Answers to Selected Problems

Chapter 1

19. c. $x(t) = \frac{2}{5} - e^{-4t}\left(\frac{2}{5}\cos 3t + \frac{8}{15}\sin 3t\right)$

20. b. $x(t) = -e^{-t} + 9te^{-t} + 5e^{-2t} + t - 2$

Chapter 2

3. b. $x(t) = \frac{15}{26}e^{-2t} - \frac{3}{10}e^{-4t} - \frac{18}{65}\cos 3t - \frac{1}{65}\sin 3t$

7. $\frac{Y(s)}{X(s)} = \frac{s^3 + 4s^2 + 6s + 8}{s^3 + 3s^2 + 5s + 1}$

8. c. $\frac{d^3x}{dt^3} + 11\frac{d^2x}{dt^2} + 12\frac{dx}{dt} + 18x = \frac{df}{dt} + 3f(t)$

16. a. $\frac{V_o(s)}{V_i(s)} = \frac{1}{s+2}$

18. b. $\frac{V_o(s)}{V_i(s)} = \frac{s^2 + 2s + 2}{s^4 + 2s^3 + 3s^2 + 3s + 2}$

33. $\frac{\theta_2(s)}{T(s)} = \frac{3}{20s^2 + 13s + 4}$

34. $\frac{\theta_2(s)}{T(s)} = \frac{1}{130s^2 + 400s + 55}$

43. $\frac{\theta_2(s)}{E_a(s)} = \frac{0.0833}{s(s + 0.75)}$

Chapter 3

1. $$\dot{\mathbf{x}} = \begin{bmatrix} -\frac{2}{3} & -\frac{1}{3} & \frac{1}{3} \\ -\frac{1}{3} & -\frac{2}{3} & \frac{2}{3} \\ -\frac{1}{3} & -\frac{2}{3} & -\frac{1}{3} \end{bmatrix} \begin{bmatrix} i_{L_1} \\ i_{L_2} \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{2}{3} \\ \frac{1}{3} \\ \frac{1}{3} \end{bmatrix} v_i$$

$$y = [0 \quad 0 \quad 1] \begin{bmatrix} i_{L_1} \\ i_{L_2} \\ v_o \end{bmatrix}$$

Note: L_1 is left-most inductor in Figure P3.1 in the text.

11. a. $$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -13 & -5 & -1 & -5 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} r(t)$$

$$c(t) = [10 \quad 8 \quad 0 \quad 0]\mathbf{x}$$

14. a. $$\frac{Y(s)}{R(s)} = \frac{10}{s^3 + 5s^2 + 2s + 3}$$

19. $$\dot{\mathbf{x}} = \begin{bmatrix} -\frac{D_{eq}}{J_{eq}} & 0 & \frac{K_t N_1}{J_{eq} N_2} \\ 1 & 0 & 0 \\ -\frac{K_b N_2}{L_a N_1} & 0 & -\frac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} \omega_L \\ \theta_L \\ i_a \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_a} \end{bmatrix} e_a$$

$$y = \begin{bmatrix} 0 & \frac{N_2}{N_1} & 0 \end{bmatrix} \begin{bmatrix} \omega_L \\ \theta_L \\ i_a \end{bmatrix}$$

Chapter 4

14. $$x(t) = \frac{1}{5}\left[1 - \sqrt{\frac{20}{19}} e^{-0.5t} \cos\left(\frac{\sqrt{19}}{2}t - \arctan\frac{1}{\sqrt{19}}\right)\right]$$

20. a. $\zeta = 0.375$; $\omega_n = 4$ rad/s; $T_s = 2.67$ s; $T_p = 0.847$ s; $\%OS = 28.06$

23. a. $s = -6.67 \pm j9.88$

35. $s = -5.79, -1.21$

36. a. $s^3 - 8s^2 - 11s + 8 = 0$ **b.** $s = 9.11, 0.534, -1.64$

40. $$y(t) = \frac{2}{5} - \frac{2}{5}e^{-5t}$$

43.

$$\Phi(t) = \begin{bmatrix} 1.0455e^{-0.20871t} - 0.045545e^{-4.7913t} & 0.21822e^{-0.20871t} - 0.21822e^{-4.7913t} \\ -0.21822e^{-0.20871t} + 0.21822e^{-4.7913t} & -0.045545e^{-0.20871t} + 1.0455e^{-4.7913t} \end{bmatrix}$$

$$\mathbf{x}(t) = \begin{bmatrix} 1.0455e^{-0.20871t} - 0.045545e^{-4.7913t} \\ -0.21822e^{-0.20871t} + 0.21822e^{-4.7913t} \end{bmatrix}$$

$$y(t) = 0.60911e^{-0.20871t} + 0.39089e^{-4.7913t}$$

73. $D = 0.143$ N-m-s/rad

76. $R = 912\,\Omega$

Chapter 5

2. $\dfrac{C(s)}{R(s)} = \dfrac{G_3(G_1G_2 + 1)}{1 + G_1H_1}$

4. $\dfrac{C(s)}{R(s)} = \dfrac{G_1G_2 + G_3}{1 + G_3H + G_1G_2H + G_2G_4}$

6. $\dfrac{C(s)}{R(s)} = \dfrac{G_1G_5}{1 + G_1G_2 + G_1G_3G_4G_5 + G_1G_3G_5G_6G_7 + G_1G_5G_8}$

9. $\dfrac{C(s)}{R(s)} = \dfrac{G_4G_6 + G_2G_5G_6 + G_3G_5G_6}{1 + G_6 + G_1G_2 + G_1G_3 + G_1G_2G_6 + G_1G_3G_6 + G_4G_6G_7 + G_2G_5G_6G_7 + G_3G_5G_6G_7}$

26. $\dfrac{C(s)}{R(s)} = \dfrac{G_1G_2G_3G_4}{2 + G_2G_3G_4 + 2G_3G_4 + 2G_4}$

27. $\dfrac{C(s)}{R(s)} = \dfrac{G_1G_6G_7(G_2 + G_3)(G_4 + G_5)}{1 - G_6G_7H_3(G_2 + G_3)(G_4 + G_5) - G_6H_1 - G_7H_2 + G_6G_7H_1H_2}$

28. $\dfrac{C(s)}{R(s)} = \dfrac{s^3 + 1}{2s^4 + s^2 + 2s}$

30. b. $\dot{\mathbf{x}} = \begin{bmatrix} -5 & 1 & 0 & 0 \\ 0 & -5 & 0 & 0 \\ 0 & 0 & -7 & 1 \\ 0 & 0 & 0 & -7 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} r(t)$

$$y = \begin{bmatrix} -\frac{3}{4} & 1 & -\frac{5}{4} & -1 \end{bmatrix} \mathbf{x}$$

37. $\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & -1 & 0 & 0 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} r(t)$

$c = [-1 \quad 1 \quad 0 \quad 0]\mathbf{x}$

73. $D_L = 3560$ N-m-s/rad

Chapter 6

1. 2 rhp, 3 lhp, 0 $j\omega$

3. 3 rhp, 2 lhp, 0 $j\omega$

4. 1 rhp, 0 lhp, 4 $j\omega$
5. 0 rhp, 2 lhp, 2 $j\omega$
9. Unstable
17. 1 rhp, 2 lhp, 4 $j\omega$
23. $K > \frac{3}{4}$; $K < -1$
39. **a.** $-4 < K < 20.41$; **b.** 1.36 rad/s
41. **a.** $0 < K < 19.69$; **b.** $K = 19.69$; **c.** $s = \pm j1.118, -4.5, -3.5$
42. $-\frac{2}{3} < K < 0$

Chapter 7

4. $e_{\text{step}}(\infty) = 0$; $e_{\text{ramp}}(\infty) = 127.5$; $e_{\text{parabola}}(\infty) = \infty$
7. $\dot{e}(\infty) = 0.9$
10. **a.** $\%OS = 14.01$; **b.** $T_s = 0.107$ sec; **c.** $e_{\text{step}}(\infty) = 0$;
d. $e_{\text{ramp}}(\infty) = 0.075$; **e.** $e_{\text{parabola}}(\infty) = \infty$
13. **a.** $K_p = \frac{1}{3}$, $K_v = 0$, $K_a = 0$; **b.** $e(\infty) = 37.5, \infty, \infty,$ respectively;
c. Type 0
20. $K = 110,000$
27. $\beta = 1$, $K = 1.16$, $\alpha = 7.76$, or $\beta = -1$, $K = 5.16$, $\alpha = 1.74$
31. **a.** $K = 831,744$, $a = 831.744$
35. $K_1 = 125,000$, $K_2 = 0.016$
41. **a.** Step: $e(\infty) = 1.098$; ramp: $e(\infty) = \infty$

Chapter 8

16. Breakaway point $= -2.333$; asymptotes: $\sigma_a = -5$; $j\omega$-axis crossing $= \pm j7.35$
19. **b.** Asymptotes: $\sigma_a = -\frac{8}{3}$; **c.** $K = 140.8$; **d.** $K = 13.12$
20. $K = 9997$; $\alpha = 7$
23. **a.** $\sigma_a = -\frac{5}{2}$; **b.** $s = -1.38, -3.62$; **c.** $0 < K < 126$; **d.** $K = 10.3$
26. **b.** $K = 9.4$; **c.** $T_s = 4.62$ s, $T_p = 1.86$ s; **d.** $s = -4.27$; **e.** $0 < K < 60$
30. $\alpha = 9$
39. **a.** $0 < K < 4366$; **b.** $K = 827.2$; **c.** $K = 527.6$
42. **a.** $K = 170.1$; **b.** $K = 16.95$

Chapter 9

1. $G_c(s) = \frac{s + 0.1}{s}$; $K \simeq 72.23$ for both cases; $K_{p_O} = 2.44$; $K_{p_N} = \infty$;
$\%OS_O = \%OS_N = 16.3$; $T_{s_O} = T_{s_N} = 2.65$ s

9. **a.** $s = -2.5 \pm j5.67$; **b.** Angle $= -59.27°$; **c.** $s = -5.87$
d. $K = 225.79$; **e.** $s = -11.59, -1.36$

10. **a.** $s = -2.4 \pm j4.16$; **b.** $s = -6.06$; **c.** $K = 29.12$;
d. $s = -1.263$; **f.** $K_a = 4.8$

14. **a.** $G_c(s) = \dfrac{s+7}{s+37.42}$, $K = 5452$; dominant poles $= -4.13 \pm j10.78$

24. **a.** $K_{uc} = 10$; $K_c = 9.95$; **b.** $K_{p_{uc}} = 1.25$; $K_{p_c} = 6.22$;
c. $\%OS_{uc} = \%OS_c = 4.32$;
d. Uncompensated: exact second-order system, approximation OK; compensated: closed-loop pole at -0.3, closed-loop zero at -0.5, simulate
e. Approach to final value longer than settling time of uncompensated system
f. $G_{\text{LLC}}(s) = \dfrac{404.1(s+0.5)(s+4)}{(s+2)(s+4)(s+0.1)(s+28.36)}$ yields approximately a 5 times improvement in speed.

25. $G_c(s) = \dfrac{(s+6.93)(s+0.1)}{s}$, $K = 3.08$

28. Poles $= -0.747 \pm j1.237, -2.51$; zeros—none

Chapter 10

10. System 1: $0 < K < 490.2$; System 2: $0 < K < 1.4$; System 3: $1 < K < \infty$ (Answers are from exact frequency response)

11. **a.** System 1: $G_M = -6.38$ dB; $\Phi_M = -20.3°$ (Answers are from exact frequency response)

15. **c.** $\omega_{\text{BW}} = 2.29$ rad/s

23. System 2: $T_s = 2.23$ sec, $T_p = 0.476$ s, $\%OS = 42.62$ (Answers are from exact frequency response)

44. $G_M = 1.17$ dB, $\Phi_M = 6.01°$ (Answers are from exact frequency response)

Chapter 11

1. **a.** $K = 2113$ (Answer is from exact frequency response)

2. **a.** $K = 2365$ (Answer is from exact frequency response)

3. **a.** $K = 575$ (Answer is from exact frequency response)

12. $G_c(s) = \dfrac{s+2.701}{s+5.954}$, $K = 7936$

(Answer is from exact frequency response)

21. $G_c(s) = \dfrac{(s+0.097)(s+2.16)}{s}$, $K = 25.189$

(Answer is from exact frequency response)

Chapter 12

1. **d.** For function **i**: $T(s) = \dfrac{s+3}{s^2 + (k_2+8)s + (k_1+16)}$

3. b. For function **i**: $G(s) = \dfrac{6.25}{s} - \dfrac{27.5}{s+10} + \dfrac{71.25}{s+20}, \quad T(s) = \dfrac{200(s^2+7s+25)}{4s^3+as^2+bs+c}$

where $a = (25k_3 - 110k_2 + 285k_1 + 120)$
$b = (750k_3 - 2200k_2 + 2850k_1 + 800)$
$c = 5000k_3$
and $\mathbf{C} = [1 \quad 1 \quad 1]$; $\mathbf{B} = [71.25 \quad -27.5 \quad 6.25]^T$ was used

11. a. Uncontrollable; **b.** Controllable; **c.** Controllable

14. $\mathbf{K} = [92.35 \quad 36.78 \quad -7]$ for a characteristic polynomial of $(s+6)(s^2+8s+45.78) = s^3 + 14s^2 + 93.78s + 274.7$

23. $\mathbf{L} = [-671.19 \quad 1472.4]^T$ for a characteristic polynomial of $s^2 + 144s + 14,400$

Chapter 13

3. a. $f(kT) = 229.5(0.4)^k - 504(0.6)^k + 275.5(0.8)^k$

6. c. $G(z) = 0.395 \dfrac{(z + 0.2231)}{(z - 0.2231)(z^2 + 0.1857z + 0.04979)}$

8. b. $G(z) = 0.0517 \dfrac{z^2 + 2.2699z + 0.2995}{(z-1)(z-0.2231)(z-0.4065)}$

9. a. $T(z) = \dfrac{G_1(z)G_2(z)}{1 + G_1(z)G_2H(z)}$

14. $0 < K < 15.76$

15. a. $K_p = \dfrac{1}{2}$, $e^*(\infty) = \dfrac{2}{3}$; $K_v = 0$, $e^*(\infty) = \infty$; $K_a = 0$, $e^*(\infty) = \infty$

17. $K = 14.18$ for 16.3% of overshoot; $0 < K < 109.28$ for stability

Credits

Figure and Photo Credits

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Chapter 1

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Chapter 2

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Chapter 4

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Chapter 5

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Chapter 6

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