Chapter 14

Exercise Solutions

E14.1

$v_{ICM}(\max) = V^+ - V_{SD1}(sat) - V_{SG1}$

$v_{ICM}(\min) = V^- + V_{DS4}(sat) + V_{SD1}(sat) - V_{SG1}$

We have:

$I_{REF} = 100\ \mu A,\ k_n' = 80\ \mu A/V^2,\ k_p' = 40\ \mu A/V^2,$

$\left(\frac{W}{L}\right) = 25$

For M_1:

$I_D = 50 = \left(\frac{40}{2}\right)(25)(V_{SG1} + V_{TP})^2$

So $50 = 500(V_{SG1} - 0.5)^2 \Rightarrow V_{SG1} = 0.816\,V$

$V_{SD1}(sat) = 0.816 - 0.5 = 0.316\,V$

Then

$v_{CM}(\max) = V^+ - 0.316 - 0.816 = V^+ - 1.13\,V$

For M_4:

$I_D = 100 = \left(\frac{80}{2}\right)(25)(V_{GS4} - V_{TN})^2$

So $100 = 1000(V_{GS4} - 0.5)^2 \Rightarrow V_{GS4} = 0.816\,V$

$V_{DS4}(sat) = 0.816 - 0.5 = 0.316\,V$

$v_{CM}(\min) = V^- + 0.316 + 0.316 - 0.816 = V^- - 0.184$

So

$\underline{V^- - 0.184 \le v_{CM} \le V^+ - 1.13\,V}$

E14.2

$v_o(\max) = V^+ - V_{SD8}(sat) - V_{SD10}(sat)$

$v_o(\min) = V^- + V_{DS4}(sat) + V_{DS6}(sat)$

Now

$V_{SG8} = V_{SG10} = \sqrt{\frac{50}{(40/2)(25)}} + 0.5 = 0.816\,V$

$V_{SD8}(sat) = V_{SD10}(sat) = 0.316\,V$

So $v_o(\max) = V^+ - 0.316 - 0.316 = V^+ - 0.632$

Also

$V_{GS6} = \sqrt{\frac{50}{(80/2)(25)}} + 0.5 = 0.724\,V$

$V_{GS4} = \sqrt{\frac{100}{(80/2)(25)}} + 0.5 = 0.816\,V$

$V_{DS6}(sat) = 0.724 - 0.5 = 0.224\,V$

$V_{DS4}(sat) = 0.816 - 0.5 = 0.316\,V$

So $v_o(\min) = V^- + 0.316 + 0.224 = V^- + 0.54$

Then

$\underline{V^- + 0.54 \le v_o \le V^+ - 0.632\,V}$

E14.3

a. $A_{CL} = \dfrac{-50}{\left[1 + \left(\frac{1}{5 \times 10^4}\right)(51)\right]}$

$\Rightarrow \underline{A_{CL} = -49.949}$

b. $\dfrac{dA_{CL}}{A_{CL}} = 10 \times \dfrac{51}{5 \times 10^4} \Rightarrow \underline{\dfrac{dA_{CL}}{A_{CL}} = 0.0102\%}$

$A_{CL} = \dfrac{-50}{\left[1 + \frac{51}{4.5 \times 10^4}\right]} \Rightarrow \underline{A_{CL} = -49.943}$

E14.4

$A_{CL}(\text{ideal}) = -\dfrac{500}{20} = -25$

Within 0.1% $\Rightarrow -25 + (0.001)(25)$

$\Rightarrow A_{CL} = -24.975$

$-24.975 = \dfrac{-25}{\left[1 + \frac{26}{A_{OL}}\right]}$

$\dfrac{26}{A_{OL}} = \dfrac{-25}{-24.975} - 1 = 0.0010$

$\underline{A_{OL} = 25,974}$

E14.5

a. $A_{CL} = \dfrac{A_{CL}(\infty)}{1 + \left[\frac{A_{CL}(\infty)}{A_{OL}}\right]}$

$A_{CL}(\infty) = 1 + \dfrac{R_2}{R_1} = 1 + \dfrac{495}{5} = 100$

$A_{CL} = \dfrac{100}{1 + \frac{100}{10^5}} \Rightarrow \underline{A_{CL} = 99.90}$

$\underline{A_{CL}(\infty) = 100}$

b. $\dfrac{dA_{CL}}{A_{CL}} = 10 \times \dfrac{100}{10^5} = \underline{0.01\%}$

$A_{CL} = 99.90 - (0.0001)(99.90)$

$\Rightarrow \underline{A_{CL} = 99.89}$

E14.6

$\dfrac{A_{CL}(\infty) - A_{CL}}{A_{CL}(\infty)} = 1 - \dfrac{A_{CL}}{A_{CL}(\infty)} = 1 - \dfrac{1}{1 + \frac{A_{CL}(\infty)}{A_{CL}}}$

So $0.001 = \dfrac{1 + \frac{A_{CL}(\infty)}{A_{CL}} - 1}{1 + \frac{A_{CL}(\infty)}{A_{CL}}} = \dfrac{\frac{A_{CL}(\infty)}{A_{CL}}}{1 + \frac{A_{CL}(\infty)}{A_{CL}}}$

$$0.001 = 0.999 \cdot \frac{A_{CL}(\infty)}{A_{0L}}$$
$$A_{CL}(\infty) = \frac{0.001}{0.999} \cdot A_{0L} = \frac{0.001}{0.999} \cdot (10^4)$$
$$\Rightarrow \underline{A_{CL}(\infty) = 10.010}$$

or

$$A_{CL} = (1 - 0.001)(10.010)$$
$$\Rightarrow \underline{A_{CL} = 10.0}$$

E14.7

a. For $R_0 = 0$

$$\frac{1}{R_{if}} = \frac{1}{10} + \frac{1}{10}(1 + 10^4) = 0.1 + 10^3$$
$$\Rightarrow \underline{R_{if} = 10^{-3}\ \text{k}\Omega = 1\ \Omega}$$

b. For $R_0 = 10\ \text{k}\Omega$

$$\frac{1}{R_{if}} = \frac{1}{10} + \frac{1}{10} \times \left[\frac{1 + 10^4 + 1}{1 + 1 + 1}\right] \cong 0.1 + \frac{10^4}{3(10)}$$
$$R_{if} = 3 \times 10^{-3}\ \text{k}\Omega$$
$$\Rightarrow \underline{R_{if} = 3\ \Omega}$$

E14.8

$$\frac{i_f}{i_1} = \left(\frac{R_{if}}{R_i}\right)$$

a. $\dfrac{i_f}{i_1} = \dfrac{0.1}{10^4} = \underline{1 \times 10^{-5}}$

b. $\dfrac{i_f}{i_1} = \dfrac{10}{10^4} = \underline{1 \times 10^{-3}}$

E14.9

$$R_{if} = \frac{40(1 + 10^4) + 99\left(1 + \frac{40}{1}\right)}{1 + \frac{99}{1}}$$
$$\cong \frac{4 \times 10^5 + 4.059 \times 10^3}{100}$$
$$R_{if} = 4.04 \times 10^3\ \text{k}\Omega \Rightarrow \underline{R_{if} = 4.04\ \text{M}\Omega}$$

E14.10

Voltage follower $R_2 = 0,\ R_1 = \infty$

$$R_{if} = R_i(1 + A_{0L}) = 10(1 + 5 \times 10^5)$$
$$\cong 5 \times 10^6\ \text{k}\Omega \Rightarrow \underline{R_{if} = 5000\ \text{M}\Omega}$$

E14.11

$$1 + \frac{R_2}{R_1} = 100$$

a. $\dfrac{1}{R_{0f}} = \dfrac{1}{100}\left[\dfrac{10^5}{100}\right] = 10$

$$\Rightarrow \underline{R_{0f} = 0.1\ \Omega}$$

b. $\dfrac{1}{R_{0f}} = \dfrac{1}{10}\left[\dfrac{10^5}{100}\right] = 10^2$

$$R_{0f} = 10^{-2}\ \text{k}\Omega \Rightarrow \underline{R_{0f} = 10\ \Omega}$$

E14.12

From Equation (14.43)

$$A_{CL}(f) = \frac{A_{CL0}}{1 + j \cdot \dfrac{f}{f_{PD}(A_0/A_{CL0})}}$$
$$= \frac{25}{1 + j \cdot \dfrac{f}{(50)(10^4/25)}} = \frac{25}{1 + j \cdot \dfrac{f}{2 \times 10^4}}$$

a. For $f = 2\ \text{kHz}$

$$\frac{v_O}{v_I} = 25 \Rightarrow \underline{v_O(\text{peak}) = 1.25\ \text{mV}}$$

b. $f = 20\ \text{kHz}$

$$\frac{v_O}{v_I} = \frac{1}{\sqrt{2}} \cdot 25 \Rightarrow \underline{v_O(\text{peak}) = 0.884\ \text{mV}}$$

c. $f = 100\ \text{kHz}$

$$\frac{v_O}{v_I} = \frac{25}{\sqrt{1 + (100/20)^2}} = \frac{25}{5.099} = 4.90$$
$$\Rightarrow \underline{v_O = 0.245\ \text{mV}}$$

E14.13

Full-scale response $= 1 \times 5 = 5$ V

$$t = \frac{5}{2} \Rightarrow \underline{t = 2.5\ \mu s}$$

E14.14

a. $FPBW = \dfrac{SR}{2\pi V_0(\max)} = \dfrac{0.63 \times 10^6}{2\pi(1)}$

$$FPBW = 1.0 \times 10^5 \Rightarrow \underline{FPBW = 100\ \text{kHz}}$$

b. $FPBW = \dfrac{0.63 \times 10^6}{2\pi(10)} = 1.0 \times 10^4$

$$\Rightarrow \underline{FPBW = 10\ \text{kHz}}$$

E14.15

$$f_{3dB} = \frac{f_T}{A_{CLO}} = \frac{(10^5)(10)}{50} \Rightarrow 20 \text{ kHz}$$

$$f_{max} = f_{3dB} = \frac{SR}{2\pi V_0(\max)}$$

$$V_0(\max) = \frac{SR}{2\pi f_{3dB}} = \frac{0.8 \times 10^6}{2\pi(20 \times 10^3)}$$

$$\Rightarrow \underline{V_0(\max) = 6.37 \text{ V}}$$

E14.16

$$|V_{OS}| = \left|V_T \ln\left(\frac{I_{S2}}{I_{S1}}\right)\right| = (0.026)\ln\left(\frac{1.35 \times 10^{-14}}{2 \times 10^{-14}}\right)$$

$$\Rightarrow \underline{V_{OS} = 2.03 \text{ mV}}$$

E14.17

We need

$i_{C1} = i_{C2}$, $v_{EC3} = v_{EC4} = 0.6$ V, and

$v_{CE1} = v_{CE2} = 10$ V

By Equation (14.60(a))

$$i_{C1} = I_{S1}\left[\exp\left(\frac{v_{BE1}}{V_T}\right)\right]\left(1 + \frac{10}{50}\right)$$

$$= I_{S3}\left[\exp\left(\frac{v_{EB3}}{V_T}\right)\right]\left(1 + \frac{0.6}{50}\right)$$

By Equation (14.60(b))

$$i_{C2} = I_{S2}\left[\exp\left(\frac{v_{BE2}}{V_T}\right)\right]\left(1 + \frac{10}{50}\right)$$

$$= I_{S4}\left[\exp\left(\frac{v_{EB4}}{V_T}\right)\right]\left(1 + \frac{0.6}{50}\right)$$

$I_{S1} = I_{S2}$, take the ratio:

$$\exp\left(\frac{v_{BE1} - v_{BE2}}{V_T}\right) = \frac{I_{S3}}{I_{S4}}$$

$$v_{BE1} - v_{BE2} = V_{OS} = V_T \ln\left(\frac{I_{S3}}{I_{S4}}\right)$$

$$= 0.026 \cdot \ln(1.05)$$

$$\Rightarrow \underline{V_{OS} = 1.27 \text{ mV}}$$

E14.18

$$V_{os} = \frac{1}{2}\cdot\sqrt{\frac{I_Q}{2K_n}}\cdot\left(\frac{\Delta K_n}{K_n}\right)$$

$$0.020 = \frac{1}{2}\cdot\sqrt{\frac{150}{2(50)}}\cdot\left(\frac{\Delta K_n}{50}\right)$$

$$\Rightarrow \underline{\Delta K_n = 1.63\ \mu A / V^2}$$

$$\Rightarrow \frac{\Delta K_n}{K_n} = \frac{1.63}{50} \Rightarrow \underline{3.26\ \%}$$

E14.19

$$\text{Want } \left(\frac{R_5}{R_5 + R_4}\right)V^+ = 5 \text{ mV}$$

$$R_5 \ll R_4 \text{ so } \frac{R_5}{R_4} \times V^+ = 0.005$$

$$R_5 = \frac{(0.005)(100)}{10} = 0.05 \text{ k}\Omega$$

$$\Rightarrow \underline{R_5 = 50\ \Omega}$$

E14.20

$R_1' = 25\|1 = 0.9615$ kΩ

$R_2' = 75\|1 = 0.9868$ kΩ

For $I_Q = 100\ \mu$A $\Rightarrow i_{C1} = i_{C2} = 50\ \mu$A

From Equation (14.75)

$$(0.026)\ln\left(\frac{50 \times 10^{-6}}{10^{-14}}\right) + (0.050)(0.9615)$$

$$= (0.026)\ln\left(\frac{i_{C2}}{I_{S4}}\right) + (0.050)(0.9868)$$

$$0.58065 + 0.048075$$

$$= (0.026)\ln\left(\frac{i_{C2}}{I_{S4}}\right) + 0.04934$$

$$\ln\left(\frac{i_{C2}}{I_{S4}}\right) = 22.284$$

$$\frac{50 \times 10^{-6}}{I_{S4}} = 4.7625 \times 10^9$$

$$\underline{I_{S4} \cong 1.05 \times 10^{-14} \text{ A}}$$

E14.21

From Equation (14.79)

$$v_0 = I_{B1}R_2 - I_{B2}R_3\left(1 + \frac{R_2}{R_1}\right)$$

For $v_0 = 0$

$$0 = (1.1 \times 10^{-6})(100 \text{ k}\Omega) - (1.0 \times 10^{-6})R_3\left(1 + \frac{100}{10}\right)$$

$$R_3(11) = (1.1)(100 \text{ k}\Omega) \Rightarrow \underline{R_3 = 10 \text{ k}\Omega}$$

E14.22

a. $v_0 = I_{B1}R_3 = (10^{-6})(200 \times 10^3)$

$$\Rightarrow \underline{v_0 = 0.20 \text{ V}}$$

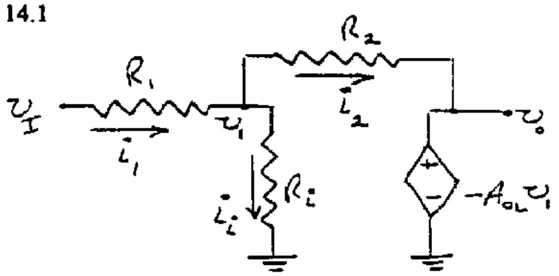
b. $R_4 = R_1\|R_2\|R_3 = 100\|50\|200$

$$\Rightarrow \underline{R_4 = 28.6 \text{ k}\Omega}$$

Chapter 14

Problem Solutions

14.1



$$\frac{v_I - v_1}{R_1} = \frac{v_1 - v_0}{R_2} + \frac{v_1}{R_i} \text{ and } v_0 = -A_{OL}v_1$$

so that $v_1 = -\dfrac{v_0}{A_{OL}}$

$$\frac{v_I}{R_1} + \frac{v_0}{R_2} = v_1\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_i}\right)$$

So

$$\frac{v_I}{R_1} = -v_0\left[\frac{1}{R_2} + \frac{1}{A_{OL}}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_i}\right)\right]$$

Then

$$\frac{v_0}{v_I} = \frac{-(1/R_1)}{\left[\frac{1}{R_2} + \frac{1}{A_{OL}}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_i}\right)\right]} = A_{CL}$$

From Equation (14.20) for $R_L = \infty$ and $R_0 = 0$

$$\frac{1}{R_{if}} = \frac{1}{R_i} + \frac{1}{R_2} \cdot \frac{(1 + A_{OL})}{1}$$

a. For $R_i = 1\ \text{k}\Omega$

$$A_{CL} = \frac{-(1/20)}{\left[\frac{1}{100} + \frac{1}{10^3}\left(\frac{1}{20} + \frac{1}{100} + \frac{1}{1}\right)\right]} = \frac{-0.05}{[0.01 + 1.06 \times 10^{-3}]}$$

or

$$\Rightarrow \underline{A_{CL} = -4.52}$$

$$\frac{1}{R_{if}} = \frac{1}{1} + \frac{1 + 10^3}{100} \Rightarrow \underline{R_{if} = 90.8\ \Omega}$$

b. For $R_i = 10\ \text{k}\Omega$

$$A_{CL} = \frac{-(1/20)}{\left[\frac{1}{100} + \frac{1}{10^3}\left(\frac{1}{20} + \frac{1}{100} + \frac{1}{10}\right)\right]} = \frac{-0.05}{[0.01 + 1.6 \times 10^{-4}]}$$

or

$$\Rightarrow \underline{A_{CL} = -4.92}$$

$$\frac{1}{R_{if}} = \frac{1}{10} + \frac{1 + 10^3}{100} \Rightarrow \underline{R_{if} = 98.9\ \Omega}$$

c. For $R_i = 100\ \text{k}\Omega$

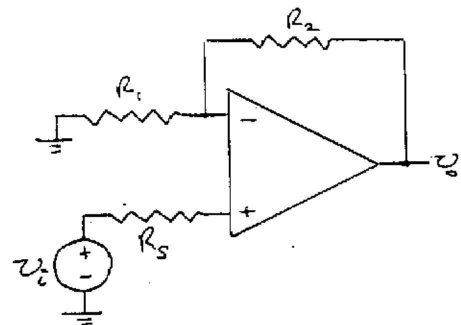
$$A_{CL} = \frac{-(1/20)}{\left[\frac{1}{100} + \frac{1}{10^3}\left(\frac{1}{20} + \frac{1}{100} + \frac{1}{100}\right)\right]} = \frac{-0.05}{[0.01 + 7 \times 10^{-5}]}$$

or

$$\Rightarrow \underline{A_{CL} = -4.965}$$

$$\frac{1}{R_{if}} = \frac{1}{100} + \frac{1 + 10^3}{100} \Rightarrow \underline{R_{if} = 99.8\ \Omega}$$

14.2



$$A_{CL} = \frac{v_o}{v_i} = \frac{\left(1 + \frac{R_2}{R_1}\right)}{\left[1 + \frac{1}{A_{OL}}\left(1 + \frac{R_2}{R_1}\right)\right]}$$

For the ideal:

$$\left(1 + \frac{R_2}{R_1}\right) = \frac{0.10}{0.002} = 50$$

$$v_o(actual) = (0.10)(1 - 0.001) = 0.0999$$

So

$$\frac{0.0999}{0.002} = \frac{50}{1 + \frac{1}{A_{OL}}(50)} = 49.95$$

which yields

$$\underline{A_{OL} = 1000}$$

14.3

$$A_{vf1} = \frac{v_{o1}}{v_1} = \frac{-\left(\frac{A_{OL}}{R_o} - \frac{1}{R_2}\right)}{\left(\frac{1}{R_L} + \frac{1}{R_o} + \frac{1}{R_2}\right)}$$

Or

$$v_{o1} = \frac{-\left(\frac{5x10^3}{1} - \frac{1}{100}\right)}{\left(\frac{1}{10} + \frac{1}{1} + \frac{1}{100}\right)} \cdot v_1 = \frac{-(4.99999x10^3)}{1.11} \cdot v_1$$

$v_{o1} = -4.504495x10^3 \cdot v_1$

Now

$$\frac{i_1}{v_1} = \frac{v_i - v_1}{R_1 v_1} \equiv K$$

Then

$v_i - v_1 = KR_1 v_1$

which yields

$$v_1 = \frac{v_i}{KR_1 + 1}$$

Now

$$K = \frac{1}{10} + \frac{1}{100}\left[\frac{1 + 5x10^3 + \frac{1}{10}}{1 + \frac{1}{10} + \frac{1}{100}}\right]$$

$$= (0.1) + (0.01)\left[\frac{5.0011x10^3}{1.11}\right] = 45.15495$$

Then

$$v_1 = \frac{v_i}{(45.15495)(10) + 1} = \frac{v_i}{452.5495}$$

We find

$$v_{o1} = -4.504495x10^3\left[\frac{v_i}{452.5495}\right]$$

Or

$$A_{vf1} = \frac{v_{o1}}{v_i} = -9.9536$$

For the second stage, $R_L = \infty$

$$v_{o2} = \frac{-\left(\frac{5x10^3}{1} - \frac{1}{100}\right)}{\left(\frac{1}{1} + \frac{1}{100}\right)} \cdot v_1' = -4.950485x10^3 \cdot v_1'$$

$$K = \frac{1}{10} + \frac{1}{100}\left[\frac{1 + 5x10^3}{1 + \frac{1}{100}}\right] = 49.61485$$

$$v_1' = \frac{v_{o1}}{KR_1 + 1} = \frac{v_{o1}}{(49.61485)(10) + 1} = \frac{v_{o1}}{497.1485}$$

Then

$$\frac{v_{o2}}{v_{o1}} = \frac{-4.950485x10^3}{497.1485} = -9.95776$$

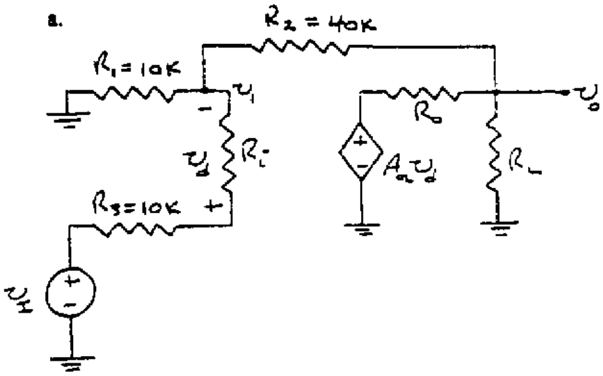
So

$$A_{vf} = \frac{v_{o2}}{v_i} = (-9.9536)(-9.95776) \Rightarrow$$

$$A_{vf} = 99.12$$

14.4

a.



$$\frac{v_1 - v_I}{R_3 + R_i} + \frac{v_1}{R_1} + \frac{v_1 - v_0}{R_2} = 0 \quad (1)$$

$$v_1\left[\frac{1}{R_3 + R_i} + \frac{1}{R_1} + \frac{1}{R_2}\right] = \frac{v_0}{R_2} + \frac{v_I}{R_3 + R_i}$$

$$\frac{v_0}{R_L} + \frac{v_0 - A_{0L}v_d}{R_0} + \frac{v_0 - v_1}{R_2} = 0 \quad (2)$$

or

$$v_0\left[\frac{1}{R_L} + \frac{1}{R_0} + \frac{1}{R_2}\right] = \frac{v_1}{R_2} + \frac{A_{0L}v_d}{R_0}$$

$$v_d = \left(\frac{v_I - v_1}{R_3 + R_i}\right) \cdot R_i \quad (3)$$

So substituting numbers:

$$v_1\left[\frac{1}{10 + 20} + \frac{1}{10} + \frac{1}{40}\right] = \frac{v_0}{40} + \frac{v_I}{10 + 20} \quad (1)$$

or

$$v_1[0.15833] = v_0[0.025] + v_I[0.03333]$$

$$v_0\left[\frac{1}{1} + \frac{1}{0.5} + \frac{1}{40}\right] = \frac{v_1}{40} + \frac{(10^4)v_d}{0.5} \quad (2)$$

or

$$v_0[3.025] = v_1[0.025] + (2 \times 10^4)v_d$$

$$v_d = \left(\frac{v_I - v_1}{10 + 20}\right) \cdot 20 = 0.6667(v_I - v_1) \quad (3)$$

So

$$v_0[3.025] = v_1[0.025] + (2 \times 10^4)(0.6667)(v_I - v_1)$$

or (2)

$$v_0[3.025] = 1.333 \times 10^4 v_I - 1.333 \times 10^4 v_1$$

From (1):

$v_1 = v_0(0.1579) + v_I(0.2105)$

Then

$v_0[3.025] = 1.333 \times 10^4 v_I$
$\qquad - 1.333 \times 10^4[v_0(0.1579) + v_I(0.2105)]$

$v_0[2.1078 \times 10^3] = v_I[1.0524 \times 10^4]$

or

$$\underline{A_{CL} = \frac{v_0}{v_I} = 4.993}$$

To find R_{if}: Use Equation (14.27)

$$i_I\left(1 + \frac{0.5}{1} + \frac{0.5}{40}\right)$$
$$= v_1\left\{\left(\frac{1}{10} + \frac{1}{40}\right)\left(1 + \frac{0.5}{1} + \frac{0.5}{40}\right) - \frac{0.5}{(40)^2}\right\} - \frac{(10^3)v_d}{40}$$

$i_I(1.5125) = v_1\{(0.125)(1.5125) - 0.0003125\} - 25v_d$

or

$i_I(1.5125) = v_I\{0.18875\} - 25v_d$

Now

$v_d = i_I R_i = i_I(20)$ and $v_1 = v_I - i_I(20)$

So

$i_I(1.5125) = [v_I - i_I(20)] \cdot [0.18875] - 25 i_I(20)$

$i_I[505.3] = v_I(0.18875)$

or

$\frac{v_I}{i_I} = 2677\ \text{k}\Omega$

Now $R_{if} = 10 + 2677 \Rightarrow \underline{R_{if} = 2.687\ \text{M}\Omega}$

To determine R_{of}: Using Equation (14.36)

$$\frac{1}{R'_{0f}} = \frac{1}{R_0}\cdot\left[\frac{A_{0L}}{1 + \frac{R_2}{R_1\|R_i}}\right] = \frac{1}{0.5}\cdot\left[\frac{10^3}{1 + \frac{40}{10\|20}}\right]$$

or $R'_{0f} = 3.5\ \Omega$

Then $R_{0f} = 1\ \text{k}\Omega \| 3.5\ \Omega$

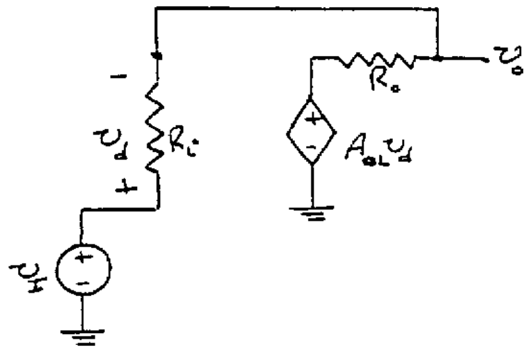
$\qquad \Rightarrow \underline{R_{0f} = 3.49\ \Omega}$

b. Using Equation (14.16)

$$\frac{dA_{CL}}{A_{CL}} = (-10)\left(\frac{5}{10^3}\right) \Rightarrow \underline{\frac{dA_{CL}}{A_{CL}} = -(0.05)\%}$$

14.5

a.



$$\frac{v_0 - A_{0L}v_d}{R_0} + \frac{v_0 - v_I}{R_i} = 0 \text{ and } v_d = v_I - v_0$$

So

$$\frac{v_0}{R_0} - \frac{A_{0L}}{R_0}\cdot(v_I - v_0) + \frac{v_0}{R_i} - \frac{v_I}{R_i} = 0$$

$$v_0\left[\frac{1}{R_0} + \frac{A_{0L}}{R_0} + \frac{1}{R_i}\right] = v_I\left[\frac{1}{R_i} + \frac{A_{0L}}{R_0}\right]$$

$$v_0\left[\frac{1}{0.2} + \frac{(10^4)}{0.2} + \frac{1}{100}\right] = v_I\left[\frac{1}{100} + \frac{(10^4)}{0.2}\right]$$

$v_0[5.000501 \times 10^4] = v_I[5.000001 \times 10^4]$

So $\underline{A_{CL} = \frac{v_0}{v_I} = 0.9999}$

b. Set $v_I = 0$

$$i_0 = \frac{v_0 - A_{0L}v_d}{R_0} + \frac{v_0}{R_i} \text{ and } v_d = -v_0$$

$$i_0 = v_0\left[\frac{1}{R_0} + \frac{A_{0L}}{R_0} + \frac{1}{R_i}\right]$$

Then

$$\frac{1}{R_{0f}} = \frac{1}{R_0} + \frac{A_{0L}}{R_0} + \frac{1}{R_i}$$

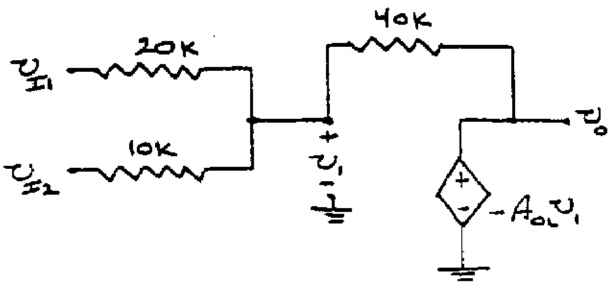
or

$$\frac{1}{R_{0f}} = \frac{1}{0.2} + \frac{(10^4)}{0.2} + \frac{1}{100}$$

which yields

$$\underline{R_{0f} \cong 0.02\ \Omega}$$

14.6



$$\frac{v_{I1}-v_1}{20}+\frac{v_{I2}-v_1}{10}=\frac{v_1-v_0}{40}$$

$$\frac{v_{I1}}{20}+\frac{v_{I2}}{10}+\frac{v_0}{40}=v_1\left[\frac{1}{20}+\frac{1}{10}+\frac{1}{40}\right]$$

and $v_0=-A_{OL}v_1$ so that $v_1=-\dfrac{v_0}{A_{OL}}$

Then

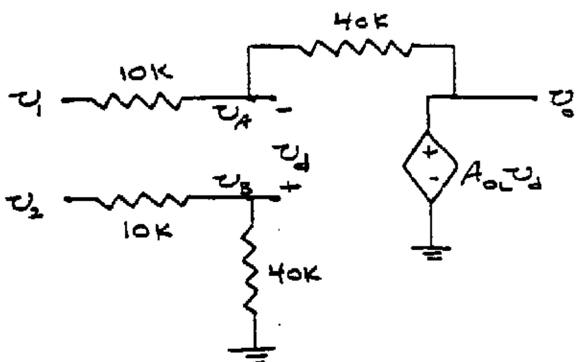
$$v_{I1}(0.05)+v_{I2}(0.10)=-v_0\left\{\frac{1}{40}+\frac{1}{2\times 10^3}\cdot\left(\frac{7}{40}\right)\right\}$$

$$=-v_0\left[2.50875\times 10^{-2}\right]$$

$$\Rightarrow \underline{v_0=-1.993v_{I1}-3.986v_{I2}}$$

$$\frac{\Delta v_0}{v_0}=\frac{2-1.993}{2}\Rightarrow \underline{\frac{\Delta v_0}{v_0}=0.35\%}$$

14.7



$$v_B=\left(\frac{40}{40+10}\right)v_2=\left(\frac{4}{5}\right)v_2=0.8v_2 \qquad (1)$$

$$\frac{v_1-v_A}{10}=\frac{v_A-v_0}{40}$$

$$\frac{v_1}{10}+\frac{v_0}{40}=v_A\left(\frac{1}{10}+\frac{1}{40}\right)$$

$$v_1(0.1)+v_0(0.025)=v_A(0.125) \qquad (2)$$

$$v_0=A_{OL}v_d=A_{OL}(v_B-v_A) \qquad (3)$$

or

$$v_0=A_{OL}[0.8v_2-v_A]$$

$$\frac{v_0}{A_{OL}}-0.8v_2=-v_A$$

$$\Rightarrow \underline{v_A=0.8v_2-\frac{v_0}{A_{OL}}}$$

Then

$$v_1(0.1)+v_0(0.025)=(0.125)\left[0.8v_2-\frac{v_0}{A_{OL}}\right]$$

$$v_1(0.1)-v_2(0.1)=-v_0\left[0.025+\frac{0.125}{10^3}\right]$$

$$=-v_0\left[2.5125\times 10^{-2}\right]$$

$$\Rightarrow \underline{A_d=\frac{v_0}{v_2-v_1}=3.9801}$$

$$\Rightarrow \frac{\Delta A_d}{A_d}=\frac{0.0199}{4}\Rightarrow \underline{0.4975\%}$$

14.8

a. Considering the second op-amp and Equation (14.20), we have

$$\frac{1}{R_{if2}}=\frac{1}{10}+\frac{1}{0.1}\cdot\left[\frac{1+100}{1+\frac{1}{0.1}}\right]=0.10+\frac{101}{(0.1)(11)}$$

So $R_{if2}=0.0109$ kΩ

The effective load on the first op-amp is then

$$R_{L1}=0.1+R_{if2}=0.1109 \text{ k}\Omega$$

Again using Equation (14.20), we have

$$\frac{1}{R_{if}}=\frac{1}{10}+\frac{1}{1}\cdot\frac{1+100+\frac{1}{0.1109}}{1+\frac{1}{0.1109}+\frac{1}{1}}=0.10+\frac{110.017}{11.017}$$

so that

$$\underline{R_{if}=99.1\ \Omega}$$

b. To determine R_{of}:
For the first op-amp, we can write, using Equation (14.36)

$$\frac{1}{R_{of1}}=\frac{1}{R_0}\cdot\left[\frac{A_{OL}}{1+\frac{R_2}{R_1\|R_i}}\right]=\frac{1}{1}\cdot\left[\frac{100}{1+\frac{40}{1\|10}}\right]$$

which yields $R_{of1}=0.021$ kΩ

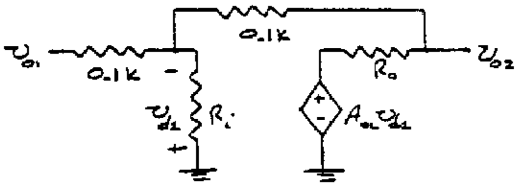
For the second op-amp, then

$$\frac{1}{R_{of}} = \frac{1}{R_o} \cdot \left[\frac{A_{OL}}{1 + \frac{R_2}{(R_1 + R_{of1}) \| R_i}} \right]$$

$$= \frac{1}{1} \cdot \left[\frac{100}{1 + \frac{0.10}{(0.121) \| 10}} \right]$$

or $\underline{R_{of} = 18.4\ \Omega}$

c. To find the gain, consider the second op-amp.



$$\frac{v_{01} - (-v_{d2})}{0.1} + \frac{v_{d2}}{R_i} = \frac{-v_{d2} - v_{02}}{0.1} \tag{1}$$

$$\frac{v_{01}}{0.1} + v_{d2}\left(\frac{1}{0.1} + \frac{1}{10} + \frac{1}{0.1}\right) = -\frac{v_{02}}{0.1}$$

or

$$v_{01}(10) + v_{d2}(20.1) = -v_{02}(10)$$

$$\frac{v_{02} - A_{OL}v_{d2}}{R_o} + \frac{v_{02} - (-v_{d2})}{0.1} = 0 \tag{2}$$

$$\frac{v_{02}}{1} - v_{d2}\left(\frac{100}{1} - \frac{1}{0.1}\right) + \frac{v_{02}}{0.1} = 0$$

$$v_{02}(11) - v_{d2}(90) = 0$$

or

$$v_{d2} = v_{02}(0.1222)$$

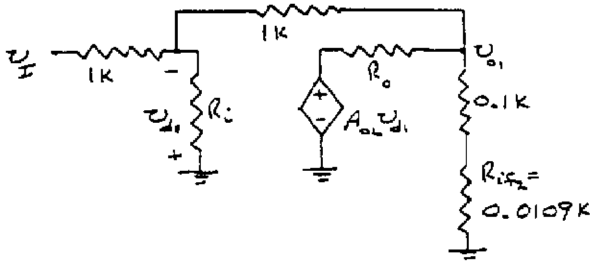
Then Equation (1) becomes

$$v_{01}(10) + v_{02}(0.1222)(20.1) = -v_{02}(10)$$

or

$$v_{01} = -v_{02}(1.246)$$

Now consider the first op-amp.



$$\frac{v_I - (-v_{d1})}{1} + \frac{v_{d1}}{R_i} = \frac{-v_{d1} - v_{01}}{1} \tag{1}$$

$$v_I(1) + v_{d1}\left(\frac{1}{1} + \frac{1}{10} + \frac{1}{1}\right) = -v_{01}(1)$$

or

$$v_I(1) + v_{d1}(2.1) = -v_{01}(1)$$

$$\frac{v_{01}}{0.1109} + \frac{v_{01} - A_{OL}v_{d1}}{R_o} + \frac{v_{01} - (-v_{d1})}{1} = 0 \tag{2}$$

$$v_{01}\left(\frac{1}{0.1109} + \frac{1}{1} + \frac{1}{1}\right) - v_{d1}\left(\frac{100}{1} - \frac{1}{1}\right) = 0$$

$$v_{01}(11.017) - v_{d1}(99) = 0$$

or

$$v_{d1} = v_{01}(0.1113)$$

Then Equation (1) becomes

$$v_I(1) + v_{01}(0.1113)(2.1) = -v_{01}$$

or $v_I = -v_{01}(1.234)$

We had $v_{01} = -v_{02}(1.246)$

So $v_I = v_{02}(1.246)(1.234)$

or $\underline{\frac{v_{02}}{v_I} = 0.650}$

d. Ideal $\frac{v_{02}}{v_I} = 1$

So ratio of actual to ideal = 0.650.

14.9

The open loop gain can be written as

$$A_{OL}(f) = \frac{A_0}{\left(1 + j \cdot \frac{f}{f_{PD}}\right)\left(1 + j \cdot \frac{f}{5 \times 10^6}\right)}$$

where $A_0 = 2 \times 10^5$.
The closed-loop response is

$$A_{CL} = \frac{A_{OL}}{1 + \beta A_{OL}}$$

At low frequency,

$$100 = \frac{2 \times 10^5}{1 + \beta(2 \times 10^5)}$$

So that $\beta = 9.995 \times 10^{-3}$.
Assuming the second pole is the same for both the open-loop and closed-loop, then

$$\phi = -\tan^{-1}\left(\frac{f}{f_{PD}}\right) - \tan^{-1}\left(\frac{f}{5 \times 10^6}\right)$$

For a phase margin of 80°, $\phi = -100°$.
So

$$-100 = -90 - \tan^{-1}\left(\frac{f}{5 \times 10^6}\right)$$

or

$$f = 8.816 \times 10^5 \text{ Hz}$$

Then

$$|A_{OL}| = 1$$

$$= \frac{2 \times 10^5}{\sqrt{1 + \left(\frac{8.816 \times 10^5}{f_{PD}}\right)^2}\sqrt{1 + \left(\frac{8.816 \times 10^5}{5 \times 10^6}\right)^2}}$$

or

$$\frac{8.816 \times 10^5}{f_{PD}} \cong 1.9696 \times 10^5$$

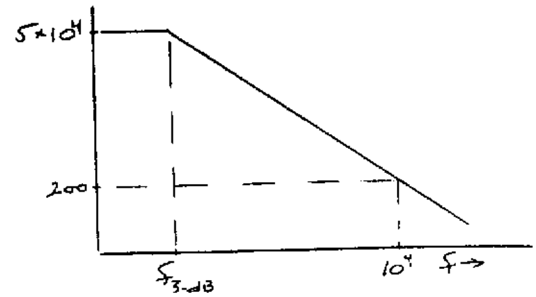
or

$$\underline{f_{PD} = 4.48 \text{ Hz}}$$

14.10

(a) 1st stage
$(10)f_{3-dB} = 1\ MHz \Rightarrow f_{3-dB} = 100\ kHz$
2nd stage
$(50)f_{3-dB} = 1\ MHz \Rightarrow f_{3-dB} = 20\ kHz$
Bandwidth of overall system $\cong 20\ kHz$
(b) If each stage has the same gain, so
$K^2 = 500 \Rightarrow K = 22.36$
Then bandwidth of each stage
$(22.36)f_{3-dB} = 1\ MHz \Rightarrow f_{3-dB} = 44.7\ kHz$

14.11



$$A = \frac{A_o}{1 + j\frac{f}{f_{3-dB}}}$$

$$|A| = \frac{A_o}{\sqrt{1 + \left(\frac{f}{f_{3-dB}}\right)^2}} \Rightarrow$$

$$200 = \frac{5x10^4}{\sqrt{1 + \left(\frac{10^4}{f_{3-dB}}\right)^2}} \Rightarrow \underline{f_{3-dB} = 40\ Hz}$$

Then

$$f_T = (5x10^4)(40) \Rightarrow \underline{f_T = 2\ MHz}$$

14.12

$(5x10^4)f_{PD} = 10^6 \Rightarrow \underline{f_{PD} = 20\ Hz}$

$(25)f_{3-dB}10^6 \Rightarrow \underline{f_{3-dB} = 40\ kHz}$

$$A_v = \frac{A_{vo}}{1 + j\frac{f}{f_{3-dB}}} \Rightarrow |A_v| = \frac{25}{\sqrt{1 + \left(\frac{f}{40x10^3}\right)^2}}$$

At $f = 0.5 f_{3-dB} = 20\ kHz$

$$|A_v| = \frac{25}{\sqrt{1 + (0.5)^2}} = 22.36$$

At $f = 2 f_{3-dB} = 80\ kHz$

$$|A_v| = \frac{25}{\sqrt{1 + (2)^2}} = 11.18$$

14.13

$$(20x10^3) \cdot |A_{vf}|_{MAX} = 10^6 \Rightarrow \underline{|A_{vf}|_{MAX} = 50}$$

14.14

From Equation (14.55),

$$FPBW = \frac{SR}{2\pi V_{P0}} = \frac{10 \times 10^6}{2\pi(10)}$$

or

$$\underline{FPBW = f_{max} = 159 \text{ kHz}}$$

14.15

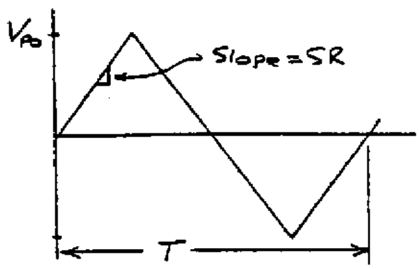
a. Using Equation (14.55),

$$V_{P0} = \frac{8 \times 10^6}{2\pi(250 \times 10^3)}$$

or

$$\underline{V_{P0} = 5.09 \text{ V}}$$

b.



Period $T = \frac{1}{f} = \frac{1}{250 \times 10^3} = 4 \times 10^{-6}$ s

One-fourth period = 1 μs

Slope $= \frac{V_{P0}}{1\ \mu s} = SR = 8$ V/μs

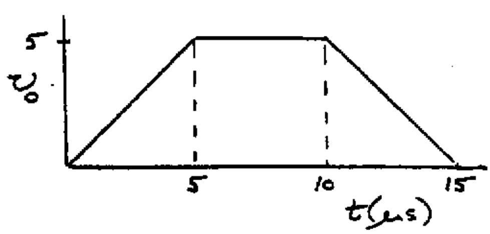
$\Rightarrow \underline{V_{P0} = 8 \text{ V}}$

14.16

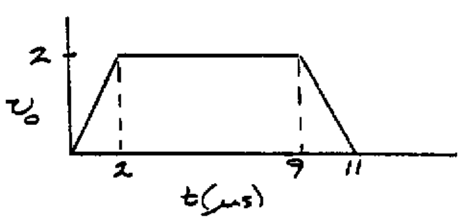
For input (a), maximum output is 5 V.

$SR = 1$ V/μs

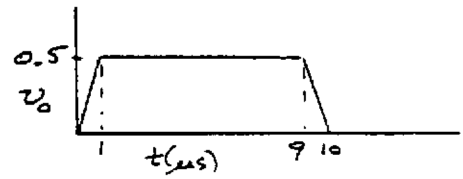
so



For input (b), maximum output is 2 V.

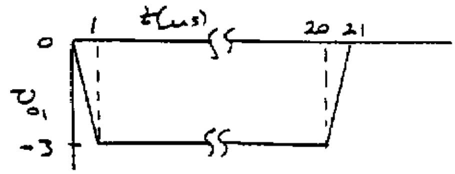


For input (c), maximum output is 0.5 V so the output is

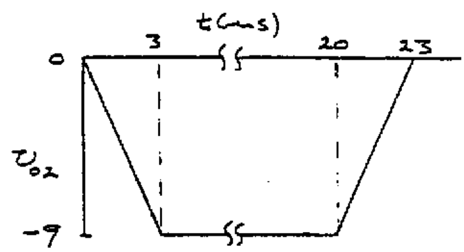


14.17

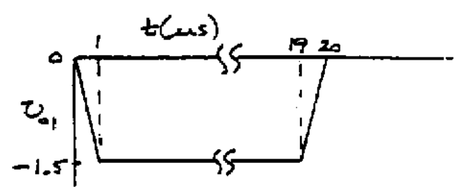
For input (a), $\max|v_{01}| = 3$ V.



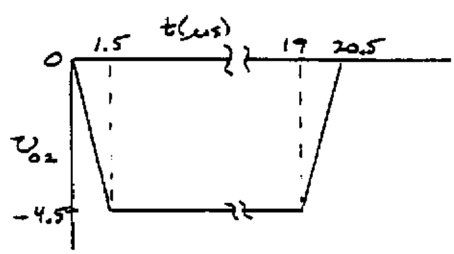
Then $|v_{02}|_{max} = 3(3) = 9$ V



For input (b), $\max|v_{01}| = 1.5$ V.



Then $|v_{02}|_{max} = 3(1.5) = 4.5$ V



14.18

$f_{MAX} = 20\ kHz$, $SR = 0.8\ V/\mu s$

$$V_{po} = \frac{SR}{2\pi f_{MAX}} = \frac{0.8x10^6}{2\pi(20x10^3)} \Rightarrow$$

$$\underline{V_{po} = 6.37\ V}$$

14.19

$$I_1 = I_{S1}\exp\left(\frac{V_{BE1}}{V_T}\right), \quad I_2 = I_{S2}\exp\left(\frac{V_{BE2}}{V_T}\right)$$

Want $I_1 = I_2$, so

$$\frac{I_1}{I_2} = 1 = \frac{5x10^{-14}(1+x)\exp\left(\frac{V_{BE1}}{V_T}\right)}{5x10^{-14}(1-x)\exp\left(\frac{V_{BE2}}{V_T}\right)}$$

$$= \frac{(1+x)}{(1-x)}\exp\left(\frac{V_{BE1}-V_{BE2}}{V_T}\right)$$

Or

$$\frac{1+x}{1-x} = \exp\left(\frac{V_{BE2}-V_{BE1}}{V_T}\right) = \exp\left(\frac{V_{OS}}{V_T}\right)$$

$$= \exp\left(\frac{0.0025}{0.026}\right) = 1.10$$

Now

$$1+x = (1-x)(1.10) \Rightarrow$$

$$x = 0.0476 \Rightarrow 4.76\%$$

14.20

From Equation (14.62),

$$\left(\frac{1+\frac{v_{CE1}}{V_{AN}}}{1+\frac{v_{EB}}{V_{AP}}}\right) = \frac{I_{S3}}{I_{S4}}\cdot\left(\frac{1+\frac{v_{CE2}}{V_{AN}}}{1+\frac{v_{EC4}}{V_{AP}}}\right)$$

For $v_{CE2} = 0.6$ V, then $v_{EC4} = 5$ V. We have $v_{CE1} = 5$ V so

$$\left(\frac{1+\frac{5}{80}}{1+\frac{0.6}{80}}\right) = \frac{I_{S3}}{I_{S4}}\cdot\left(\frac{1+\frac{0.6}{80}}{1+\frac{5}{80}}\right)$$

or

$$\frac{I_{S3}}{I_{S4}} = \frac{(1.0625)^2}{(1.0075)^2} = 1.112$$

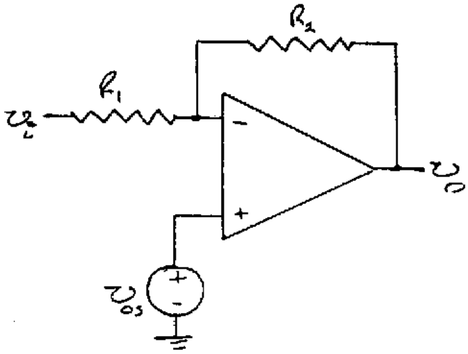
So

$$I_{S3} = (10^{-14})(1.112)$$

or

$$\underline{I_{S3} = 1.112 \times 10^{-14}\ \text{A}}$$

14.21



By superposition:

$$v_o(v_i) = -\frac{R_2}{R_1}\cdot v_i = -50v_i$$

$$v_o(v_{os}) = \left(1+\frac{R_2}{R_1}\right)\cdot v_{os} = 51v_{os}$$

So

$$v_o = v_o(v_i) + v_o(v_{os}) = -50v_i + 51v_{os}$$

For $v_i = 20\ mV$ and $v_{os} + 2.5\ mV$

$$v_o = -50(0.02) + 51(0.0025) = -0.8725\ V$$

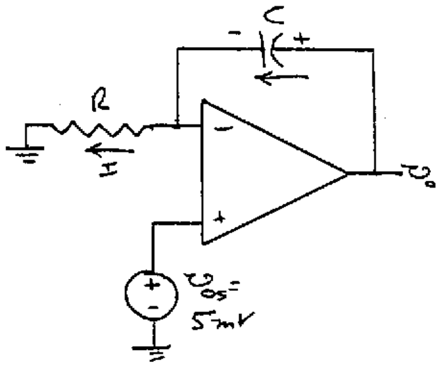
For $v_i = 20\ mV$ and $v_{os} = -2.5\ mV$

$$v_o = -50(0.02) + 51(-0.0025) = -1.1275\ V$$

So

$$-1.1275 \le v_o \le -0.8725\ V$$

14.22



$$I = \frac{0.5x10^{-3}}{10^4} = 5x10^{-8}\ A$$

Also

$$I = C\frac{dV_o}{dt} \Rightarrow V_o = \frac{1}{C}\int_0^t I dt = \frac{I}{C}\cdot t$$

Then

$$5 = \frac{5x10^{-8}}{10x10^{-6}}t \Rightarrow \underline{t = 10^3\ s}$$

14.23

a.

$|v_{01}| = 10\left(1 + \frac{100}{10}\right)$ or $\underline{|v_{01}| = 110 \text{ mV}}$

Then

$|v_{02}| = |v_{01}|(5) + 10\left(1 + \frac{50}{10}\right) = (110)(5) + (10)(6)$

or

$$\underline{|v_{02}| = 610 \text{ mV}}$$

14.24

v_0 due to v_I

$v_0 = (0.5)\left(1 + \frac{1}{1.1}\right) = 0.9545 \text{ V}$

Wiper arm at $V^+ = 10$ V, (using superposition)

$$v_1 = \left(\frac{R_1\|R_5}{R_1\|R_5 + R_4}\right)(10) = \left(\frac{0.0909}{0.0909 + 10}\right)(10)$$
$$= 0.090$$

Then $v_{01} = -\left(\frac{1}{1}\right)(0.090) = -0.090$

Wiper arm in center, $v_1 = 0$ and $v_{02} = 0$

Wiper arm at $V^- = -10$ V, $v_1 = -0.090$
So

$$v_{03} = 0.090$$

Finally, total output v_0: (from superposition)

Wiper arm at V^+,

$$\underline{v_0 = 0.8645 \text{ V}}$$

Wiper arm in center,

$$\underline{v_0 = 0.9545 \text{ V}}$$

Wiper arm at V^-,

$$\underline{v_0 = 1.0445 \text{ V}}$$

14.25

a. $R_1' = R_2' = 0.5\|25 = 0.490 \text{ k}\Omega$

or

$$\underline{R_1' = R_2' = 490 \ \Omega}$$

b. From Equation (14.75),

$$(0.026)\ln\left(\frac{125 \times 10^{-6}}{2 \times 10^{-14}}\right) + (0.125)R_1'$$
$$= (0.026)\ln\left(\frac{125 \times 10^{-6}}{2.2 \times 10^{-14}}\right) + (0.125)R_2'$$

$0.586452 + (0.125)R_1' = 0.583974 + (0.125)R_2'$

$0.002478 = (0.125)(R_2' - R_1')$

So $R_2' - R_1' = 0.0198 \text{ k}\Omega \Rightarrow 19.8 \ \Omega$

Then

$$\frac{R_2(1-x)R_x}{R_2 + (1-x)R_x} - \frac{R_1 x R_x}{R_1 + xR_x} = 0.0198$$
$$\frac{(0.5)(1-x)(50)}{(0.5) + (1-x)(50)} - \frac{(0.5)(50)x}{(0.5) + x(50)} = 0.0198$$
$$\frac{25(1-x)}{50.5 - 50x} - \frac{25x}{0.5 + 50x} = 0.0198$$

$$\frac{(0.5 + 50x)(25 - 25x) - (25x)(50.5 - 50x)}{(50.5 - 50x)(0.5 + 50x)}$$
$$= 0.0198$$

$$25\{0.5 - 0.5x + 50x - 50x^2 - 50.5x + 50x^2\}$$
$$= 0.0198\{25.25 + 2525x - 25x - 2500x^2\}$$

$25\{0.5 - x\} = 0.0198\{25.25 + 2500x - 2500x^2\}$

$0.5 - x = 0.019998 + 1.98x - 1.98x^2$

$1.98x^2 - 2.98x + 0.48 = 0$

$$x = \frac{2.98 \pm \sqrt{(2.98)^2 - 4(1.98)(0.48)}}{2(1.98)}$$

So

$$\underline{x = 0.183}$$

and

$$\underline{1 - x = 0.817}$$

14.26

$R_1' = R_1\|15 = 0.5\|15 = 0.4839 \text{ k}\Omega$
$R_2' = R_2\|35 = 0.5\|35 = 0.4930 \text{ k}\Omega$

From Equation (14.75),

$$(0.026)\ln\left(\frac{i_{C1}}{I_{S3}}\right) + i_{C1}R_1' = (0.026)\ln\left(\frac{i_{C2}}{I_{S4}}\right) + i_{C2}R_2'$$
$$(0.026)\ln\left(\frac{i_{C1}}{i_{C2}}\right) = i_{C2}R_2' - i_{C1}R_1'$$
$$(0.026)\ln\left(\frac{i_{C1}}{i_{C2}}\right) = i_{C2}R_2'\left[1 - \frac{i_{C1}}{i_{C2}} \cdot \frac{R_1'}{R_2'}\right]$$
$$(0.026)\ln\left(\frac{i_{C1}}{i_{C2}}\right) = i_{C2}(0.4930)\left[1 - (0.9815)\left(\frac{i_{C1}}{i_{C2}}\right)\right]$$

By trial and error:

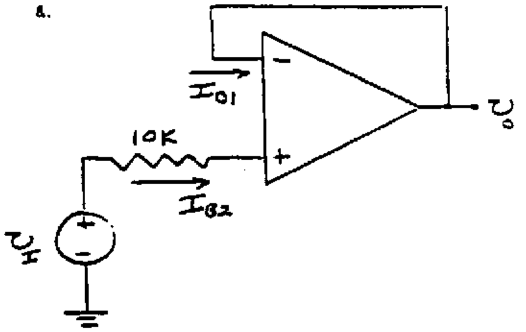
$\underline{i_{C1} = 252\ \mu A}$ and $\underline{i_{C2} = 248\ \mu A}$

or

$$\underline{\frac{i_{C1}}{i_{C2}} = 1.0155}$$

14.27

a.

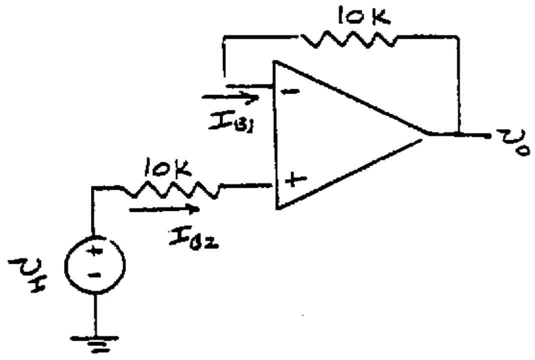


For $I_{B2} = 1\ \mu A$, then $v_O = -(10^{-6})(10^4)$

or

$$\underline{v_O = -0.010\ V}$$

b. If a 10 kΩ resistor is included in the feedback loop



Now $v_O = -I_{B2}(10) + I_{B1}(10) = 0$

Circuit is compensated if $I_{B1} = I_{B2}$.

14.28

From Equation (14.83), we have

$$v_O = R_2 I_{OS}$$

where $R_2 = 40$ kΩ and $I_{OS} = 3\ \mu A$.

Then

$$v_O = (40 \times 10^3)(3 \times 10^{-6})$$

or

$$\underline{v_O = 0.12\ V}$$

14.29

a. Assume all bias currents are in the same direction and into each op-amp.

$v_{O1} = I_{B1}(100\text{ k}\Omega) = (10^{-6})(10^5) \Rightarrow \underline{v_{O1} = 0.1\ V}$

Then

$$v_{O2} = v_{O1}(-5) + I_{B1}(50\text{ k}\Omega)$$

$$= (0.1)(-5) + (10^{-6})(5 \times 10^4)$$

$$= -0.5 + 0.05$$

or

$$\underline{v_{O2} = -0.45\ V}$$

b. Connect $R_3 = 10\|100 = 9.09$ kΩ resistor to noninverting terminal of first op-amp, and $R_3 = 10\|50 = 8.33$ kΩ resistor to noninverting terminal of second op-amp.

14.30

a. For a constant current through a capacitor,

$$v_O = \frac{1}{C}\int_0^t I\,dt$$

or $v_O = \dfrac{0.1 \times 10^{-6}}{10^{-6}} \cdot t \Rightarrow \underline{v_O = (0.1)t}$

b. At $t = 10$ s, $v_O = 1$ V

c. Then

$$v_O = \frac{100 \times 10^{-12}}{10^{-6}} \cdot t \Rightarrow v_O = (10^{-4})t$$

At $t = 10$ s, $\underline{v_O = 1\text{ mV}}$

14.31

a. Assume all bias currents are into the op-amp.

$$v_{O1} = I_{B1}(50\text{ k}\Omega) = (10 \times 10^{-6})(50 \times 10^3)$$

or

$$\underline{v_{O1} = v_{O2} = 0.5\ V}$$

$$v_{O3} = (-1)(v_{O1}) + (10 \times 10^{-6})(20 \times 10^3)$$

or

$$\underline{v_{O3} = -0.3\ V}$$

b. $R_A = 10\|50 \Rightarrow \underline{R_A = 8.33\text{ k}\Omega}$

$R_B = 20\|20 \Rightarrow \underline{R_B = 10\text{ k}\Omega}$

c. Assume the worst case offset current, that is, $I_{OS} = I_{B1} - I_{B2}$ or $I_{OS} = I_{B2} - I_{B1}$.
From Equation (14.83),

$$v_{O1} = R_2 I_{OS} = (50 \times 10^3)(2 \times 10^{-6})$$

or

$$\underline{v_{O1} = v_{O2} = 0.1 \text{ V}}$$

$$v_{O3} = (-1)v_{O1} - I_{OS}R_2$$
$$= (-1)(0.1) - (2 \times 10^{-6})(20 \times 10^3)$$

or

$$\underline{v_{O3} = -0.14 \text{ V}}$$

14.32

a. Using Equation (14.79),

Circuit (a).

$$v_O = (0.8 \times 10^{-6})(50 \times 10^3) - (0.8 \times 10^{-6})(25 \times 10^3)\left(1 + \frac{50}{50}\right)$$

or

$$\underline{v_O = 0}$$

Circuit (b).

$$v_O = (0.8 \times 10^{-6})(50 \times 10^3) - (0.8 \times 10^{-6})(10^6)\left(1 + \frac{50}{50}\right)$$
$$= 4 \times 10^{-2} - 1.6$$

or

$$\underline{v_O = -1.56 \text{ V}}$$

b. Assume $I_{B1} = 0.7\ \mu$A and $I_{B2} = 0.9\ \mu$A, then using Equation (14.79):

Circuit (a).

$$v_O = (0.7 \times 10^{-6})(50 \times 10^3) - (0.9 \times 10^{-6})(25 \times 10^3)\left(1 + \frac{50}{50}\right)$$
$$= 0.035 - 0.045$$

or

$$\underline{v_O = -0.010 \text{ V}}$$

Circuit (b).

$$v_O = (0.7 \times 10^{-6})(50 \times 10^3) - (0.9 \times 10^{-6})(10^6)\left(1 + \frac{50}{50}\right)$$
$$= 0.035 - 1.8$$

or

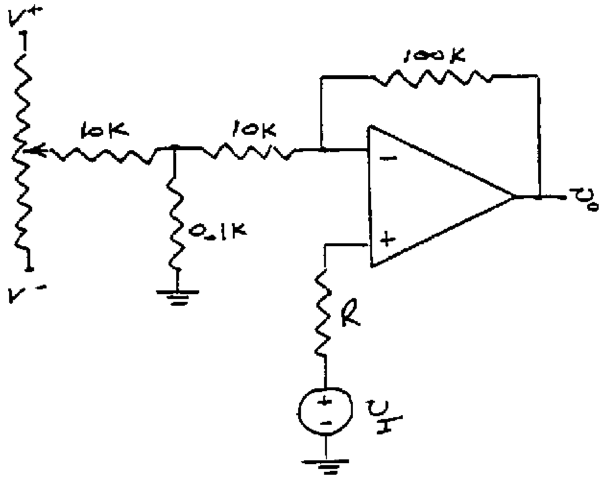
$$\underline{v_O = -1.765 \text{ V}}$$

14.33

a. If $R = 0$,

$$v_{O,max} = \left(1 + \frac{100}{10}\right)V_{OS} + I_B(100 \text{ k}\Omega)$$
$$= (11)(10 \times 10^{-3}) + (2 \times 10^{-6})(100 \times 10^3)$$
$$v_{O,max} = 0.110 + 0.20$$
$$\Rightarrow \underline{v_{O,max} = 0.310 \text{ V}}$$

b.



$$R = 10.1\|100 = \underline{9.17 \text{ k}\Omega = R}$$

14.34

a. $\left(\dfrac{R_i}{R_i + R_2}\right)(15) = 0.010$ V

$$\frac{15}{15 + R_2} = 0.0006667$$
$$15(1 - 0.0006667) = 0.0006667 R_2$$

Then

$$\underline{R_2 = 22.48 \text{ M}\Omega}$$

b. $R_1 = R_i\|R_F = 15\|10 \Rightarrow \underline{R_1 = 6 \text{ k}\Omega}$

14.35

a. Assume the offset voltage polarities are such as to produce the worst case values, but the bias currents are in the same direction.

Use superposition:
Offset voltages

$$|v_{01}| = \left(1+\frac{100}{10}\right)(10) = \underline{110\text{ mV} = |v_{01}|}$$

$$|v_{02}| = (5)(110) + \left(1+\frac{50}{10}\right)(10)$$

$$\Rightarrow \underline{|v_{02}| = 610\text{ mV}}$$

Bias Currents:

$$v_{01} = I_B(100\text{ k}\Omega) = (2\times10^{-6})(100\times10^3) = 0.2\text{ V}$$

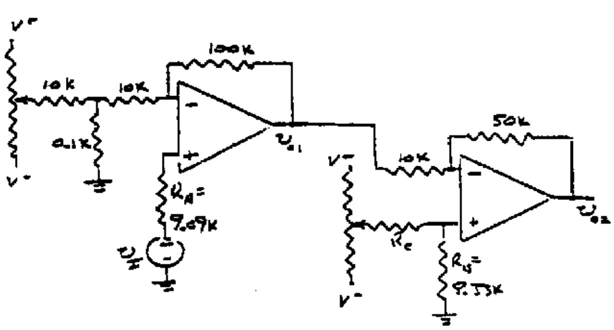
Then

$$v_{02} = (-5)(0.2) + (2\times10^{-6})(50\times10^3) = -0.9\text{ V}$$

Worst case: v_{01} is positive and v_{02} is negative, then

$$\underline{v_{01} = 0.31\text{ V}} \text{ and } \underline{v_{02} = -1.51\text{ V}}$$

b. Compensation network:



If we want

$$\left(\frac{R_B}{R_B+R_C}\right)V^+ = 20\text{ mV and } V^+ = 10\text{ V}$$

$$\left(\frac{8.33}{8.33+R_C}\right)(10) = 0.020$$

or

$$\underline{R_C \cong 4.15\text{ M}\Omega}$$

14.36

Assume bias currents are in same direction, but assume polarity of offset voltages are such as to produce the worst case output.

a. Let $I_{B1} = 5.5\ \mu\text{A}$, $I_{B2} = 4.5\ \mu\text{A}$

Bias Current Effects:

$$v_{01} = I_{B1}(50\text{ k}\Omega) = 0.275\text{ V} \Rightarrow v_{02} = 0.275\text{ V}$$

$$v_{03} = I_{B1}(20\text{ k}\Omega) - v_{01} \Rightarrow v_{03} = -0.165\text{ V}$$

Offset Voltage Effects:

$$v_{01} = (5)\left(1+\frac{50}{10}\right) = 30\text{ mV} \Rightarrow v_{02} = 30\text{ mV}$$

$$v_{03} = -v_{01} - 5\left(1+\frac{20}{20}\right) \Rightarrow v_{03} = -40\text{ mV}$$

Total Effect:

$$\underline{v_{01} = 0.305\text{ V}} \text{ and } \underline{v_{02} = 0.305\text{ V}}$$

$$\underline{v_{03} = -0.205\text{ V}}$$

14.37

For circuit (a), effect of bias current:

$$v_0 = (50\times10^3)(100\times10^{-9}) \Rightarrow 5\text{ mV}$$

Effect of offset voltage

$$v_0 = (2)\left(1+\frac{50}{50}\right) = 4\text{ mV}$$

So net output voltage is $\underline{v_0 = 9\text{ mV}}$

For circuit (b), effect of bias current:

Let $I_{B2} = 550$ nA, $I_{B1} = 450$ nA, then from Equation (14.79),

$$v_0 = (450\times10^{-9})(50\times10^3) - (550\times10^{-9})(10^6)\left(1+\frac{50}{50}\right)$$

$$= 2.25\times10^{-2} - 1.1$$

or

$$v_0 = -1.0775\text{ V}$$

If the offset voltage is negative, then

$$v_0 = (-2)(2) = -4\text{ mV}$$

So the net output voltage is

$$\underline{v_0 = -1.0815\text{ V}}$$

14.38

a. At $T = 25°\text{C}$, $V_{OS} = 2$ mV so the output voltage for each circuit is

$$\underline{v_0 = 4 \text{ mV}}$$

b. For $T = 50°\text{C}$, the offset voltage for is

$$V_{OS} = 2 \text{ mV} + (0.0067)(25) = 2.1675 \text{ mV}$$

so the output voltage for each circuit is

$$\underline{v_0 = 4.335 \text{ mV}}$$

14.39

a. At $T = 25°\text{C}$, $V_{OS} = 1$ mV, then

$$v_{01} = (1)\left(1 + \frac{50}{10}\right) \Rightarrow \underline{v_{01} = 6 \text{ mV}}$$

and

$$v_{02} = v_{01}\left(1 + \frac{60}{20}\right) + (1)\left(1 + \frac{60}{20}\right)$$
$$= 6(4) + (1)(4) \Rightarrow \underline{v_{02} = 28 \text{ mV}}$$

b. At $T = 50°\text{C}$, $V_{OS} = 1 + (0.0033)(25) = 1.0825$ mV, then

$$v_{01} = (1.0825)(6) \Rightarrow \underline{v_{01} = 6.495 \text{ mV}}$$

and

$$v_{02} = (6.495)(4) + (1.0825)(4)$$

or

$$\underline{v_{02} = 30.31 \text{ mV}}$$

14.40

$25°\text{C}$; $I_B = 500$ nA, $I_{OS} = 200$ nA

$50°\text{C}$, $I_B = 500 \text{ nA} + (8 \text{ nA}/°\text{C})(25°\text{C}) = 700$ nA

$I_{OS} = 200 \text{ nA} + (2 \text{ nA}/°\text{C})(25°\text{C}) = 250$ nA

a. Circuit (a): For I_B, bias current cancellation, $\underline{v_0 = 0}$

Circuit (b): For I_B, Equation (14.79),

$$v_0 = (500 \times 10^{-9})(50 \times 10^3) - (500 \times 10^{-9})(10^6)\left(1 + \frac{50}{50}\right)$$
$$= 0.025 - 1.00 \Rightarrow \underline{v_0 = -0.975 \text{ V}}$$

b. Due to offset bias currents.

Circuit (a):

$$v_0 = (200 \times 10^{-9})(50 \times 10^3) \Rightarrow \underline{v_0 = 0.010 \text{ V}}$$

Circuit (b):

Let $I_{B2} = 600$ nA

$I_{B1} = 400$ nA

Then

$$v_0 = (400 \times 10^{-9})(50 \times 10^3) - (600 \times 10^{-9})(10^6)\left(1 + \frac{50}{50}\right)$$
$$= 0.020 - 1.20 \Rightarrow \underline{v_0 = -1.18 \text{ V}}$$

c. Circuit (a): Due to I_B, $\underline{v_0 = 0}$

Circuit (b): Due to I_B,

$$v_0 = (700 \times 10^{-9})(50 \times 10^3) - (700 \times 10^{-9})(10^6)\left(1 + \frac{50}{50}\right)$$
$$= 0.035 - 1.40 \Rightarrow \underline{v_0 = -1.365 \text{ V}}$$

Circuit (a): Due to I_{OS},

$$v_0 = (250 \times 10^{-9})(50 \times 10^3) \Rightarrow \underline{v_0 = 0.0125 \text{ V}}$$

Circuit (b): Due to I_{OS},

Let $I_{B2} = 825$ nA

$I_{B1} = 575$ nA

Then

$$v_0 = (575 \times 10^{-9})(50 \times 10^3) - (825 \times 10^{-9})(10^6)\left(1 + \frac{50}{50}\right)$$
$$= 0.02875 - 1.65 \Rightarrow \underline{v_0 = -1.62 \text{ V}}$$

14.41

$25°\text{C}$; $I_B = 2\ \mu\text{A}$, $I_{OS} = 0.2\ \mu\text{A}$

$50°\text{C}$, $I_B = 2\ \mu\text{A} + (0.020\ \mu\text{A}/°\text{C})(25°\text{C}) = 2.5\ \mu\text{A}$

$$I_{OS} = 0.2\ \mu\text{A} + (0.005\ \mu\text{A}/°\text{C})(25°\text{C}) = 0.325\ \mu\text{A}$$

a. Due to I_B: (Assume bias currents into op-amp).

$$v_{01} = I_B(50 \text{ k}\Omega) = (2 \times 10^{-6})(50 \times 10^3) \Rightarrow \underline{v_{01} = 0.10 \text{ V}}$$

$$v_{02} = v_{01}\left(1 + \frac{60}{20}\right) + I_B(60 \text{ k}\Omega) - I_B(50 \text{ k}\Omega)\left(1 + \frac{60}{20}\right)$$
$$= (0.1)(4) + (2 \times 10^{-6})(60 \times 10^3) - (2 \times 10^{-6})(50 \times 10^3)(4)$$

or

$$\underline{v_{O2} = 0.12 \text{ V}}$$

b. Due to I_{OS}:

1st op-amp. Let $I_{B1} = 2.1\ \mu\text{A}$

2nd op-amp. Let $I_{B1} = 2.1\ \mu\text{A}$

$I_{B2} = 1.9\ \mu\text{A}$

$$v_{O1} = I_{B1}(50\text{ k}\Omega) = (2.1 \times 10^{-6})(50 \times 10^3)$$

$$\Rightarrow \underline{v_{O1} = 0.105 \text{ V}}$$

$$v_{O2} = v_{O1}\left(1 + \frac{60}{20}\right) + I_{B1}(60\text{ k}\Omega) - I_{B2}(50\text{ k}\Omega)\left(1 + \frac{60}{20}\right)$$

$$= (0.105)(4) + (2.1 \times 10^{-6})(60 \times 10^3) - (1.9 \times 10^{-6})(50 \times 10^3)(4)$$

or

$$\underline{v_{O2} = 0.166 \text{ V}}$$

c. Due to I_B:

$$v_{O1} = (2.5 \times 10^{-6})(50 \times 10^3) \Rightarrow \underline{v_{O1} = 0.125 \text{ V}}$$

$$v_{O2} = v_{O1}\left(1 + \frac{60}{20}\right) + I_B(60\text{ k}\Omega) - I_B(50\text{ k}\Omega)\left(1 + \frac{60}{20}\right)$$

$$= (0.125)(4) + (2.5 \times 10^{-6})(60 \times 10^3) - (2.5 \times 10^{-6})(50 \times 10^3)(4)$$

or

$$\underline{v_{O2} = 0.15 \text{ V}}$$

Due to I_{OS}:

Let $I_{B1} = 2.6625\ \mu\text{A}$

$I_{B2} = 2.3375\ \mu\text{A}$

$$v_{O1} = I_{B1}(50\text{ k}\Omega) = (2.6625 \times 10^{-6})(50 \times 10^3)$$

$$\Rightarrow \underline{v_{O1} = 0.133 \text{ V}}$$

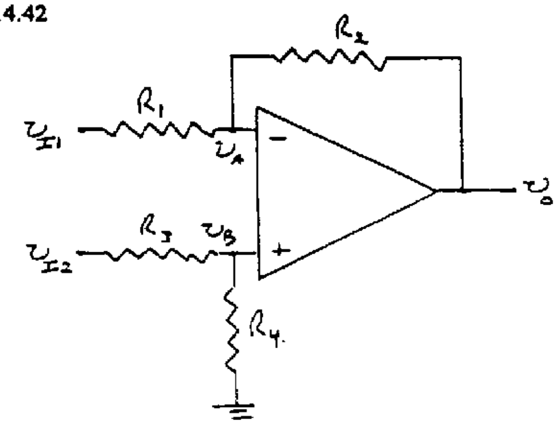
$$v_{O2} = v_{O1}\left(1 + \frac{60}{20}\right) + I_{B1}(60\text{ k}\Omega) - I_{B2}(50\text{ k}\Omega)\left(1 + \frac{60}{20}\right)$$

$$= (0.133)(4) + (2.6625 \times 10^{-6})(50 \times 10^3) - (2.3375 \times 10^{-6})(50 \times 10^3)(4)$$

or

$$\underline{v_{O2} = 0.224 \text{ V}}$$

14.42



$$v_B = \left(\frac{R_4}{R_3 + R_4}\right)v_{I2} \text{ and } v_O(v_{I2}) = v_B\left(1 + \frac{R_2}{R_1}\right)$$

or

$$v_O(v_{I2}) = \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)v_{I2}$$

For v_{I1},

$$v_O(v_{I1}) = -\frac{R_2}{R_1}\cdot v_I$$

Then

$$v_O = \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)v_{I2} - \frac{R_2}{R_1}\cdot v_{I1}$$

We can write $v_{I2} = V_{cm} + \frac{V_d}{2}$ and $v_{I1} = V_{cm} - \frac{V_d}{2}$. Then

$$v_O = \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)\left(V_{cm} + \frac{V_d}{2}\right) - \frac{R_2}{R_1}\cdot\left(V_{cm} - \frac{V_d}{2}\right)$$

Common-mode gain

$$A_{cm} = \frac{v_O}{V_{cm}} = \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1}$$

Differential mode gain

$$A_d = \frac{v_O}{V_d} = \frac{1}{2}\left[\left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right) + \frac{R_2}{R_1}\right]$$

Then

$$CMRR = \left|\frac{A_d}{A_{cm}}\right| = \frac{\frac{1}{2}\cdot\left[\left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right) + \frac{R_2}{R_1}\right]}{\left[\left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1}\right]}$$

$$CMRR = \frac{\frac{1}{2}\cdot\left[\frac{R_4}{R_3}\cdot\frac{1}{\left(1+\frac{R_4}{R_3}\cdot\right)}\cdot\left(1+\frac{R_2}{R_1}\right)+\frac{R_2}{R_1}\right]}{\left[\frac{R_4}{R_3}\cdot\frac{1}{\left(1+\frac{R_4}{R_3}\cdot\right)}\cdot\left(1+\frac{R_2}{R_1}\right)-\frac{R_2}{R_1}\right]}$$

Minimum $CMRR$ $\Rightarrow$Maximum denominator

$\Rightarrow$ maximum $\frac{R_4}{R_3}$ and minimum $\frac{R_2}{R_1}$. Then

$$\frac{R_4}{R_3} = \frac{(1.02)(50)}{(0.98)(10)} = 5.204$$
$$\frac{R_2}{R_1} = \frac{(0.98)(50)}{(1.02)(10)} = 4.804$$

Then

$$CMRR = \frac{\frac{1}{2}\left[\frac{5.204}{6.204}\cdot(5.804)+(4.804)\right]}{\left[\frac{5.204}{6.204}\cdot(5.804)-(4.804)\right]}$$
$$= \frac{\frac{1}{2}\cdot(9.6725)}{(0.06447)}$$

$$CMRR = 75.0 \Rightarrow CMRR_{dB} = 20\log_{10}(75.0)$$
$$\Rightarrow \underline{CMRR_{dB} = 37.5 \text{ dB}}$$

14.43

Use the results of Problem 14.42:

Let $\frac{R_4}{R_3} = \frac{1+x}{1-x}\cdot\left(\frac{50}{10}\right) \approx (1+2x)(5)$

Let $\frac{R_2}{R_1} = \frac{1-x}{1+x}\cdot\left(\frac{50}{10}\right) \approx (1-2x)(5)$

Then

$$CMRR = \frac{\frac{1}{2}\left[\frac{(1+2x)5}{6+10x}\cdot(6-10x)+(1-2x)(5)\right]}{\left[\frac{(1+2x)5}{6+10x}\cdot(6-10x)-(1-2x)(5)\right]}$$
$$= \frac{\frac{1}{2}\left[30+10x-100x^2+30-10x-100x^2\right]}{\left[30+10x-100x^2-(30-10x-100x^2)\right]}$$
$$= \frac{\frac{1}{2}\cdot\left[60-200x^2\right]}{20x} = \frac{30-100x^2}{20x}$$

a. For $CMRR_{dB} = 90$ dB $\Rightarrow CMRR = 31,623$
x will be small, neglect the x^2 term. Then

$$20x = \frac{30}{31,623} \Rightarrow x = 0.0000474 = \underline{0.00474\%}$$

b. For $CMRR_{dB} = 60$ dB $\Rightarrow CMRR = 1000$. Then

$$20x = \frac{30}{1000} \Rightarrow x = 0.0015 = \underline{0.15\%}$$