Lecture 11 Feedback and Stability

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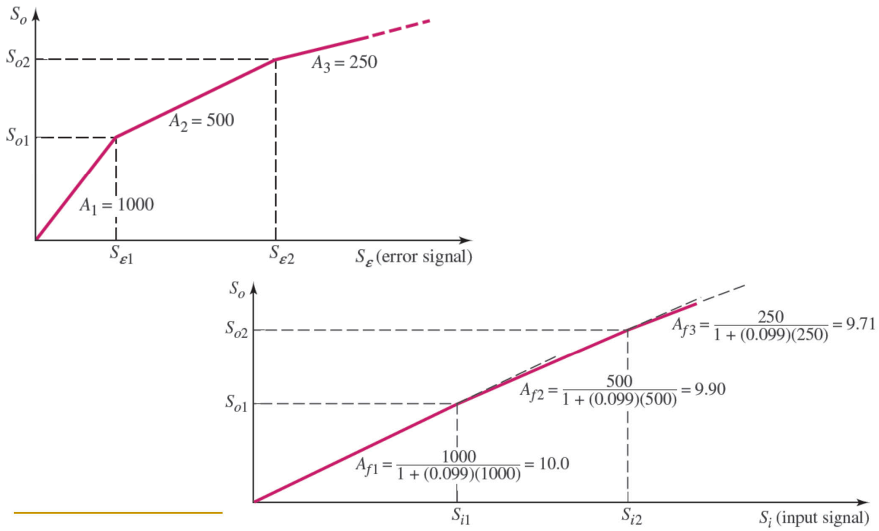
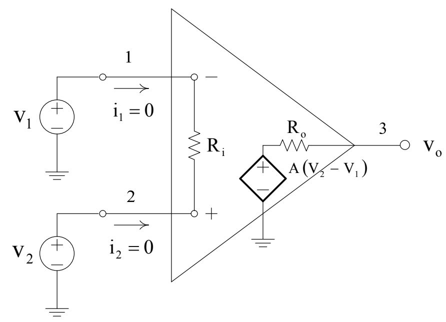
Outline

บทนำ (Introduction)



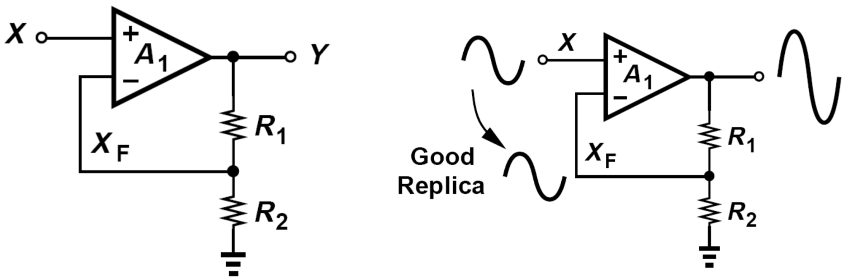
บทนำ (Introduction)



Op-Amp

$$v_o = A_o\left(v_{(+)} - v_{(-)}\right)$$

บทนำ (Introduction)



Non-inverting Amplifier

Advantages and disadvantages of feedback

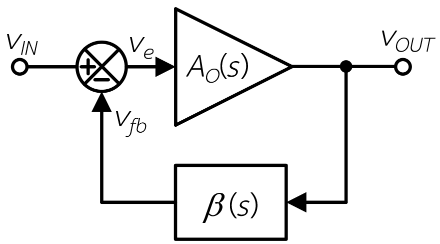
Advantages

1. *Gain sensitivity*. Variations in the circuit transfer function (gain) as a result of changes in transistor parameters are reduced by feedback. This reduction in sensitivity is one of the most attractive features of negative feedback.
2. *Bandwidth extension*. The bandwidth of a circuit that incorporates negative feedback is larger than that of the basic amplifier.
3. *Noise sensitivity*. Negative feedback may increase the signal-to-noise ratio if noise is generated within the feedback loop.
4. *Reduction of nonlinear distortion*. Since transistors have nonlinear characteristics, distortion may appear in the output signals, especially at large signal levels. Negative feedback reduces this distortion.
5. *Control of impedance levels*. The input and output impedances can be increased or decreased with the proper type of negative feedback circuit.

Disadvantages

1. *Circuit gain*. The overall amplifier gain, with negative feedback, is reduced compared to the basic amplifier used in the circuit.
2. *Stability*. There is a possibility that the feedback circuit may become unstable (oscillate) at high frequencies.

Basic feedback concept

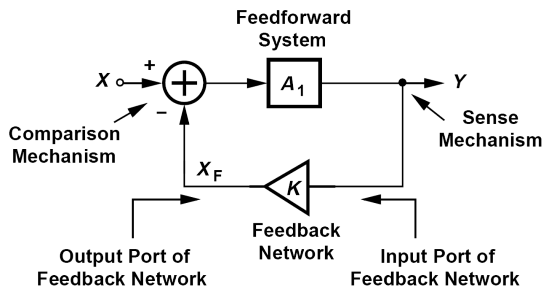


$$T = A\beta$$

$$A_f(s) = \frac{A(s)}{1 + A(s)\beta(s)}$$

$$A_f \cong \frac{A}{\beta A} = \frac{1}{\beta}$$

Basic feedback concept



EXAMPLE **12.1**

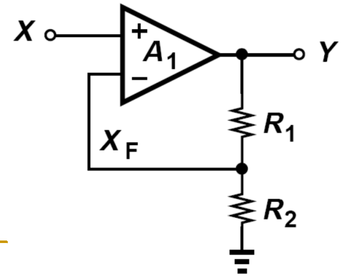
Objective: Calculate the feedback transfer function β, given A and A_f.

Case A. Assume that the open-loop gain of a system is $A = 10^5$ and the closed-loop gain is $A_f = 50$.

Solution: From Equation (12.5), the closed-loop gain is

$$A_f = \frac{A}{(1+\beta A)} \qquad \text{or} \qquad 50 = \frac{10^5}{1+\beta(10^5)}$$

which yields $\beta = 0.01999$ or $1/\beta = 50.025$.



Case B. Now assume that the open-loop gain is $A = -10^5$ and the close-loop gain is $A_f = -50$.

Solution: Again, from Equation (12.5), the closed-loop gain is

$$A_f = \frac{A}{(1+\beta A)} \qquad \text{or} \qquad -50 = \frac{-10^5}{1+\beta(-10^5)}$$

which yields $\beta = -0.01999$ or $1/\beta = -50.025$.

Comment: From these typical parameter values, we see that $A_f \cong 1/\beta$, as Equation (12.8) predicts. We also see that if the open-loop gain A is negative, then the closed-loop gain A_f and feedback transfer function β will also be negative for a negative feedback network.

EXERCISE PROBLEM

Ex 12.1: (a) The open-loop gain of an amplifier is $A = 5 \times 10^4$ and the closed-loop gain is $A_f = 50$. (i) What is the feedback transfer function? (ii) What is the ratio of A_f to $1/\beta$? (b) Repeat part (a) for $A = 100$ and $A_f = 20$. (Ans. (a) (i) 0.01998, (ii) 0.9990; (b) (i) 0.04, (ii) 0.80)

12.2.3 Bandwidth Extension

The amplifier bandwidth is a function of feedback. Assume the frequency response of the basic amplifier can be characterized by a single pole. We can then write

$$A(s) = \frac{A_o}{1 + \frac{s}{\omega_H}} \quad \textbf{(12.13)}$$

where A_o is the low-frequency or midband gain, and ω_H is the upper 3 dB or corner frequency.

$$A_f(s) = \frac{A_o}{(1+\beta A_o)} \cdot \frac{1}{1 + \frac{s}{\omega_H(1+\beta A_o)}} \quad \textbf{(12.15)}$$

From Equation (12.15), we see that the low-frequency closed-loop gain is smaller than the open-loop gain by a factor of $(1 + \beta A_o)$, but the closed-loop 3 dB frequency is larger than the open-loop value by a factor of $(1 + \beta A_o)$.

If we multiply the low-frequency open-loop gain A_o by the bandwidth (3 dB frequency) ω_H, we obtain $A_o\omega_H$, which is the gain–bandwidth product. The product of the low-frequency closed-loop gain and the closed-loop band-width is

$$\frac{A_o}{(1+\beta A_o)}[\omega_H(1+\beta A_o)] = A_o\omega_H \quad \textbf{(12.16)}$$

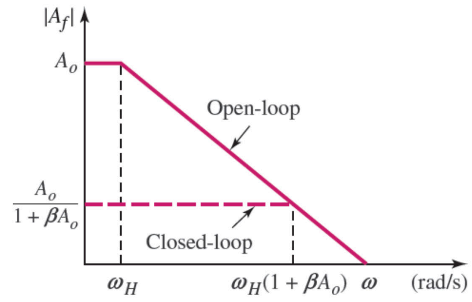


Figure 12.2 Open-loop and closed-loop gain versus frequency, illustrating bandwidth extension

EXAMPLE 12.3

Objective: Determine the bandwidth of a feedback amplifier.

Consider a feedback amplifier with an open-loop low-frequency gain of $A_o = 10^4$, an open-loop bandwidth of $\omega_H = (2\pi)(100)$ rad/s, and a closed-loop low-frequency gain of $A_f(0) = 50$.

which yields

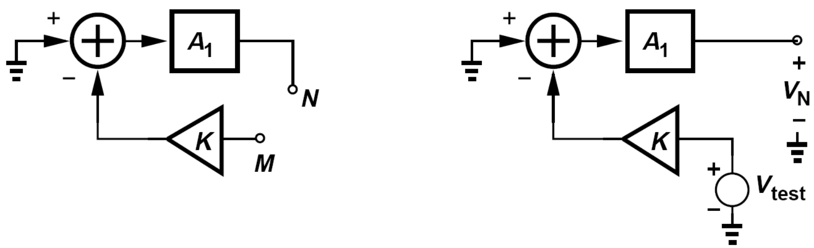
$$(1+\beta A_o) = \frac{10^4}{50} = 200$$

From Equation (12.15), the closed-loop bandwidth is

$$\omega_{fH} = \omega_H(1+\beta A_o) = (2\pi)(100)(200) = (2\pi)(20 \times 10^3)$$

Comment: The bandwidth increases from 100 Hz to 20 kHz as the gain decreases from 10^4 to 50.

Loop gain



(a) (b)

Computation of the loop gain by (a) breaking the loop and (b) applying a test signal

$$V_N = -KV_{test}A_1$$

$$KA_1 = -\frac{V_N}{V_{test}}$$

Example 12.3

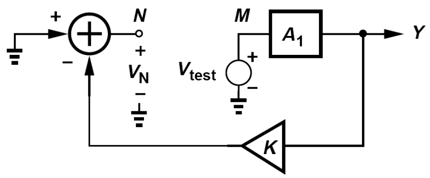
Compute the loop gain of the feedback system of Fig. 12.1 by breaking the loop at the input of A_1.

Solution

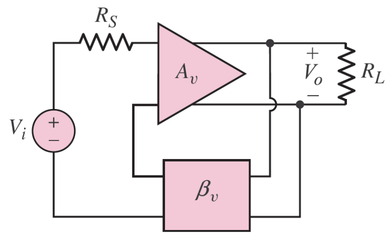
Illustrated in Fig. 12.5 is the system with the test signal applied to the input of A_1. The output of the feedback network is equal to KA_1V_{test}, yielding

$$V_N = -KA_1V_{test} \tag{12.9}$$

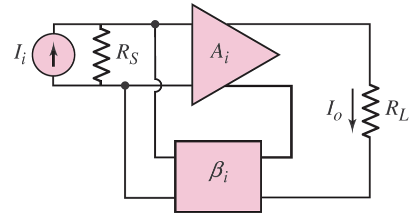
and hence the same result as in (12.8).



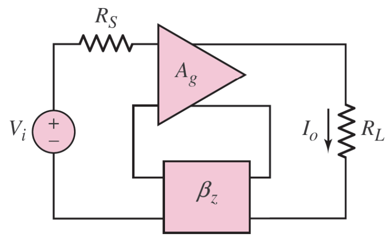
Feedback circuits



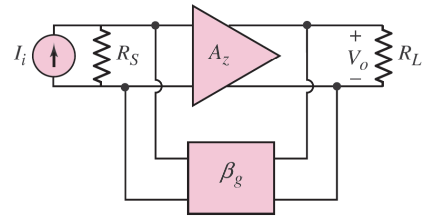
(a) Series–shunt



(b) Shunt–series

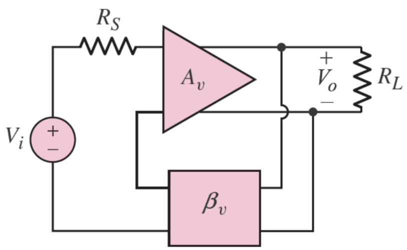


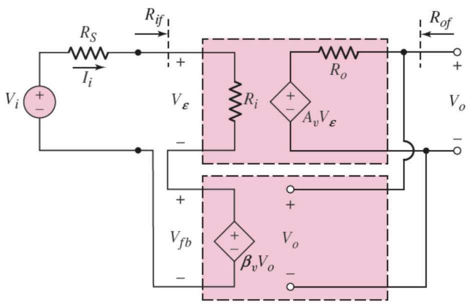
(c) Series–series



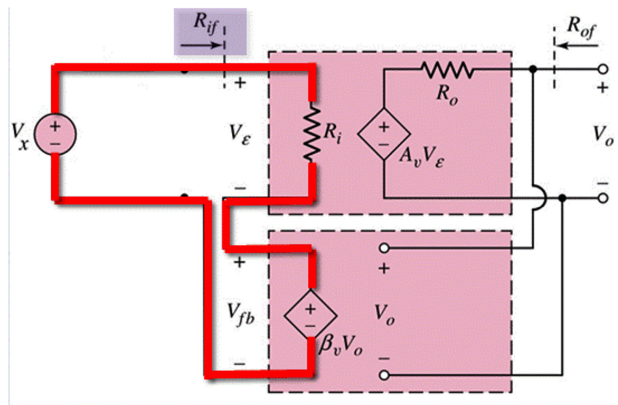
(d) Shunt–shunt

Voltage-voltage feedback Configuration (Series-Shunt)





$$A_{vf} = \frac{A_v}{1+\beta_v A_v}$$



$$R_{if} = \frac{V_X}{I_X} = R_i(1+\beta_v A_v)$$

$$R_{of} = \frac{V_X}{I_X} = \frac{R_o}{1+\beta_v A_v}$$

EXAMPLE 12.5

Objective: Determine the input resistance of a series input connection and the output resistance of a shunt output connection for an ideal feedback voltage amplifier.

Consider a series–shunt feedback amplifier in which the open-loop gain is $A_v = 10^5$ and the closed-loop gain is $A_{vf} = 50$. Assume the input and output resistances of the basic amplifier are $R_i = 10\ \text{k}\Omega$ and $R_o = 20\ \text{k}\Omega$, respectively.

Solution: The ideal closed-loop voltage transfer function is, from Equation (12.22),

$$A_{vf} = \frac{A_v}{(1+\beta_v A_v)}$$

or

$$(1+\beta_v A_v) = \frac{A_v}{A_{vf}} = \frac{10^5}{50} = 2 \times 10^3$$

From Equation (12.25), the input resistance is

$$R_{if} = R_i(1+\beta_v A_v) = (10)(2\times 10^3)\ \text{k}\Omega \Rightarrow 20\ \text{M}\Omega$$

and, from Equation (12.28), the output resistance is

$$R_{of} = \frac{R_o}{(1+\beta_v A_v)} = \frac{20}{2\times 10^3}\ \text{k}\Omega \Rightarrow 10\ \Omega$$

EXERCISE PROBLEM

Ex 12.5: An ideal series–shunt feedback amplifier is shown in Figure 12.6. Assume R_S is negligibly small. (a) If $V_i = 100$ mV, $V_{fb} = 99$ mV, and $V_o = 5$ V, determine A_v, β_v, and A_{vf}, including units. (b) Using the results of part (a), determine R_{if} and R_{of}, for $R_i = 5\ \text{k}\Omega$ and $R_o = 4\ \text{k}\Omega$. (Ans. (a) $A_v = 5000$ V/V, $\beta_v = 0.0198$ V/V, $A_{vf} = 50$ V/V (b) $R_{if} = 500\ \text{k}\Omega$, $R_{of} = 40\ \Omega$)

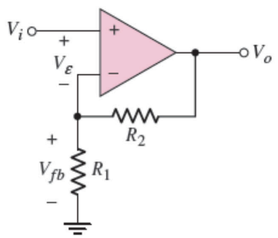
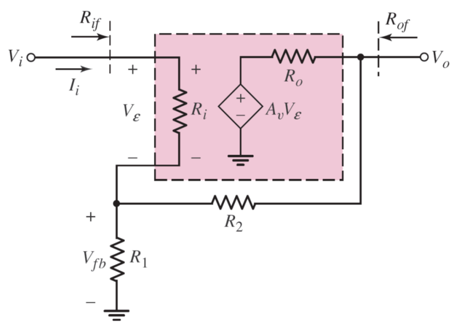


Figure 12.16 Example of an op-amp series–shunt feedback circuit



$$\beta_v = \frac{1}{\left(1+\frac{R_2}{R_1}\right)}$$

$$A_{vf} = \frac{V_O}{V_i} = \left(1+\frac{R_2}{R_1}\right)$$

EXAMPLE 12.7

Objective: Determine the expected input resistance of the noninverting op-amp circuit.

Consider the noninverting op-amp in Figure 12.16, with parameters $R_i = 50\ \text{k}\Omega$, $R_1 = 10\ \text{k}\Omega$, $R_2 = 90\ \text{k}\Omega$, and $A_v = 10^4$.

Solution: The feedback transfer function β_v is

$$\beta_v = \frac{1}{\left(1+\frac{R_2}{R_1}\right)} = \frac{1}{\left(1+\frac{90}{10}\right)} = 0.10$$

The input resistance is therefore

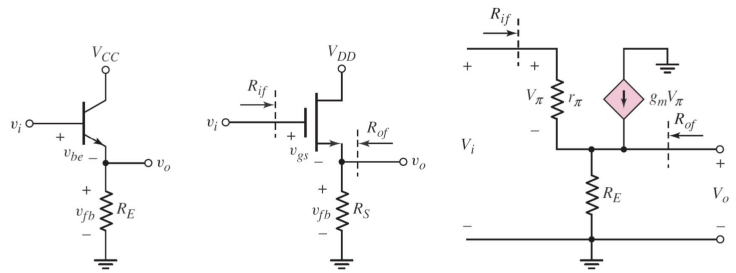
$$R_{if} = R_i(1+\beta_v A_v) = (50)[1+(0.10)(10^4)]$$

or

$$R_{if} \cong 50 \times 10^3\ \text{k}\Omega = 50\ \text{M}\Omega$$

EXERCISE PROBLEM

Ex 12.7: Consider the noninverting op-amp circuit shown in Figure 12.16, with parameters $R_1 = 15\,\text{k}\Omega$, $R_2 = 60\,\text{k}\Omega$, and $A_v = 5 \times 10^4$. Assume $R_i = \infty$. Let the input signal voltage be $V_i = 0.10$ V. (a) What is the ideal voltage gain and the ideal output voltage? (b) (i) Determine the actual closed-loop gain and the actual output voltage. (ii) What is the error voltage V_ε? (c) If the open-loop gain increases by a factor of 10, what are the values of (i) the closed-loop gain and (ii) the error voltage? (Ans. (a) $A_f = 5.00$, $V_o = 0.500$ V; (b) (i) $A_f = 4.9995$, $V_o = 0.49995$ V, (ii) $V_\varepsilon = 9.999\,\mu$V; (c) (i) $A_f = 4.99995$, (ii) $V_\varepsilon = 0.99999\,\mu$V)

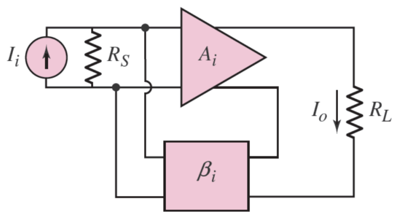


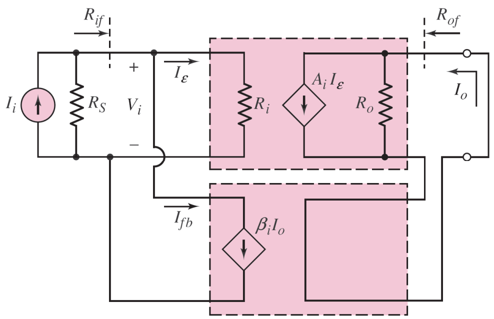
$$A_v = \left(\frac{1}{r_\pi} + g_m\right) R_E = \frac{R_E}{r_e}$$

$$R_{of} = \frac{R_E}{1 + \left(\frac{1}{r_\pi} + g_m\right) R_E}$$

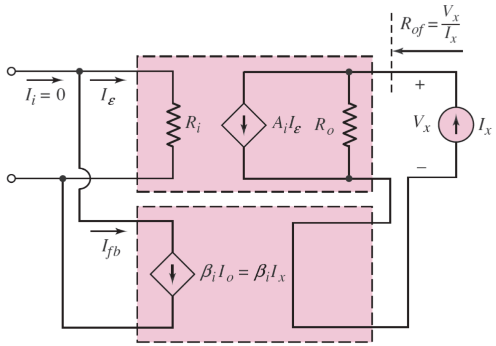
$$R_{if} = r_\pi + (1 + h_{FE}) R_E = r_\pi \left[1 + \left(\frac{1}{r_\pi} + g_m\right) R_E\right]$$

Current-current feedback configuration (Shunt-Series)

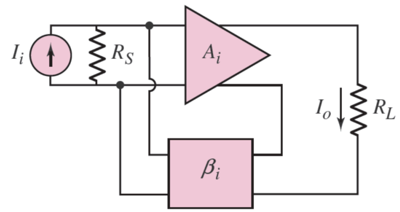


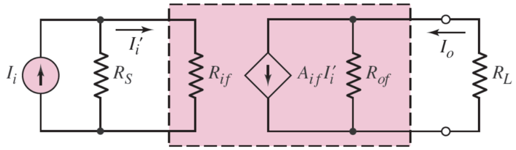


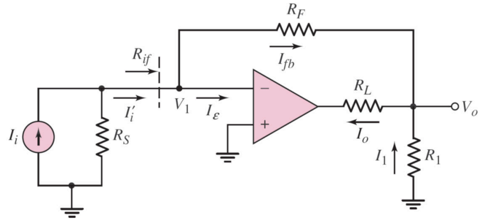
$$A_{if} = \frac{I_o}{I_i} = \frac{A_i}{(1 + \beta_i A_i)} \qquad R_{if} = \frac{V_i}{I_i} = \frac{R_i}{(1 + \beta_i A_i)}$$



$$R_{of} = R_o (1 + \beta_i A_i)$$







If we assume initially that I_ε is negligible, then, from Figure 12.20, we have

$$I_i \cong I_i' = I_{fb}$$

The output voltage V_o, assuming V_1 is at virtual ground, is

$$V_o = -I_{fb}R_F = -I_i R_F$$

and current I_1 is

$$I_1 = -V_o/R_1$$

The output current can be expressed

$$I_o = I_{fb} + I_1 = I_i + \left(-\frac{1}{R_1}\right)(-I_i R_F) = I_i\left(1 + \frac{R_F}{R_1}\right) \quad \textbf{(12.57)}$$

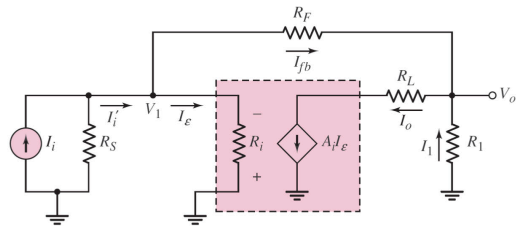
Therefore, the ideal current gain is

$$\frac{I_o}{I_i} = 1 + \frac{R_F}{R_1} \quad \textbf{(12.58)}$$

In the ideal feedback circuit, the amplification factor A_i is very large; consequently, the current transfer function, from Equation (12.32), becomes

$$A_{if} = \frac{I_o}{I_i} \cong \frac{1}{\beta_i} \quad \textbf{(12.59)}$$

Comparing Equation (12.59) with (12.58), we see that the current feedback transfer function for the ideal op-amp current amplifier is



$$\beta_i = \frac{1}{\left(1 + \frac{R_F}{R_1}\right)}$$

We can take the finite amplifier gain into account by considering the equivalent circuit in Figure 12.21. The parameter A_i is the open-loop current gain. We have

$$I_o = A_i I_\varepsilon \quad \textbf{(12.61)}$$

and

$$I_\varepsilon = I_i' - I_{fb} \cong I_i - I_{fb} \quad \textbf{(12.62)}$$

therefore,

$$I_o = A_i(I_i - I_{fb}) \quad \textbf{(12.63)}$$

If we again assume that V_1 is at virtual ground, voltage V_o is given by

$$V_o = -I_{fb}R_F \quad \textbf{(12.64)}$$

We can then write

$$I_1 = -\frac{V_o}{R_1} = -\left(\frac{1}{R_1}\right)(-I_{fb}R_F) = I_{fb}\left(\frac{R_F}{R_1}\right) \qquad \textbf{(12.65)}$$

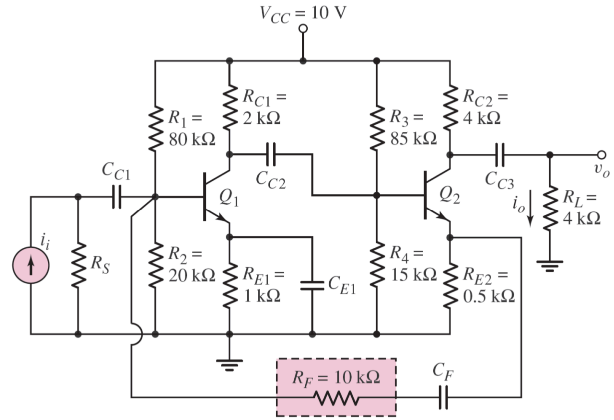
The output current is also expressed as

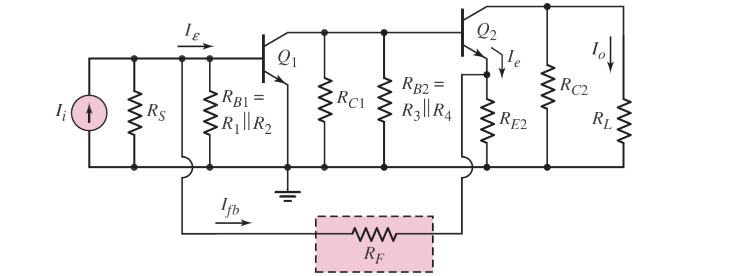
$$I_o = I_{fb} + I_1 = I_{fb} + I_{fb}\left(\frac{R_F}{R_1}\right) \qquad \textbf{(12.66)}$$

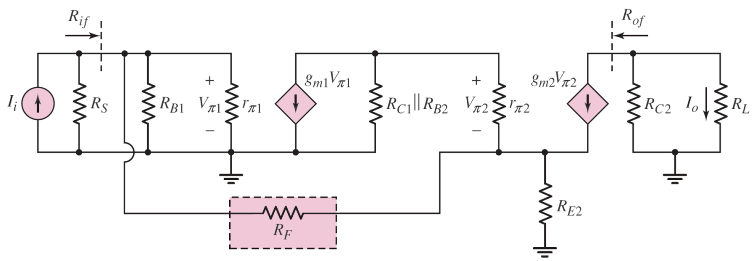
Solving for I_{fb} from Equation (12.66), substituting that into Equation (12.63), and rearranging terms yields the closed-loop current gain

$$A_{if} = \frac{I_o}{I_i} = \frac{A_i}{1 + \dfrac{A_i}{\left(1 + \dfrac{R_F}{R_1}\right)}} \qquad \textbf{(12.67)}$$

Ex







EXAMPLE 12.9

Objective: Determine the closed-loop current gain and input resistance of a discrete shunt–series transistor feedback circuit.

Consider the circuit in Figure 12.24(a), with transistor parameters $h_{FE} = 100$ and $V_A = \infty$. Assume the source resistance is $R_S = 10\ \text{M}\Omega$. The capacitors are large enough to act as short circuits to the signal currents.

Solution: A PSpice analysis shows that the closed-loop current gain is

$$A_{if} = I_o/I_i = 9.58$$

The input resistance R_{if} is defined as the ratio of the signal voltage at the base of Q_1 to the input signal current. The PSpice results show that $R_{if} = 134\ \Omega$. This low input resistance is expected for the shunt input connection.

EXERCISE PROBLEM

***Ex 12.9:** Consider the common-base circuit in Figure 12.23(a), with transistor parameters $h_{FE} = 80$, $V_{EB}(\text{on}) = 0.7$ V, and $V_A = \infty$. Assume the transistor is biased at $I_{CQ} = 0.5$ mA. Redesign the circuit such that the closed-loop current gain is greater than 0.95. (Ans. $R_E(\text{min}) = 1.30$ kΩ, and $V^+(\text{min}) = 1.36$ V)

DESIGN EXAMPLE 12.10

Objective: Design a feedback amplifier to provide a given current gain.

Specifications: Assume that a signal current source has a nominal output resistance of $R_S = 10$ kΩ and that the amplifier will drive a nominal load of $R_L = 50$ Ω. A current gain of 10 is required.

Choices: An op-amp with the same characteristics described in Example 12.8 is available.

Solution (Design Approach): An amplifier with a low input resistance and a large output resistance is required, to minimize loading effects at the input and output. For these reasons, a shunt–series feedback configuration, or current amplifier, will be used.

The closed-loop gain is

$$A_{if} = 10 \cong 1/\beta_i$$

Referring to Table 12.1, we expect the input resistance to be

$$R_{if} = 10/10^5 \text{ k}\Omega \rightarrow 0.1 \text{ }\Omega$$

and the output resistance to be

$$R_{of} = (100)(10^5) \text{ }\Omega \rightarrow 10 \text{ M}\Omega$$

These resistance values will minimize any loading effects at the amplifier input and output.

For the shunt–series configuration in Figure 12.20, we have

$$\frac{1}{\beta_i} = 1 + \frac{R_F}{R_1} = 10$$

or

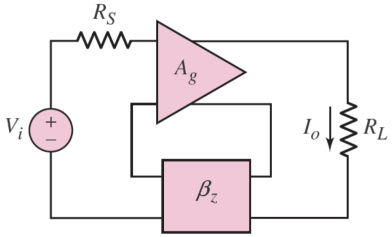
$$R_F/R_1 = 9$$

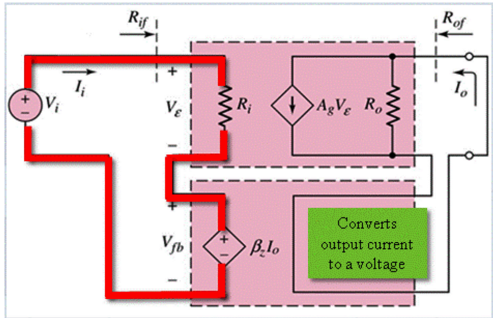
For our purposes, R_1 must be fairly small, to avoid a loading effect at the output. However, R_1 must not be too small, to avoid large currents in the amplifier. Therefore, we choose $R_1 = 1$ kΩ and $R_F = 9$ kΩ.

EXERCISE PROBLEM

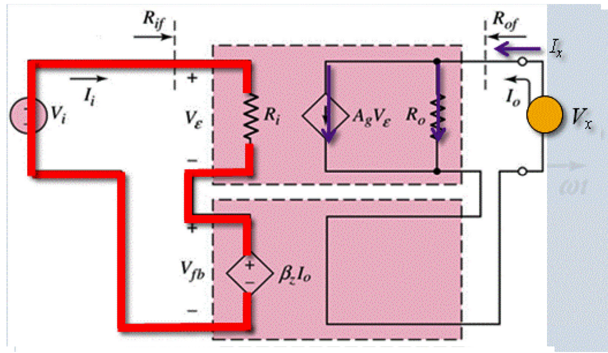
Ex 12.10: Design a feedback current amplifier to provide a current gain of 15. The nominal current source resistance is $R_S = 500$ Ω, and the nominal load is $R_L = 200$ Ω. An op-amp with parameters $R_i = 5$ kΩ, $R_o = 50$ Ω, and a low-frequency open-loop voltage gain of $A_v = 5 \times 10^3$ is available. Correlate the design with a PSpice analysis to determine the current gain, input resistance, and output resistance.

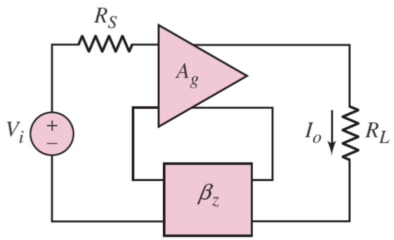
Current-voltage feedback configuration (Series-Series)

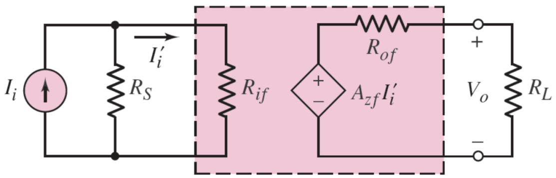




$$A_{gf}=\frac{I_o}{V_i}=\frac{A_g}{(1+\beta_z A_g)}$$

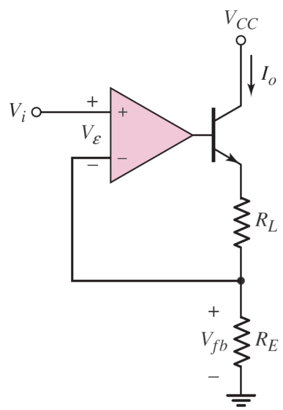


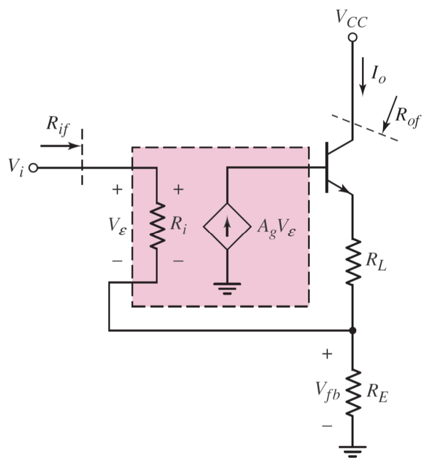




$$R_{if}=R_i\left(1+\beta_z A_g\right)$$

$$R_{of}=R_O\left(1+\beta_z A_g\right)$$





$$A_{gf} = \frac{I_o}{V_i} \cong \frac{1}{\beta_z} \tag{12.70}$$

Assuming an ideal op-amp circuit and neglecting the transistor base current, we have

$$V_i = V_{fb} = I_o R_E$$

and

$$A_{gf} = \frac{I_o}{V_i} = \frac{1}{R_E} \tag{12.71}$$

Comparing Equations (12.70) and (12.71), we see that the ideal feedback transfer function is

$$\beta_z = R_E \tag{12.72}$$

We can take a finite amplifier gain into account by considering the equivalent circuit in Figure 12.28. The parameter A_g is the open-loop transconductance gain of the amplifier. Assuming the collector and emitter currents are nearly equal and R_i is very large, we can write that

$$I_o = \frac{V_{fb}}{R_E} = h_{FE} I_b = h_{FE} A_g V_\varepsilon \tag{12.73}$$

Also,

$$V_\varepsilon = V_i - V_{fb} = V_i - I_o R_E \tag{12.74}$$

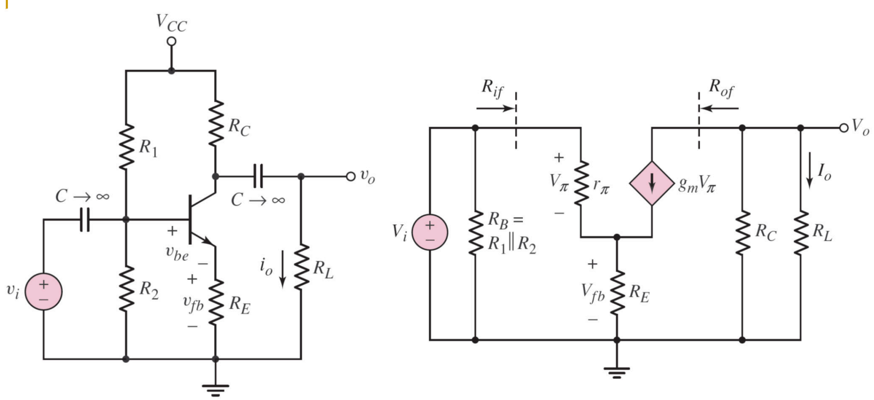
Substituting Equation (12.74) into Equation (12.73) yields

$$I_o = h_{FE} A_g (V_i - I_o R_E) \tag{12.75}$$

which can be rearranged to yield the closed-loop transfer function,

$$A_{gf} = \frac{I_o}{V_i} = \frac{(h_{FE} A_g)}{1 + (h_{FE} A_g) R_E} \tag{12.76}$$

which has the same form as that of the ideal theory. In this example, we see that in this feedback network, the transistor current gain is part of the basic amplifier gain.



$$I_o = -(g_m V_\pi)\left(\frac{R_C}{R_C + R_L}\right) \tag{12.77}$$

and the feedback voltage is

$$V_{fb} = \left(\frac{V_\pi}{r_\pi} + g_m V_\pi\right) R_E \tag{12.78}$$

A KVL equation around the B–E loop yields

$$V_i = V_\pi + V_{fb} = V_\pi \left[1 + \left(\frac{1}{r_\pi} + g_m\right) R_E\right] \tag{12.79}$$

Solving Equation (12.79) for V_π, substituting that into Equation (12.77), and rearranging terms produces the expression for the transconductance transfer function,

$$A_{gf} = \frac{I_o}{V_i} = \frac{-g_m\left(\frac{R_C}{R_C + R_L}\right)}{1 + \left(\frac{1}{r_\pi} + g_m\right) R_E} \tag{12.80}$$

EXAMPLE 12.11

Objective: Determine the transconductance gain of a transistor feedback circuit.

Consider the circuit in Figure 12.29, with transistor parameters $h_{FE} = 100$, $V_{BE}(\text{on}) = 0.7$ V, and $V_A = \infty$. The circuit parameters are: $V_{CC} = 10$ V, $R_1 = 55\ \text{k}\Omega$, $R_2 = 12\ \text{k}\Omega$, $R_E = 1\ \text{k}\Omega$, $R_C = 4\ \text{k}\Omega$, and $R_L = 4\ \text{k}\Omega$.

Solution: From a dc analysis of the circuit, the quiescent values are $I_{CQ} = 0.983$ mA and $V_{CEQ} = 5.08$ V. The transistor small-signal parameters are found to be $r_\pi = 2.64\ \text{k}\Omega$ and $g_m = 37.8$ mA/V.

From Equation (12.80), the transconductance transfer function is

$$A_{gf} = \frac{-(37.8)\left(\dfrac{4}{4+4}\right)}{1 + \left(\dfrac{1}{2.64} + 37.8\right)(1)} = -0.482\ \text{mA/V}$$

As a first approximation, we have

$$A_{gf} = \frac{1}{\beta_z} = \frac{1}{-R_E} = \frac{1}{-1\ \text{k}\Omega} = -1\ \text{mA/V}$$

The term $R_C/(R_C + R_L)$ introduces the largest discrepancy between the actual and ideal transconductance values.

This circuit is often used as a voltage amplifier. The output voltage is directly proportional to the output current. Therefore,

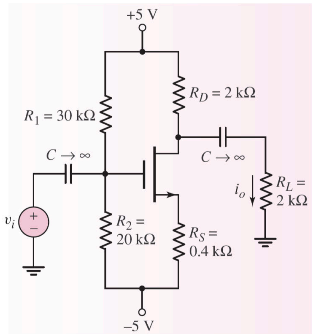
$$A_{vf} = \frac{v_o}{v_i} = \frac{i_o R_L}{v_i} = A_{gf} R_L$$

which yields

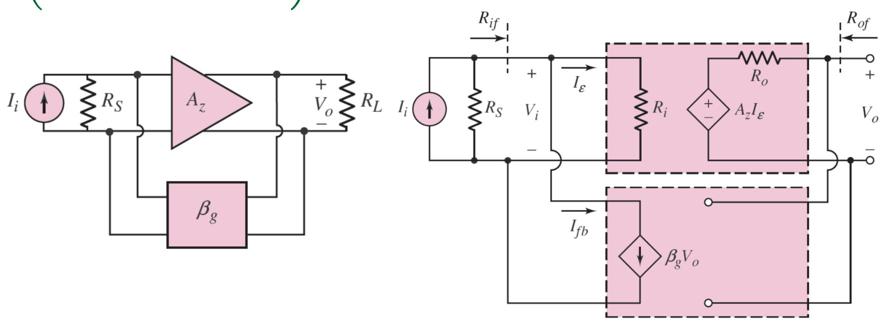
$$A_{vf} = (-0.482)(4) = -1.93$$

EXERCISE PROBLEM

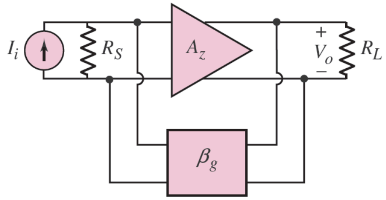
Ex 12.11: For the circuit in Figure 12.31, the transistor parameters are $K_n = 2\ \text{mA/V}^2$, $V_{TN} = 2$ V, and $\lambda = 0$. (a) Determine (i) I_{DQ} and (ii) the transconductance transfer function $A_{gf} = i_o/v_i$. (b) If the conductance parameter decreases by 10 percent to $K_n = 1.8\ \text{mA/V}^2$, determine (i) the new value of I_{DQ} and (ii) the percent change in A_{gf}. (Ans. (a) (i) $I_{DQ} = 2.31$ mA, (ii) $A_{gf} = -0.7904$ mA/V; (b) (i) $I_{DQ} = 2.22$ mA, (ii) −2.68%)

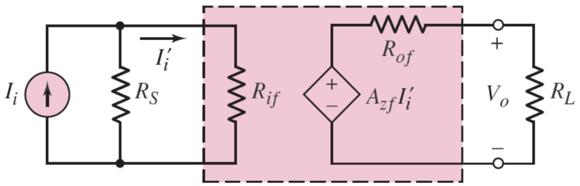


Voltage-current feedback configuration (Shunt-Shunt)

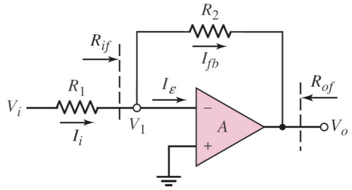


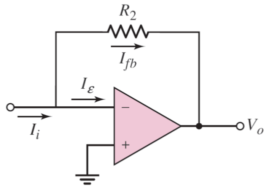
$$A_{zf} = \frac{V_o}{I_i} = \frac{A_z}{(1 + \beta_g A_z)}$$





$$R_{if} = \frac{R_i}{(1+\beta_g A_z)} \qquad R_{of} = \frac{R_o}{(1+\beta_g A_z)}$$





In the ideal feedback circuit, the amplification factor A_z is very large, and the transresistance transfer function is, from Equation (12.40),

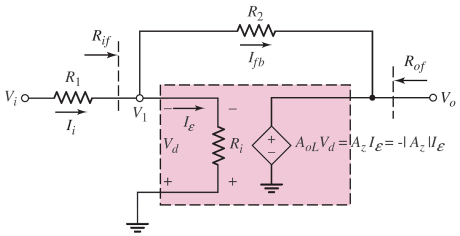
$$A_{zf} = \frac{V_o}{I_i} \cong \frac{1}{\beta_g} \tag{12.81}$$

For the ideal inverting op-amp circuit, V_1 is at virtual ground, and

$$V_o = -I_{fb}R_2$$

Also for the ideal op-amp, $I_{fb} = I_i$, and the ideal transresistance transfer function is

$$A_{zf} = \frac{V_o}{I_i} = -R_2 \tag{12.82}$$



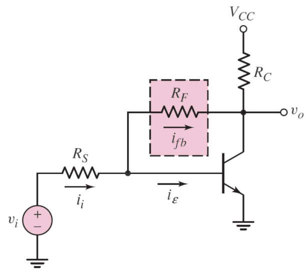
Comparing Equation (12.82) to Equation (12.81), we see that the feedback transfer function for the ideal inverting op-amp circuit is

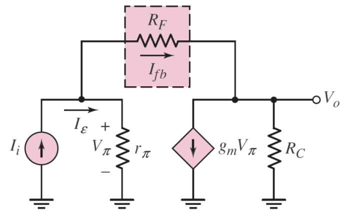
$$\beta_g = -\frac{1}{R_2} \tag{12.83}$$

$$A_{zf} = \frac{V_o}{I_i} = \frac{-|A_z|}{1+\dfrac{|A_z|}{R_2}} \tag{12.84}$$

From Equation (12.83), the feedback transfer function is $\beta_g = -1/R_2$, and Equation (12.84) becomes

$$A_{zf} = \frac{V_o}{I_i} = \frac{-|A_z|}{1+(-|A_z|)\beta_g} = \frac{A_z}{1+A_z\beta_g} \tag{12.85}$$





The small-signal equivalent circuit is shown in Figure 12.36. The input signal is assumed to be an ideal signal current source. Also the Early voltage of the transistor is assumed to be infinite.

Writing a KCL equation at the output node, we find

$$\frac{V_o}{R_C} + g_m V_\pi + \frac{V_o - V_\pi}{R_F} = 0 \tag{12.86}$$

A KCL equation at the input node yields

$$I_i = \frac{V_\pi}{r_\pi} + \frac{V_\pi - V_o}{R_F} \tag{12.87}$$

Solving Equation (12.87) for V_π and substituting that result into Equation (12.86), we obtain

$$V_o\left(\frac{1}{R_C} + \frac{1}{R_F}\right)\left(\frac{1}{r_\pi} + \frac{1}{R_F}\right) + \left(g_m - \frac{1}{R_F}\right)\left(I_i + \frac{V_o}{R_F}\right) = 0 \tag{12.88}$$

The transresistance transfer function is then

$$A_{zf} = \frac{V_o}{I_i} = \frac{-\left(g_m - \frac{1}{R_F}\right)}{\left(\frac{1}{R_C} + \frac{1}{R_F}\right)\left(\frac{1}{r_\pi} + \frac{1}{R_F}\right) + \frac{1}{R_F}\left(g_m - \frac{1}{R_F}\right)} \tag{12.89}$$

The open-loop transresistance gain factor A_z is found by setting $R_F = \infty$. We find

$$A_z = \frac{-g_m}{\left(\frac{1}{R_C}\right)\left(\frac{1}{r_\pi}\right)} = -g_m r_\pi R_C = -h_{FE} R_C \tag{12.90}$$

$$A_{zf} = \frac{V_o}{I_i} = \frac{+\left(A_z + \frac{r_\pi R_C}{R_F}\right)}{\left(1 + \frac{R_C}{R_F}\right)\left(1 + \frac{r_\pi}{R_F}\right) - \frac{1}{R_F}\left(A_z + \frac{r_\pi R_C}{R_F}\right)} \tag{12.91}$$

$$h_{FE} = g_m r_\pi \gg (r_\pi / R_F)$$

If we also assume that $R_C \ll R_F$ and $r_\pi \ll R_F$, then Equation (12.91) reduces to

$$A_{zf} = \frac{V_o}{I_i} \cong \frac{A_z}{1 + (A_z)\left(\frac{-1}{R_F}\right)} \tag{12.92}$$

Consequently, the feedback transfer function is approximately

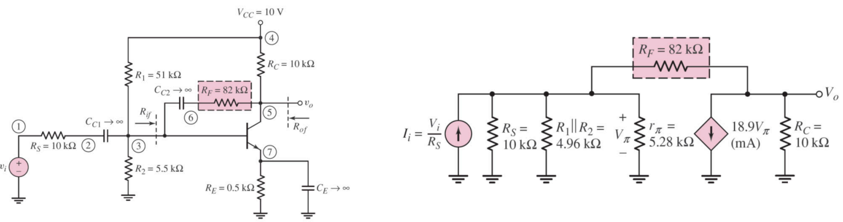
$$\beta_g \cong \frac{-1}{R_F} \tag{12.93}$$

EXAMPLE 12.13

Objective: Determine the transresistance and voltage gain of a single-transistor shunt–shunt feedback circuit.

Consider the circuit in Figure 12.37(a). The transistor parameters are: $h_{FE} = 100$, $V_{BE}(\text{on}) = 0.7$ V, and $V_A = \infty$. Since the input signal current is directly proportional to the input voltage, the voltage gain of this shunt–shunt configuration has the same general properties as the transresistance transfer function.

As with many circuits considered in this chapter, several capacitors are included. In the circuit in Figure 12.37(a), R_1 and C_{C2} may be removed. Resistor R_F can be used for biasing, and the circuit can be redesigned to provide the same feedback properties.



Solution: By including C_{C2} in the circuit, the feedback is a function of the ac signal only, which means that the transistor quiescent values are not affected by feedback. The quiescent parameters are found to be $I_{CQ} = 0.492$ mA and $V_{CEQ} = 5.08$ V, and the small-signal parameters are $r_\pi = 5.28$ kΩ and $g_m = 18.92$ mA/V.

In the small-signal equivalent circuit, which is shown in Figure 12.37(b), the Thevenin equivalent input source is converted to a Norton equivalent circuit. Writing a KCL equation at the output, we obtain

$$\frac{V_o}{10} + (18.9)V_\pi + \frac{V_o - V_\pi}{82} = 0$$

A KCL equation at the input yields

$$I_i = \frac{V_\pi}{10} + \frac{V_\pi}{4.96} + \frac{V_\pi}{5.28} + \frac{V_\pi - V_o}{82}$$

Combining these two equations and eliminating V_π, we find the small-signal transresistance gain, which is

$$A_{zf} = \frac{V_o}{I_i} = -65.87 \text{ k}\Omega$$

Since this unit of gain is not as familiar as voltage gain, we determine the voltage gain from

$$I_i = V_i/R_S = V_i/10$$

Therefore,

$$\frac{V_o}{V_i} = -(65.8)(0.10) = -6.587$$

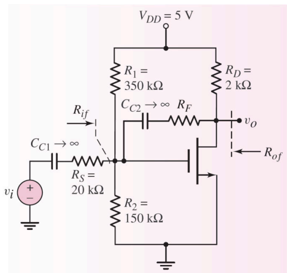
If the current gain h_{FE} of the transistor decreases from 100 to 75, the transistor quiescent values change slightly to $I_{CQ} = 0.478$ mA and $V_{CEQ} = 5.22$ V. The small-signal parameters become $r_\pi = 4.08$ kΩ and $g_m = 18.4$ mA/V.

The closed-loop small-signal voltage gain then becomes

$$V_o/V_i = -6.41$$

EXERCISE PROBLEM

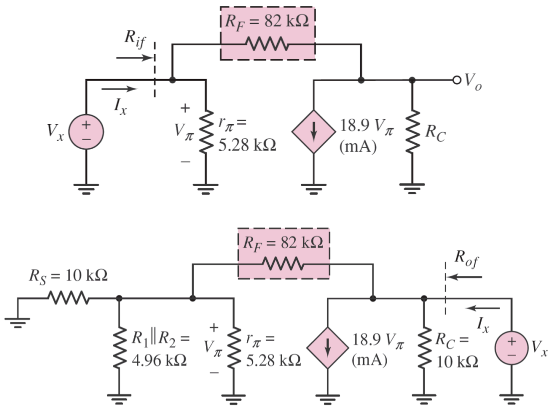
Ex 12.13: Consider the circuit in Figure 12.39, with transistor parameters $V_{TN} = 0.8$ V, $K_n = 1.5$ mA/V^2, and $\lambda = 0$. (a) (i) Find the open-loop gain for $R_F = \infty$. (ii) Find the closed-loop gain for $R_F = 47$ kΩ. (b) Repeat part (a) if the conductance parameter decreases by 15 percent to $K_n = 1.275$ mA/V^2. What is the percent change in the magnitude of each gain factor? (Ans. (a) (i) $A_v = -3.528$, (ii) $A_{vf} = -1.204$; (b) (i) $A_v = -3.0$, -15% change; (ii) $A_{vf} = -1.107$, -8.06% change)



EXAMPLE 12.14

Objective: Determine the input and output resistances of a single-transistor shunt–shunt feedback circuit.

Consider the circuit in Figure 12.37(a), with transistor parameters: $h_{FE} = 100$, $V_{BE}(\text{on}) = 0.7$ V, and $V_A = \infty$.



Solution: Input Resistance: The small-signal equivalent circuit for calculating the input resistance R_{if} is shown in Figure 12.40(a). The small-signal transistor parameters were determined in Example 12.13.

Writing a KCL equation at the input, we have

$$I_x = \frac{V_\pi}{r_\pi} + \frac{V_\pi - V_o}{R_F} = \frac{V_\pi}{5.28} + \frac{V_\pi - V_o}{82}$$

From a KCL equation at the output node, we have

$$\frac{V_o}{R_C} + g_m V_\pi + \frac{V_o - V_\pi}{R_F} = \frac{V_o}{10} + (18.9)V_\pi + \frac{V_o - V_\pi}{82} = 0$$

Combining these two equations, eliminating V_o, and noting that $V_\pi = V_x$, we find that

$$R_{if} = \frac{V_x}{I_x} = 0.443\ \text{k}\Omega$$

Output Resistance: The small-signal equivalent circuit for calculating the output resistance R_{of} is shown in Figure 12.40(b). If we define

$$R_{eq} = r_\pi \| R_1 \| R_2 \| R_S$$

then a KCL equation at node V_x yields

$$I_x = \frac{V_x}{R_C} + g_m V_\pi + \frac{V_x}{R_F + R_{eq}}$$

From a voltage divider equation, we find that

$$V_\pi = \left(\frac{R_{eq}}{R_{eq} + R_F}\right) V_x$$

Combining these two equations, we find the output resistance to be

$$R_{of} = \frac{V_x}{I_x} = 1.75\ \text{k}\Omega$$

Comment: The input resistance with no feedback would be $r_\pi = 5.28\ \text{k}\Omega$. The shunt input feedback connection has lowered the input resistance to $R_{if} = 0.443\ \text{k}\Omega$. Similarly, the output resistance with no feedback would be $R_C = 10\ \text{k}\Omega$. The shunt output feedback connection has lowered the output resistance to $R_{of} = 1.75\ \text{k}\Omega$. The decrease in both the input and output resistances agrees with the ideal feedback theory.

Thank you