

***Introduction to Mechatronics and Measurement
Systems 5th edition Alciatore Solutions Manual***

SKU: 9781259892349-SOLUTIONS

INTRODUCTION TO MECHATRONICS AND MEASUREMENT SYSTEMS

5th edition

2018

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.

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2.1 $D = 0.06408 \text{ in} = 0.001628 \text{ m}$.

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

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

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

2.2

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

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

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

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

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

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

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.

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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: $50\Omega + 50\Omega = 100\Omega$

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 $R_{eq} = \frac{R_1 R_2 R_3}{R_2 R_3 + R_1 R_3 + R_1 R_2}$

2.11 From Ohm's Law and Question 2.10, $V = \frac{I_s}{R_{eq}} = \frac{I_s}{\frac{R_2 R_3 + R_1 R_3 + R_1 R_2}{R_1 R_2 R_3}}$

and for one resistor, $V = I_1 R_1$

Therefore, $I_1 = \left(\frac{R_2 R_3}{R_2 R_3 + R_1 R_3 + R_1 R_2} \right) I_s$

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

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

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

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Therefore,

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

2.14 $V = V_1 = V_2$

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

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

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2.19 Combining R_2 and R_3 in parallel,

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

and combining this with R_1 in series,

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

(a) Using Ohm's Law,

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

(b) Using current division,

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

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

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

2.20

(a) From Ohm's Law,

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

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

2.21

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.23 Using superposition,

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

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

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

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

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

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

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 $1M\Omega$.

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- 2.29 Since the input impedance of the oscilloscope is $1\text{ M}\Omega$, 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.

$$2.30 \quad R_{23} = \frac{R_2 R_3}{R_2 + R_3}$$

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

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

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

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

$$2.31 \quad V_{\text{out}} = \frac{R_2}{R_1 + R_2} V_{\text{in}}$$

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

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

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

- 2.32 The theoretical value of the voltage is:

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

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:

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

Therefore, the percent error in the measurement is:

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

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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:

$$R_{TH} = \frac{R_1 R_2 R_3}{R_2 R_3 + R_1 R_3 + R_1 R_2}$$

2.35 $V_{in} = 5 \angle 45^\circ$

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

$$Z_{R_2 LC} = \frac{(R_2 + Z_L)Z_C}{(R_2 + Z_L) + Z_C} = 1860.52 \angle -60.25^\circ = 923.22 - 1615.30j$$

Using voltage division,

$$V_C = \frac{Z_{R_2 LC}}{R_1 + Z_{R_2 LC}} V_{in}$$

where

$$R_1 + Z_{R_2 LC} = 1000 + 923.22 - 1615.30j = 2511.57 \angle -40.02^\circ$$

so

$$V_C = \frac{1860.52 \angle -60.25^\circ}{2511.57 \angle -40.02^\circ} 5 \angle 45^\circ = 3.70 \angle 24.8^\circ = 3.70 \angle 0.433 \text{ rad}$$

Therefore,

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

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

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

2.37

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

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

(b) $\omega = \pi$

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

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

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

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

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

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

So

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

2.38

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

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

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

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

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

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

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

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

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

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

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

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

$$2.42 \quad \text{For } V_{\text{rms}} = 120 \text{ V}, \quad V_m = \sqrt{2} V_{\text{rms}} = 169.7 \text{ V}, \quad \text{and } f = 60 \text{ Hz},$$
$$V(t) = V_m \sin(2\pi f t + \phi) = 169.7 \sin(120\pi t + \phi)$$

2.43 From Ohm's Law,

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

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

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

giving

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

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

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

so a 1/2 W resistor should be specified.

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

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

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

2.44 Using KVL and KCL gives:

$$V_1 = I_{R_1} R_1$$

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

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

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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:

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

$$10 - 5 = (I_1 - 10\text{m} - I_2)3\text{k} - I_24\text{k}$$

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:

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

$$(a) \quad V_{\text{out}} = I_2R_4 - V_2 = -4.23\text{V}$$

$$(b) \quad P_1 = I_1V_1 = 121\text{mW}, \quad P_2 = I_2V_2 = 0.962\text{mW}, \quad P_3 = -I_2V_3 = -1.92\text{mW}$$

2.45 Using KVL and KCL gives:

$$V_1 = I_{R_1}R_1$$

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

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

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:

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

$$10 - 5 = (I_1 - 10\text{m} - I_2)2\text{k} - I_21\text{k}$$

or

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

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

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Solving these equations gives:

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

$$(a) \quad V_{\text{out}} = I_2 R_4 - V_2 = -5\text{V}$$

$$(b) \quad P_1 = I_1 V_1 = 125\text{mW}, \quad P_2 = I_2 V_2 = 0\text{mW}, \quad P_3 = -I_2 V_3 = 0\text{mW}$$

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

Using the product formula trigonometric identity,

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

Therefore,

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

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

Using the double angle trigonometric identity,

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

Therefore,

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

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

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

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