INTRODUCTION TO MECHATRONICS AND MEASUREMENT SYSTEMS

5th edition

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SOLUTIONS MANUAL

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Solutions Manual

This manual contains solutions to the end-of-chapter problems in the fifth edition of "Introduction to Mechatronics and Measurement Systems." Only a few of the open-ended problems that do not have a unique answer are left for your creative solutions. More information, including an example course outline, a suggested laboratory syllabus, Mathcad/Matlab files for examples in the book, and other supplemental material are provided on the book website at:

mechatronics.colostate.edu

We have class-tested the textbook for many years, and it should be relatively free from errors. However, if you notice any errors or have suggestions or advice concerning the textbook's content or approach, please feel free to contact me via e-mail at David.Alciatore@colostate.edu. I will post corrections for reported errors on the book website.

Thank you for choosing my book. I hope it helps you provide your students with an enjoyable and fruitful learning experience in the exciting cross-disciplinary subject of mechatronics.

2.1 D = 0.06408 in = 0.001628 m.

$$A = \frac{\pi D^2}{4} = 2.082 \times 10^{-6}$$

$\rho = 1.7 \text{ x } 10^{-8}\ \Omega\text{m}$, L = 1000 m

$$R = \frac{\rho L}{A} = 8.2\Omega$$

2.2

(a) $R_1 = 21 \times 10^4 \pm 20\%$ so $168\text{k}\Omega \le R_1 \le 252\text{k}\Omega$

(b) $R_2 = 07 \times 10^3 \pm 20\%$ so $5.6\text{k}\Omega \le R_2 \le 8.4\text{k}\Omega$

(c) $R_s = R_1 + R_2 = 217\text{k}\Omega \pm 20\%$ so $174\text{k}\Omega \le R_s \le 260\text{k}\Omega$

(d) $$R_p = \frac{R_1 R_2}{R_1 + R_2}$$

$$R_{p_{MIN}} = \frac{R_{1_{MIN}} R_{2_{MIN}}}{R_{1_{MIN}} + R_{2_{MIN}}} = 5.43\text{k}\Omega$$

$$R_{p_{MAX}} = \frac{R_{1_{MAX}} R_{2_{MAX}}}{R_{1_{MAX}} + R_{2_{MAX}}} = 8.14\text{k}\Omega$$

2.3 $R_1 = 10 \times 10^2$, $R_2 = 25 \times 10^1$

$$R = \frac{R_1 R_2}{R_1 + R_2} = \frac{(10 \times 10^2)(25 \times 10^1)}{10 \times 10^2 + 25 \times 10^1} = 20 \times 10^1$$

a = 2 = red, b = 0 = black, c = 1 = brown, d = gold

2.4 In series, the trim pot will add an adjustable value ranging from 0 to its maximum value to the original resistor value depending on the trim setting. When in parallel, the trim pot could be 0Ω perhaps causing a short. Furthermore, the trim value will not be additive with the fixed resistor.

2.5 When the last connection is made, a spark occurs at the point of connection as the completed circuit is formed. This spark could ignite gases produced in the battery. The negative terminal of the battery is connected to the frame of the car, which serves as a ground reference throughout the vehicle.

2.6 No, as long as you are consistent in your application, you will obtain correct answers. If you assume the wrong current direction, the result will be negative.

2.7 Place two 100Ω resistors in parallel and you immediately have a 50Ω resistance.

2.8 Put two 50Ω resistors in series: 50Ω + 50Ω = 100Ω

2.9 Put a 100Ω resistor in series with the parallel combination of two 100Ω resistors:

$100\Omega + (100\Omega * 100\Omega)/(100\Omega + 100\Omega) = 150\Omega$

2.10 From KCL, $I_s = I_1 + I_2 + I_3$

so from Ohm's Law $\frac{V_s}{R_{eq}} = \frac{V_s}{R_1} + \frac{V_s}{R_2} + \frac{V_s}{R_3}$

Therefore, $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$ so $R_{eq} = \frac{R_1R_2R_3}{R_2R_3 + R_1R_3 + R_1R_2}$

2.11 From Ohm's Law and Question 2.10, $V = \frac{I_s}{R_{eq}} = \frac{I_s}{\frac{R_2R_3 + R_1R_3 + R_1R_2}{R_1R_2R_3}}$

and for one resistor, $V = I_1R_1$

Therefore, $I_1 = \left(\frac{R_2R_3}{R_2R_3 + R_1R_3 + R_1R_2}\right)I_s$

2.12 $\lim_{R_1 \to \infty}\left(\frac{R_1R_2}{R_1 + R_2}\right) = \frac{R_1R_2}{R_1} = R_2$

2.13 $I = C_{eq}\frac{dV}{dt} = C_1\frac{dV_1}{dt} = C_2\frac{dV_2}{dt}$

From KVL,

$$V = V_1 + V_2$$

so

$$\frac{dV}{dt} = \frac{dV_1}{dt} + \frac{dV_2}{dt}$$

Therefore,

$$\frac{I}{C_{eq}} = \frac{I}{C_1} + \frac{I}{C_2} \quad \text{so} \quad \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} \quad \text{or} \quad C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

2.14 $V = V_1 = V_2$

$I_1 = C_1 \frac{dV_1}{dt} = C_1 \frac{dV}{dt}$ and $I_2 = C_2 \frac{dV_2}{dt} = C_2 \frac{dV}{dt}$

From KCL,

$$I = I_1 + I_2 = C_1 \frac{dV}{dt} + C_2 \frac{dV}{dt} = \frac{dV}{dt}(C_1 + C_2)$$

Since $I = C_{eq} \frac{dV}{dt}$

$$C_{eq} = C_1 + C_2$$

2.15 $I = I_1 = I_2$

From KVL,

$$V = V_1 + V_2 = L_1 \frac{dI}{dt} + L_2 \frac{dI}{dt} = \frac{dI}{dt}(L_1 + L_2)$$

Since $V = L_{eq} \frac{dI}{dt}$

$$L_{eq} = L_1 + L_2$$

2.16 $V = L \frac{dI}{dt} = L_1 \frac{dI_1}{dt} = L_2 \frac{dI_2}{dt}$

From KCL, $I = I_1 + I_2$ so $\frac{dI}{dt} = \frac{dI_1}{dt} + \frac{dI_2}{dt}$

Therefore, $\frac{V}{L} = \frac{V}{L_1} + \frac{V}{L_2}$ so $\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2}$ or $L = \frac{L_1 L_2}{L_1 + L_2}$

2.17 $V_o = 1V$, regardless of the resistance value.

2.18 From Voltage Division, $V_o = \frac{40}{10 + 40}(5 - 15) = -8V$

2.19 Combining R_2 and R_3 in parallel,

$$R_{23} = \frac{R_2R_3}{R_2 + R_3} = \frac{2(3)}{2+3} = 1.2k$$

and combining this with R_1 in series,

$$R_{123} = R_1 + R_{23} = 2.2k$$

(a) Using Ohm's Law,

$$I_1 = \frac{V_{in}}{R_{123}} = \frac{5V}{2.2k} = 2.27mA$$

(b) Using current division,

$$I_3 = \frac{R_2}{R_2 + R_3}I_1 = \frac{2}{5}2.27mA = 0.909mA$$

(c) Since R_2 and R_3 are in parallel, and since V_{in} divides between R_1 and R_{23},

$$V_3 = V_{23} = \frac{R_{23}}{R_1 + R_{23}}V_{in} = \frac{1.2}{2.2}5V = 2.73V$$

2.20

(a) From Ohm's Law,

$$I_4 = \frac{V_{out} - V_1}{R_{24}} = \frac{14.2V - 10V}{6k} = 0.7mA$$

(b) $V_5 = V_6 = V_{56} = V_{out} - V_2 = 14.2V - 20V = -5.8V$

2.21

(a) $R_{45} = R_4 + R_5 = 5k\Omega$

$$R_{345} = \frac{R_3R_{45}}{R_3 + R_{45}} = 1.875k\Omega$$

$$R_{2345} = R_2 + R_{345} = 3.875k\Omega$$

$$R_{eq} = \frac{R_1R_{2345}}{R_1 + R_{2345}} = 0.795k\Omega$$

(b) $V_A = \dfrac{R_{345}}{R_2 + R_{345}}V_s = 4.84V$

(c) $I_{345} = \frac{V_A}{R_{345}} = 2.59\text{mA}$

$I_5 = \frac{R_3}{R_3 + R_{45}} I_{345} = 0.97\text{mA}$

2.22 This circuit is identical to the circuit in Question 2.21. Only the resistance values are different:

(a) $R_{45} = R_4 + R_5 = 4\text{k}\Omega$

$R_{345} = \frac{R_3 R_{45}}{R_3 + R_{45}} = 2.222\text{k}\Omega$

$R_{2345} = R_2 + R_{345} = 6.222\text{k}\Omega$

$R_{eq} = \frac{R_1 R_{2345}}{R_1 + R_{2345}} = 1.514\text{k}\Omega$

(b) $V_A = \frac{R_{345}}{R_2 + R_{345}} V_s = 3.57\text{V}$

(c) $I_{345} = \frac{V_A}{R_{345}} = 1.61\text{mA}$

$I_5 = \frac{R_3}{R_3 + R_{45}} I_{345} = 0.89\text{mA}$

2.23 Using superposition,

$$V_{R2_1} = \frac{R_2}{R_1 + R_2} V_1 = 0.909\text{V}$$

$$V_{R2_2} = \frac{R_1}{R_1 + R_2} i_1 = 9.09\text{V}$$

$$V_{R2} = V_{R2_1} + V_{R2_2} = 10.0\text{V}$$

2.24 $R_{45} = \frac{R_4 R_5}{R_4 + R_5} = 0.5\text{k}\Omega$

$I = \frac{V_1 - V_2}{R_1 + R_2} = -0.5\text{mA}$

$$V_A = \frac{R_{45}}{R_3 + R_{45}}(V_1 - V_2) = -0.238V$$

2.25 $R_{45} = R_4 + R_5 = 9k\Omega$

$$R_{345} = \frac{R_3 R_{45}}{R_3 + R_{45}} = 2.25k\Omega$$

$$R_{2345} = R_2 + R_{345} = 4.25k\Omega$$

$$R_{eq} = \frac{R_1 R_{2345}}{R_1 + R_{2345}} = 0.81k\Omega$$

2.26 Using loop currents, the KVL equations for each loop are:

$$V_1 - I_{out}R_1 = 0$$

$$V_2 - I_5R_5 - I_3R_3 - V_1 = 0$$

$$-I_6R_6 + I_5R_5 = 0$$

$$I_3R_3 - I_{24}R_4 - I_{24}R_2 = 0$$

and using selected KCL node equations, the unknown currents are related according to:

$$I_{out} = I_2 + I_3 + I_{V_1}$$

$$I_{V_1} = I_{out} - (I_5 + I_6)$$

$$I_3 = I_5 + I_6 - I_{24}$$

This is now 7 equations in 7 unknowns, which can be solved for I_{out} and I_6. The output voltage is then given by:

$$V_{out} = V_2 - I_6R_6$$

2.27 Applying Ohm's Law to resistor combination R_{24} gives:

$$I_4 = \frac{V_{out} - V_1}{R_{24}} = \frac{4.2V}{6k\Omega} = 0.7mA$$

The voltage across R_5 is:

$$V_5 = V_6 = V_{56} = V_+ - V_- = V_{out} - V_2 = -5.8V$$

2.28 It will depend on your instrumentation, but the oscilloscope typically has an input impedance of 1 MΩ.

2.29 Since the input impedance of the oscilloscope is 1 MΩ, the impedance of the source will be in parallel, and the oscilloscope impedance will affect the measured voltage. Draw a sketch of the equivalent circuit to convince yourself.

2.30 $R_{23} = \dfrac{R_2 R_3}{R_2 + R_3}$

$$V_{out} = \frac{R_{23}}{R_1 + R_{23}} V_{in}$$

(a) $R_{23} = 9.90\text{k}\Omega$, $V_{out} = 0.995 V_{in}$

(b) $R_{23} = 333\text{k}\Omega$, $V_{out} = 1.00 V_{in}$

When the impedance of the load is lower (10k vs. 500k), the accuracy is not as good.

2.31 $V_{out} = \dfrac{R_2}{R_1 + R_2} V_{in}$

(a) $V_{out} = \dfrac{10}{10.05} V_{in} = 0.995 V_{in}$

(b) $V_{out} = \dfrac{500}{500.05} V_{in} = 0.9999 V_{in}$

For a larger load impedance, the output impedance of the source less error.

2.32 The theoretical value of the voltage is:

$$V_{theor} = \frac{R}{R + R} V_s = \frac{1}{2} V_s$$

The equivalent resistance of the parallel combination of the resistor and the voltmeter input impedance is:

$$\frac{R \cdot 5R}{R + 5R} = \frac{5}{6} R$$

And the measured voltage across this resistance is:

$$V_{meas} = \frac{\frac{5}{6} R}{R + \frac{5}{6} R} V_s = \frac{5}{11} V_s$$

Therefore, the percent error in the measurement is:

$$\frac{V_{meas} - V_{theor}}{V_{theor}} = -9\%$$

2.33 It will depend on the supply; check the specifications before answering.

2.34 With the voltage source shorted, all three resistors are in parallel, so, from Question 2.10:

$$R_{TH} = \frac{R_1R_2R_3}{R_2R_3 + R_1R_3 + R_1R_2}$$

2.35 $V_{in} = 5\langle 45°\rangle$

Combining R_2 and L in series and the result in parallel with C gives:

$$Z_{R_2LC} = \frac{(R_2 + Z_L)Z_C}{(R_2 + Z_L) + Z_C} = 1860.52\langle -60.25°\rangle = 923.22 - 1615.30j$$

Using voltage division,

$$V_C = \frac{Z_{R_2LC}}{R_1 + Z_{R_2LC}}V_{in}$$

where

$$R_1 + Z_{R_2LC} = 1000 + 923.22 - 1615.30j = 2511.57\langle -40.02°\rangle$$

so

$$V_C = \frac{1860.52\langle -60.25°\rangle}{2511.57\langle -40.02°\rangle}5\langle 45°\rangle = 3.70\langle 24.8°\rangle = 3.70\langle 0.433\text{rad}\rangle$$

Therefore,

$$V_C(t) = 3.70\cos(3000t + 0.433)V$$

2.36 With steady state dc V_s, C is open circuit. So

$$V_C = V_s = 10V \text{ so } V_{R_1} = 0V \text{ and } V_{R_2} = V_s = 10V$$

2.37

(a) In steady state dc, C is open circuit and L is short circuit. So

$$I = \frac{V_s}{R_1 + R_2} = 0.025mA$$

(b) $\omega = \pi$

$$Z_C = \frac{-j}{\omega C} = \frac{-10^6}{\pi}j = \frac{10^6}{\pi}\angle -90°\Omega$$

$$Z_{LR_2} = Z_L + R_2 = j\omega L + R_2 = (10^5 + 20\pi j)\Omega = 10^5\angle 0.036°\Omega$$

$$Z_{CLR_2} = \frac{Z_C Z_{LR_2}}{Z_C + Z_{LR_2}} = (91040 - 28550j)\Omega = 95410\angle{-17.4°}\Omega$$

$$Z_{eq} = R_1 + Z_{CLR_2} = (191040 - 28550j)\Omega = 193200\angle{-8.50°}\Omega$$

$$I_s = \frac{V_s}{Z_{eq}} = 0.0259\angle 8.50°\text{mA}$$

$$I = \frac{Z_C}{Z_C + Z_{LR_2}} I_s = (0.954\angle{-17.44°})I_s = 0.0247\angle{-8.94°}\text{mA}$$

So

$$I(t) = 24.7\cos(\pi t - 0.156)\mu\text{A}$$

2.38

(a) $\omega = \pi\frac{\text{rad}}{\text{sec}}, \ f = \frac{\omega}{2\pi} = 0.5\text{Hz}$

$A_{pp} = 2A = 4.0, \ dc_{offset} = 0$

(b) $\omega = 2\pi\frac{\text{rad}}{\text{sec}}, \quad f = \frac{\omega}{2\pi} = 1\text{Hz}$

$A_{pp} = 2A = 2, \ dc_{offset} = 10.0$

(c) $\omega = 2\pi\frac{\text{rad}}{\text{sec}}, \quad f = \frac{\omega}{2\pi} = 1\text{Hz}$

$A_{pp} = 2A = 6.0, \ dc_{offset} = 0$

(d) $\omega = 0\frac{\text{rad}}{\text{sec}}, \quad f = \frac{\omega}{2\pi} = 0\text{Hz}$

$A_{pp} = 2A = 0, \ dc_{offset} = \sin(\pi) + \cos(\pi) = -1$

2.39 $P = \frac{V_{rms}^2}{R} = 100\text{W}$

2.40 $V_{rms} = \left(\frac{V_{pp}}{2}\right)/(\sqrt{2}) = 35.36\text{V}$

$$P = \frac{V_{rms}^2}{R} = 12.5\text{W}$$

2.41 $V_m = \sqrt{2}V_{rms} = 169.7\text{V}$

2.42 For $V_{rms} = 120\text{V}$, $V_m = \sqrt{2}V_{rms} = 169.7\text{V}$, and f = 60 Hz,

$$V(t) = V_m \sin(2\pi f + \phi) = 169.7\sin(120\pi t + \phi)$$

2.43 From Ohm's Law,

$$I = \frac{5V - 2V}{R} = \frac{3V}{R}$$

Since $10\text{mA} \le I \le 100\text{mA}$,

$$10\text{mA} \le \frac{3V}{R} \le 100\text{mA}$$

giving

$$\frac{3V}{100\text{mA}} \le R \le \frac{3V}{10\text{mA}} \quad \text{or} \quad 30\Omega \le R \le 300\Omega$$

For a resistor, $P = \frac{V^2}{R}$, so the smallest allowable resistance would need a power rating of at least:

$$P = \frac{(3V)^2}{30\Omega} = 0.3\text{W}$$

so a 1/2 W resistor should be specified.

The largest allowable resistance would need a power rating of at least:

$$P = \frac{(3V)^2}{300\Omega} = 0.03\text{W}$$

so a 1/4 W resistor would provide more than enough capacity.

2.44 Using KVL and KCL gives:

$$V_1 = I_{R_1}R_1$$

$$V_1 = (I_1 - I_{R_1})R_2 + (I_1 - I_{R_1} - I_2)R_3$$

$$V_3 - V_2 = (I_1 - I_{R_1} - I_2)R_3 - I_2R_4$$

The first loop equation gives:

$$I_{R_1} = \frac{V_1}{R_1} = 10\text{mA}$$

Using this in the other two loop equations gives:

$$10 = (I_1 - 10\text{m})2\text{k} + (I_1 - 10\text{m} - I_2)3\text{k}$$

$$10 - 5 = (I_1 - 10\text{m} - I_2)3\text{k} - I_2 4\text{k}$$

or

$$(5\text{k})I_1 - (3\text{k})I_2 = 60$$

$$(3\text{k})I_1 - (7\text{k})I_2 = 35$$

Solving these equations gives:

$$I_1 = 12.12\text{mA} \quad \text{and} \quad I_2 = 0.1923\text{mA}$$

(a) $V_{out} = I_2 R_4 - V_2 = -4.23\text{V}$

(b) $P_1 = I_1 V_1 = 121\text{mW}$, $P_2 = I_2 V_2 = 0.962\text{mW}$, $P_3 = -I_2 V_3 = -1.92\text{mW}$

2.45 Using KVL and KCL gives:

$$V_1 = I_{R_1} R_1$$

$$V_1 = (I_1 - I_{R_1})R_2 + (I_1 - I_{R_1} - I_2)R_3$$

$$V_3 - V_2 = (I_1 - I_{R_1} - I_2)R_3 - I_2 R_4$$

The first loop equation gives:

$$I_{R_1} = \frac{V_1}{R_1} = 10\text{mA}$$

Using this in the other two loop equations gives:

$$10 = (I_1 - 10\text{m})2\text{k} + (I_1 - 10\text{m} - I_2)2\text{k}$$

$$10 - 5 = (I_1 - 10\text{m} - I_2)2\text{k} - I_2 1\text{k}$$

or

$$(4\text{k})I_1 - (2\text{k})I_2 = 50$$

$$(2\text{k})I_1 - (3\text{k})I_2 = 25$$

Solving these equations gives:

$$I_1 = 12.5\text{mA} \quad \text{and} \quad I_2 = 0\text{mA}$$

(a) $V_{out} = I_2R_4 - V_2 = -5V$

(b) $P_1 = I_1V_1 = 125\text{mW},\ P_2 = I_2V_2 = 0\text{mW},\ P_3 = -I_2V_3 = 0\text{mW}$

2.46 $P_{avg} = \frac{1}{T}\int_0^T V(t)I(t)dt = \frac{V_mI_m}{T}\int_0^T \sin(\omega t + \phi_V)\sin(\omega t + \phi_I)dt$

Using the product formula trigonometric identity,

$$P_{avg} = \frac{V_mI_m}{2T}\int_0^T (\cos(\phi_V - \phi_I) - \cos(2\omega t + \phi_V + \phi_I))dt$$

Therefore,

$$P_{avg} = \frac{V_mI_m}{2}\cos(\phi_V - \phi_I) = \frac{V_mI_m}{2}\cos(\theta)$$

2.47 $I_{rms} = \sqrt{\frac{1}{T}\int_0^T I_m^2 \sin^2(\omega t + \phi_I)dt}$

Using the double angle trigonometric identity,

$$I_{rms} = \sqrt{\frac{I_m^2}{T}\int_0^T \left(\frac{1}{2} - \cos[2(\omega t + \phi_I)]\right)dt}$$

Therefore,

$$I_{rms} = \sqrt{\frac{I_m^2}{T}\left(\frac{T}{2}\right)} = \frac{I_m}{2}$$

2.48 $R_{23} = \frac{R_2R_3}{R_2 + R_3} = 5k\Omega$

$$V_o = \frac{R_{23}}{R_1 + R_{23}}V_i = \frac{1}{2}\sin(2\pi t)$$

This is a sin wave with half the amplitude of the input with a period of 1s.

2.49 No. A transformer requires a time varying flux to induce a voltage in the secondary coil.

2.50 $\frac{N_p}{N_s} = \frac{V_p}{V_s} = \frac{120V}{24V} = 5$

2.51 $R_L = R_i = 8\Omega$ for maximum power

2.52 The BNC cable is far more effective in shielding the input signals from electromagnetic interference since no loops are formed.