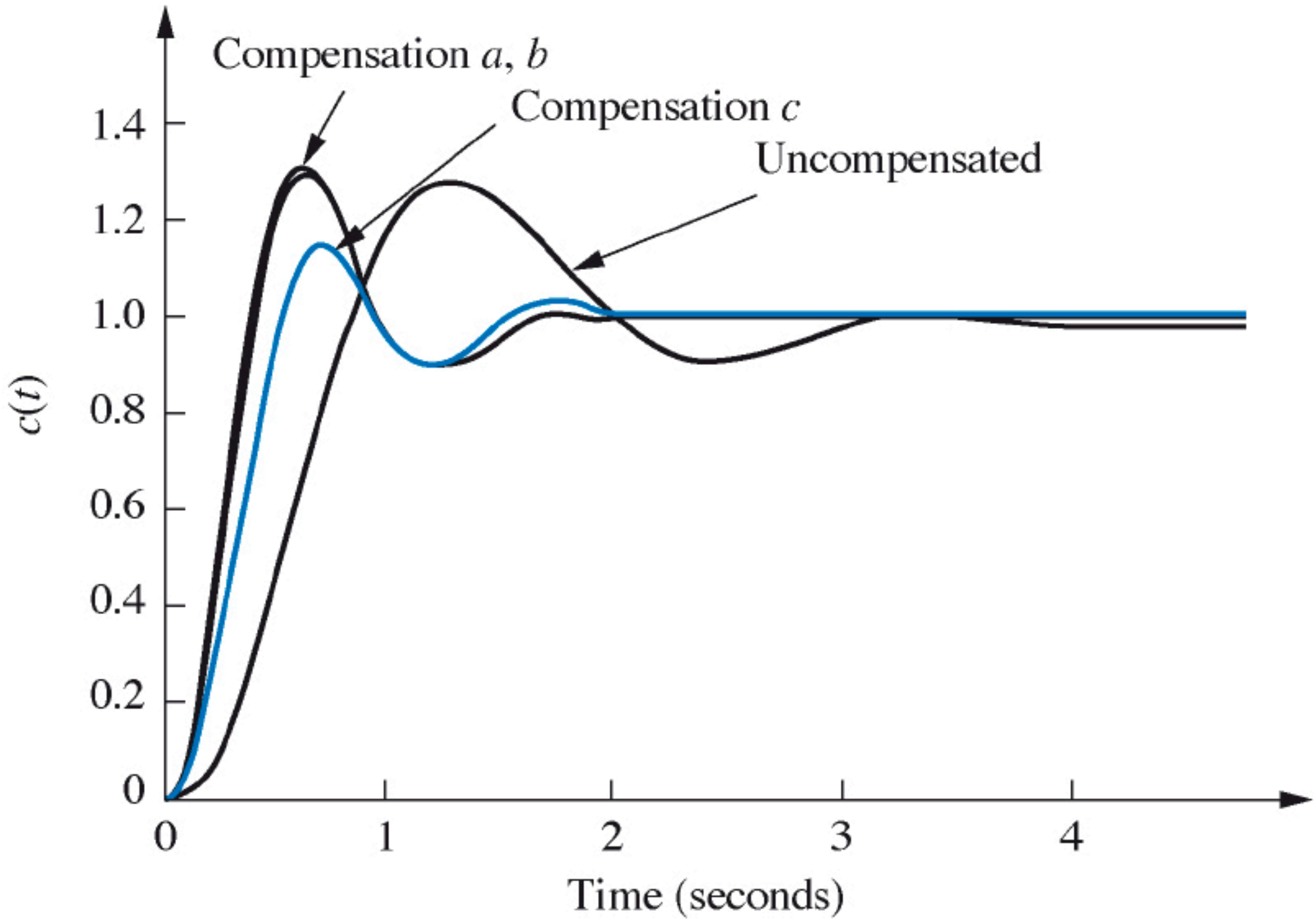
*Simulation results are shown in parentheses.

Exemplo 9.4...



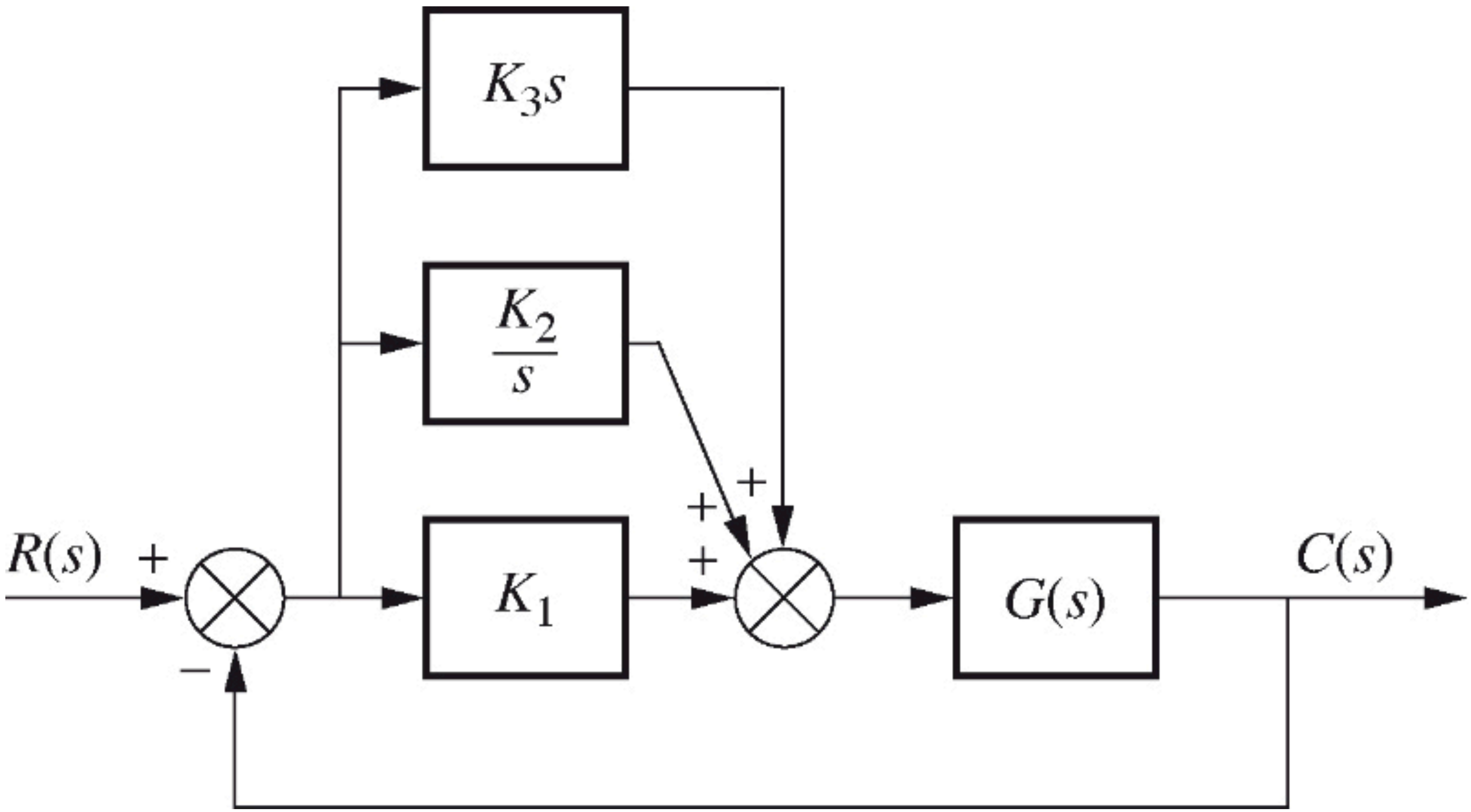
Note: This figure is not drawn to scale.

Exemplo 9.4...

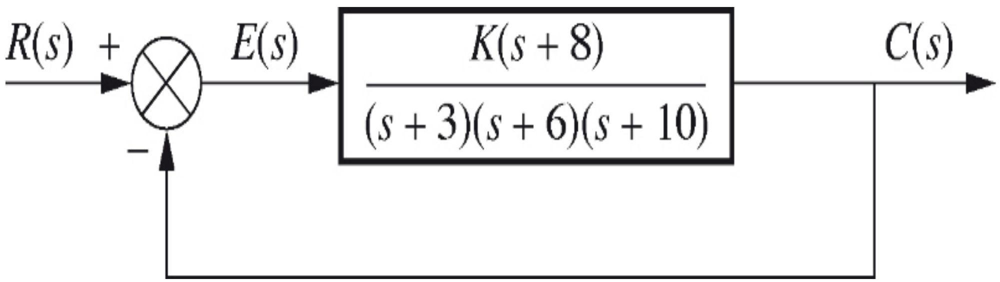


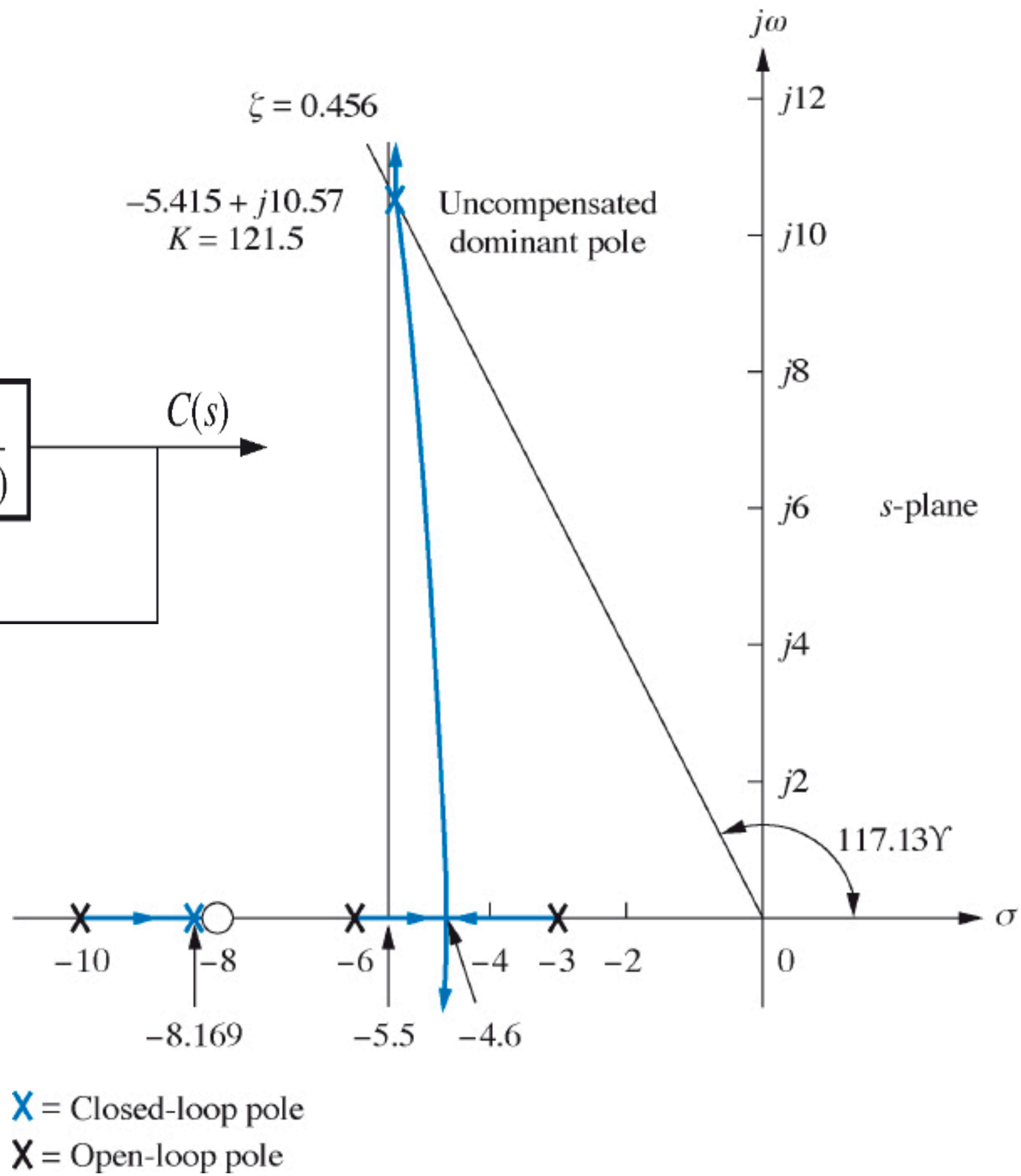
Compensation a, b
Compensation c
Uncompensated
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
c(t)
0
1
2
3
4
Time (seconds)

Melhorando e_{SS} e a resposta transitória: PID

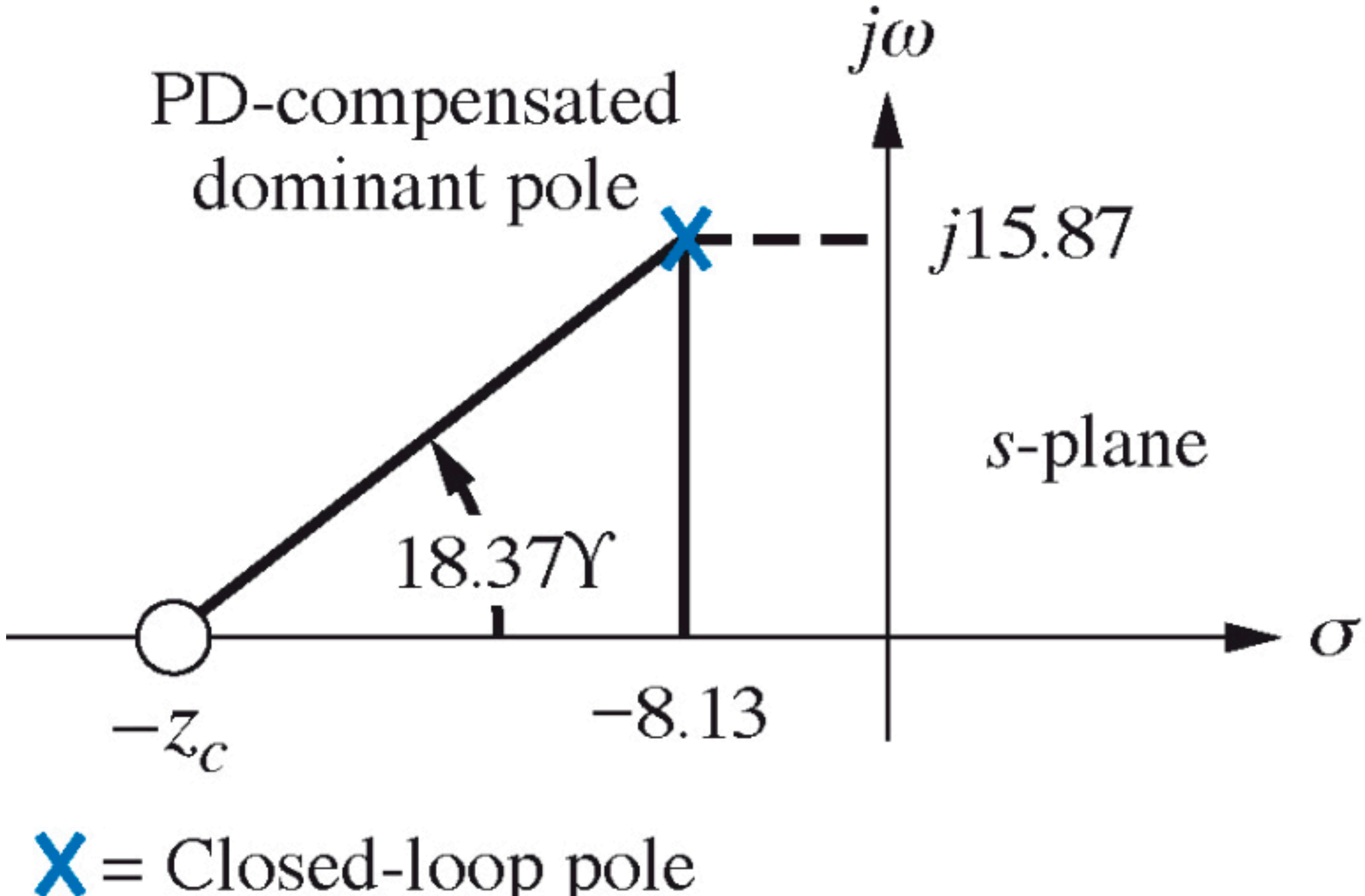


Exemplo 9.5...


R(s)
+
E(s)
K(s + 8)
(s + 3)(s + 6)(s + 10)
C(s)
–

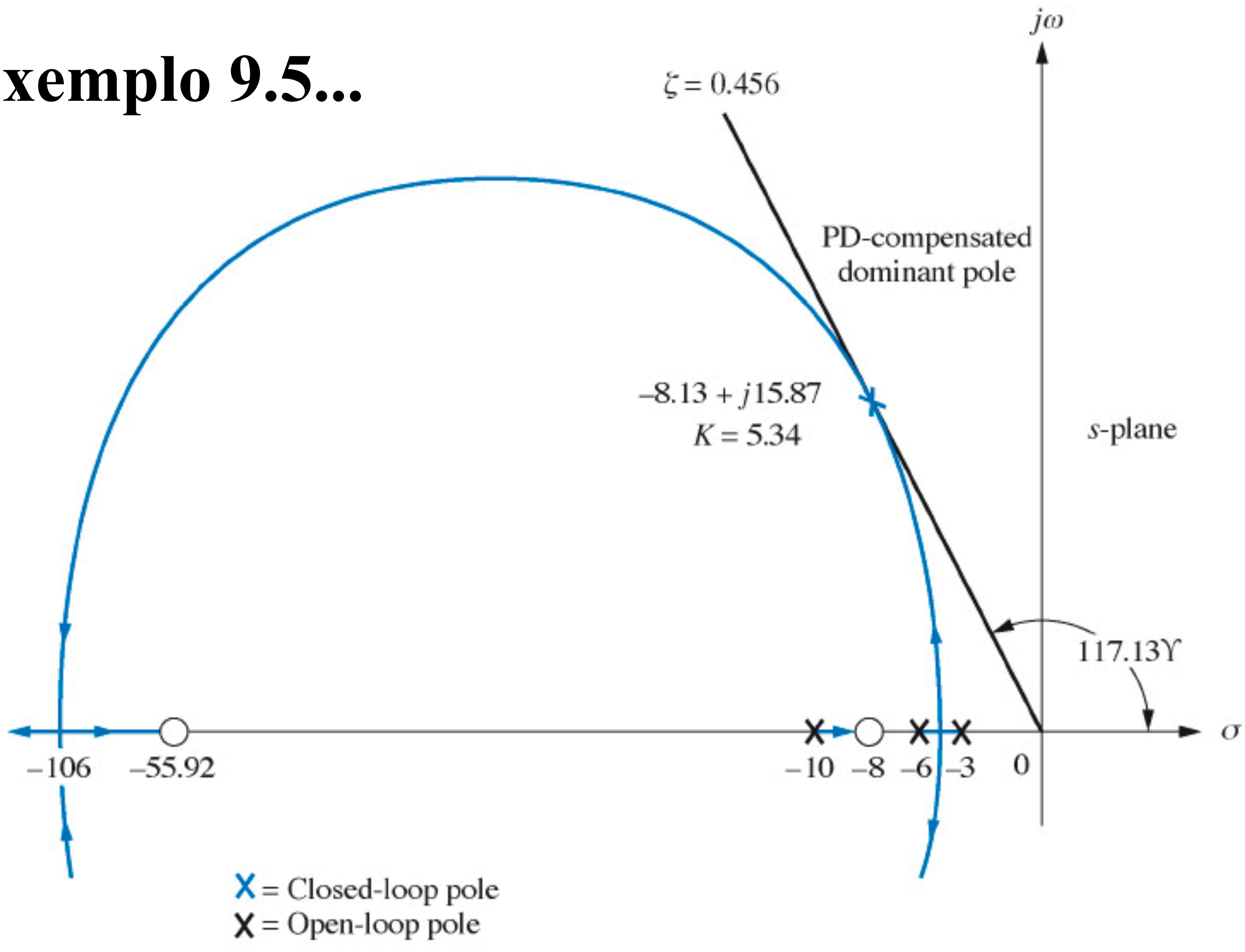

jω
j12
j10
j8
j6
j4
j2
ζ = 0.456
–5.415 + j10.57
K = 121.5
Uncompensated
dominant pole
s-plane
117.13Υ
σ
–10
–8
–6
–4
–3
–2
0
–8.169
–5.5
–4.6
= Closed-loop pole
= Open-loop pole

Exemplo 9.5...



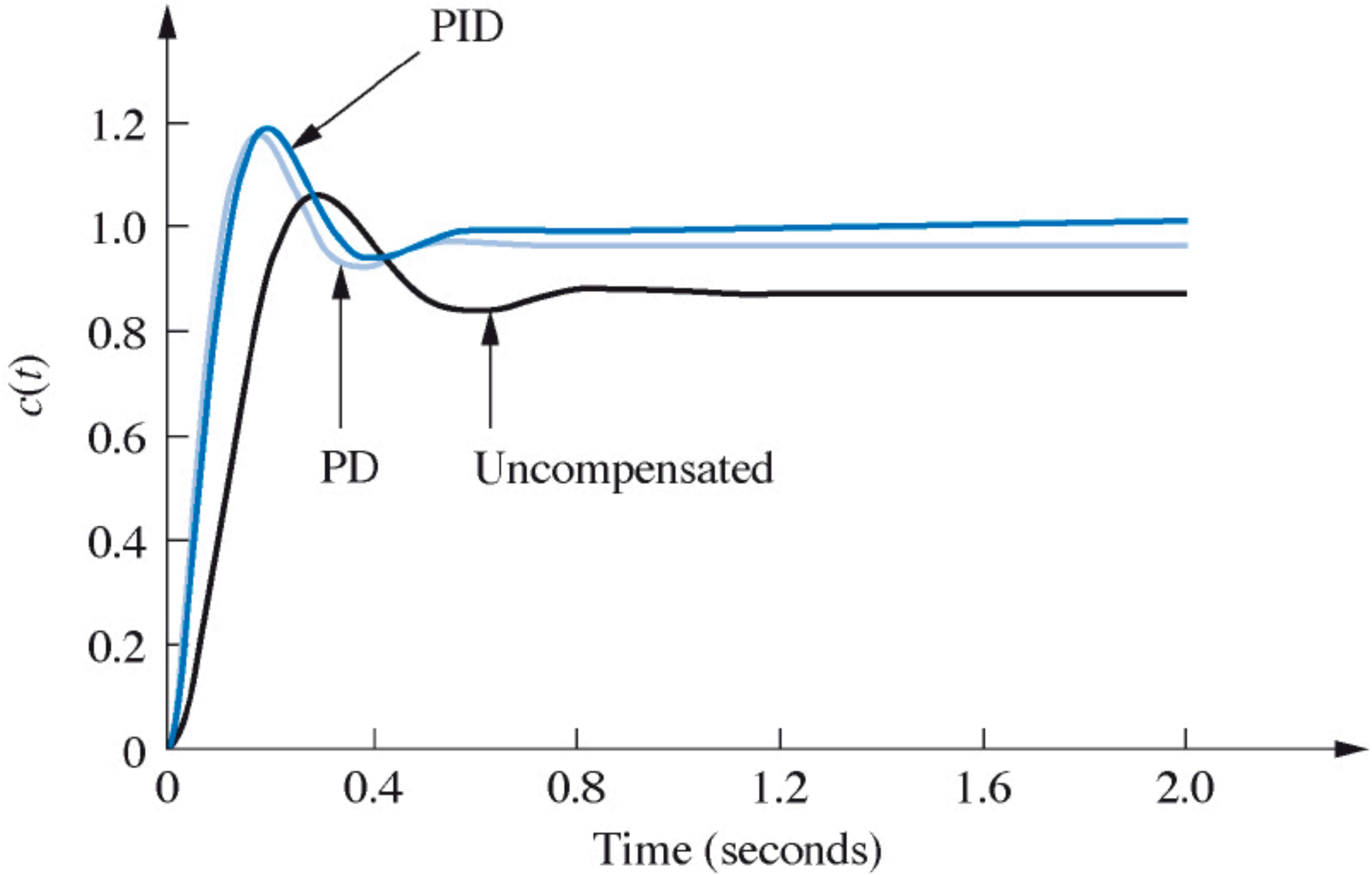
Note: This figure is not drawn to scale.

Exemplo 9.5...



Note: This figure is not drawn to scale.

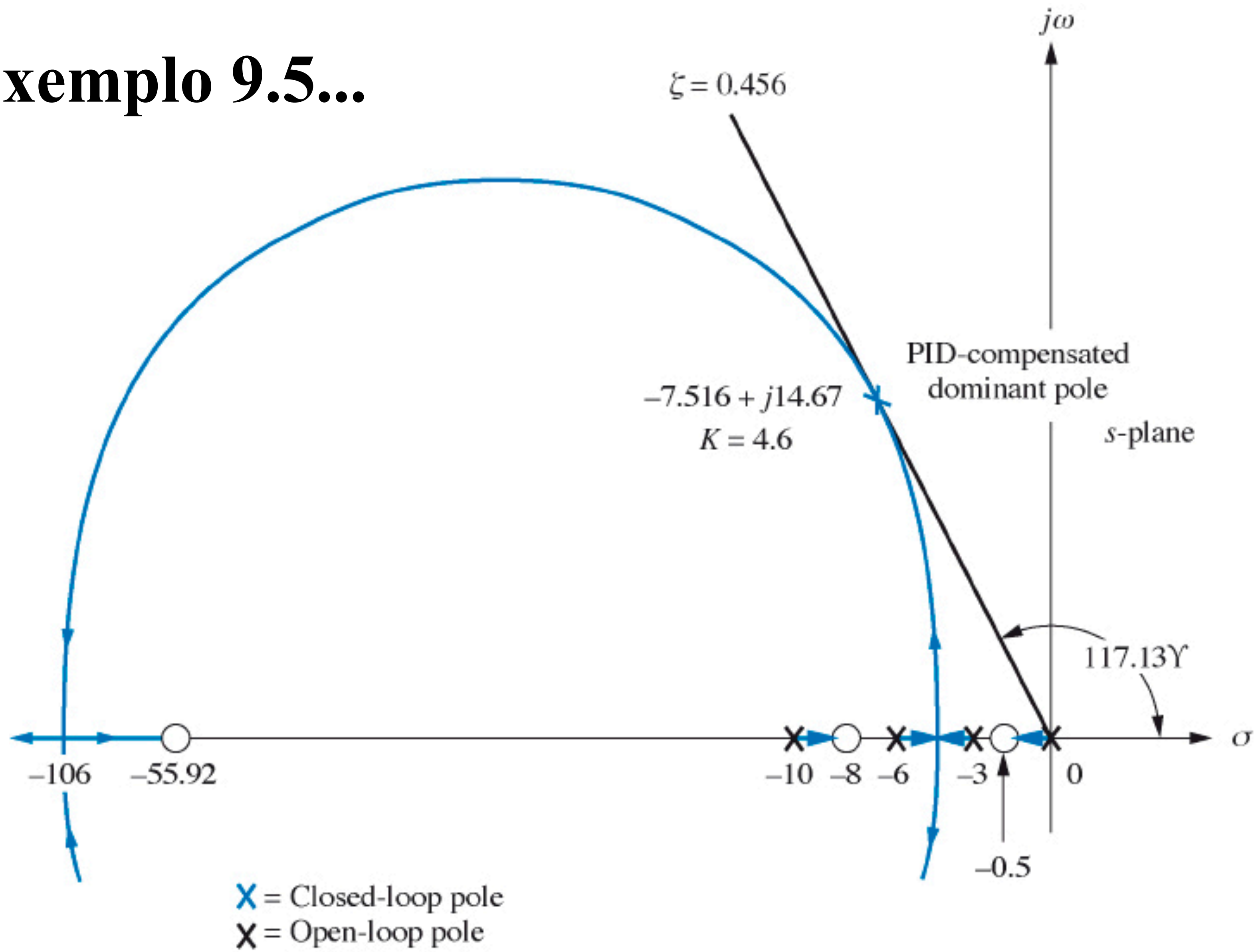
Exemplo 9.5...


PID
1.2
1.0
0.8
0.6
0.4
0.2
0
c(t)
PD
Uncompensated
0
0.4
0.8
1.2
1.6
2.0
Time (seconds)

Exemplo 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	Zeros at −55.92 and −0.5 not canceled

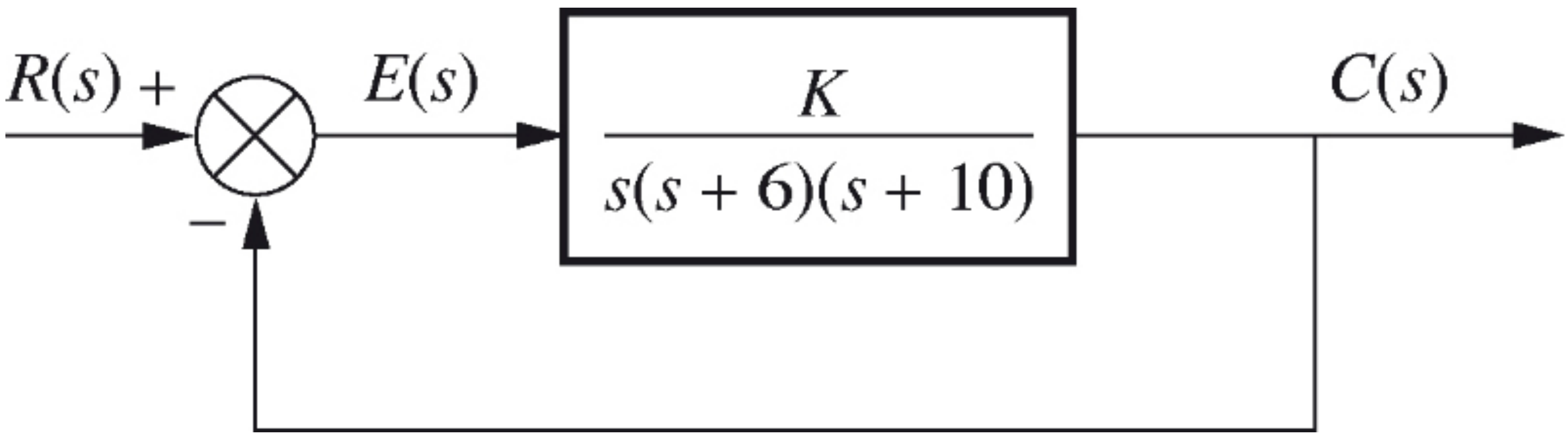
Exemplo 9.5...



Note: This figure is not drawn to scale.

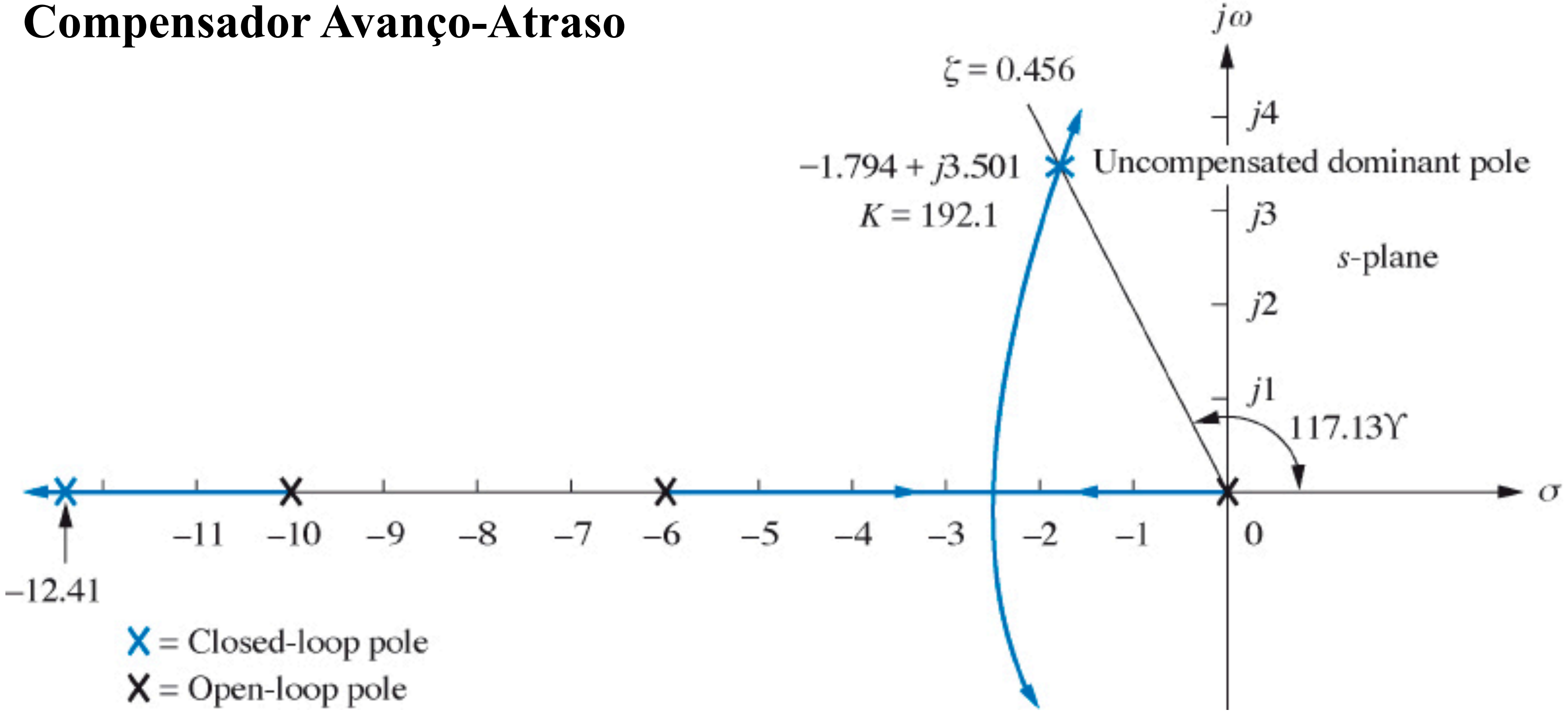
Compensador Avanço-Atraso

Exemplo 9.6

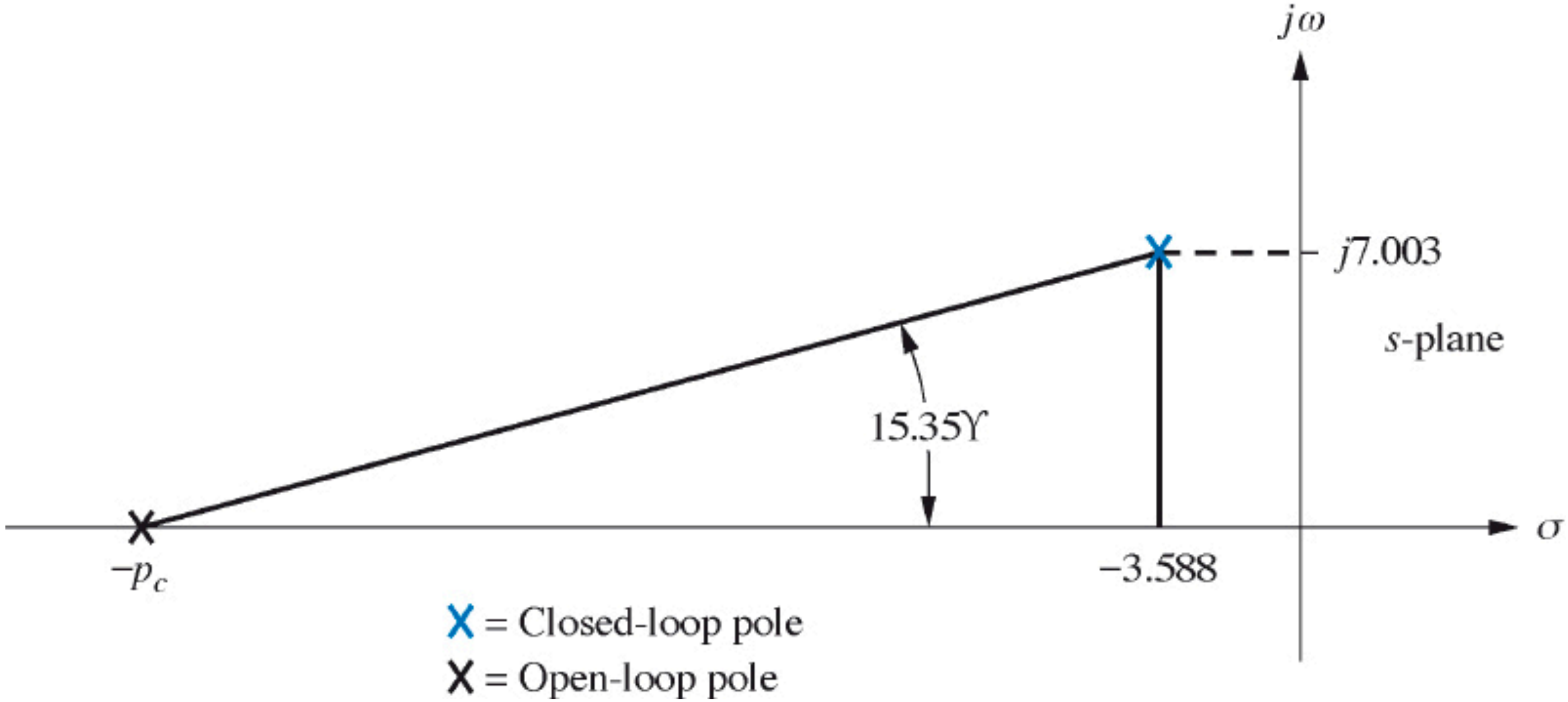


Exemplo 9.6

Compensador Avanço-Atraso

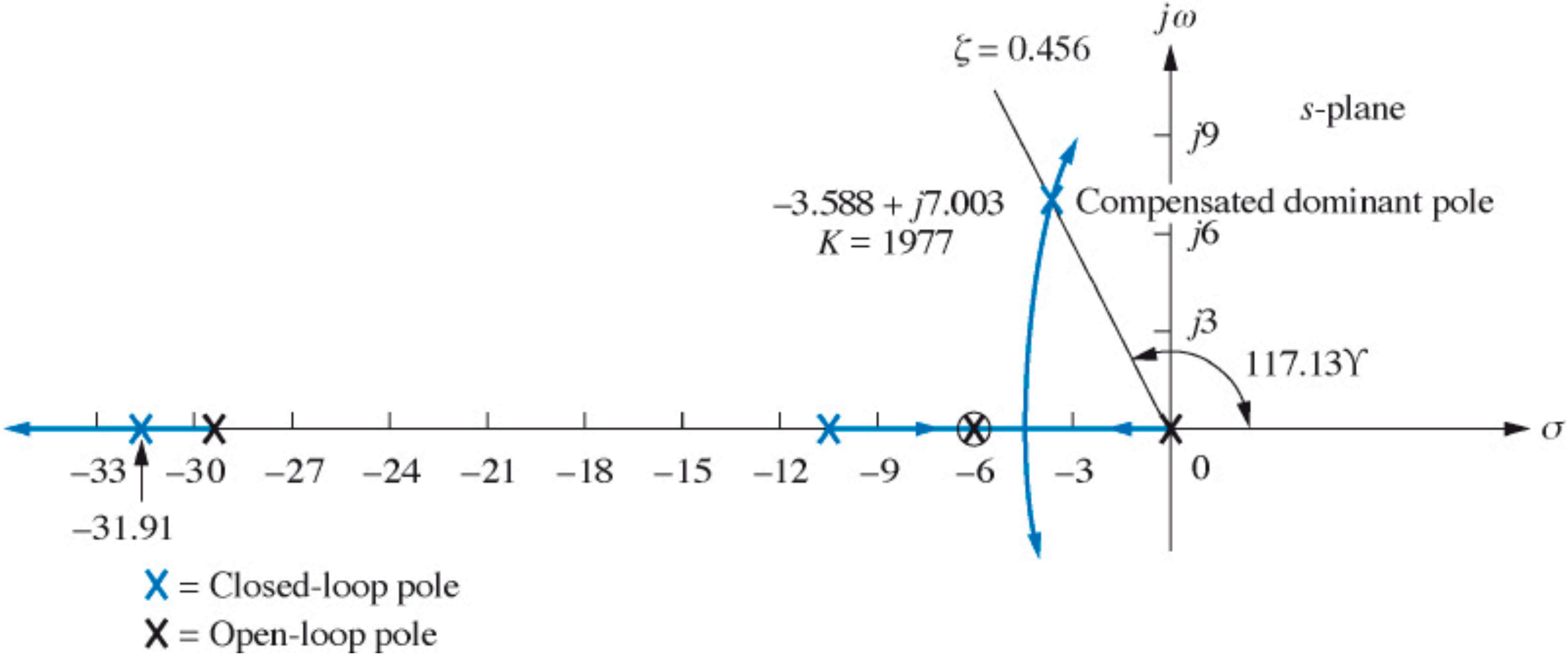


Exemplo 9.6



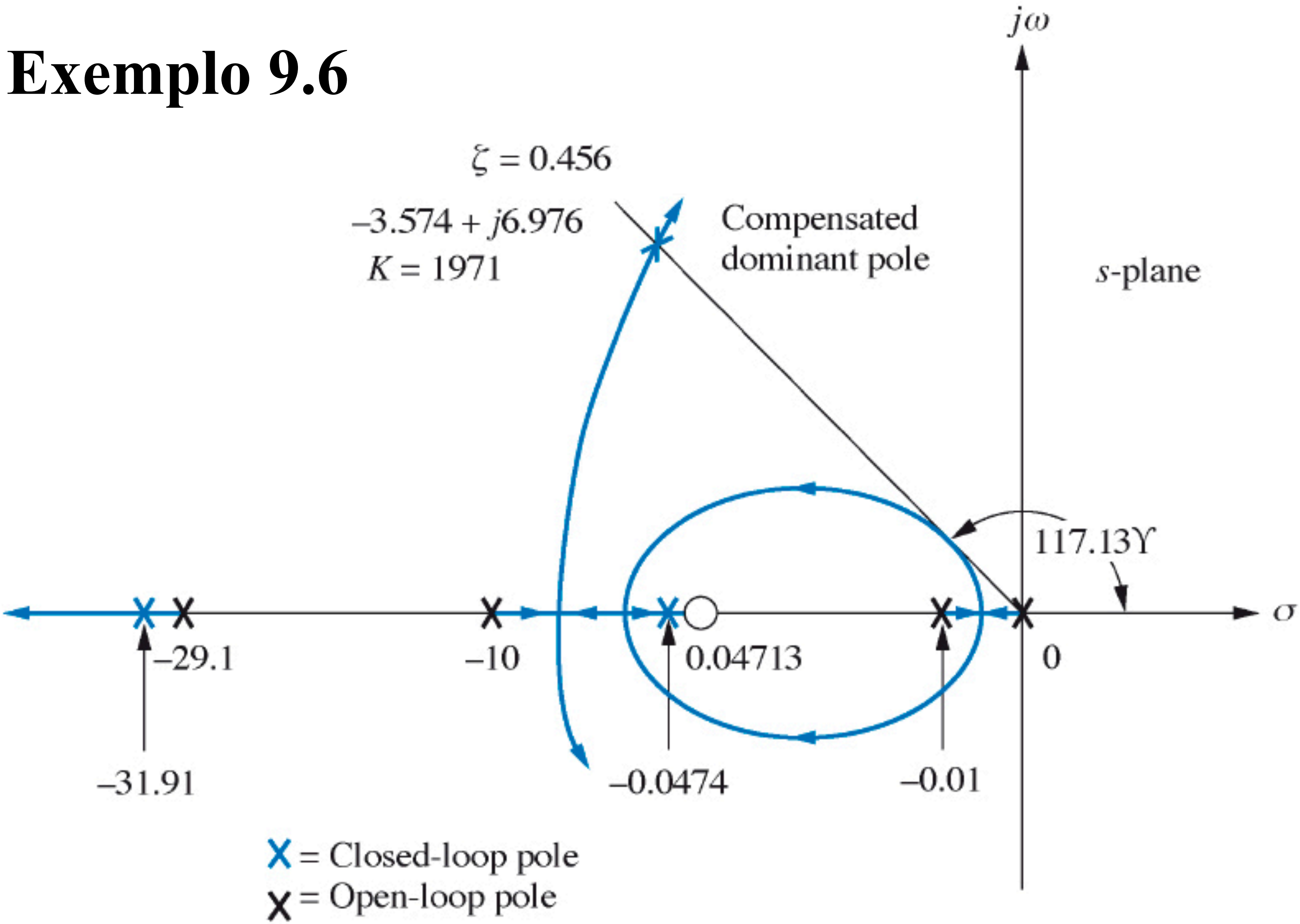
jω
j7.003
s-plane
15.35Υ
σ
−p_c
−3.588
= Closed-loop pole
= Open-loop pole

Exemplo 9.6



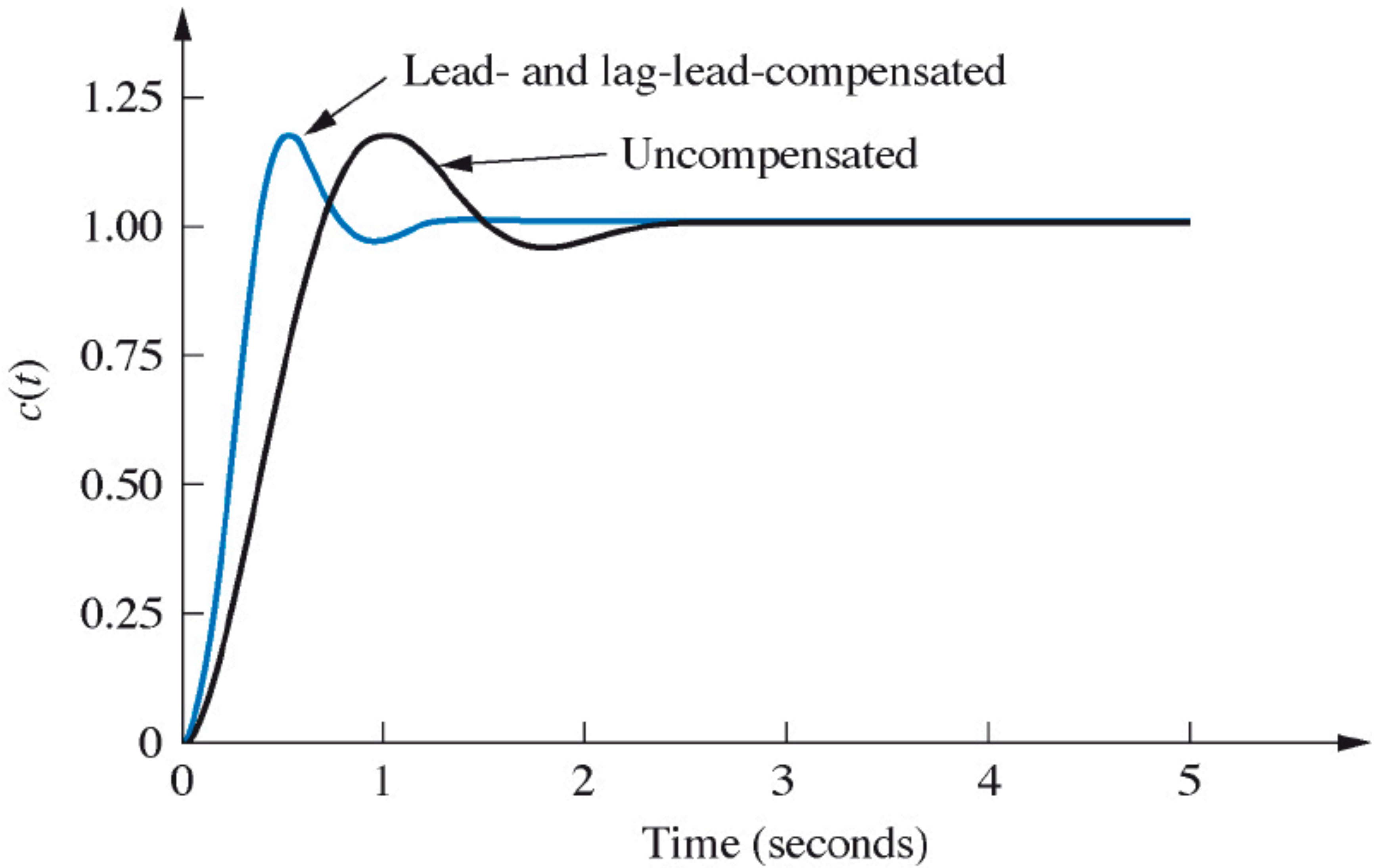
jω
ζ = 0.456
s-plane
j9
–3.588 + j7.003
K = 1977
Compensated dominant pole
j6
j3
117.13Υ
σ
–33
–30
–27
–24
–21
–18
–15
–12
–9
–6
–3
0
–31.91
X = Closed-loop pole
X = Open-loop pole

Exemplo 9.6



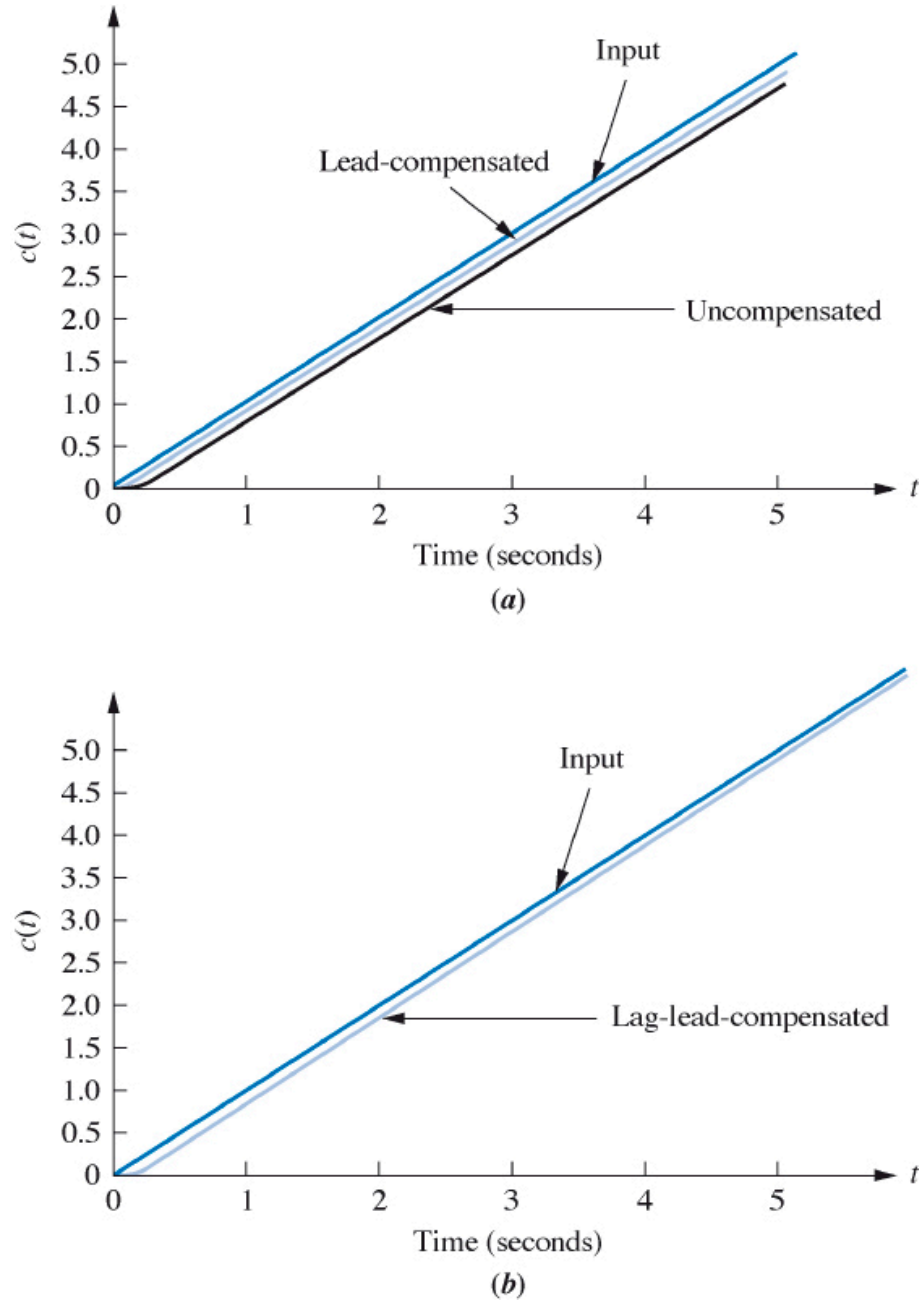
Note: This figure is not drawn to scale.

Exemplo 9.6



Lead- and lag-lead-compensated
Uncompensated
1.25
1.00
0.75
0.50
0.25
0
c(t)
0
1
2
3
4
5
Time (seconds)

Exemplo 9.6


5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
c(t)
Input
Lead-compensated
Uncompensated
0
1
2
3
4
5
t
Time (seconds)
(a)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
c(t)
Input
Lag-lead-compensated
0
1
2
3
4
5
t
Time (seconds)
(b)

Exemplo 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