

Op-amps with resistive components

Q1. [Problem 8.1]

Solution:

- Known quantities:

For the circuit shown in Figure P8.1:

$$G = \frac{P_o}{P_s} \quad R_s = 0.6 \text{ k}\Omega \quad R_L = 0.6 \text{ k}\Omega$$

$$R_{i1} = 3 \text{ k}\Omega \quad R_{i2} = 3 \text{ k}\Omega \quad R_{o1} = 2 \text{ k}\Omega \quad R_{o2} = 2 \text{ k}\Omega$$

$$A_{vo1} = 100 \quad G_{M2} = 350 \text{ m}\Omega^{-1} \quad V_{i2} = V_{i2} \quad V_{i1} = V_{i1}$$

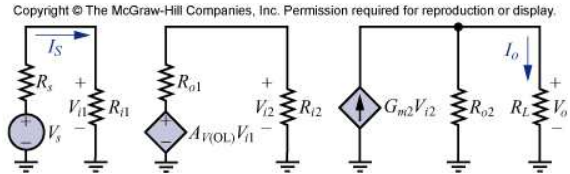


Figure P8.1

- Find:

The power gain $G = P_o/P_s$, in dB.

- Analysis:

Starting from the last stage and going backward, we get

$$V_o = G_{M2} V_{i2} \frac{R_{o2} R_L}{R_{o2} + R_L} = 161.5 V_{i2} \Rightarrow P_o = V_o I_o = \frac{V_o^2}{R_L} = 43.49 V_{i2}^2$$

$$V_{i2} = A_{vo1} V_{i1} \frac{R_{i2}}{R_{i2} + R_{o1}} = 60 V_{i1} \Rightarrow P_o = 1.566 \cdot 10^5 V_{i1}^2$$

$$V_{i1} = V_s \frac{R_{i1}}{R_{i1} + R_s} = 0.833 V_s \Rightarrow P_o = 1.0875 \cdot 10^5 V_s^2$$

$$I_s = V_s \frac{1}{R_{i1} + R_s} = 2.778 \cdot 10^{-4} V_s \Rightarrow P_s = V_s I_s = 2.778 \cdot 10^{-4} V_s^2$$

$$G = \frac{P_o}{P_s} = \frac{1.0875 \cdot 10^5}{2.778 \cdot 10^{-4}} = 3.915 \cdot 10^8 = 10 \text{ dB Log}_{10}[3.915 \cdot 10^8] = 85.9 \text{ dB}$$

Q2. [Problem 8.2]

Solution:

- Known quantities:

The temperature sensor shown in Figure P8.2 produces a no load (i.e., sensor current = 0) voltage:

$$v_s = V_{so} \cos \omega t \quad R_s = 400 \Omega \quad V_{so} = 500 \text{ mV} \quad \omega = 6.28 \text{ k} \frac{\text{rad}}{\text{s}}$$

The temperature is monitored on a display (the load) with a vertical line of light emitting diodes. Normal conditions are indicated when a string of the bottommost diodes 2 cm in length are on. This requires that a voltage be supplied to the display input terminals where: $R_L = 12 \text{ k}\Omega$ $v_o = V_o \cos \omega t$ $V_o = 6 \text{ V}$.

The signal from the sensor must therefore be amplified. Therefore, a voltage amplifier is connected between the sensor and CRT with: $R_i = 2 \text{ k}\Omega$ $R_o = 3 \text{ k}\Omega$.

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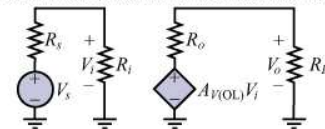


Figure P8.2

- Find:

The required no load gain of the amplifier.

- Analysis:

The overall loaded voltage gain, using the amplitudes of the sensor voltage and the specified CRT voltage must be:

$$A_V = \frac{V_o}{V_{so}} = \frac{6 \text{ V}}{500 \text{ mV}} = 12$$

An expression for the overall voltage gain can also be obtained using two voltage divider relationships:

$$V_o = A_{vo} V_{io} \frac{R_L}{R_o + R_L} = A_{vo} \left[V_{so} \frac{R_i}{R_i + R_s} \right] \frac{R_L}{R_o + R_L}$$

$$A_{vo} = \frac{V_o}{V_{so}} = \frac{A_v [R_s + R_i] [R_o + R_L]}{R_i R_L} = \frac{[12][0.4 + 2][3 + 12]}{[2][12]} = 18$$

The loss in gain due to the two voltage divisions or "loading" is characteristic of all practical amplifiers. Ideally, there is no reduction in gain due to loading. This would require an ideal signal source with a source resistance equal to zero and a load resistance equal to infinity.

Q3. [Problem 8.19]

Solution:

- Known quantities:
The circuit of Figure P8.19.

- Find:
Show that this circuit is a non-inverting summer.

- Analysis:

Applying KCL at the inverting terminal: $V_3 = (1 + \frac{R_f}{R})V^-$

Applying KCL at the noninverting terminal:

$$\left(\frac{1}{R_2} + \frac{1}{R_1}\right)V^+ - \frac{V_2}{R_2} - \frac{V_1}{R_1} = 0$$

$$\text{or } V^+ = \frac{R_1}{R_1 + R_2}V_2 + \frac{R_2}{R_1 + R_2}V_1$$

therefore,

$$V_3 = (1 + \frac{R_f}{R})\left(\frac{R_1}{R_1 + R_2}V_2 + \frac{R_2}{R_1 + R_2}V_1\right) \text{ and the circuit does indeed compute the weighted sum of the inputs}$$

Q4. [Problem 8.9]

Solution:

- Known quantities:
The circuit of Figure P8.9.

- Find:
The overall gain $A_v = v_o/v_i$; input conductance $G_{in} = i_i/i_o$.

- Analysis:

Applying KVL at node 1:

$$\frac{v_1 - v_i}{2} + \frac{v_1 - v_2}{4} + \frac{v_1 - v_o}{4} = 0 \text{ or } -2v_i + 4v_1 - v_2 = v_o \quad (1)$$

Again, at node 2:

$$\frac{v_2 - v_1}{4} + \frac{v_2}{4} = 0 \text{ or } 2v_2 = v_1 \quad (2)$$

Similarly, at node 3:

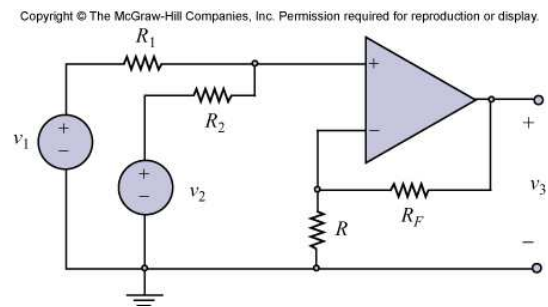


Figure P8.19

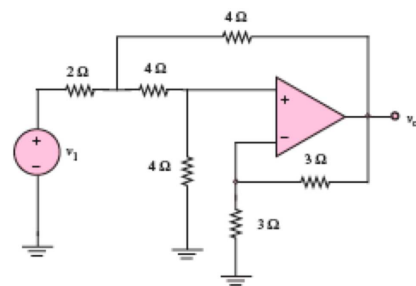


Figure P8.9

$$\frac{v_2}{3} + \frac{v_2 - v_o}{3} = 0 \text{ or } v_2 = \frac{1}{2}v_o \quad (3)$$

Substituting (3) into (2):

$$v_o = v_1$$

Substituting (2) and (3) into (3):

$$-2v_i = v_o + \frac{1}{2}v_o - 8\left(\frac{1}{2}v_o\right) \text{ or } \frac{v_o}{v_i} = \frac{4}{5}$$

$$\therefore A_v = \frac{4}{5}$$

Now, since

$$i_i = \frac{v_i - v_1}{2} = \frac{v_i - v_o}{2} = \frac{v_i - 0.8v_i}{2} = 0.1v_i$$

Therefore, $G = v_i/i_i = 0.1 \text{ S}$

Q5. [Problem 8.21]

Solution:

- Known quantities:

The circuit of Figure P8.21: $\Delta R = \alpha(\pm \Delta T)$

- Find:

- Thevenin equivalent seen from point a and b.
- Expression for $v_{out}(\Delta T)$, if $|\Delta R| = K\Delta T$.

- Analysis:

- The circuit can be reduced to the following form using Thévenin equivalent circuits:

The equivalent circuit seen at the inverting node (node a) is:

$$R_o - |\Delta R| = R_o \left(1 - \frac{|\Delta R|}{R_o}\right)$$

$$R_o + |\Delta R| = R_o \left(1 + \frac{|\Delta R|}{R_o}\right)$$

The Thévenin (open circuit) voltage is:

$$V_{OC(a)} = \frac{R_o \left(1 - \frac{|\Delta R|}{R_o}\right) V_S}{R_o \left(1 + \frac{|\Delta R|}{R_o}\right) + 1 - \frac{|\Delta R|}{R_o}} = \frac{\left(1 - \frac{|\Delta R|}{R_o}\right) V_S}{2}$$

and the Thévenin resistance is:

$$R_{T(a)} = R_o \left(1 + \frac{|\Delta R|}{R_o}\right) \parallel R_o \left(1 + \frac{|\Delta R|}{R_o}\right) = \frac{R_o}{2} \left(1 - \left(\frac{|\Delta R|}{R_o}\right)^2\right)$$

The equivalent circuit seen at the non-inverting node (node b) is:

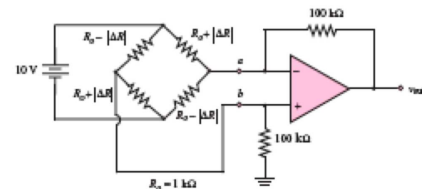
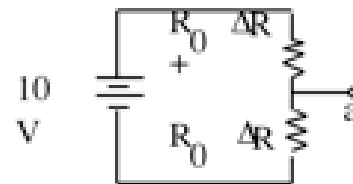
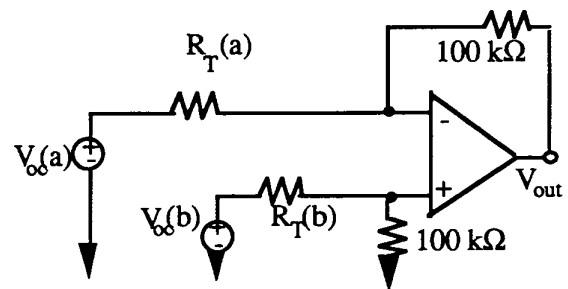


Figure P8.21



The Thévenin (open circuit) voltage is:

$$V_{OC(b)} = \frac{(1 + \frac{|\Delta R|}{R_o})V_S}{2}$$

$$R_{T(b)} = \frac{R_o}{2} (1 - (\frac{|\Delta R|}{R_o}))$$

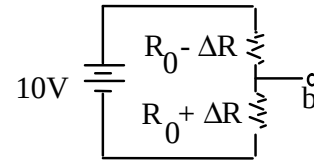
Assuming $|\Delta R|^2 \ll R_o$

$$V_{OC(a)} = (1 - \frac{|\Delta R|}{R_o}) \cdot 5 \text{ V}$$

$$R_{T(a)} = 500 \text{ } \Omega$$

$$V_{OC(b)} = (1 + \frac{|\Delta R|}{R_o}) \cdot 5 \text{ V}$$

$$R_{T(b)} = 500 \text{ } \Omega$$



(b) For a difference amplifier:

$$\begin{aligned} V_{out} &= \frac{R_f}{R_s} (V_{OC(b)} - V_{OC(a)}) \\ &= \frac{100^5}{500} (V_{OC(b)} - V_{OC(a)}) \\ &= 200 \cdot 5 \cdot (1 + \frac{|\Delta R|}{R_o}) - (1 - \frac{|\Delta R|}{R_o}) \\ &= 2 |\Delta R| \end{aligned}$$

But if $|\Delta R| = K\Delta T$, then

$$V_{out} = 2K\Delta T$$

Q6. [Problem 8.34]

Solution:

- Known quantities:

If, in the circuit shown in Figure P8.34:

$$v_{S1} = v_{S2} = 7 \text{ mV} \quad R_1 = 850 \text{ } \Omega \quad R_2 = 1.5 \text{ k}\Omega \quad R_F = 2.2 \text{ k}\Omega$$

Op Amp: *Motorola MC1741C*

$$r_i = 2 \text{ M}\Omega \quad \mu = 200,000 \quad r_o = 25 \text{ } \Omega$$

- Find:

- The output voltage.
- The voltage gain for the two input signals.

- Analysis:

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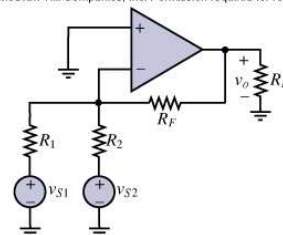


Figure P8.34

- a) The op amp has a very large input resistance, a very large "open loop gain" $[\mu]$, and a very small output resistance. Therefore, it can be modeled with small error as an ideal op amp with:

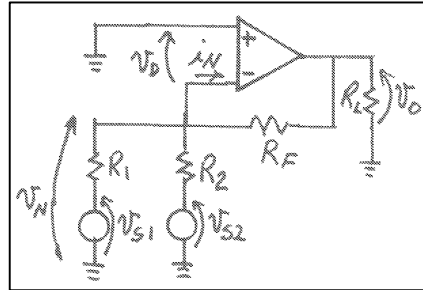
$$\text{KVL: } v_D + v_N = 0$$

$$v_D \approx 0 \Rightarrow v_N \approx 0$$

$$\text{KCL:}$$

$$i_N + \frac{v_N - v_{S2}}{R_2} + \frac{v_N - v_{S1}}{R_1} + \frac{v_N - v_O}{R_F} = 0$$

$$v_N \approx 0 \quad i_N \approx 0$$



$$\begin{aligned} \Rightarrow v_O &= -\frac{R_F}{R_1} v_{S1} - \frac{R_F}{R_2} v_{S2} = \left[-\frac{2.2}{0.85} \right] [7 \text{ mV}] + \left[-\frac{2.2}{1.5} \right] [7 \text{ mV}] \\ &= [-2.588] [7 \text{ mV}] + [-1.467] [7 \text{ mV}] = -28.38 \text{ mV} \end{aligned}$$

- b) Using the results above: $A_{v1} = -2.588$ $A_{v2} = -1.467$.

Note: The output voltage and gain are not dependent on either the op amp parameters or the load resistance. This result is extremely important in the majority of applications where amplification of a signal is required.

Q7. [Problem 8.36]

Solution:

- Known quantities:

- Find:

In a differential amplifier, if: $A_{v1} = -20$ $A_{v2} = +22$, derive expressions for and then determine the value of the common and differential mode gains.

- Analysis

First consider the case when both inputs are in phase with equal amplitude (common mode).

$\Rightarrow$ This means that $V_1 = V_2 = V_{in}$

$$V_{o-cm} = (A_{v1} + A_{v2})V_{in}$$

Now, the common mode gain equals the common mode output (V_{o-cm}) over the input V_{in}

$$\Rightarrow A_{cm} = V_{o-cm}/V_{in} = A_{v1} + A_{v2} = 2$$

Now consider the case when the input are out of phase with equal amplitude (differential mode).

$\Rightarrow$ This means that $V_2 = -V_1 = V_{in}$

$$V_{o-dm} = (-A_{v1} + A_{v2})V_{in}$$

Now, the common mode gain equals the common mode output (V_{o-cm}) over the twice of V_{in} . This is because the differential input is given by: $V_2 - V_1 = 2V_{in}$

$$\Rightarrow A_{dm} = V_{o-cm}/2V_{in} = (-A_{v1} + A_{v2})/2 = 21$$

NOTE: When considering the differential mode output, it does not matter whether we set V_{in} follow V_2 or V_1 . This is because we are not interested in the sign of A_{dm} but simply its magnitude.

Q8. [Problem 8.44]Solution:

• Known quantities:
Circuit in Figure P8.44.

• Find:
The output voltage v_o .

• Analysis:
The circuit is a cascade of a noninverting op-amp with an inverting op-amp. Assuming ideal op-amps, the input-output voltage gain is equal to the product of the single gains, therefore

$$v_o = -\frac{R_{F2}}{R_{S2}} \left(1 + \frac{R_{F1}}{R_{S1}} \right) v_S$$

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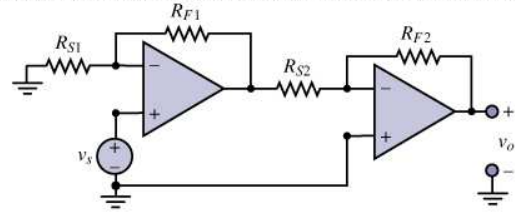


Figure P8.44

Q9. [Problem 8.41]Solution:

• Known quantities:
The circuit shown in Figure P8.41.

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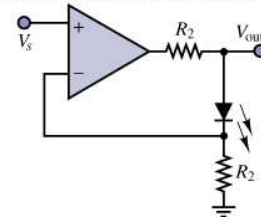


Figure P8.41

• Find:
Show that the current I_{out} through the light-emitting diode is proportional to the source voltage V_S as long as $V_S > 0$.

• Analysis:

Assume the op amp is ideal:
$$\left. \begin{array}{l} V^- \approx V^+ = V_S \\ I^- \approx 0 \end{array} \right\} \Rightarrow \text{if } V_S > 0 \quad I_{out} = \frac{V^-}{R_2} = \frac{V_S}{R_2}.$$