31.1 An op-amp is designed so that the open-loop gain is guaranteed to be 150,000 ± 10 percent V/V. If the amplifier is to be used in a closed-loop configuration with β = 0.1 V/V, determine the tolerance of the closed-loop gain.

$$A_{OL} = 150k \pm 10\% \text{ V/V and } \beta = 0.1 \text{ V/V}$$

$$135k \le A_{OL} \le 165k$$

$$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} \rightarrow \frac{135k}{1 + 135k \cdot (0.1)} \le A_{CL} \le \frac{165k}{1 + 165k \cdot (0.1)}$$

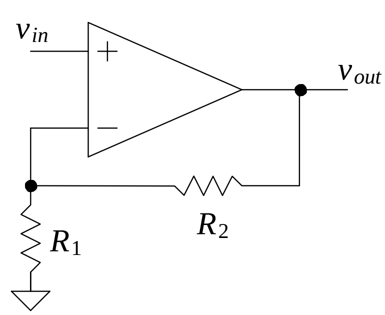
$$9.999259 \le A_{CL} \le 9.999394 \text{ where ideally } A_{CL} = \frac{1}{\beta} = 10$$

$$\frac{dA_{CL}}{A_{CL}} = \frac{135 \times 10^{-6}}{10} = 0.00135\% \text{ or } \pm 0.00067\%$$

noting that we could have used a closed-loop gain of 9.9993 in the denominator and arrived at essentially the same answer. We could also use Eq. (31.9)

$$\frac{dA_{CL}}{A_{CL}} = \frac{1}{1 + A_{OL}\beta} \cdot \frac{dA_{OL}}{A_{OL}} = \frac{1}{1 + (150k) \cdot (0.01)} \cdot (\pm 0.1) = \pm 0.00067\% \; \blacksquare$$

31.2 What is the maximum possible value of β using resistors in the feedback loop of a noninverting op-amp circuit? Sketch this op-amp circuit when β = 1/2.



The non-inverting op-amp configuration is seen below.

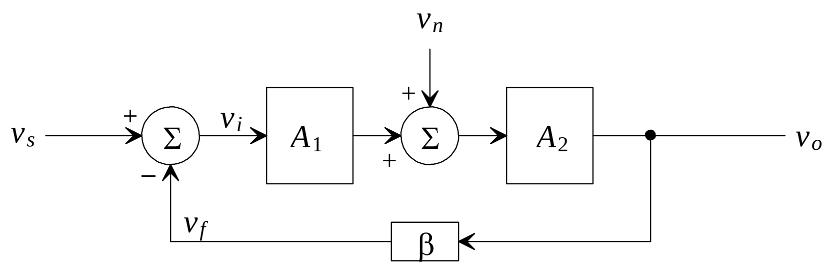
$$\frac{v_{out}}{v_{in}} = \frac{R_1 + R_2}{R_1} = \frac{1}{\beta} \text{ (ideal op-amp with } A_{OL} = \infty)$$

$$\rightarrow \beta = \frac{R_1}{R_1 + R_2} \rightarrow \max \text{ is 1 if } R_2 \text{ is very small (a short) and } R_1 \text{ is very big (an open)}$$

$$\text{for } \beta = \frac{1}{2} = \frac{R_1}{R_1 + R_2} \rightarrow R_1 = R_2$$

Note that this is an example of *series-shunt feedback* (a voltage amplifier). ■

31.3 Examine the feedback loop in the figure seen below. A noise source, v_n, is injected in the system between two amplifier stages. (a) Determine an expression for v_o which includes both the noise and the input signal, v_s. (b) Repeat (a) for the case where there is no feedback ($\beta = 0$). (c) If $A_1 = A_2 = 200$, and feedback is again applied around the circuit, what value of β will be required to reduce the noise by one-half as compared to the case stated in (b)?



a)
$$v_o = v_i A_1 A_2 + v_n A_2 \quad (1)$$
$$v_i = v_s - v_f \quad (2)$$
$$v_f = \beta \cdot v_o \quad (3)$$
$$\text{(3) into (2) yields: } v_i = v_s - \beta v_o \quad (4)$$
$$\text{(4) into (1) yields: } v_o = A_1 A_2 \cdot (v_s - \beta v_o) + A_2 v_n$$
$$v_o = A_1 A_2 v_s - A_1 A_2 \beta v_o + A_2 v_n$$
$$\rightarrow v_o = \frac{A_1 A_2 v_s + A_2 v_n}{1 + A_1 A_2 \beta} = \frac{A_1 A_2 v_s}{1 + A_1 A_2 \beta} + \frac{A_2 v_n}{1 + A_1 A_2 \beta} \text{ or}$$
$$v_o = \frac{A_1 A_2}{1 + A_1 A_2 \beta} \cdot (v_s + \frac{v_n}{A_1}) = \frac{A_{OL}}{1 + A_{OL}\beta} \cdot (v_s + \frac{v_n}{A_1})$$

where the noise has been referred to the input, v_i, and the open loop gain, A_{OL}, is $A_1 A_2$.

b) If $\beta = 0 \rightarrow v_o = A_1 A_2 \cdot \left(v_s + \frac{v_n}{A_1} \right)$ which indicates that the feedback doesn't affect the noise performance as mentioned in Sec. 8.3.2. In other words the noise always adds to the input source signal independent of the feedback. Notice that if we can increase A_1 without increasing v_n then we can reduce the input-referred noise (see Fig. 8.11).

c) If $A_1 = A_2 = 200$ what β value is required to reduce v_n by 1/2 as compared to $\beta = 0$?

As seen above if $\beta = 0$ then the noise component of v_o is $A_2 v_n$. We can then write

$$\frac{A_2 v_n}{1 + A_1 A_2 \beta} = \frac{A_2 v_n}{2} \rightarrow 1 + (200)^2 \beta = 2 \rightarrow \beta = \frac{2-1}{(200)^2} = 25 \times 10^{-6}$$

for a closed-loop *signal gain* half of the open-loop gain (very little feedback),

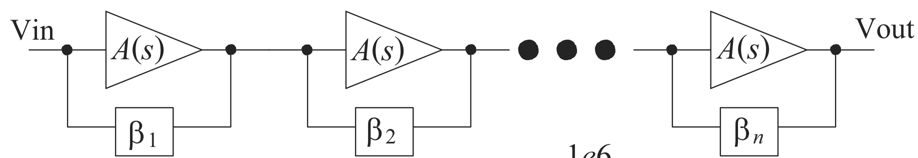
$$\frac{v_o}{v_s} = \frac{A_1 A_2}{1 + A_1 A_2 \beta} = \frac{A_1 A_2}{2}$$

Once again, however, note that when v_n is referred to the input it adds directly to the input signal independent of the (amount of) feedback employed. ■

31.4 An amplifier can be characterized as follows:

$$A(s) = 10,000 \cdot \frac{100}{s+100} \text{ V/V}$$

A series of these amplifiers are connected in cascade, and feedback is used around each amplifier. Determine the number of stages needed to produce an overall gain of 1,000 with a high-frequency rolloff (at − 20 dB/decade) occurring at 100,000 rad/sec. Assume that the first stage produces the desired high-frequency pole and that the remaining stages are designed so that their high-frequency poles are at least a factor of four greater.



$$A(s) = \frac{1e6}{s+100}$$

The first stage provides the desired pole. The other stages are designed, by selecting their feedback factors, so that

$$\frac{v_{out}}{v_{in}} = \frac{1000}{\left(\frac{s}{100,000}+1\right)\cdot\left(\frac{s}{400,000}+1\right)^{n-1}}$$

$$\text{first stage: } \frac{A(s)}{1+A(s)\cdot\beta_1} = \frac{1e6}{s+\underbrace{100+1e6\cdot\beta_1}_{100,000}} = \frac{10}{\frac{s}{100,000}+1} \rightarrow \beta_1 \approx 0.1$$

The other stages have identical βs with a pole at ω = 400,000 rads/s

$$\rightarrow \frac{1e6}{s+100+1e6\cdot\beta_{2\rightarrow n}} = \frac{1e6}{400,000}\cdot\frac{1}{\frac{s}{400,000}+1} = \frac{2.5}{\frac{s}{400k}+1} \rightarrow \beta_{2\rightarrow n} \approx 0.4$$

$$\rightarrow \frac{1000}{\left(\frac{s}{100k}+1\right)\left(\frac{s}{400k}+1\right)^{n-1}} \approx \frac{\left(\frac{1}{\beta_1}\right)\left(\frac{1}{\beta_{2\rightarrow n}}\right)^{n-1}}{\left(\frac{s}{100k}+1\right)\left(\frac{s}{400k}+1\right)^{n-1}}$$

$$= \frac{10\cdot 2.5^{n-1}}{\left(\frac{s}{100k}+1\right)\left(\frac{s}{400k}+1\right)^{n-1}}$$

$$\rightarrow 2.5^{n-1} = \frac{1000}{10} \rightarrow n-1 = \frac{\log(100)}{\log(2.5)} \approx 5$$

$$\rightarrow n = 6 \blacksquare$$

31.5 An amplifier can be characterized as follows:

$$A(s) = 1,000 \cdot \frac{s}{s+100} \text{ V/V}$$

and is connected in a feedback loop with a variable β. Determine the value of β for which the low-frequency rolloff is 50 rad/sec. What is the value of the closed-loop gain at that point?

$$A_{OLL}(s) = 1,000 \cdot \frac{s}{s+100}$$

$$A_{CLL}(s) = \frac{A_{OLL}(s)}{1 + A_{OLL}(s) \cdot \beta} = \frac{1,000 \cdot \frac{s}{s+100}}{1 + \beta \cdot 1,000 \cdot \frac{s}{s+100}} = \frac{10^3 \cdot s}{s + 100 + 10^3 s\beta}$$

$$= \frac{10^3 s}{s(1 + 10^3\beta) + 100} = \left(\frac{10^3}{1 + 10^3\beta}\right)\left(\frac{s}{s + \frac{100}{1+10^3\beta}}\right)$$

we want the form $A_{CLL}(\text{midband}) \cdot \frac{s}{s + \omega_{LCL}} = A_{CLL}(\text{mid}) \cdot \frac{s}{s+50}$

$$\rightarrow \frac{100}{1 + 10^3\beta} = 50 \rightarrow 10^3\beta + 1 = 2 \rightarrow \beta = 10^{-3}$$

and $A_{CLL}(\text{mid}) = \frac{10^3}{1 + 10^3 \cdot 10^{-3}} = 500$ V/V ■

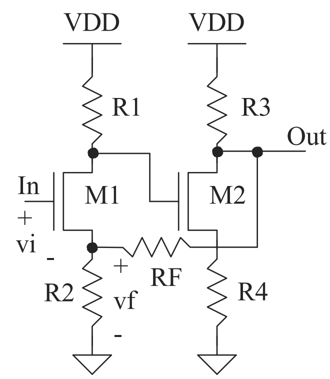
31.6 Make a table summarizing the four feedback topologies according to the following categories: input variable, output variable, units of A_{OL}, units of β, method to calculate $R_{\beta i}$ and $R_{\beta o}$, and expressions for A_{CL}, R_{if}, and R_{of}.

feedback topology	i/p var	o/p var	A_{OL} units	β units	$R_{\beta i}$ method	$R_{\beta o}$ method	A_{CL}	R_{if}	R_{of}
series-shunt	V	V	V/V	V/V	short o/p to gnd $R_{\beta i}$ = input to β network	"out-of-socket" i/p device	$\frac{A_{OL}}{1+\beta A_{OL}}$	$R_i(1 + A_{OL}\beta)$	$\frac{R_o}{(1+A_{OL}\beta)}$
series-series	V	A	A/V	V/A	"out-of-socket" o/p device	"out-of-socket" i/p device	$\frac{A_{OL}}{1+\beta A_{OL}}$	$R_i(1 + A_{OL}\beta)$	$R_o(1 + A_{OL}\beta)$
shunt-shunt	A	V	V/A	A/V	short o/p to gnd	short i/p to gnd	$\frac{A_{OL}}{1+\beta A_{OL}}$	$\frac{R_i}{(1+A_{OL}\beta)}$	$\frac{R_o}{(1+A_{OL}\beta)}$
shunt-series	A	A	A/A	A/A	"out-of-socket" o/p device	short i/p to gnd	$\frac{A_{OL}}{1+\beta A_{OL}}$	$\frac{R_i}{(1+A_{OL}\beta)}$	$R_o(1 + A_{OL}\beta)$

■

31.7 Using the two n-channel common source amplifiers shown in the figure and the addition of a single resistor, draw (a) a series-shunt feedback amplifier, (b) a series-series feedback amplifier, (c) a shunt-shunt feedback amplifier, and (d) a shunt-series amplifier. For each case, identify the forward and feedback paths, ensure that the feedback is negative by counting the inversions around the loop, and label the input variable, the feedback variable, and the output variable. Assume that the input voltage, v_{IN}, has a DC component that biases M1.

a) Series-shunt (voltage amplifier, voltage in and out)

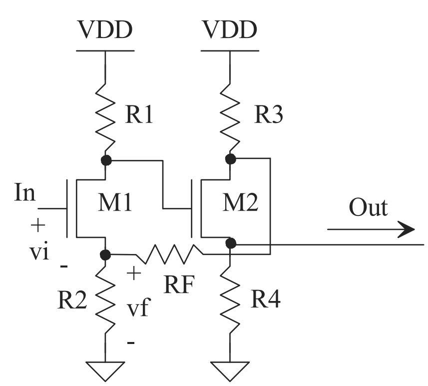


Forward Path: M1 gate to M1 drain/M2 gate to M2 drain (the output)

Feedback Path: M2 drain to M1 source via RF

=> 2 inversions for negative feedback with series mixing

b) Series-series (transconductance amplifier, voltage in and current out)



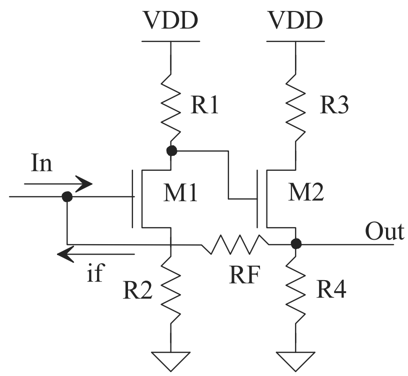
Forward Path: M1 gate to M1 drain/M2 gate to M2 source (the output)

Feedback Path: M2 drain to M1 source via RF

=> 2 inversions for negative feedback with series mixing

31.7 (continued)

c) Shunt-shunt (transimpedance amplifier, current in and voltage out)

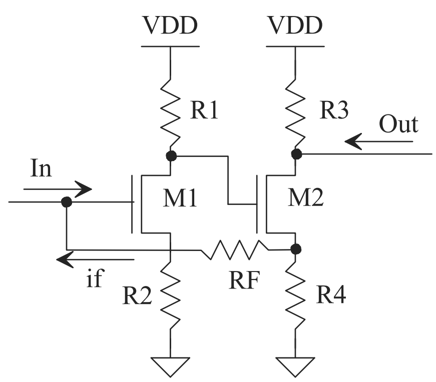


Forward Path: M1 gate to M1 drain/M2 gate to M2 source (the output)

Feedback Path: M2 source to M1 gate via RF

=> 1 inversion for negative feedback with shunt mixing

d) Shunt-series (current amplifier, current in and out)



Forward Path: M1 gate to M1 drain/M2 gate to M2 drain (the output)

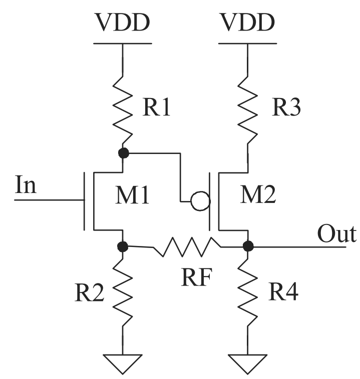
Feedback Path: M2 source to M1 gate via RF

=> 1 inversion for negative feedback with shunt mixing

■

31.8 Repeat Problem 31.7 using the two-transistor circuit shown in the figure.

a) Series-shunt (voltage amplifier, voltage in and out)

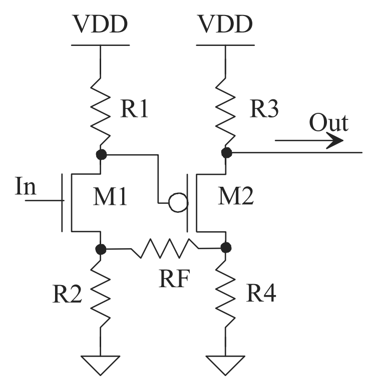


Forward Path: M1 gate to M1 drain/M2 gate to M2 drain (the output)

Feedback Path: M2 drain to M1 source via RF

=> 2 inversions for negative feedback with series mixing

b) Series-series (transconductance amplifier, voltage in and current out)



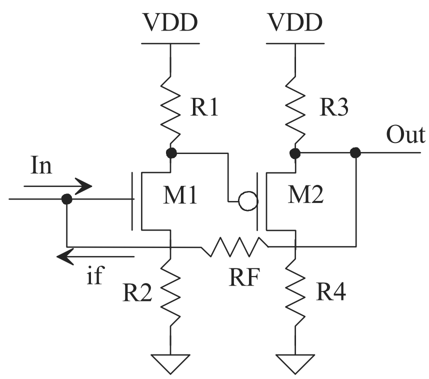
Forward Path: M1 gate to M1 drain/M2 gate to M2 source (the output)

Feedback Path: M2 drain to M1 source via RF

=> 2 inversions for negative feedback with series mixing

31.8 (continued)

c) Shunt-shunt (transimpedance amplifier, current in and voltage out)

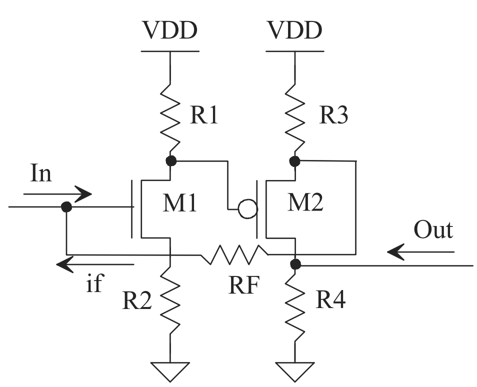


Forward Path: M1 gate to M1 drain/M2 gate to M2 source (the output)

Feedback Path: M2 source to M1 gate via RF

=> 1 inversion for negative feedback with shunt mixing

d) Shunt-series (current amplifier, current in and out)



Forward Path: M1 gate to M1 drain/M2 gate to M2 drain (the output)

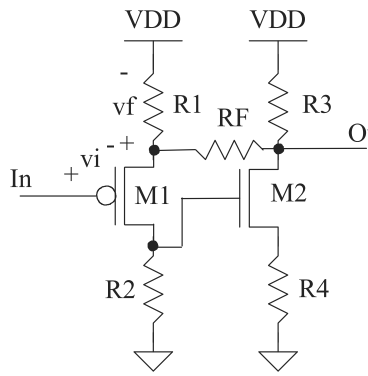
Feedback Path: M2 source to M1 gate via RF

=> 1 inversion for negative feedback with shunt mixing

■

31.9 Repeat Problem 31.7 using the figure.

a) Series-shunt (voltage amplifier, voltage in and out)

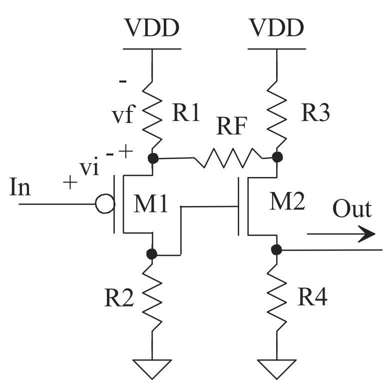


Forward Path: M1 gate to M1 drain/M2 gate to M2 drain (the output)

Feedback Path: M2 drain to M1 source via RF

=> 2 inversions for negative feedback with series mixing

b) Series-series (transconductance amplifier, voltage in and current out)



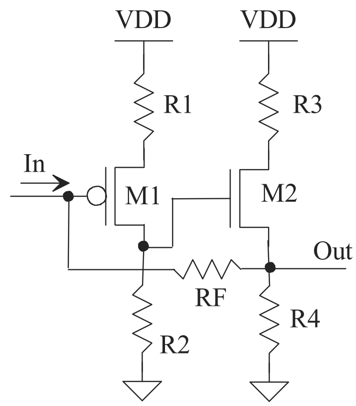
Forward Path: M1 gate to M1 drain/M2 gate to M2 source (the output)

Feedback Path: M2 drain to M1 source via RF

=> 2 inversions for negative feedback with series mixing

31.9 (continued)

c) Shunt-shunt (transimpedance amplifier, current in and voltage out)

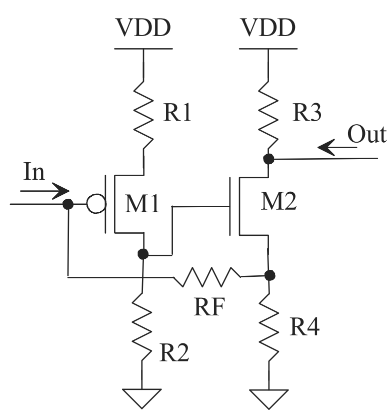


Forward Path: M1 gate to M1 drain/M2 gate to M2 source (the output)

Feedback Path: M2 source to M1 gate via RF

=> 1 inversion for negative feedback with shunt mixing

d) Shunt-series (current amplifier, current in and out)



Forward Path: M1 gate to M1 drain/M2 gate to M2 drain (the output)

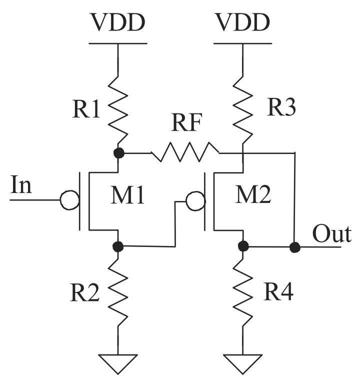
Feedback Path: M2 source to M1 gate via RF

=> 1 inversion for negative feedback with shunt mixing

■

31.10 Repeat Problem 31.7 using the figure.

a) Series-shunt (voltage amplifier, voltage in and out)

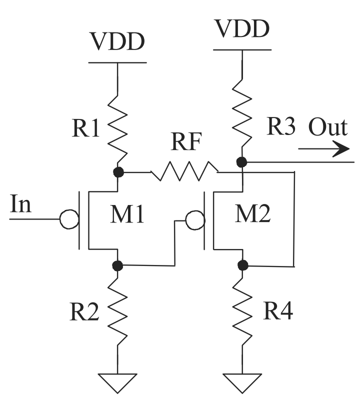


Forward Path: M1 gate to M1 drain/M2 gate to M2 drain (the output)

Feedback Path: M2 drain to M1 source via RF

=> 2 inversions for negative feedback with series mixing

b) Series-series (transconductance amplifier, voltage in and current out)



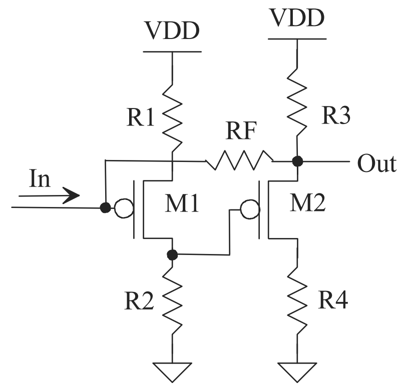
Forward Path: M1 gate to M1 drain/M2 gate to M2 source (the output)

Feedback Path: M2 drain to M1 source via RF

=> 2 inversions for negative feedback with series mixing

31.10 (continued)

c) Shunt-shunt (transimpedance amplifier, current in and voltage out)

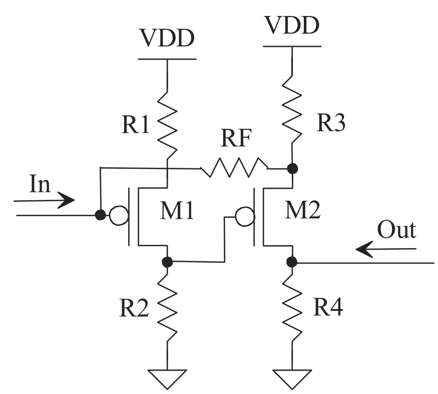


Forward Path: M1 gate to M1 drain/M2 gate to M2 source (the output)

Feedback Path: M2 source to M1 gate via RF

=> 1 inversion for negative feedback with shunt mixing

d) Shunt-series (current amplifier, current in and out)



Forward Path: M1 gate to M1 drain/M2 gate to M2 drain (the output)

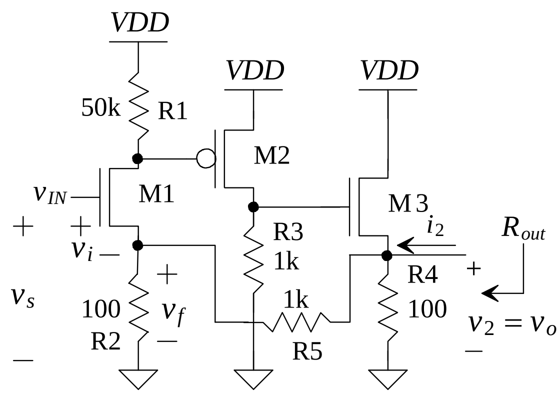
Feedback Path: M2 source to M1 gate via RF

=> 1 inversion for negative feedback with shunt mixing

■

For each of the following feedback analysis problems, assume that the circuit has been properly DC biased and that MOSFETs have been characterized. The n-channel devices have g_m = 0.06 A/V and r_o = 70 kΩ. The p-channel devices have g_m = 0.04 A/V and r_o = 50 kΩ.

31.11 Using the series-shunt amplifier shown in the figure, (a) identify the feedback topology by labeling the mixing variables and output variable, (b) verify that negative feedback is employed, (c) draw the closed-loop small-signal model, and (d) find the expression for the resistors $R_{\beta i}$ and $R_{\beta o}$.



a) Series-shunt since both input variables, v_i and v_f, and output variable, v_o, are voltages.

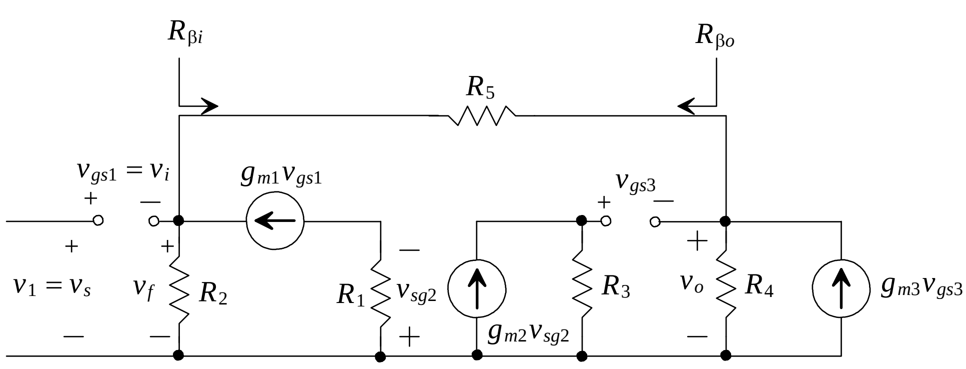
b) Negative feedback since 2 inversions and series mixing

M1 gate to M1 drain = inversion #1

M2 gate to M2 drain = inversion #2

M3 gate to M3 source = no inversion

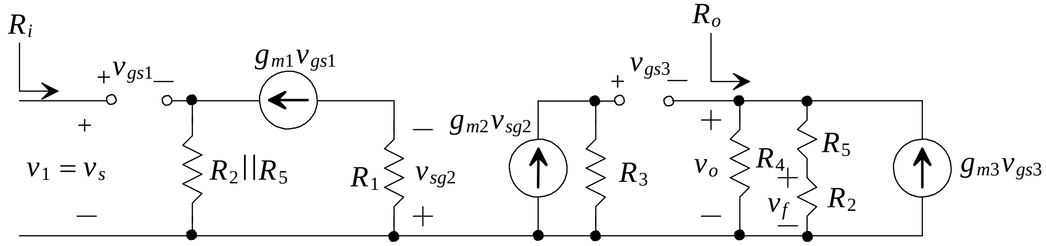
c) closed-loop small-signal model



d) $R_{\beta i} = R_5 = 1$ kΩ and $R_{\beta o} = R_5 + R_2 = 1.1$ kΩ. ■

31.12 Using the figure and the results from Problem 31.11, (a) draw the small-signal open-loop model for the circuit and (b) find the expressions for the open-loop parameters, A_{OL}, β, R_i, and R_o and (c) the closed-loop parameters, A_{CL} and R_{out}. Note that finding R_{in} is a trivial matter since the signal is input into the gate of M1.

a) small-signal open-loop model



b)

$$v_o = g_{m3}v_{gs3} \cdot R_4||(R_2 + R_5) \ (1)$$

$$v_{gs3} = g_{m2}v_{sg2} \cdot R_3 - v_o \ (2)$$

$$v_{sg2} = g_{m1}v_{gs1} \cdot R_1 \ (3)$$

$$v_{gs1} = v_s - g_{m1}v_{gs1} \cdot R_2||R_5 \rightarrow v_{gs1} = \frac{v_s}{1 + g_{m1} \cdot R_2||R_5} \ (4)$$

plugging (4) => (3) and solving for v_{sg2}

$$v_{sg2} = \frac{g_{m1} \cdot R_1 \cdot v_s}{1 + g_{m1} \cdot R_2||R_5} \ (5)$$

plugging (2) => (1)

$$v_o = g_{m3}(g_{m2}v_{sg2} \cdot R_3 - v_o) \cdot R_4||(R_2 + R_5)$$

$$v_o = v_{sg2} \cdot (g_{m2}R_3) \cdot \left(\frac{g_{m3} \cdot [R_4||(R_2 + R_5)]}{1 + g_{m3} \cdot [R_4||(R_2 + R_5)]} \right) \ (6)$$

Finally, plugging (5) => (6) and solving for the open-loop gain results in

$$A_{OL} = \frac{v_o}{v_s} = \left(\frac{g_{m1} \cdot R_1}{1 + g_{m1} \cdot R_2||R_5} \right)(g_{m2}R_3)\left(\frac{g_{m3} \cdot R_4||(R_2 + R_5)}{1 + g_{m3} \cdot R_4||(R_2 + R_5)} \right)$$

$$\beta = \frac{v_f}{v_o} = \frac{R_2}{R_2 + R_5}$$

$$R_i = \infty$$

$$R_o = R_4||(R_5 + R_2)$$

c)

$$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} \text{ and } R_{out} = \frac{R_o}{1 + A_{OL}\beta}$$

■

31.13 Using the series-shunt amplifier shown in Fig. 31.57, (a) verify the feedback topology by labeling the mixing variables and the output variable closed-loop small-signal model and (b) find the values of $R_{\beta i}$ and $R_{\beta o}$.

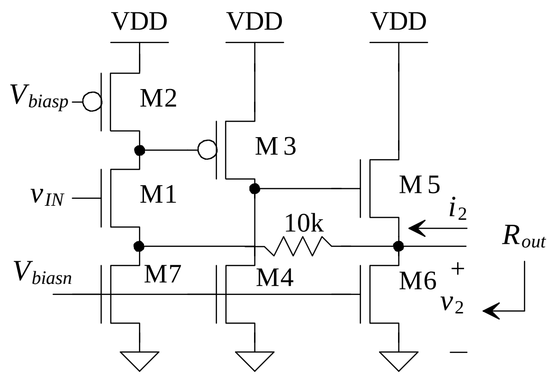
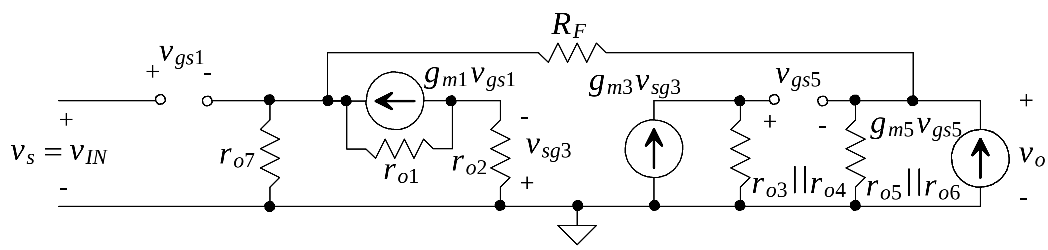
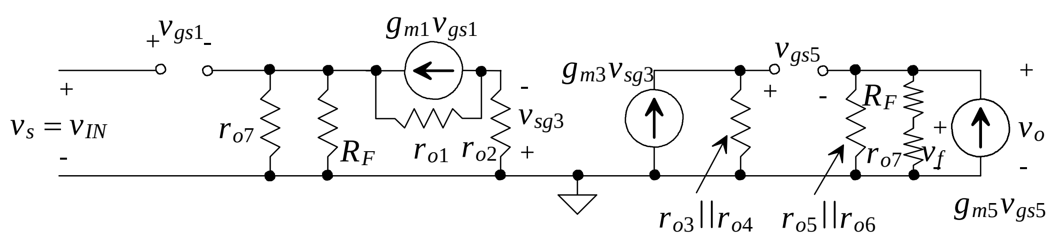


Figure 31.57 A series-shunt amplifier with source-follower output buffer.



b) $R_{\beta i} = R_F = 10\text{k}$, $R_{\beta o} = R_F + r_{o7} = 80\text{k}$ ■

31.14 Using the series-shunt amplifier shown in Fig. 31.57 and the results from problem 31.13, (a) draw the small-signal open-loop model for the circuit and (b) calculate the open-loop parameters, A_{OL} , β, R_i , and R_o and (c) the closed-loop parameters, A_{CL} , and R_{out}. Note that Fig. 31.57 is identical to Fig. 31.56 except that the resistors have been replaced with active loads.



$$A_{OL} = \frac{v_o}{v_s} = \left[\frac{g_{m1}\cdot r_{o1}||r_{o2}}{g_{m1}\cdot r_{o7}||R_F + 1}\right][g_{m3}\cdot r_{o3}||r_{o4}]\left[\underbrace{\frac{g_{m5}\cdot r_{o5}||r_{o6}||(R_F + r_{o7})}{g_{m5}\cdot r_{o5}||r_{o6}||(R_F + r_{o7}) + 1}}_{\approx 1}\right] = 3.89k \text{ V/V}$$

$$\beta = \frac{v_f}{v_o} = \frac{r_{o7}}{r_{o7} + R_F} = 0.875 \text{ V/V},\ R_i = \infty,\ R_o = r_{o5}||r_{o6}||(R_F + r_{o7}) = 29.17k||80k = 21.38\ k\Omega$$

b) $A_{CL} = \frac{R_o}{1+\beta A_{OL}} = 1.14$ V/V and $R_{out} = \frac{R_o}{1+\beta A_{OL}} = 6.28\ \Omega$ ■

31.15 Using the principles of feedback analysis, find the value of the voltage gain, $\frac{v_2}{v_{in}}$ and $\frac{v_2}{i_2}$ for the series-shunt circuit shown in Fig. 31.58.

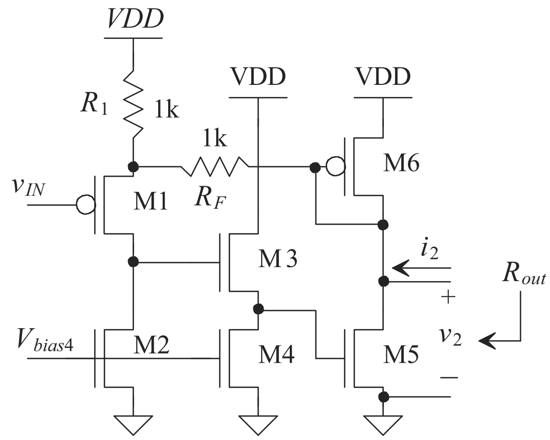


Figure 31.58 Feedback amplifier used in problem 31.15.

$$A_{OL} \approx \left[\frac{r_{o2}||r_{o1}}{r_{o2}||r_{o1} + (1/g_{m1} + R_1||R_F)}\right] \underbrace{\left[\frac{r_{o4}||r_{o3}}{r_{o4}||r_{o3} + 1/g_{m3}}\right]}_{\approx 1} \left[g_{m5} \cdot \left(\frac{1}{g_{m6}}||r_{o6}||r_{o5}||(R_F + R_1)\right)\right]$$

$$\approx \left[\frac{r_{o2}||r_{o1}}{r_{o2}||r_{o1} + (1/g_{m1} + R_1||R_F)}\right] \left[g_{m5} \cdot \left(\frac{1}{g_{m6}}||r_{o6}||r_{o5}||(R_F + R_1)\right)\right] = 82.34 \text{ V/V}$$

$$\beta = \frac{v_f}{v_2} = \frac{R_1}{R_1 + R_2} = 0.5 \rightarrow A_{CL} = \frac{v_2}{v_{in}} \cdot \frac{A_{OL}}{1 + \beta A_{OL}} = 1.952 \text{ V/V}$$

$$R_{out} = \frac{v_2}{i_2} = \frac{R_o}{1 + \beta A_{OL}} \approx \frac{\frac{1}{g_{m6}}||(R_1 + R_F)}{1 + \beta A_{OL}} = 0.586\ \Omega$$

■

31.16 A shunt-shunt feedback amplifier is shown in Fig. 31.59. (a) Identify the feedback topology by labeling the input mixing variables and the output variables, (b) verify that negative feedback is employed, (c) draw the closed-loop small-signal model, and (d) find the values of $R_{\beta i}$ and $R_{\beta o}$.

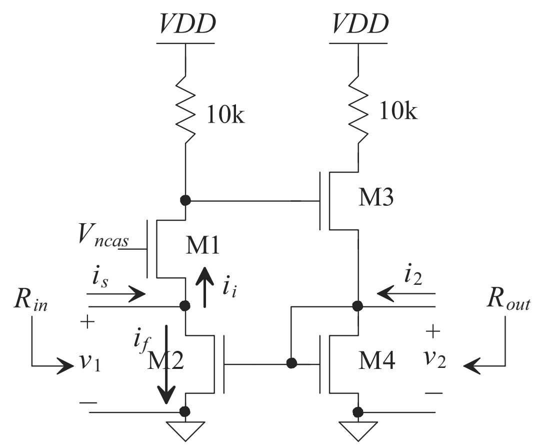
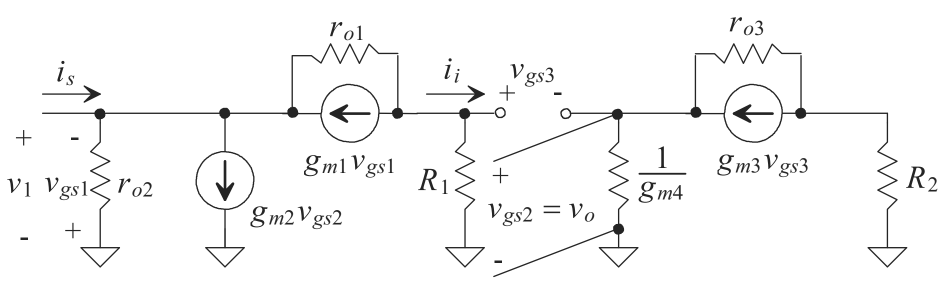


Figure 31.59 A shunt-shunt feedback amplifier.

a) shunt-shunt feedback, see labels above

b) 1 inversion => negative feedback with shunt mixing

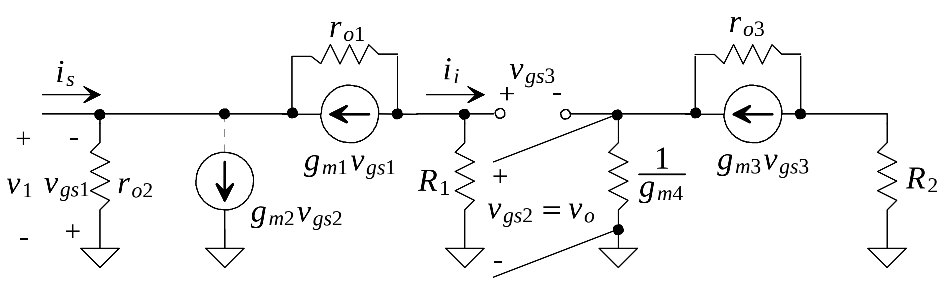
c)



d) $R_{\beta o} = \infty = R_{G2} || R_{G4}$ and $R_{\beta i} = r_{o2} = 70\ k\Omega$ ■

31.17 Using the shunt-shunt amplifier shown in Fig. 31.59 and the results from problem 31.16, (a) draw the small-signal open-loop model for the circuit and (b) calculate expressions for the open-loop parameters, A_{OL}, β, R_i, and R_o and (c) the closed-loop parameters, A_{CL}, R_{in}, and R_{out}.

a)



b)

$$\frac{v_o}{v_i} = [CG]\cdot[CD] = \left[\frac{R_1}{r_{o2}}\right]\cdot\left[\frac{g_{m3}\cdot\frac{1}{g_{m4}}}{g_{m3}\cdot\frac{1}{g_{m4}}+1}\right] = \left[\frac{1}{7}\right]\cdot\left[\frac{1}{2}\right] = \frac{1}{14} = .0714 \text{ V/V}$$

$$R_i = r_{o2}||R_{ins1} = r_{o2}||\frac{1+\frac{R_1}{r_{o1}}}{\frac{1}{r_{o1}}+g_{m1}} \approx \frac{1+\frac{1}{7}}{\frac{1}{70k}+0.06} = 19.04\ \Omega$$

$$A_{OL} = \frac{v_o}{i_s} = \frac{v_o}{v_1}\cdot R_i = \left(\frac{1}{14}\right)(19.04) = 1.36 \text{ V/A}$$

$$\beta = \frac{i_f}{v_o} = \frac{g_{m2}v_{gs2}}{v_{gs2}} = g_{m2} = 60 \text{ mA/V}$$

$$R_o = \frac{1}{g_{m4}}||R_{ins1} = \frac{1}{g_{m4}}||\frac{1+\frac{R_1}{r_{o1}}}{\frac{1}{r_{o1}}+g_{m1}} = 16.67||19.04 = 8.9\ \Omega$$

c)

$$A_{CL} = \frac{A_{OL}}{1+\beta A_{OL}} = \frac{1.36}{1+0.06\cdot 1.36} = 1.26 \text{ V/A}$$

$$R_{out} = \frac{R_o}{1+\beta A_{OL}} = \frac{8.9}{1+0.06\cdot 1.36} = 8.23\ \Omega$$

$$R_{in} = \frac{R_i}{1+\beta A_{OL}} = \frac{19.04}{1+0.06\cdot 1.36} = 17.6\ \Omega$$

■

31.18 Using the principles of feedback analysis, find the value of the voltage gain, $\frac{v_2}{v_1}$, $\frac{v_1}{i_1}$, and $\frac{v_2}{i_2}$ for the shunt-shunt circuit shown in Fig. 31.60.

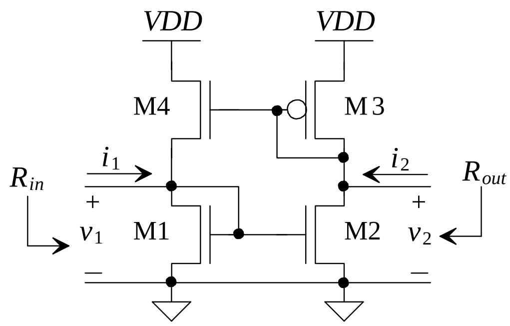
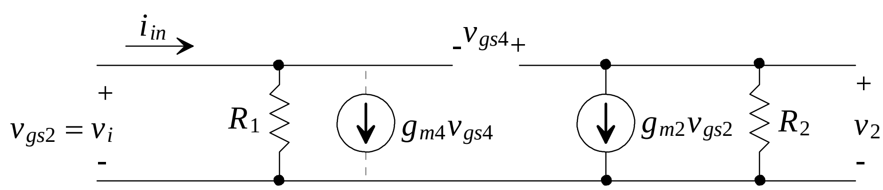


Figure 31.60 A shunt-shunt feedback amplifier, see problem 31.18.



$$R_1 = \frac{1}{g_{m1}}||r_{o1}||r_{o4} \approx \frac{1}{g_{m1}} = 16.67\ \Omega$$

$$R_2 = \frac{1}{g_{m3}}||r_{o2}||r_{o3} \approx \frac{1}{g_{m3}} = 25\ \Omega$$

$$A_{OL} = \frac{v_2}{v_i} \cdot R_1 = \frac{v_2}{i_1} = -g_{m2} \cdot R_1 \cdot R_2 = -25\ \text{V/A}$$

$$\beta = \frac{i_f}{v_o} \approx \frac{-g_{m4}}{1 + g_{m4}R_1} = -0.03\ \text{A/V} \rightarrow A_{CL} = \frac{v_2}{i_1} = \frac{A_{OL}}{1 + \beta A_{OL}} = -14.3\ \text{V/A}$$

$$R_i = \frac{1}{g_{m1}} = 16.67\ \Omega, \quad R_{in} = \frac{v_1}{i_1} = \frac{R_i}{1 + \beta A_{OL}} = 9.5\ \Omega$$

$$R_o = \frac{1}{g_{m3}} = 25\ \Omega, \quad R_{out} = \frac{v_2}{i_2} = \frac{R_o}{1 + \beta A_{OL}} = 14.3\ \Omega$$

$$\frac{v_2}{v_1} = \frac{v_2}{i_1} \cdot \frac{i_1}{v_1} = A_{CL} \cdot \frac{1}{R_{in}} = -1.5\ \text{V/V}$$

■

31.19 Using the series-series feedback amplifier shown in Fig. 31.61, (a) identify the feedback topology, (b) verify that negative feedback is employed, (c) draw the closed-loop small-signal model, and (d) find the values of $R_{\beta i}$ and $R_{\beta o}$.

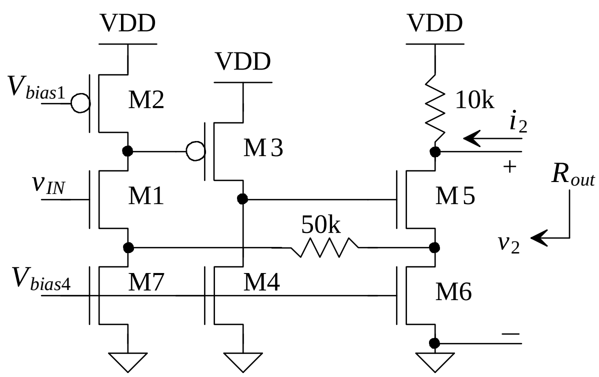
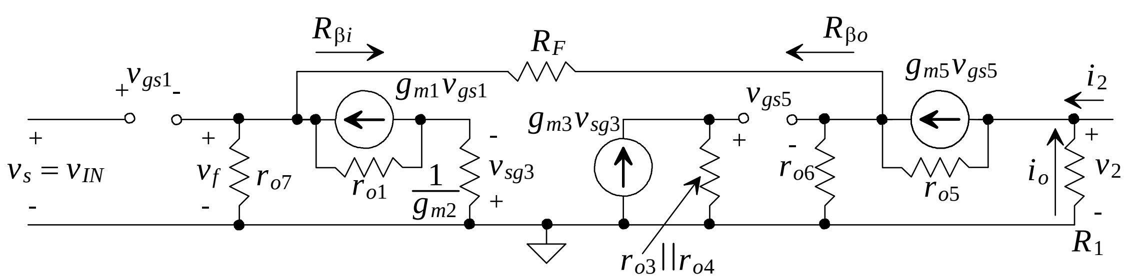


Figure 31.61 Series-series feedback amplifier with source-follower output buffer.

a) series-series, $v_i = v_{gs1}$, v_f is the voltage dropped across M7, $v_s = v_{IN}$.

b) two inversions for negative feedback with series mixing

c)



d)

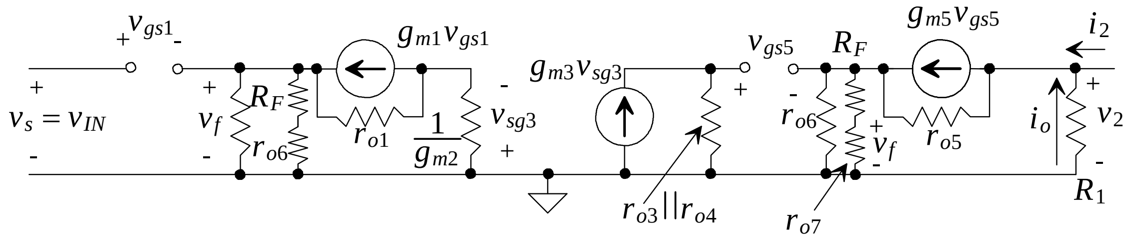
$$R_{\beta i} = R_F + r_{o6} = 120\ k\Omega$$

$$R_{\beta o} = R_F + r_{o7} = 120\ k\Omega$$

■

31.20 Using the series-series amplifier shown in Fig. 31.61 and the results from problem 31.19, (a) draw the small-signal open-loop model for the circuit and (b) calculate the open-loop parameters, A_{OL}, β, R_i, and R_o and (c) the closed-loop parameters, A_{CL}, R_{in}, and R_{out}.

a)



b)

$$A_{OL} = \frac{i_o}{v_s} = \frac{-v_2}{v_s} \cdot \frac{1}{R_1} = \left[\frac{g_{m1} \cdot \left(r_{o1}||\frac{1}{g_{m2}}\right)}{g_{m1}(r_{o7}||(R_F + r_{o6}) + 1)}\right][g_{m3}(r_{o3}||r_{o4})]\left[\frac{g_{m5}}{g_{m5}(r_{o6}||R_F + r_{o7}) + 1}\right]$$

$$= 14.924 \times 10^{-6} \text{ A/V}$$

$$\beta = \frac{v_f}{i_o} = \left(\frac{r_{o7}}{r_{o7} + R_F}\right)\left(\frac{r_{o6}(r_{o7} + R_F)}{r_{o6} + r_{o7} + R_F}\right) = 25,789 \text{ V/A}$$

$$R_i = \infty$$

$$R_o = R_1 + \underbrace{(r_{o6}||R_F + r_{o7})}_{R_s} + r_{o5}\left(1 + g_{m5}\underbrace{(r_{o6}||R_F + r_{o7})}_{R_s}\right) = 186 \text{ MEG}$$

c)

$$A_{CL} = \frac{A_{OL}}{1 + \beta A_{OL}} = 10.776 \times 10^{-6} \text{ A/V}$$

$$R_{in} = \infty$$

$$R_{out} = R_1||(R_o - R_1) \approx R_1 = 10k$$

■

31.21 Using the shunt-series amplifier in Fig. 31.35, derive the expressions for A_{OL}, R_{in}, and R_{out}.

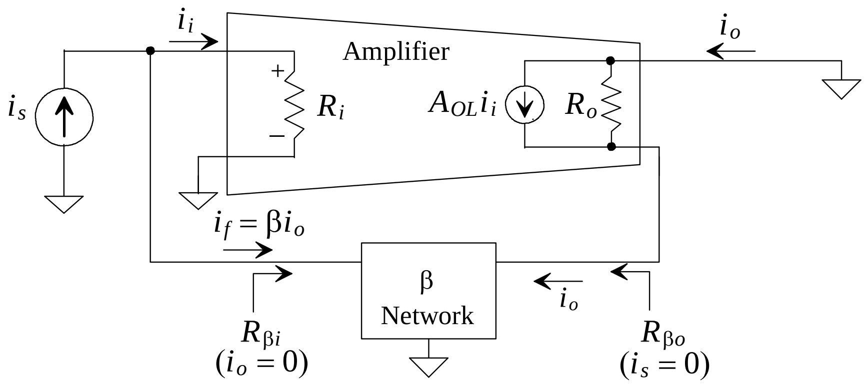


Figure 31.35 An ideal current feedback amplifier.

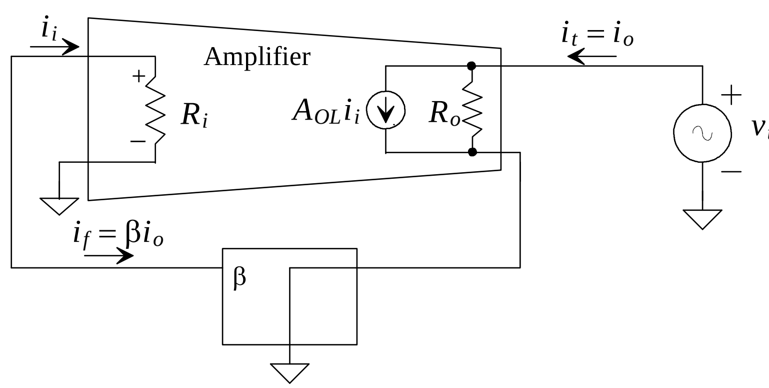
$$A_{CL} = \frac{i_o}{i_s} = \frac{i_o}{i_i + i_f} = \frac{i_o}{i_i + \beta i_o} = \frac{i_i \cdot A_{OL}}{i_i(1 + \frac{i_o}{i_i} \cdot \beta)} \ \{\text{assuming } R_o = \infty\}$$

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

$$i_s = i_i + i_f = \frac{v_s}{R_i} + \beta i_o = \frac{v_s}{R_i} + \beta A_{OL} i_i \ \{\text{again assuming } R_o = \infty\}$$

$$i_s = \frac{v_s}{R_i}(1 + A_{OL}\beta) \rightarrow R_{in} = \frac{v_s}{i_s} = \frac{R_i}{1 + A_{OL}\beta}$$

And finally for R_{of} let's apply a test voltage to the output with the input open-circuited.



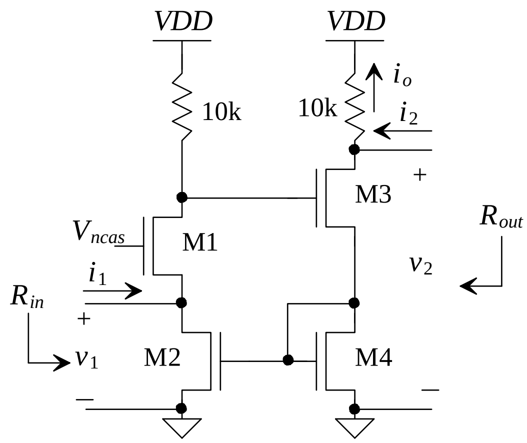
$$i_o = A_{OL} i_i + \frac{v_t}{R_o} = -A_{OL} i_f + \frac{v_t}{R_o} = -A_{OL}\beta i_o + \frac{v_t}{R_o}$$

$$i_o(1 + A_{OL}\beta) = \frac{v_t}{R_o}$$

$$\rightarrow \frac{v_t}{i_o} = R_{out} = R_o(1 + A_{OL}\beta) \ \blacksquare$$

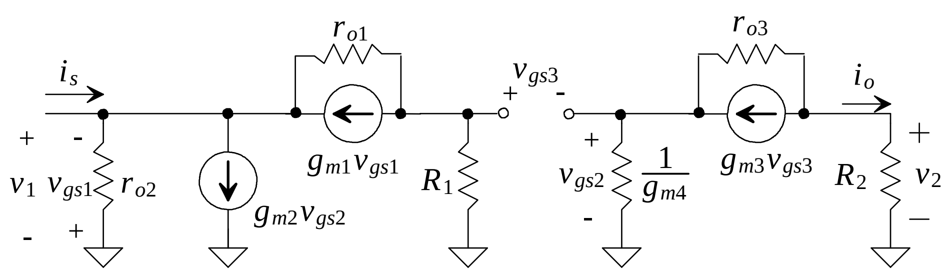
31.22 Convert the shunt-shunt amplifier shown in Fig. 31.59 into a shunt-series feedback amplifier without adding any components. (a) Identify the feedback topology, (b) verify that negative feedback is employed, (c) draw the closed-loop small-signal model, and (d) find the values of $R_{\beta i}$ and $R_{\beta o}$.

a) Shunt-series topology seen below.



b) 1 inversion -> negative feeback with shunt mixing.

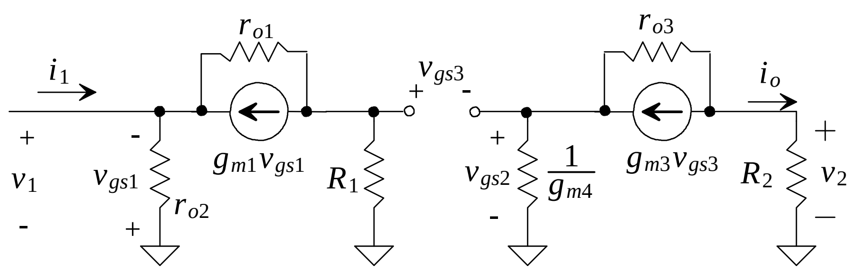
c) small-signal model is seen below.



d) $R_{\beta i} = r_{o2} = 70k$ and $R_{\beta o} = \infty$ ■

31.23 Using the shunt-series amplifier from problem 31.22, (a) draw the small-signal open-loop model for the circuit and (b) calculate the open-loop parameters, A_{OL}, β, R_i, and R_o and (c) the closed-loop parameters, A_{CL}, R_{in}, and R_{out}.

a) The small-signal model is seen below.



b) Feedback current is via M2

$$\beta = \frac{i_f}{i_o} = \frac{g_{m2} \cdot v_{gs2}}{-v_{gs2} \cdot \left(\frac{1}{g_{m4}}\right)^{-1}} = -\frac{g_{m2}}{g_{m4}} = -1\ \frac{A}{A} = \beta$$

$$R_i = R_{inD3} || R_{inS1} = 19.04\ \Omega = R_i$$

$$R_o = R_2 + R_{inD3} = R_2 + \frac{1}{g_{m4}} + r_{o3}(1 + \frac{g_{m3}}{g_{m4}}) \approx R_2 + 2r_{o3} = 150k = R_o$$

$$A_{OL} = \frac{i_o}{i_s} = \frac{v_o}{v_s} \cdot \frac{R_i}{R_s} = (CG) \cdot (CS) \cdot \frac{R_i}{R_2} = \left(\frac{R_1}{r_{o2}}\right)\left(\frac{-g_{m3}R_2||r_{o3}}{g_{m3}/g_{m4} + 1}\right)\left(\frac{R_i}{R_2}\right) = -0.0714\ \frac{A}{A} = A_{OL}$$

c) $$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} = 0.06664\ \frac{A}{A} = A_{CL}$$

$$R_{in} = \frac{R_i}{1 + A_{OL} \cdot \beta} = 18.7\ \Omega = R_{in}$$

$$R_{out} = R_2 || [R_o(1 + A_{OL}\beta) - R_2] \approx R_2 = 10\ k\Omega = R_{out}\ \blacksquare$$

31.24 A feedback amplifier is shown in Fig. 31.62. Identify the feedback topology and determine the value of the voltage gain, $\frac{v_2}{v_1}$, R_{in}, and R_{out}.

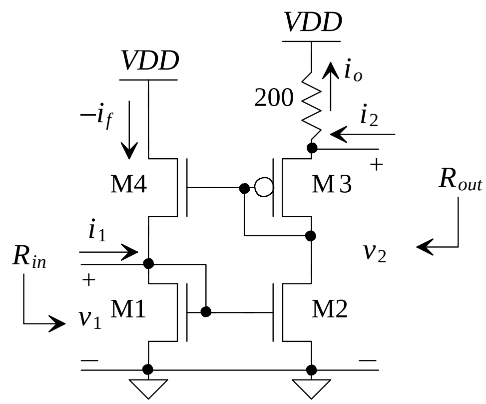
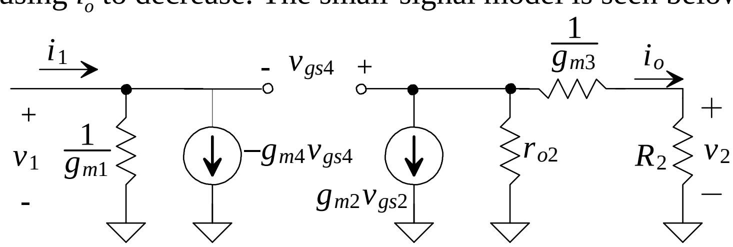


Figure 31.62 Feedback amplifier used in problem 31.24.

This is a shunt-series topology (current amplifier). As i_1 goes up v_{gs2} goes up. This turns M2 and M3 on causing i_o to decrease. The small-signal model is seen below.



$$R_i = \frac{1}{g_{m1}}||\frac{1}{g_{m4}} = 8.34\ \Omega \text{ and } R_o = R_2||\left(\frac{1}{g_{m3}} + r_{o2}\right) \approx R_2 = 200\ \Omega$$

$$A_{OL} = \frac{i_o}{i_1} = \frac{v_2}{v_1}\cdot\frac{R_i}{R_o} = \frac{R_i}{R_o}\cdot\left[\frac{R_2}{R_2+\frac{1}{g_{m3}}}\right]\left[-g_{m2}(R_2+\frac{1}{g_{m3}})\right] = \frac{8.34}{200}\cdot\frac{200}{216.67}\cdot(-0.6)\cdot 216.67$$

$$= -0.5\ \frac{A}{A}$$

$$\beta = \frac{i_f}{i_o} = \frac{-g_{m4}\cdot v_{gs4}}{v_{gs4}\left(1+\frac{g_{m4}}{g_{m1}}\right)}\cdot(R_2+g_{m1}) = -6.5\ \frac{A}{A}$$

$$\rightarrow R_{in} = \frac{R_i}{1+A_{OL}\beta} = \frac{8.34}{1+0.5(6.5)} = 1.96\ \Omega = R_{in}$$

Following the discussion in Sec. 31.6 we can calculate the output resistance using

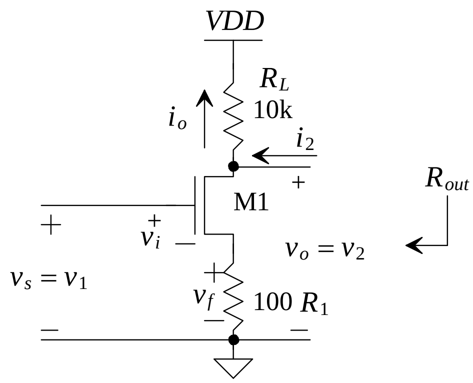
$$R_{out} = R_2||(R_{of}-R_2) = R_2||(R_o(1+A_{OL}\beta)-R_2) = 200||650 = 153\ \Omega = R_{out}$$

$$A_{CL} = \frac{i_2}{i_1} = \frac{A_{OL}}{1+A_{OL}\beta} = \frac{-0.5}{4.25} = -0.118\ \frac{A}{A}$$

$$\frac{v_2}{v_1} = \frac{i_2}{i_1}\cdot\frac{R_{out}}{R_{in}} = (-0.118)\cdot\left(\frac{153}{1.96}\right) = -9.2\ \frac{V}{V}$$

■

31.25 Notice that the amplifier shown in Fig. 31.63 is a simple common source amplifier with source resistance. Explain how this is actually a very simple feedback amplifier and determine the type of feedback used. Determine A_{OL} and β.



Series-series feedback is used.

In words, any increase in v_s causes a decrease in v_o. As v_o gets smaller the AC current through R_L gets larger which is also flowing through R_1. This increased current through R_1 raises v_f causing the feedback.

Neglecting the resistance looking into the drain of M1 we can write

$$A_{OL} = \frac{i_o}{v_s} = \frac{v_o}{v_s} \cdot \frac{1}{R_L} = [CS] \cdot \frac{1}{R_L} = \frac{-R_L}{1/g_{m1} + R_1} \cdot \frac{1}{R_L} = \frac{-1}{16.67 + 100}$$

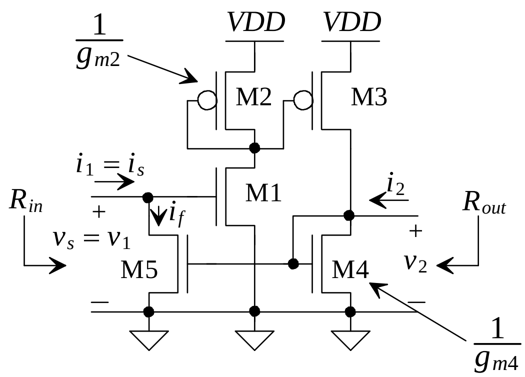
$$\rightarrow A_{OL} = -8.6 \times 10^{-3} \frac{A}{V}$$

$$\beta = \frac{v_f}{i_o} = \frac{-i_o R_1}{i_o} = -R_1$$

$$\rightarrow \beta = -100 \frac{V}{A}$$

■

31.26 A feedback amplifier is shown in Fig. 31.64. Identify the feedback topology and determine the value of the voltage gain, $\frac{v_2}{v_1}$, R_{in}, and R_{out}.



Shunt-shunt feeback is used.

3 inversions for negative feedback with shunt mixing.

$$R_{\beta o} = \infty \text{ and } R_{\beta i} = R_{inD5} = r_{o5}$$

$$R_i = r_{o5};\ R_o = \frac{1}{g_{m4}};\ \frac{v_2}{v_1} = (CS)(CS) = \left(\frac{-g_{m1}}{g_{m2}}\right)\left(\frac{-g_{m3}}{g_{m4}}\right) = 1\ \frac{V}{V}$$

$$A_{OL} = \frac{v_2}{i_s} = \frac{v_2}{v_1} \cdot R_i = 1 \cdot r_{o5} \rightarrow A_{OL} = 70k\ \frac{V}{A}$$

$$\beta = \frac{i_f}{v_2} = \frac{g_{m5} \cdot v_{gs5}}{v_{gs5}} = g_{m5} \rightarrow \beta = 0.06\ \frac{A}{V}$$

$$1 + A_{OL}\beta = 4,201,\ A_{OL}\beta \approx 4.2k$$

$$R_{in} = R_{if} = \frac{R_i}{1 + A_{OL}\beta} \rightarrow R_{in} = 16.67\ \Omega$$

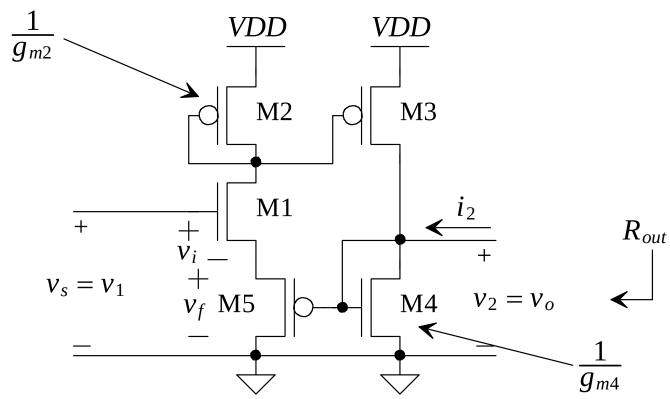
$$R_{out} = R_{of} = \frac{R_o}{1 + A_{OL}\beta} \rightarrow R_{out} = 0.004\ \Omega$$

$$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} = 16.7\ \frac{V}{A} = \frac{v_2}{i_s}$$

$$\rightarrow \frac{v_2}{v_1} = \frac{v_2}{i_s} \cdot \frac{1}{R_{in}} = \frac{16.7}{16.7} \rightarrow \frac{v_2}{v_1} = 1\ \frac{V}{V}$$

■

31.27 A feedback amplifier is shown in Fig. 31.65. Identify the feedback topology and determine the value of the voltage gain, $\frac{v_2}{v_1}$ and R_{out}.



Series-shunt feedback is used.

Two inversions for negative feedback.

$$A_{OL} = \frac{v_2}{v_s} = [CS] \cdot [CS] = \frac{-\frac{1}{g_{m2}}}{1/g_{m1} + r_{o5}} \cdot \frac{-1/g_{m4}}{1/g_{m3}} = 333 \times 10^{-6} \ \frac{V}{V}$$

$$\beta = \frac{v_f}{v_2} = \frac{v_{sg5}}{v_{gs4}} = 1$$

$$A_{CL} = \frac{A_{OL}}{1 + \beta A_{OL}} = \frac{v_2}{v_1} \approx 333 \times 10^{-6} \ \frac{V}{V}$$

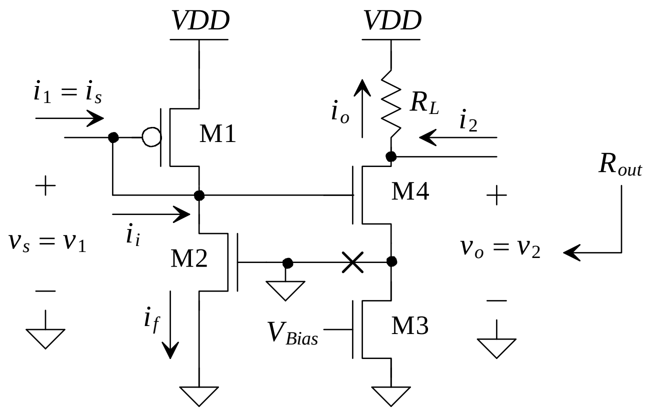
$$R_o \approx \frac{1}{g_{m4}} = 16.67 \ \Omega$$

$$R_{out} = \frac{R_o}{1 + A_{OL}\beta} = 16.67 \ \Omega$$

■

31.28 Prove that the expression for the open-loop gain derived in Ex. 31.3 is correct.

Cut the feedback connection and ground the gate of M2 as seen below.



$$\text{As seen in Fig. 31.37 } R_1 = \frac{1}{g_{m1}}||r_{o1}||r_{o2}$$

$$R_{out} = R_L||R_{intoD4} = R_L||(r_{o3} + r_{o4}(1 + g_{m4}r_{o3}))$$

$$\text{Also, } i_o = \frac{v_o}{R_L} \text{ and } i_s = \frac{v_s}{R_1}$$

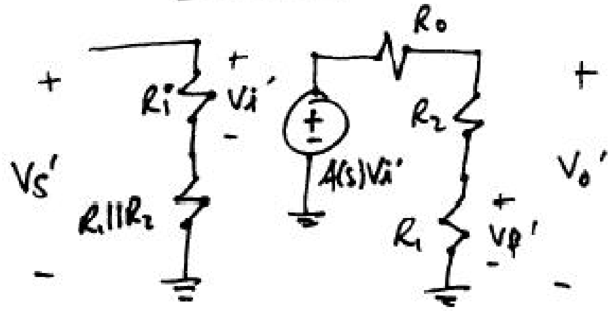
$$\text{The voltage gain from input to output is } \frac{v_o}{v_s} = \frac{-R_{out}}{1/g_{m4} + r_{o3}}$$

$$A_{OL} = \frac{i_o}{i_s} = \frac{v_o}{v_s} \cdot \frac{R_1}{R_L} = \frac{-g_{m4}R_{out}}{1 + g_{m4}r_{o3}} \cdot \frac{R_1}{R_L} = \frac{-g_{m4}R_1}{1 + g_{m4}r_{o3}} \text{ since } R_{out} \approx R_L$$

■

31.29 Determine if the amplifier seen in Fig. 31.44 is stable.

Closed - loop



$$A(s) = \frac{100{,}000}{\left(\frac{s}{200}+1\right)^3}$$

R_i : 10 MΩ

R_o : 100 Ω

$R_1 = R_2 = 10\text{K}\,\Omega$

$$A_{OL} = \frac{V_o'}{V_s'} = A(s)\cdot\left[\frac{R_2+R_1}{R_2+R_1+R_o}\right]\cdot\left[\frac{R_i}{R_i+R_1\|R_2}\right] = \frac{\cancel{994{,}520}\ 99{,}453}{\left(\frac{s}{200}+1\right)^3}$$

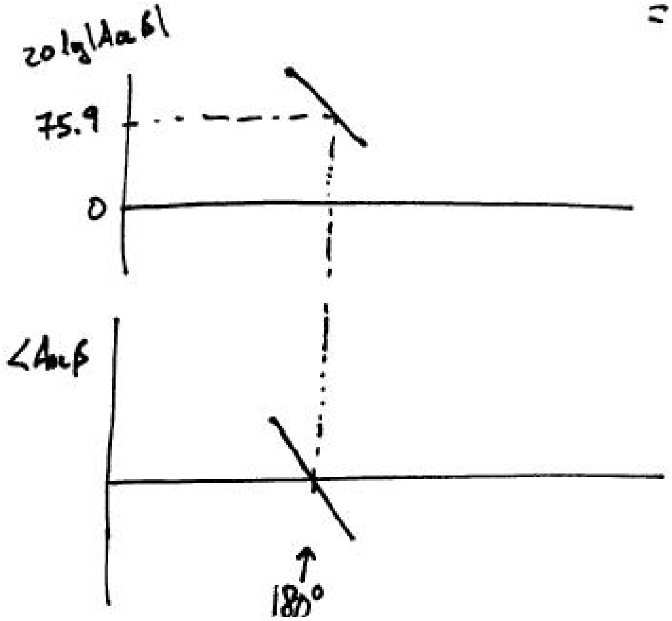
$$\beta = \frac{R_1}{R_1+R_2} = .5 \Rightarrow \text{loop gain} = A_{OL}(s)\beta = \frac{49{,}726}{\left(\frac{s}{200}+1\right)^3}$$

find ω_{180} : $-3\tan^{-1}\left(\frac{\omega_{180}}{200}\right) = -180 \Rightarrow \omega_{180} = 200\tan(60) = 346.41\ \text{r/s}$

find $|A_{OL}(j\omega)\beta|$, dB @ $\omega = \omega_{180}$: $\Rightarrow 20\log(49{,}726) - 3\left(20\log\sqrt{\left(\frac{346.41}{200}\right)^2+1}\right)$

$= 75.87\,\text{dB} > 0\,\text{dB}$

$\Rightarrow$ unstable



31.30 The op-amp shown in Fig. 31.66a can be modeled with the circuit of Fig. 31.66b. With a feedback factor, $\beta = 1$, determine if the op-amp is stable (and the corresponding phase and gain margins) for the following transfer function and $\omega_2 = 10^5$, 10^6, 10^7, and 5×10^6 rad/sec.

$$A_{OL}(j\omega) = \frac{10,000}{\left(1 + j\frac{\omega}{100}\right)\left(1 + j\frac{\omega}{\omega_2}\right)}$$

$$A_{OL}(j\omega) = \frac{10,000}{\left(1+\frac{j\omega}{100}\right)\left(1+\frac{j\omega}{\omega_2}\right)} = A_{OL}(j\omega)\cdot\beta\,, \quad \text{since } \beta = 1$$

Finding ω_{0dB}:

$$1 = \frac{10,000}{\sqrt{\left(1+\left(\frac{\omega_{0dB}}{100}\right)^2\right)\left(1+\left(\frac{\omega_{0dB}}{\omega_2}\right)^2\right)}} \Rightarrow \left(1+\left(\frac{\omega_{0dB}}{100}\right)^2\right)\left(1+\left(\frac{\omega_{0dB}}{\omega_2}\right)^2\right) = 10,000^2$$

$$\Rightarrow \frac{\omega_{0dB}^4}{100^2\cdot\omega_2^2} + \omega_0^2\left(\frac{1}{100^2}+\frac{1}{\omega_2^2}\right) - 100\times10^6 = 0$$

$$\Rightarrow \quad \omega_{0dB} \simeq \sqrt{\left(\sqrt{\left(\frac{1}{100}\right)^4 + \frac{40,000}{\omega_2^2}} - \left(\frac{1}{100}\right)^2\right)\cdot\left(5,000\cdot\omega_2^2\right)} = \text{EQN 1}$$

Finding phase margin

$$PM = \phi_m = \text{Arg}\left(A(j\omega)\beta\right)\Big|_{\omega=\omega_{0dB}} - (-180°)$$

$$\Rightarrow \phi_m = -\tan^{-1}\left(\frac{\omega_{0dB}}{100}\right) - \tan^{-1}\left(\frac{\omega_{0dB}}{\omega_2}\right) + 180°$$

and since 100 r/s is relatively small...

$$\phi_m \simeq 90° - \tan^{-1}\left(\frac{\omega_{0dB}}{\omega_2}\right) = \text{EQN 2}$$

ω_2 (given)	ω_{0dB} (EQN 1)	ϕ_m (EQN 2)	Stable?
10^5 r/s	308 k r/s	17.6°	yes
10^6 r/s	786 k r/s	51.83°	yes
10^7 r/s	995 k r/s	84.3°	yes
5×10^6 r/s	981.3 k r/s	78.9°	yes

31.31 The phase plot of an amplifier is shown in Fig. 31.67. The amplifier has a midband gain of –1,000 and 3 zeros at $\omega = \infty$ and three other unspecified poles. If the amplifier is configured in a feedback configuration and β is frequency independent, what is the exact value of β that would be necessary to cause the amplifier to oscillate?

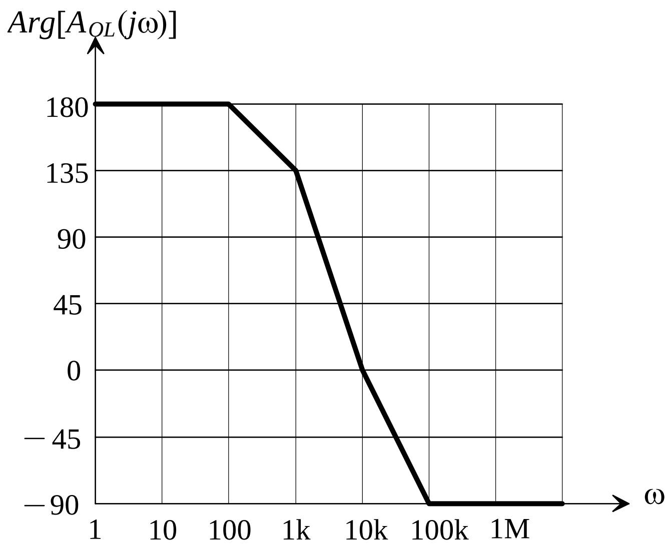
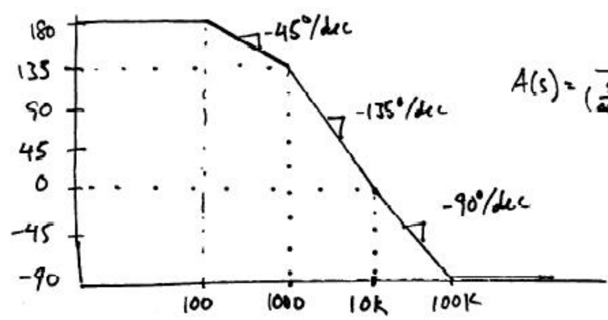


Figure 31.67 Phase response used in problem 31.31.



$$A(s) = \frac{-1000}{\left(\frac{s}{\omega_1}+1\right)\left(\frac{s}{\omega_2}+1\right)\left(\frac{s}{\omega_3}+1\right)}$$

$$\left.\begin{array}{l} \omega_1 = 1000 \\ \omega_2 = 10K \\ \omega_3 = 10K \end{array}\right\} \text{from given slopes}$$

also, $\omega_{180} = 10K$

$$A(s) = \frac{-1000}{\left(\frac{s}{1000}+1\right)\left(\frac{s}{10K}+1\right)^2}$$

$\Rightarrow$ set $|A(j\omega)\beta| = 1$ @ ω_{180}

$$\Rightarrow \frac{1000\beta}{\sqrt{\left(\frac{\omega_{180}}{1000}\right)^2+1}\left[\sqrt{\left(\frac{\omega_{180}}{10k}\right)^2+1}\right]^2} = 1 \quad \Rightarrow \boxed{\beta = .0201}$$

31.32 You have just measured the gain of the op-amp circuit shown in Fig. 31.68. You know from basic op-amp theory that the gain of the circuit should be $-R_2/R_1$ V/V. However, your measurements with $R_2 = 10$ kΩ and $R_1 = 1$ kΩ revealed that the gain was only -5 V/V. What is the open-loop gain of the op-amp?

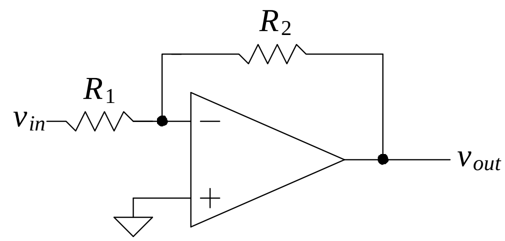
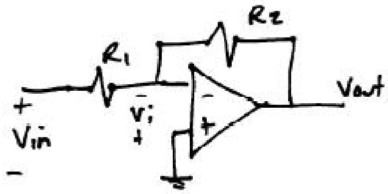
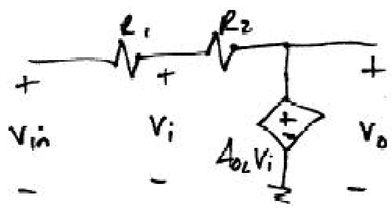


Figure 31.68 How finite open-loop gain effects closed-loop gain, problem 31.32.



$R_1 = 1k\Omega$
$R_2 = 10k\Omega$
$\frac{V_{out}}{V_{in}} = -5$ V/V

$\Downarrow$ model (assuming $R_i = \infty$, $R_o = 0$)



using superposition, $V_i = -V_{in} \cdot \frac{R_2}{R_1+R_2} - V_o \cdot \frac{R_1}{R_1+R_2}$

also, $V_i = \frac{V_{out}}{A_{OL}}$

$\Rightarrow V_{out}\left(\frac{1}{A_{OL}} + \frac{R_1}{R_1+R_2}\right) = -V_{in} \cdot \frac{R_2}{R_1+R_2}$

$\Rightarrow \frac{V_{out}}{V_{in}} = \frac{-\frac{R_2}{R_1+R_2}}{\frac{1}{A_{OL}} + \frac{R_1}{R_2}} \Rightarrow \frac{1}{A_{OL}} = \frac{-\frac{R_2}{R_1+R_2}}{\frac{V_{out}}{V_{in}}} - \frac{R_1}{R_1+R_2}$

$\Rightarrow \frac{1}{A_{OL}} = \frac{-\frac{10}{11}}{-5} - \frac{1}{11} = .0909 \Rightarrow \boxed{A_{OL} = 11 \text{ V/V}}$

31.33 Using the circuit shown in Fig. 31.69 and the *RR* method, find a value of R_1 and A_o which will cause the phase margin to equal 45° at ω = 8,000 rad/sec. The amplifier can be modeled as having an infinite input impedance and zero output resistance and has a frequency response of

$$A(s) = \frac{-A_o}{(s/200+1)(s/10,000+1)}$$

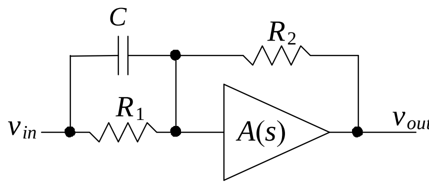
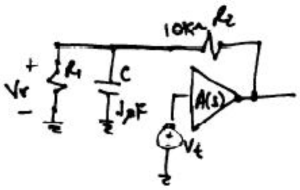


Figure 31.69 Amplifier used in problem 31.33.



$\omega_{add} = 8{,}000\ {}^{r}/s$

$\phi_m : 45°$

$A(s) = \frac{-A_o}{(\frac{s}{200}+1)(\frac{s}{10k}+1)}$ find A_o & R_1

$$\frac{V_r}{V_t} = A(s)\cdot\frac{\frac{1/c}{s+1/R_1C}}{\frac{1/c}{s+1/R_1C}+R_2} = \frac{A(s)}{R_2C}\cdot\frac{1}{s+\frac{1}{C}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)} \Rightarrow \text{let } x = \frac{1}{R_1C}$$

$$\Rightarrow \frac{V_r}{V_t} = \frac{\left(\frac{1000}{1000+x}\right)A(s)}{\left(\frac{s}{1000+x}+1\right)} = \frac{-A_o\left(\frac{1000}{1000+x}\right)}{\left(\frac{s}{1000+x}+1\right)\left(\frac{s}{200}+1\right)\left(\frac{s}{10k}+1\right)} = -A(s)\beta(s)$$

$$\phi_m = Arg(A(j\omega)\beta(j\omega))\Big|_{\omega=8k} + 180° = 45° \Rightarrow Arg(A(j\omega)\beta(j\omega))\Big|_{\omega=8k} = -135°$$

$$\Rightarrow \tan^{-1}\left(\frac{8k}{1000+x}\right) + \tan^{-1}\left(\frac{8k}{200}\right) + \tan^{-1}\left(\frac{8k}{10k}\right) = 135°$$

$$\Rightarrow \tan^{-1}\left(\frac{8k}{1000+x}\right) = 7.772 \Rightarrow x = 57.6\text{ K}$$

$$\Rightarrow \boxed{R_1 = 174\Omega}$$

$$|A(j\omega)\beta(j\omega)|\Big|_{\omega=8k} = 1 = \frac{A_o(.017)}{\sqrt{\frac{8k^2}{58.6K^2}+1}\sqrt{\frac{8k^2}{200^2}+1}\sqrt{\frac{8k^2}{10k^2}+1}}$$

$$\Rightarrow \boxed{A_o = 3{,}042\ {}^{V}/_{V}}$$

31.34 Determine if the system with a return ratio as described by Eq. (31.102) is stable.

$$RR = -\frac{v_r}{v_t} = A_{OL}(s)\beta(s) = \frac{49.726}{\left(1+\frac{s}{200}\right)^2} \text{ Is it stable?}$$

$$\text{To begin find } \omega_{180}: -3\tan^{-1}\left(\frac{\omega_{180}}{200}\right) = -180^\circ$$

$$\rightarrow \omega_{180} = 200 \cdot \tan(60^\circ) = 346.41 \text{ rad/s}$$

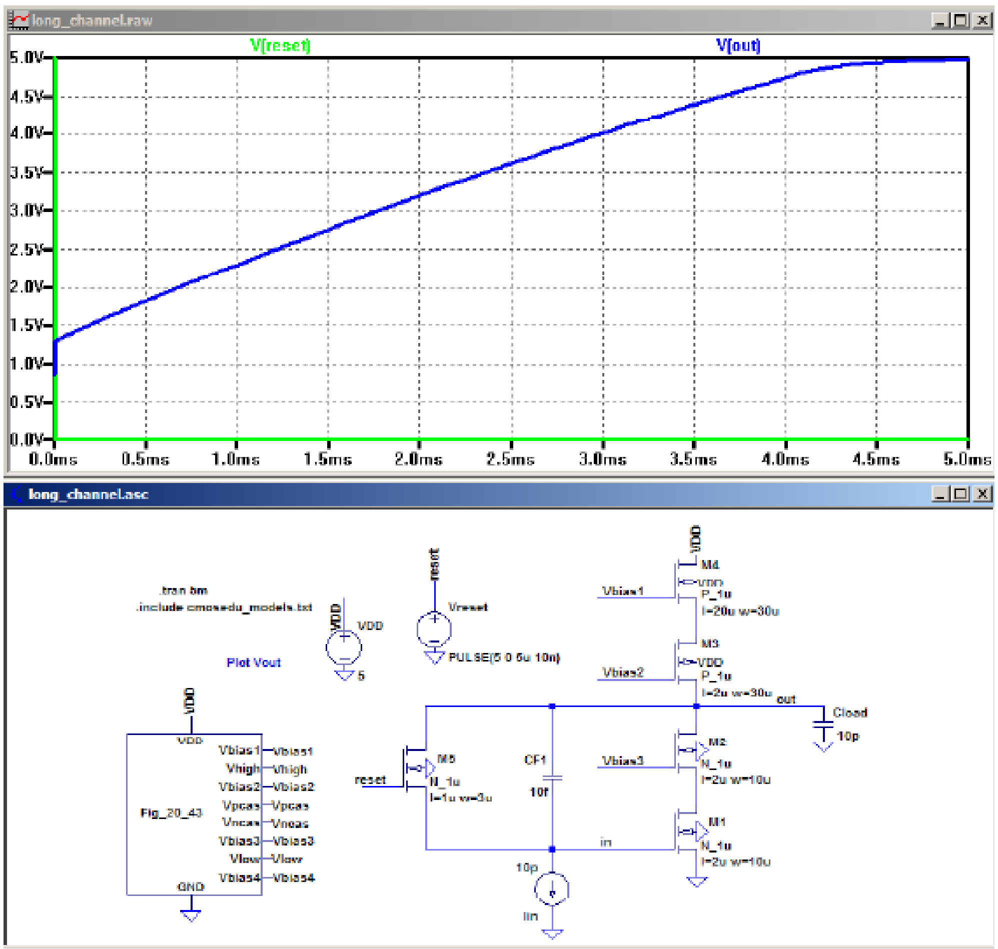
$$\text{now find } |A_{OL}(j\omega)\cdot\beta(j\omega)| = 20\log(49,726) - 3\left(20\log\sqrt{\left(\frac{346.41}{200}\right)^2 + 1}\right)$$

$$= 75.87\ dB > 0\ dB$$

$$\rightarrow \underline{\text{unstable}} \ \blacksquare$$

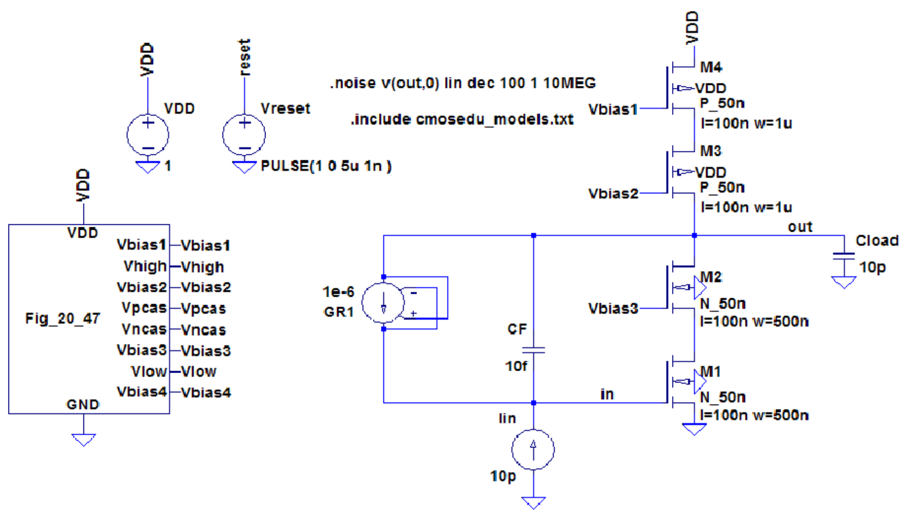
31.35 Redesign the transimpedance amplifier seen in Fig. 31.51 using the long-channel CMOS process discussed in this book.

The schematic and simulation results are seen below. It's important to minimize the size of M5 since, as discussed in the book, the charge injection and capacitive feedthrough (from a fast clock edge) can have a significant effect on the performance. Note we can estimate the output slope using, $10pA/10fF = dv_{out}dt = 1V/ms$. ■



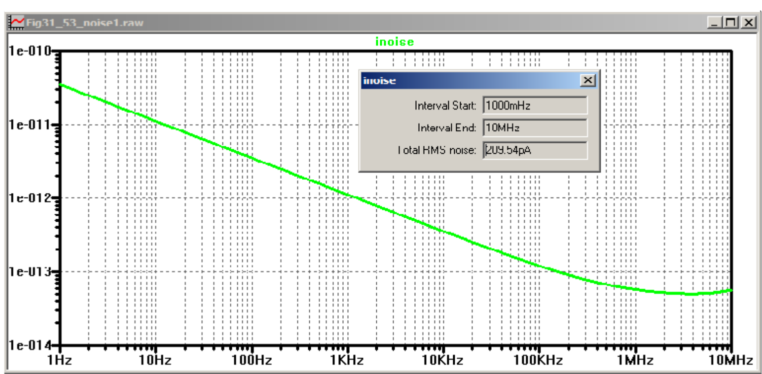
31.36 How would the input-referred noise for the TIA design presented in Sec. 31.9.2 be reduced?

Let's simulate the input referred noise performance using SPICE, below.



To ensure the TIA biases up correctly we've added a 1Meg noiseless resistor between the output and input, see Fig. 8.23. We don't want to go too much higher than this because then M1's gate current can result in a significant voltage drop across the resistor.

The simulated input referred noise spectrum is seen below. There is roughly 210 pA RMS input-referred noise.



We know from Fig. 21.44 that the cascode devices, M2 and M3, have little effect on the noise performance (this should be verified with simulation). We can, however, increase the length of M4 to reduce its contributions to input-referred noise. This also reduces the current flowing in the TIA resulting in higher gain and lower drain noise current. Increasing the length of M4 to 1 μm results in an input-referred noise current of 185 pA. Increasing the width of M1 to 5 μm increases its transconductance dropping the input-referred noise current to 163 pA. Note that to reduce the input-referred noise to < 10 pA we must use much larger devices. The drawback (in nano-CMOS), as discussed in Ch. 31 is the increase in gate leakage current. Older CMOS is generally preferable for the TIA design. The TIA doesn't have to be fast and the older devices have better noise behavior and, of course, are larger. ■