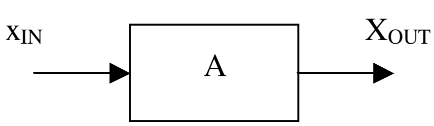
CHAPTER 2: FEEDBACK AND STABILITY

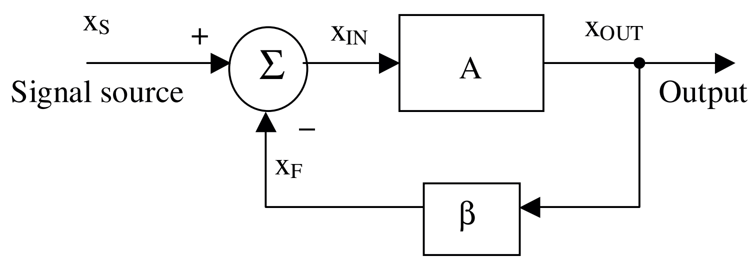
Feedback plays a major role in real-life circuits. Most of practical circuits or systems incorporate some sort of feedback. Feedback can be applied on a small scale or on a large scale and appears in both analog and digital systems. Feedback allows circuit characteristics such as gain, input impedance, output impedance, and bandwidth to be precisely controlled while making these parameters insensitive to variations in individual components parameters.

I. THE NEGATIVE-FEEDBACK LOOP

Figures below shows the block diagrams of an open-loop amplifier without feedback and a closed-loop amplifier with feedback.



a) Open-loop amplifier



b) Closed-loop amplifier

In the closed-loop amplifier, the output x_{OUT} is equal to $A.x_{IN}$. The variable x_S represents the input signal applied to the entire system by the user. The feedback network accepts x_{OUT} as its input and produces a signal x_F, called "feedback" signal. The later is subtracted from x_S at the summation node to produce x_{IN}.

$$x_{IN} = x_S - x_F$$

The relationship between x_F and x_{OUT} consists of the simple linear equation (linear feedback).

$$x_F = \beta x_{OUT}$$

where β is called the feedback factor and it is a constant.

Then the output x_{OUT} becomes:

$$x_{OUT} = Ax_{IN} = A(x_S - x_F)$$

or

$$x_{OUT} = A(x_S - \beta x_{OUT})$$

As indicated in this equation, x_{OUT} depends upon itself – a property intrinsic to the nature of a feedback path that connects the output back to the input.

Rearrange the above equation:

$$x_{OUT}(1+A\beta) = Ax_S$$

and finally put in the form:

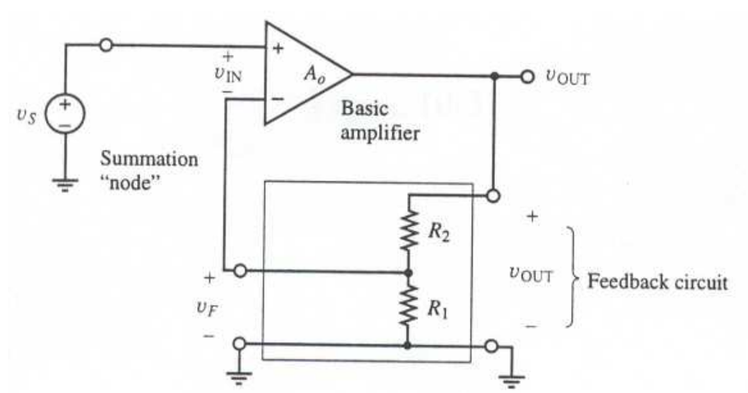
$$A_{fb} = \frac{x_{OUT}}{x_S} = \frac{A}{1+A\beta}$$

The factor A_{fb} is called the *closed-loop gain* (gain with feedback) of the circuit. It represents the net ratio of x_{OUT} to x_S when a feedback network described above is connected. Since $A\beta >> 1$, the closed-loop gain becomes:

$$\boxed{A_{fb} \approx \frac{A}{A\beta} = \frac{1}{\beta}}$$

In the other word, the closed-loop gain, A_{fb}, becomes independent of A in the limit $A\beta >> 1$, and depends only on the feedback factor β. *This feature is an important one that allows A_{fb} to be precisely set, regardless of the exact value of A.* Because the feedback network is generally made from passive (and easy-to-control) circuit elements, the many factors that affect A, including component variations, temperature, and circuit non-linearity, becomes much less important to the closed-loop circuit. This benefit is generally worth the price of reduced gain, especially because A can usually be made much larger than the closed-loop gain factor.

Example: Noninverting op-amp configuration



II. GENERAL REQUIRMENTS OF FEEDBACK CIRCUITS

The feedback diagram shown above is a general one that can be applied to many feedback amplifiers. Signals at summing node must be the same type (i.e., the three signals must either be all voltages or all currents). The amplifier output, x_{OUT}, however needs not be of the same signal type as its input.

In general, the amplification factor, A, can have dimension units of A_v=Volt/Volt, A_i=Ampere/Ampere, A_r=Volt/Ampere, or A_g=Ampere/Volt. The feedback function β must have units that are reciprocal to those of A, such that the product $A\beta$ is dimensionless. This condition ensures that x_F is of the same signal type as x_S and x_{IN}.

For the feedback circuits discussed in this section, the feedback network will be made from passive components only and the feedback factor β never exceed unity.

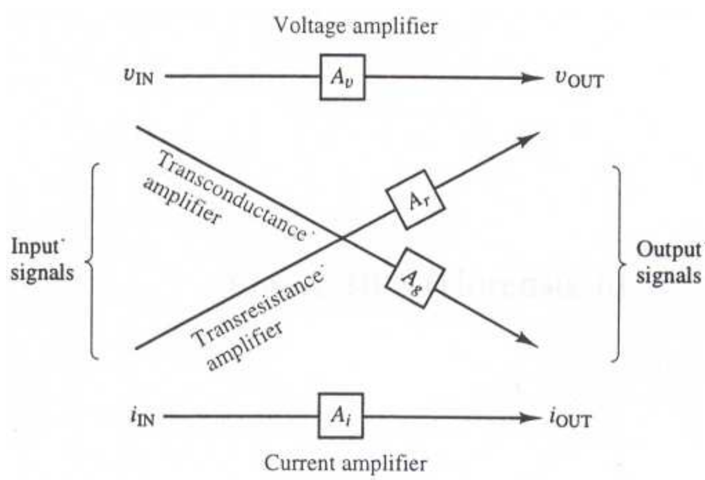
In the feedback loop, x_F is subtracted from x_S, making the feedback negative. If x_F is added to x_S at the summation node, the feedback becomes positive. Most circuits use negative feedback. Positive feedback is used in circuits called oscillators and also in a class of circuits called active filters which we will study in the later chapters.

Feedback affects the properties of all amplifiers. Negative feedback reduces amplifier non-linearity, improves input and output impedances, extends amplifier bandwidth, stabilizes amplifier gain, and reduces amplifier sensitivity to transistor parameters. These features are usually desirable ones in amplifier design.

III. THE FOUR TYPES OF NEGATIVE FEEDBACK

1. The four basic amplifier types

A circuit used for electronic amplification can be designed to response to either voltage or current as its primary input signal. Similarly, the circuit can be designed to supply either a voltage or a current as its primary output signal. Depending on its mix of input and output signals, an amplifier can be classified into one of the four basic types summarized in the Figure below.



a. A *voltage amplifier* with gain A_v accepts a voltage as its input signal and provides a voltage as its output signal.

b. A *current amplifier* with gain A_i has its input and output signals that are both currents.

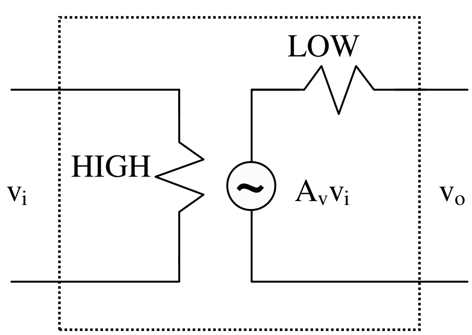
c. A circuit in which the input signal is a voltage and the output signal is a current is called a *transconductance amplifier* or sometimes a *voltage-to-current converter*. The amplification factor, A_g or g_m, for a transconductance amplifier, defined as the ratio i_{OUT}/v_{IN}, has a unit of amperes per volt, or conductance.

d. A *transresistance amplifier* with gain A_r accepts a current as its input signal and provides a voltage as its output signal. The amplification factor, A_r or r_m, of a transresistance amplifier, sometimes called a *current-to-voltage converter*, is defined as the ratio v_{OUT}/i_{IN} and has the units of volts per ampere, or resistance.

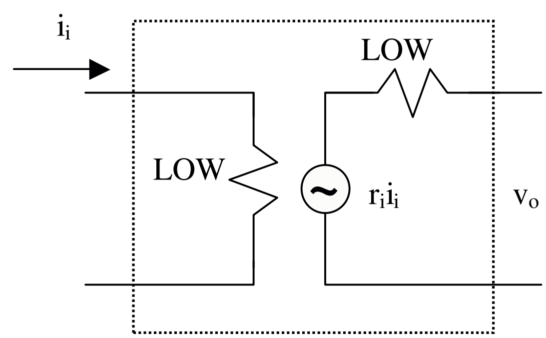
2. The four types of negative feedback

There are four types of negative feedback listed in the Table and shown the Figure below. Depending on its input and output, each negative feedback circuit has a specific application.

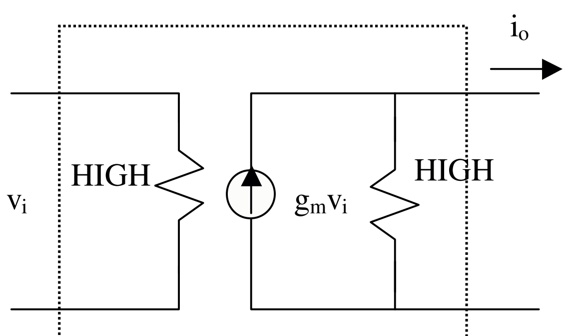
Input	Output	Circuit	z_{in}	z_{out}	Converts	Ratio	Symbol	Type of Amplifier
V	V	VCVS	∞	0	-	v_o/v_i	A_v	Voltage amplifier
I	V	ICVS	0	0	i to v	v_o/i_i	r_m	Transresistance amplifier
V	I	VCIS	∞	∞	v to I	i_o/v_i	g_m	Transconductance amplifier
I	I	ICIS	0	∞	-	i_o/i_i	A_i	Current amplifier



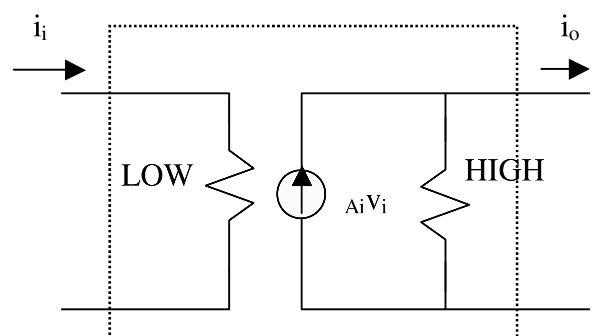
VCVS



ICVS



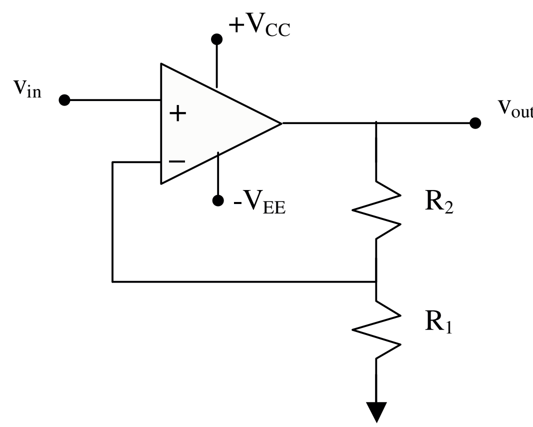
VCIS



ICIS

*** VOLTAGE-CONTROLLED VOLTAGE SOURCE (VCVS)

This is a non-inverting voltage amplifier using negative feedback. The circuit has high input impedance and low output impedance to provide a stiff voltage source. It converts a voltage input to a voltage output with an inversion factor equal to the gain of the amplifier (A_{CL}). The output voltage is controlled and proportional to the change of the input voltage.



Feedback fraction, β:

$$\beta = \frac{v_{R1}}{v_{out}} = \frac{R_1}{R_1 + R_2}$$

Closed loop gain:

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

Loop gain:

$$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} \approx \frac{A_{OL}}{A_{OL}\beta} \approx \frac{1}{\beta} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

Error between ideal and exact values:

$$\%Error = \frac{100\%}{1 + A_{OL}\beta}$$

Impedances:

$$Z_{in} = (1 + A_{OL}\beta)R_{in}$$

$$Z_{out} = \frac{R_{out}}{1 + A_{OL}\beta}$$

Output voltage: $v_{in} = Av_{out}$

As mentioned earlier, negative feedback stabilizes the voltage gain, increases the input impedance, decreases output impedance and reduces any nonlinear distortion of the amplified signal.

a. Gain stability:

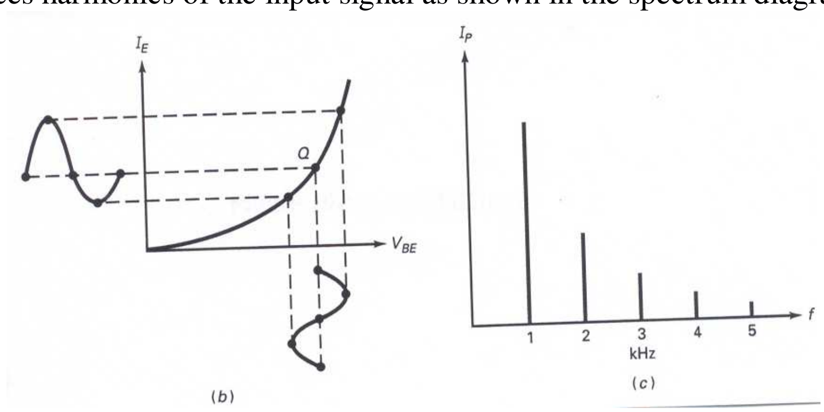
The gain of the feedback amplifier is stabilized because it depends only on the external resistances (i.e., can be precision resistors). This gain stability depends on having a low percent error between the ideal and the exact closed-loop voltage gains. The smaller the percent error, the better the stability.

The worst-case error of closed-loop voltage gain occurs when the open-loop voltage gain A_{OL} is minimum.

$$\%\text{Maximum error} = \frac{100\%}{1 + A_{OL(min)}\beta}$$

b. Nonlinear distortion:

In the later stage of an amplifier, non-linear distortion will occur with large signals because the input/output response of the amplifying devices becomes non-linear as shown in figure below. Nonlinear also produces harmonics of the input signal as shown in the spectrum diagram.



The degree of harmonic distortion is measured by the percent of total harmonic distortion, TDH, and defined as:

$$THD = \frac{\text{Total harmonic voltage}}{\text{Fundamental voltage}} 100\%$$

Negative feedback reduces harmonic distortion. The exact equation for closed-loop harmonic distortion is:

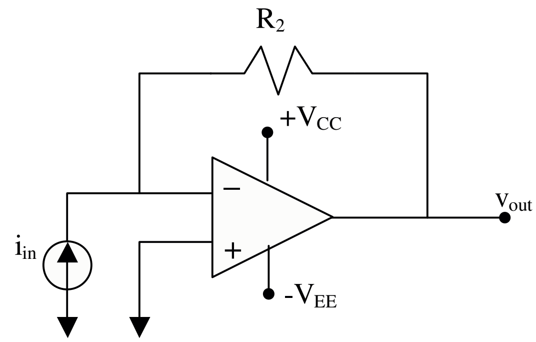
$$THD_{CL} = \frac{THD_{OL}}{1 + A_{OL}\beta}$$

As shown, the quantity $1+A_{OL}\beta$ has a curative effect. When it is large, it reduces the harmonic distortion to negligible levels, (i.e., high-fidelity sound in audio amplifier system).

Example 19-1, 19-2, 19-3, 19-4 (page 667)

*** <u>CURRENT-CONTROLLED VOLTAGE SOURCE (ICVS)</u> (19-4)

This negative feedback amplifier converts a current input to voltage output, it has a <u>low input impedance</u> and <u>low output impedance</u>. The conversion provides a stiff voltage source from a current input. The conversion factor is called <u>transresistance</u> (r_m) (i.e., output voltage is proportional to the current by a resistance).



Output voltage:

$$v_{out} = i_{in} R_2 \frac{A_{OL}}{1 + A_{OL}} = i_{in} R_2$$

The circuit is a current-to-voltage converter. Different values of R2 can be selected to have different conversion factors (transresistances). Input and output impedances:

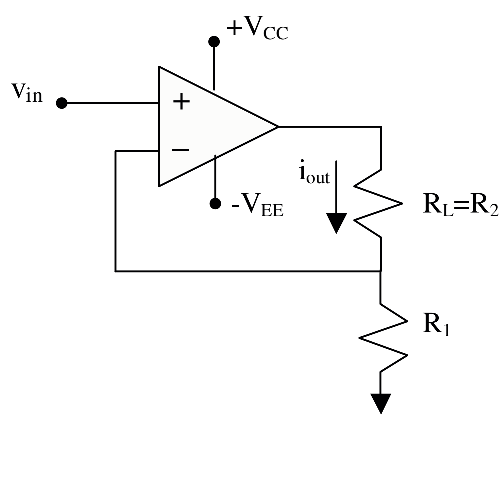
$$z_{in(CL)} = \frac{R_2}{1 + A_{OL}}$$

$$Z_{out(CL)} = \frac{R_{out}}{1 + A_{OL}}$$

Example: inverting amplifier, 19-5, 19-6 (page 674)

*** <u>VOLTAGE-CONTROLLED CURRENT SOURCE (VCIS)</u> (19-5)

This amplifier converts a voltage input to a current output with a conversion factor <u>transconductance</u>, g_m, (i.e., 1/R). <u>Both input and output impedances are high</u> in this circuit to provide a stiff current source.



Output current:

$$i_{out} = \frac{v_{in}}{R_1 + \frac{(R_1 + R_2)}{A_{OL}}}$$

$$i_{out} = \frac{v_{in}}{R_1} = g_m v_{in} \quad \text{where} \quad g_m = \frac{1}{R_1}$$

Input and output impedances:

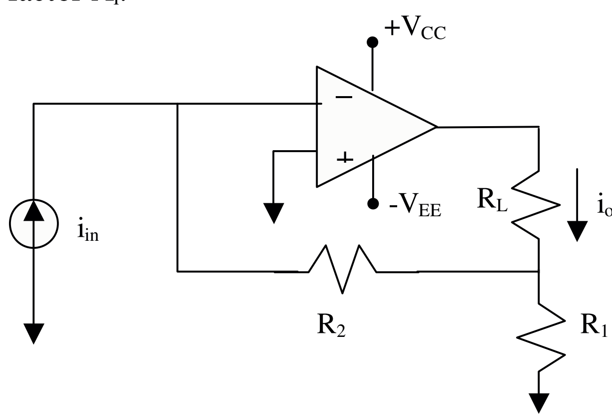
$$Z_{in(CL)} = (1 + A_{OL}\beta)R_{in}$$

$$Z_{out(CL)} = (1 + A_{OL})R_1$$

Example 19-7 (page 677)

*** CURRENT-CONTROLLED CURRENT SOURCE (ICIS)

The current amplifier has low input impedance and high output impedance, it provides a stiff current source with a current gain factor A_i.



Closed loop current gain:

$$A_i = \frac{A_{OL}(R_1 + R_2)}{R_L + A_{OL}R_1} \cong \frac{R_2}{R_1} + 1$$

Input and output impedances:

$$Z_{in(CL)} = \frac{R_2}{1 + A_{OL}\beta} \quad \text{where} \quad \beta = \frac{R_1}{R_1 + R_2}$$

$$Z_{out(CL)} = (1 + A_{OL})R_1$$

Example 19-8 (page 678)

*** BANDWIDTH

Negative feedback increases the bandwidth of an amplifier because the roll-off in open-loop voltage gain means less voltage is fed back, which produces more input voltage as a compensation. Because of this, the closed-loop cutoff frequency is higher than the open-loop cutoff frequency.

The closed-loop cutoff frequency is given by:

$$f_{2(CL)} = \frac{f_{unity}}{A_{CL}}$$

The *gain bandwidth product (GBP)* is defined as

$$GBP = Gain \cdot frequency$$

and this gain bandwidth product is constant, i.e.:

$$\boxed{A_{OL} f_{OL} = A_{CL} f_{CL}}$$

or

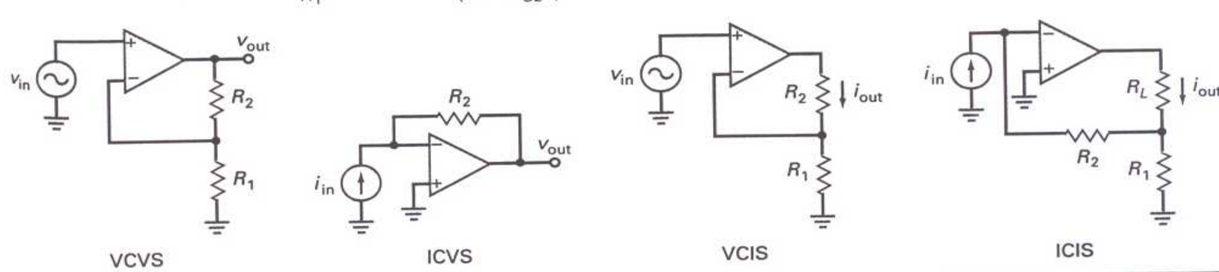
$$A_{CL} f_{2(CL)} = f_{unity}$$

The left side of this equation is the GBP and the right side of the equation, f_{unity}, is a constant for a given op-amp. Because GBP is a constant for a given op-amp, a designer has to tradeoff gain for bandwidth. The less gain used, the more bandwidth results. Conversely, if the designer wants more gain, less bandwidth results. As shown, the unity frequency determines GBP of the op-amp, higher unity frequency op-amp may be needed for specific application which requires both high gain and high bandwidth.

Example 19-9, 19-10, 19-11, 19-12, 19-13 (page 682)

Table 19-2 Four Types of Negative Feedback

Type	Stabilized	Equation	$z_{in(CL)}$	$z_{out(CL)}$	$f_{2(CL)}$	$f_{2(CL)}$	$f_{2(CL)}$
VCVS	A_v	$\frac{R_2}{R_1} + 1$	$(1 + A_{OL}B)R_{in}$	$\frac{R_{out}}{(1 + A_{OL}B)}$	$(1 + A_{OL}B)f_{2(OL)}$	$\frac{A_{OL}}{A_{CL}} f_{2(OL)}$	$\frac{f_{unity}}{A_{CL}}$
ICVS	$\frac{v_{out}}{i_{in}}$	$v_{out} = i_{in}R_2$	$\frac{R_2}{1 + A_{OL}}$	$\frac{R_{out}}{1 + A_{OL}}$	$(1 + A_{OL})f_{2(OL)}$	—	—
VCIS	$\frac{i_{out}}{v_{in}}$	$i_{out} = \frac{v_{in}}{R_1}$	$(1 + A_{OL}B)R_{in}$	$(1 + A_{OL})R_1$	$(1 + A_{OL})f_{2(OL)}$	—	—
ICIS	A_i	$\frac{R_2}{R_1} + 1$	$\frac{R_2}{(1 + A_{OL}B)}$	$(1 + A_{OL})R_1$	$(1 + A_{OL}B)f_{2(OL)}$	—	—



FEEDBACK LOOP STABILITY

Whenever a multistage amplifier like an op-amp is connected in a negative feedback configuration, the stability of the feedback loop must be examined to verify that *unwanted oscillations* will not occur.

The output of a linear system will experience a relative phase shift of -90^O if the driving frequency is increased beyond one of the poles of the system function. In a system with three or more poles, a frequency will exist at which the phase shift exceeds 180^O.

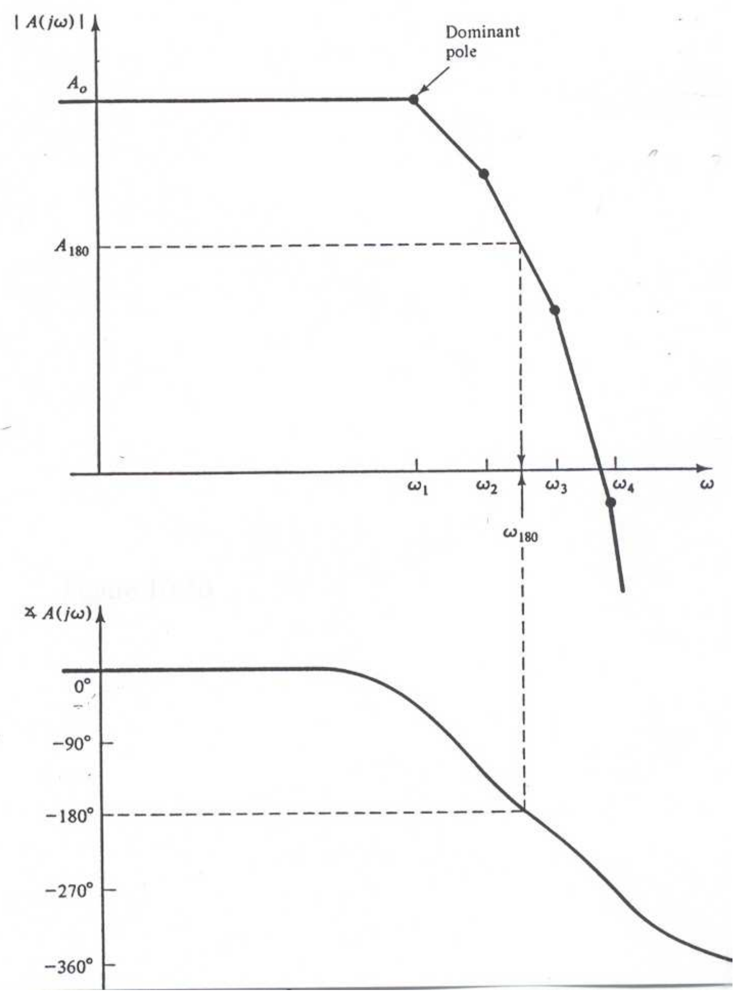
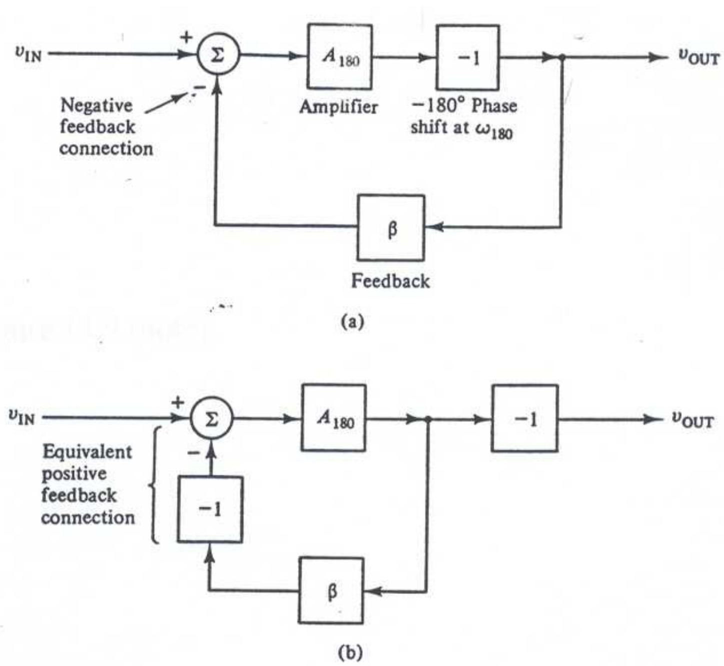


Figure 14.8 Open-loop response of op-amp with more than two poles. At ω_{180}, the phase shift is $-180°$ and the magnitude of the open-loop gain is A_{180}.

At some frequency, ω_{180}, *the -180^O phase shift will change an otherwise negative feedback loop into a positive feedback loop* as shown below.

Figure 14.9
Negative feedback becomes positive feedback at ω_{180}. The gain A_{180} is a positive number less than A_o. (a) Actual feedback loop at $\omega = \omega_{180}$, inlcuding −180° phase shift; (b) equivalent representation.



The response of the feedback loop at ω_{180} can be written as:

$$v_{out} = \frac{(-1)A_{180}}{1+(-1)A_{180}\beta}$$

If A_{180} and β are such that $A_{180}\beta=1$, the denominator becomes 0 and the output becomes infinite, even with v_{in} equal to 0.

- Such a condition is equivalent to *oscillation at the frequency* ω_{180}.
- It can be shown that the less stringent inequality $A_{180}\beta \geq 1$ also leads to oscillation at ω_{180}.

* Note: in practice, the saturation limits of the op-amp limit the magnitude of oscillation (i.e., the output voltage is not infinity).

I. FEEDBACK LOOP COMPENSATION

Unwanted oscillations at ω_{180} can be prevented by the use of frequency compensation. Compensation consists of altering the open loop response of the op-amp so that the stability condition is met:

$$\mathbf{A_{180}\beta < 1}$$

Compensation is often included in the internal design of an op-amp but may be implemented – if necessary – by adding external components to the feedback loop.

In an internal compensated op-amp, the stability condition is met up to some maximum value of β. Some op-amps (LM741) are stable under all negative feedback conditions. The value of A_{180} in these op-amps is less than unity.

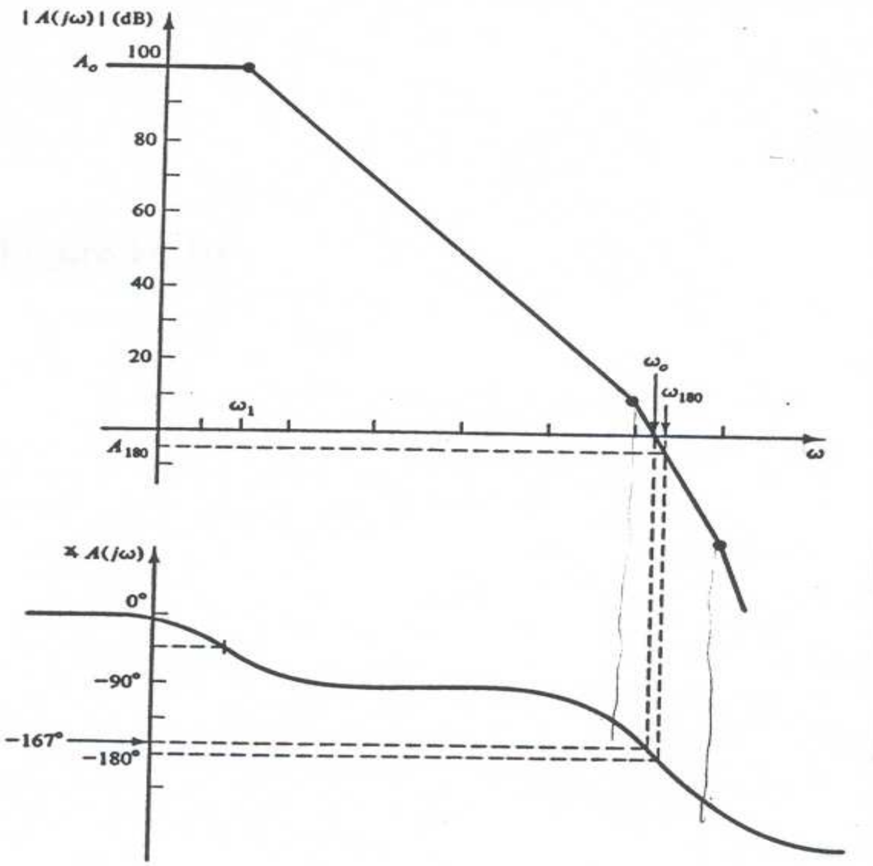


Figure 14.10 Open-loop frequency response of an internally compensated op-amp that is stable under all feedback conditions. The phase angle is equal to −167° at the unity gain frequency ω_o. The op-amp has three poles marked by circles on the Bode plot.

If an op-amp is not internal compensated for all feedback conditions, its feedback loop must be evaluated for stability. If the feedback loop is unstable, external compensation must be added. External compensation is sometimes preferred over internal compensation because the latter limits the gain bandwidth product of the feedback loop.

II. EVALUATION OF STABILITY CONDITION

The stability of a feedback loop can be determined by evaluating the gain margin and phase margin:

$$\text{Gain} - \text{Margin} \quad = 1 - \left|A(j\omega)\beta\right|_{\omega_{180}} = 1 - A_{180}\beta$$

for stability, the gain margin must be positive (i.e., $A_{180}\beta < 1$).

$$\text{Phase} - \text{Margin} = \arg(A_{(j\omega)}\beta\big|_{\omega(PM)}) - (-180^0) = 180^0 + \arg(A_{(j\omega)}\beta\big|_{\omega(PM)})$$

where $\left|A_{(j\omega)}\beta\right| = 1$ at ω_{PM}.

A negative phase margin indicates that $\left|A_{(j\omega)}\beta\right|$ is greater than unity at ω_{180} and the circuit will be unstable.

- If one margin passes the stability test, the other will also.
- To ensure stability, it is necessary to design a feedback loop with excess gain or phase margin.

Example:

The open-loop frequency response of a particular op-amp is described by the following transfer function:

$$A_{(j\omega)} = \frac{A_0}{(1+j\frac{\omega}{\omega_1})(1+j\frac{\omega}{\omega_2})(1+j\frac{\omega}{\omega_3})}$$

where $A_0=10^6$, ω_1=10rad/sec, $\omega_2=\omega_3=10^6$rad/sec.

Since $\omega_1 << \omega_2$, the dominant pole of $A(j\omega) \approx \omega_1$.

a. How large can the feedback parameter β become before instability results? Assume β is not a function of frequency.
b. Design a non-inverting amplifier that meets the stability conditions.

Solution:

Since β is not frequency dependent, ω_{180} occurs at the frequency where the angle of the transfer function is at -180^O, that is where:

$$\arg(A_{(j\omega)}) = -\tan^{-1}(\frac{\omega}{\omega_1}) - \tan^{-1}(\frac{\omega}{\omega_2}) - \tan^{-1}(\frac{\omega}{\omega_3}) = -180^0$$

solving for ω results in

$$\omega_{180} \cong 10^6 \text{ rad/sec}$$

The magnitude of $A(j\omega)$ at ω_{180} as follows:

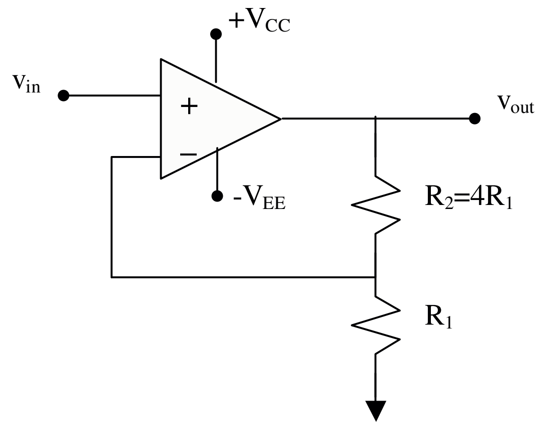
$$A_{180} = \left| \frac{10^6}{(1+j\frac{10^6}{10})(1+j\frac{10^6}{10^6})(1+j\frac{10^6}{10^6})} \right| = \frac{10^6}{(10^5)(\sqrt{2})^2} = 5$$

stability of the feedback loop required that $\left|A_{(j\omega)}\beta\right| \le 1$, therefore:

$$\beta \le \frac{1}{5} = 0.2$$

For the circuit to be stable, the closed-loop gain must therefore meet the minimum condition:

$$\frac{v_{out}}{v_{in}} = \frac{1}{\beta} \ge 5$$



In practice, β should be decreased somewhat to improve the gain and phase margin beyond their minimally stable values.

III. EXTERNAL COMPENSATION

If an op-amp in a negative feedback loop is under-compensated, a compensation network can be added to the loop.

Example: The open loop response A(jω) of particular op-amp is measured and is shown in the following figure.

a. Show that the minimum allowed β that ensures stability is 0.001.
b. To what closed-loop gain does β correspond?
c. Design a compensation network that will stabilize the op-amp in a non-inverting amplifier with a gain of 5 (i.e., 14dB).

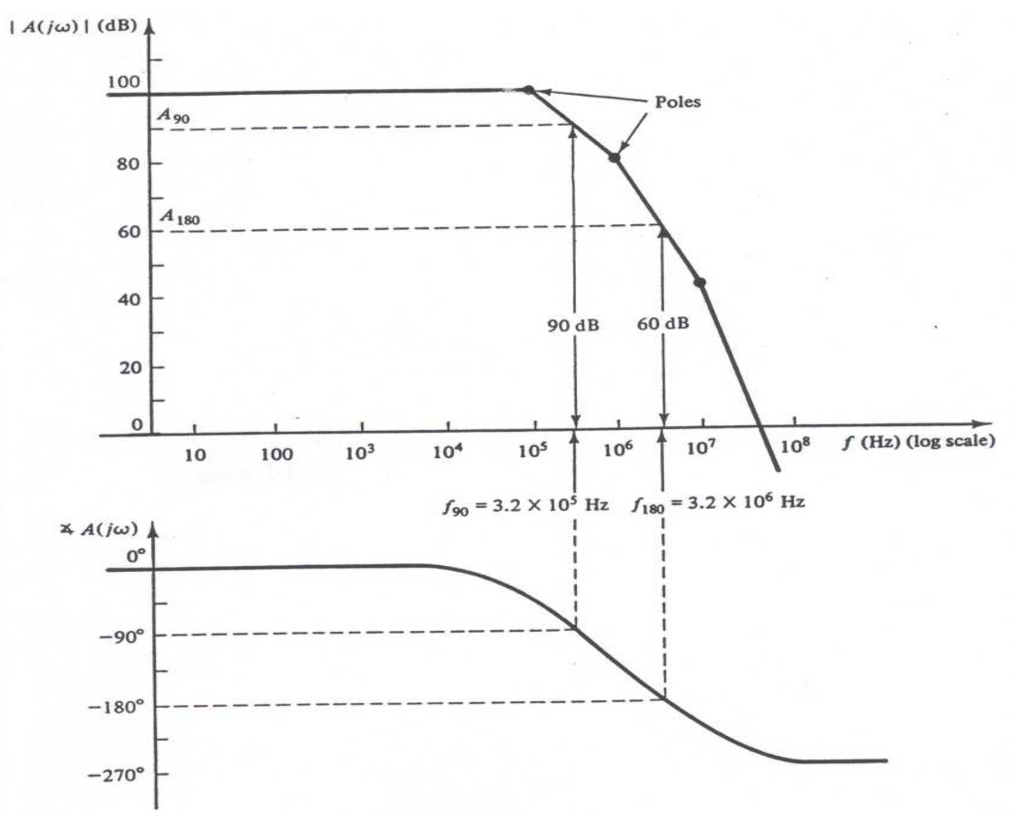


Figure 14.12 Measured Bode plot of an uncompensated op-amp. The gain is equal to +60 dB at f_{180}.

Solution:

The value of f_{180} can be obtained from the angle portion of the above Bode plot.

$$f_{180} = 3.2*10^6 \text{ Hz}$$

At this frequency, A_{180}=60dB=1000. For stability, $\left|A_{(j\omega)}\beta\right| \le 1$, therefore $\beta < 10^{-3}$.

A non-inverting amplifier, with a desired gain of 5 will have β=0.2, will be unstable unless a compensation network is added to the feedback loop. If the compensation network adds a pole to the op-amp open-loop response at a frequency well below f_{180}, the open-loop gain at f_{180} will be reduced so that the stability condition can be met.

If the pole is located below f_{90}, it will add an additional -90^O phase shift at f_{90}, bringing the total phase shift at f_{90} to -180^O. The original f_{90} before compensation will become the new f_{180} after compensation. Therefore

$$A_{90}\beta = 1 \quad \text{or} \quad \left|A_{90}\right|_{dB} + \left|\beta\right|_{dB} = 0$$

The uncompensated op-amp has a gain magnitude of 90dB at f_{90} (see figure above). If an amplifier with closed-loop gain of 5 (i.e., 14dB) is to be made, then β=1/5 (i.e., - 14dB) and A_{90} must be reduced from 90dB to 14dB (i.e., 76dB). This can be achieved with a pole at f_c =50.7Hz. The following procedure shows how to evaluate this f_c frequency.

This value can be computed by noting that above f_c , the pole at f_c will increase the roll-off by –20dB/decade.

$$f_{90} - f_c = \frac{-76\text{dB}}{-20\text{dB/decade}} = 3.8\text{decades}$$

$$f_c = \frac{f_{90}}{10^{3.8}} = \frac{3.2 \cdot 10^5 \text{Hz}}{6.31 \cdot 10^3} = 50.7\text{Hz}$$

A compensation pole at f_c can be introduced by the simple RC filter shown below. Note that $\frac{1}{R_c C_c} = 2\pi f = 319\text{rad/sec}$. Arbitrary choose resistor (or capacitor) then calculate the other.

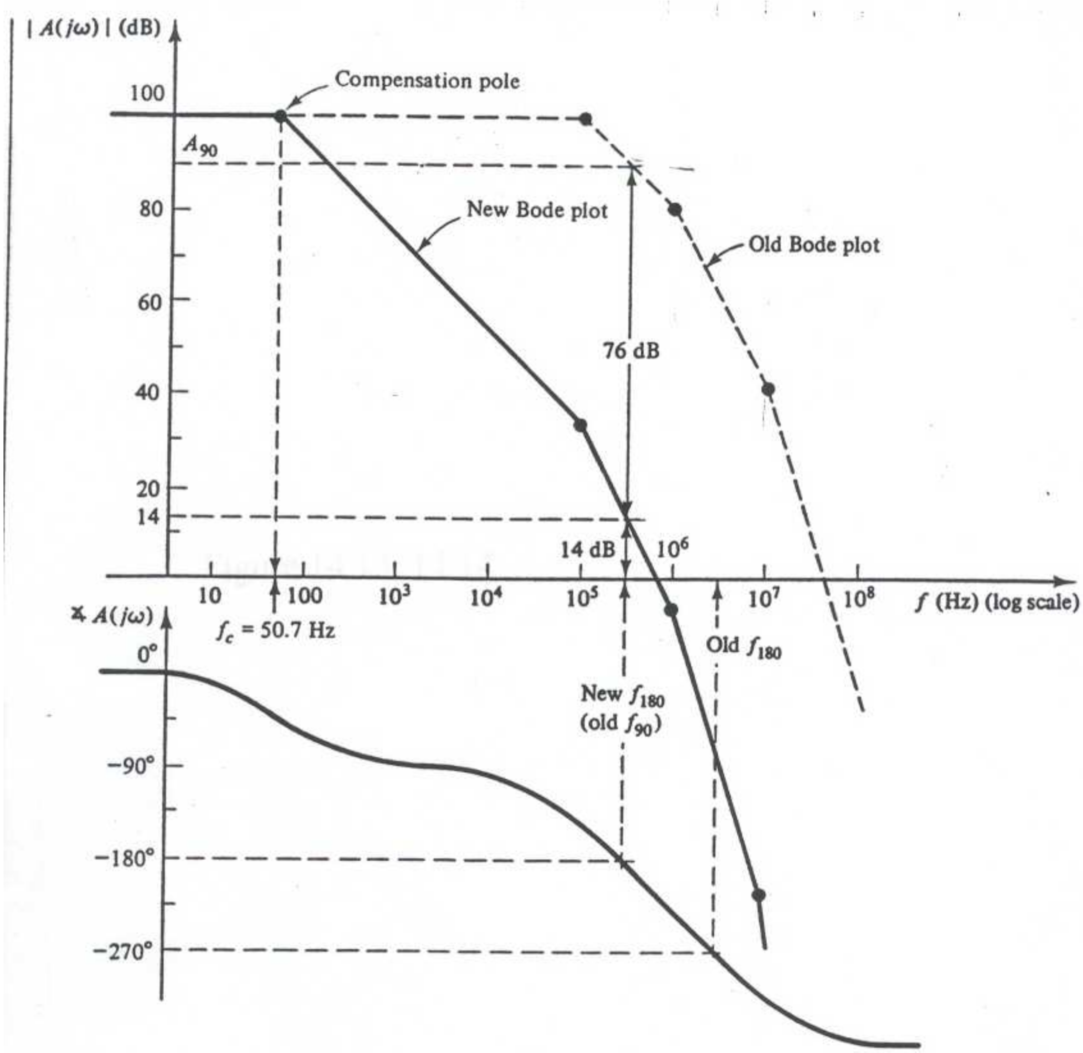
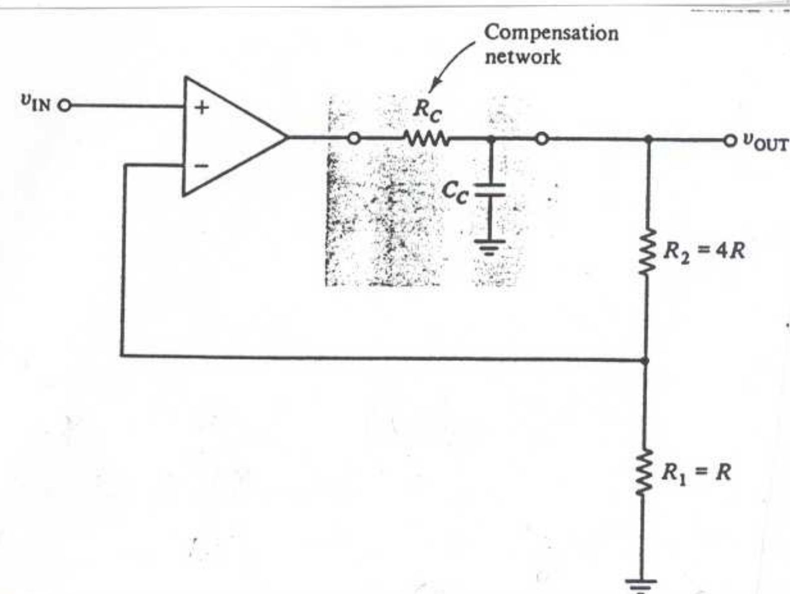


Figure 14.13 Bode plot of the op-amp of Fig. 14.12 minimally compensated for $\beta = 1/5$ by the addition of a dominant pole at $f_c = 50.7$ Hz. The gain is reduced to +14 dB at the old f_{90}. The old f_{90} becomes the new f_{180}.

Figure 14.14 Compensation pole introduced by the addition of a simple *RC* network to the feedback loop.



PROBLEMS

○ More difficult ◐ Even more difficult ● Most difficult

10.1 The Negative-Feedback Loop

10.1 An amplifier with large but varying open-loop gain A_o is connected in a negative feedback loop with $\beta = 0.01$, so that the closed-loop gain approaches the value $1/\beta = 100$. Over what range of A_o will the actual closed-loop gain fall by no more than 1% of this ideal value?

10.2 A negative feedback circuit is formed from an amplifier with open-loop gain $A_o = 10^5$ using a feedback factor of $\beta = 0.001$. What is overall gain A_{fb}? Calculate the change in A_{fb} if A_o increases by 10%.

10.3 A noninverting amplifier is made from an op-amp with $A_o = 10^6$, $R_2 = 47\,\text{k}\Omega$, and $R_1 = 5.6\,\text{k}\Omega$. What are the values of the feedback factor β and the closed-loop gain A_{fb}?

10.4 ○ Draw the feedback-loop block diagram of a two-input op-amp summation amplifier. In this case, three signals must enter the summation node of the feedback diagram. Find an expression for the feedback factor β. Show that the closed-loop gain function (10.6) approaches the two-input gain function of Chapter 2 in the limit of large open-loop op-amp gain.

10.5 ○ Draw the feedback-loop block diagram of a two-input op-amp difference amplifier of the type shown in Fig. 2.13. Find an expression for the feedback factor β. Show that the closed-loop gain function (10.6) approaches the two-input gain function of Chapter 2 in the limit of large open-loop op-amp gain.

10.2 General Requirements of Feedback Circuits

10.6 Show that the Schmitt trigger of Section 2.5.2 incorporates positive feedback. What is the output of the circuit for zero input?

10.7 Prove that the signal x_{IN} in Fig. 10.2 will always be less than x_S as long as the product $A\beta$ is positive.

10.8 How must the feedback diagram of Fig. 10.2 be modified if β is a positive number less than unity and the gain A is negative?

10.9 It is possible to create a circuit in which feedback with $\beta > 1$ is provided by active devices. Show that the combination of small gain A and large feedback factor β does not lead to large amplification in the feedback loop of Fig. 10.2.

10.3 Effects of Feedback on Amplifier Performance

10.3.1 Effect of Feedback on Amplifier Linearity

10.10 An amplifier with gain $A_o = 1000$ is connected in a negative feedback loop such that $A_{fb} = 50$. By how much will A_{fb} change if A_o changes by 10%?

10.11 An amplifier is connected in a negative feedback circuit with $\beta = 0.01$. Plot the closed-loop gain as a function of A_o for $1 < A_o < 1000$.

10.12 An amplifier has the open-loop transfer characteristic of Fig. 10.4 with slope $A_1 = 2\times10^3$ for $0 < v_{OUT} < 5\,\text{V}$, and slope $A_2 = 0.5\times10^3$ for $5\,\text{V} < v_{OUT} < 12\,\text{V}$. The amplifier is connected in a negative feedback loop with $\beta = 0.05$. Plot the resulting closed-loop transfer characteristic v_{OUT}/v_S.

10.13 An amplifier having the transfer characteristic of Fig. 10.4 with $A_1 = 1200$ and $A_2 = 400$ is connected in a negative feedback loop. Choose a value for β such that the closed-loop gain falls by no more than 5% when the amplifier operates in region 2. What is the closed-loop gain for this value of β?

10.14 A voltage amplifier has an open-loop transfer characteristic that has three regions with different slopes. Its transfer characteristic begins at the origin, and its output is equal to 2 V at $v_{IN} = 0.2\,\text{V}$, to 4 V at $v_{IN} = 0.6\,\text{V}$, and to 5 V for $v_{IN} \geq 1\,\text{V}$. The amplifier is connected in a negative feedback loop with $\beta = 0.1$. Plot v_{OUT} versus v_S over the range $0 < v_{OUT} < 5\,\text{V}$.

10.15 An amplifier has the open-loop transfer characteristic of Fig. 10.4 with slope $A_1 = 5\times10^4$ for $0 < v_{OUT} < 7\,\text{V}$, and slope $A_2 = 2\times10^4$ for $7\,\text{V} < v_{OUT} < 15\,\text{V}$.

(a) If v_{IN} consists of a ±2-V peak triangular waveform, plot the resulting output as a function of time.

(b) The amplifier is connected in a negative feedback loop with $\beta = 0.1$. Plot the output if the input v_S to the feedback amplifier is again a ±2-V triangular waveform.

10.16 Design an amplifier with an overall gain of $50 \pm 1\%$. Assume that a number of amplifier stages exist for which the open-loop gain is not precisely known, but lies somewhere in the range 1000 to 2000. Your finished design may consist of a cascade of one or more similar stages. For the purpose of this problem, assume that the feedback factor β of any single stage can be known to arbitrary accuracy.

10.17 A BJT inverter with a collector resistor of 5 kΩ, a base resistor of 10 kΩ, and an emitter that is grounded with respect to small signals is biased at $I_B = 10\,\mu A$. The circuit is made from a BJT whose β varies over the range 150 to 250. Specify the requirements of a feedback circuit that will result in a closed-loop gain that varies by no more than 1%. What is the value of A_{fb} for such a circuit?

10.18 ○ An enhancement-mode NMOS inverter with enhancement-mode NMOS pull-up load has its source grounded and is biased in the constant-current region. The *W/L* ratio of the pull-up load is known to be 0.1, but due to a masking error, the *W/L* ratio of the driven MOSFET may lie anywhere in the range 0.2 to 10. Specify the requirements of a feedback circuit that will result in a closed-loop gain that varies by no more than 5%. What is the value of A_{fb} for such a circuit? You may not be able to meet the design specifications in this case.

10.3.2 Effect of Feedback on Amplifier Bandwidth

10.19 An op-amp with a gain–bandwidth product of 4×10^5 is connected in the noninverting configuration with a closed-loop gain of 50. What is its closed-loop bandwidth?

10.20 An op-amp has an open-loop gain of 10^6 and a dominant open-loop pole at 5 Hz. If a noninverting amplifier with a gain of 100 is made from this op-amp, what is the resulting amplifier bandwidth? What is the gain–bandwidth product?

10.21 An op-amp has an open-loop gain of 10^4 and a dominant open-loop pole at 4 Hz. If an inverting amplifier with a gain of −100 is made from this op-amp, what is the resulting amplifier bandwidth? What is the gain–bandwidth product?

10.22 A noninverting amplifier with a gain of 25 and a bandwidth of at least 50 kHz is to be made from an op-amp. Specify the minimum open-loop gain for the op-amp if its dominant pole frequency is located at 4 Hz.

10.23 An inverting amplifier with a gain of −50 and a bandwidth of at least 10 kHz is to be made from an op-amp. Specify the minimum open-loop gain for the op-amp if its dominant pole frequency is located at 5 Hz.

10.24 Find the unity-gain frequency of an op-amp with an open loop gain of 10^6 and a dominant pole at 4 Hz.

10.25 Design a cascade of two or more noninverting amplifiers such that the overall cascade has a gain of 1000 and a bandwidth of at least 10 kHz. The available op-amps each have an open-loop gain of 10^5 and a dominant pole at 4 Hz.

10.26 Design an inverting amplifier that can amplify the voice signal from a dynamic microphone and deliver the resulting signal to a power amplifier. The power amplifier requires a signal on the order of 1 V peak to be driven to full power output. The dynamic microphone has an internal series resistance of 10 kΩ and produces a 10-mV peak signal when excited by a normal speaking voice. The amplifier should respond to at least the normal range of human hearing (about 20 Hz to 15 kHz).

10.27 Design an amplifier system that can add together the signals from two dynamic microphones (see Problem 10.26) and deliver the resulting signal to a power amplifier and loudspeaker. The power amplifier requires a signal of about 0.5 V peak to be driven to full-power output. The entire system should employ separate volume controls for each input and should respond to at least the normal range of human hearing (about 20 Hz to 15 kHz).

10.4 The Four Basic Amplifier Types

10.28 The output from a transconductance amplifier feeds the input to a transresistance amplifier. What is the resulting amplifier type of the overall cascade?

10.29 Show that each of the four amplifier systems depicted in Fig. 10.5 can provide power gain, regardless of amplifier type.

10.5 The Four Feedback Topologies

10.30 An ideal voltage amplifier is connected in the feedback loop of Fig. 10.14. Find values for A_v and β if $v_S = 50\,\text{mV}$, $v_F = 45\,\text{mV}$, and $v_{OUT} = 5\,\text{V}$.

10.31 An ideal current amplifier is connected in the feedback loop of Fig. 10.15. Find values for A_i and β if $i_S = 10\,\text{mA}$, $i_F = 9\,\text{mA}$, and $i_{OUT} = 1\,\text{A}$.

10.32 An ideal transresistance amplifier is connected in the feedback loop of Fig. 10.16. Find values for A_r and β if $i_S = 20\,\mu A$, $i_F = 18\,\mu A$, and $v_{OUT} = 12\,\text{V}$.

10.33 An ideal transconductance amplifier is connected in the feedback loop of Fig. 10.17. Find values for A_g and β if $v_S = 50\,\text{mV}$, $v_F = 49.5\,\text{mV}$, and $i_{OUT} = 5.2\,\text{mA}$.

10.34 An ideal current amplifier is connected in the feedback loop of Fig. 10.15. If $i_S = 10\,\text{mA}$, $A_i = 8000$, and $\beta = 0.1$, find values for i_F and i_{OUT}.

10.35 An ideal current amplifier is connected in the feedback loop of Fig. 10.15. If $A_i = 20{,}000$, $i_S = 20\,\text{mA}$, and $i_F = 8\,\text{mA}$, find i_{OUT} and β.

10.36 The feedback network β of a voltage amplifier described by the feedback diagram of Fig. 10.14 consists of a simple voltage divider formed by $R_1 = 100\,\Omega$ and $R_2 = 10\,\text{k}\Omega$, where the feedback signal is tapped from R_1. Find numerical values for β, $r_{in-\beta}$, and $r_{out-\beta}$.

10.37 The feedback function β of a current amplifier described by the feedback diagram of Fig. 10.15 consists of a current divider formed by $R_1 = 100\,\Omega$ and $R_2 = 10\,\Omega$, where the feedback current signal through R_1 is shunted from the amplifier input terminals. Find numerical values for β, $r_{in-\beta}$, and $r_{out-\beta}$.

10.38 ○ The feedback network to a voltage amplifier consists of a resistor and a forward-biased diode, as depicted in **Fig. P10.38**. The diode is kept in forward-bias conditions at all times by a dc bias component V_1 of v_{OUT}. Choose R_1 and V_1 such that $\beta \approx 0.005$ and $r_{in-\beta} = 10\,\text{k}\Omega$. What is the resulting value of $r_{out-\beta}$?

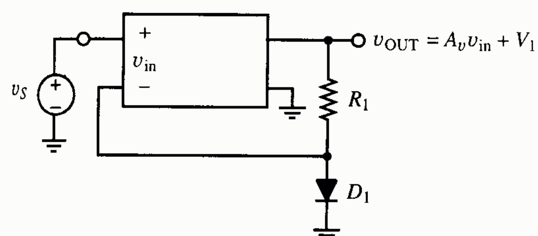


Fig. P10.38

.6 Effect of Feedback Connections n Amplifier Port Resistance

.39 A voltage amplifier with $A_v = 10^4$, $r_{in} = 1\,\text{k}\Omega$, d $r_{out} = 100\,\Omega$ is connected in a negative feedback op with $\beta = 0.1$. What are the resulting values of A_{fb}, n, and R_{out} if $r_{in-\beta} = \infty$ and $r_{out-\beta} = 0$?

.40 A voltage amplifier with $A_v = 5000$, $r_{in} = 3\,\text{k}\Omega$, d $r_{out} = 20\,\Omega$ is connected in a negative feedback loop ith $\beta = 0.02$. What are the resulting values of A_{fb}, , and R_{out} if $r_{in-\beta} = 100\,\text{k}\Omega$ and $r_{out-\beta} = 10\,\Omega$?

.41 A current amplifier with $A_i = 100$, $r_{in} = 5\,\Omega$, d $r_{out} = 1\,\text{M}\Omega$ is connected in a negative feedback p with $\beta = 0.05$. What are the resulting values of , R_{in}, and R_{out} if $r_{in-\beta} = 0$ and $r_{out-\beta} = \infty$?

10.42 A current amplifier with $A_i = 4000$, $r_{in} = 100\,\Omega$, and $r_{out} = 100\,\text{k}\Omega$ is connected in a negative feedback loop with $\beta = 0.1$. What are the resulting values of A_{fb}, R_{in}, and R_{out} if $r_{in-\beta} = 15\,\Omega$ and $r_{out-\beta} = 1\,\text{M}\Omega$?

10.43 A transresistance amplifier with $A_r = 500\,\text{V/mA}$, $r_{in} = 15\,\Omega$, and $r_{out} = 10\,\Omega$ is connected in a negative feedback loop with $\beta = 0.05$. What are the resulting values of A_{fb}, R_{in}, and R_{out} if $r_{in-\beta} = r_{out-\beta} = \infty$?

10.44 A transresistance amplifier with $A_r = 1200$ V/mA, $r_{in} = 50\,\Omega$, and $r_{out} = 80\,\Omega$ is connected in a negative feedback loop with $\beta = 0.001$. What are the resulting values of A_{fb}, R_{in}, and R_{out} if $r_{in-\beta} = r_{out-\beta} = 1\,\text{M}\Omega$?

10.45 A transconductance amplifier with $A_g = 100$ mA/V, $r_{in} = 500\,\text{k}\Omega$, and $r_{out} = 1\,\text{M}\Omega$ is connected in a negative feedback loop with $\beta = 0.5$. What are the resulting values of A_{fb}, R_{in}, and R_{out} if $r_{in-\beta} = r_{out-\beta} = 0$?

10.46 A transconductance amplifier with $A_g = 6000$ mA/V, $r_{in} = 10\,\text{M}\Omega$, and $r_{out} = 500\,\text{k}\Omega$ is connected in a negative feedback loop with $\beta = 0.5$. What are the resulting values of A_{fb}, R_{in}, and R_{out} if $r_{in-\beta} = r_{out-\beta} = 50\,\Omega$?

10.7 Examples of Real Feedback Amplifiers

10.7.1 Op-Amp Voltage Amplifier (Series/Shunt Feedback)

10.47 An op-amp has an open-loop gain of 10^6, an open-loop output resistance of $10\,\Omega$, and an open-loop input resistance of $2\,\text{M}\Omega$. If the op-amp is used to make a noninverting amplifier with a gain of 100, find the overall circuit input and output resistances.

10.48 Design a voltage amplifier using the μA741 op-amp, for which $A_v \approx 200{,}000$, $r_{in} \approx 2\,\text{M}\Omega$, and $r_{out} \approx 75\,\Omega$. Your amplifier should have an input resistance of at least $1000\,\text{M}\Omega$ and an output resistance of less than $0.1\,\Omega$. What is the largest gain achievable for these specifications?

10.49 Suppose that an op-amp voltage amplifier is required with a gain of 100 and a minimum input resistance of $1\,\text{G}\Omega$. Choose a real op-amp with sufficient open-loop gain and input resistance to meet these specifications. Possibilities to investigate include the μA741, LF411, and LM101A operational amplifiers.

10.50 ◐ Consider a voltage amplifier with a gain of 10 made from an op-amp with parameters $A_o = 5 \times 10^4$,

$r_{in} = 50\,\text{k}\Omega$, and $r_{out} = 500\,\Omega$. Suppose that the op-amp has a single pole that causes the open-loop gain to roll off at −20 dB/decade, reaching unity gain at 4 MHz. Find equivalent circuit representations for the frequency-dependent input and output impedances $\mathbf{Z}_{in}$ and $\mathbf{Z}_{out}$ of the circuit.

10.51 ◐ The differential amplifier of **Fig. P10.51** incorporates series/shunt feedback.

(a) If $R_B \gg R_3$, find an approximate expression for the closed-loop gain v_{OUT}/v_S.

(b) Choose I_o, V_{CC}, V_{EE}, and all resistor values such that the closed-loop gain is approximately 10.

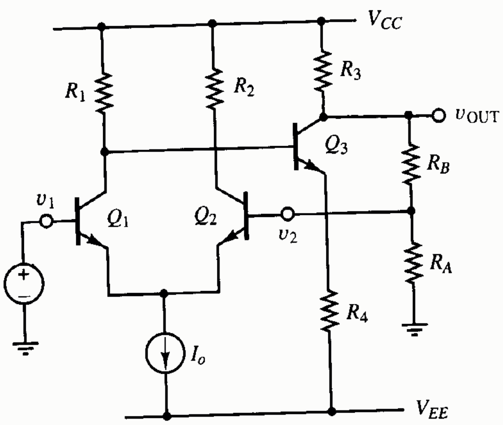


Fig. P10.51

10.52 ○ Design a modification to the circuit of **Fig. P10.51** so that the constraint $R_B \gg R_3$ is not needed. This design change will enable the conditions $r_{in\text{-}\beta} \gg r_{out}$ and $r_{out\text{-}\beta} \ll r_{in}$ to be more closely met.

10.7.2 MOSFET Transconductance Amplifier with Feedback Resistor (Series/Series Feedback)

10.53 Consider the MOSFET amplifier of Fig. 10.23. Derive expressions for the closed-loop gain and overall output resistance R_{out} directly from the circuit's small-signal model. Include the effects of the small-signal MOSFET output resistance r_o. Compare to the results obtained using feedback analysis.

10.54 ◐ In this problem, the overall output resistance R_{out} of the MOSFET transconductance amplifier of Fig. 10.23 is examined.

(a) Derive an expression for R_{out} directly from the small-signal amplifier model.

(b) Attempt to evaluate R_{out} by substituting the open-loop gain (10.56) into Eq. (10.51) and compare with the correct answer from part (a).

The results of parts (a) and (b) show an inconsistency because the open-loop gain substituted into Eq. (10.51) must be the *unloaded* value. The analysis leading to Eq. (10.51) already accounts for the loading of the output port by R_F. Also including output loading in the expression for the open-loop gain in Eq. (10.51) is tantamount to accounting for the loading effect twice.

(c) Compute the open-loop gain of the amplifier with $r_{in\text{-}\beta} = R_F$ replaced by a short circuit in the output loop. Retain $r_{out\text{-}\beta} = R_F$ in the input loop. Show that substituting this open-loop gain into Eq. (10.51) results in the correct expression for R_{out}.

10.55 ○ Consider the MOSFET transconductance amplifier of Fig. 10.23. Suppose that the MOSFET has parameters $K = 2\,\text{mA/V}^2$, $V_{TR} = 2\,\text{V}$, and $V_A = 20\,\text{V}$. Choose values for V_{SS} and R_F such that a closed-loop gain of approximately 2 mA/V is realized.

10.56 ◐ The circuit of **Fig. P10.56**, called the *series/series triple*, utilizes series input mixing and series output sampling. Suppose that $R_{C1} = 9\,\text{k}\Omega$, $R_{C2} = 5\,\text{k}\Omega$, $R_{C3} = 600\,\Omega$, $R_{E1} = R_{E2} = 100\,\Omega$, and $R_F = 640\,\Omega$.

(a) Find an expression and value for the open-loop gain with the loading by the feedback circuit included.

(b) Find an expression and value for the feedback function $\beta = v_F/i_{E3}$. Note that R_F is much larger in value than R_{E1} and R_{E2}.

(c) What is the closed-loop gain of the amplifier?

(d) Can such an amplifier be made from two stages?

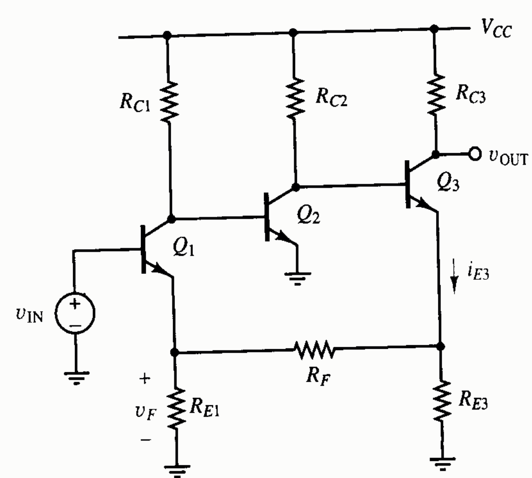


Fig. P10.56

10.57 ○ The series/series feedback circuit of **Fig. P10.57** can be used to produce large output currents from a signal voltage v_S.

(a) What is the open-loop transconductance gain A_g of the op-amp–transistor–resistor combination? What practical limitation exists to this circuit?

(b) If the feedback loop is closed, what is the value of the feedback factor $\beta = v_F/i_{OUT}$? (Assume that $i_E \approx i_{OUT}$ and use the ideal op-amp approximation.)

(c) Choose a value for R_F such that $A_g = 100\,\text{mA/V}$.

(d) Now suppose that the op-amp has parameters $r_{in} = 50\,\text{k}\Omega$, $A_v = 500$, and $r_{out} = 1\,\text{k}\Omega$. If $R_S = 1\,\text{k}\Omega$, what is new value of A_{fb}?

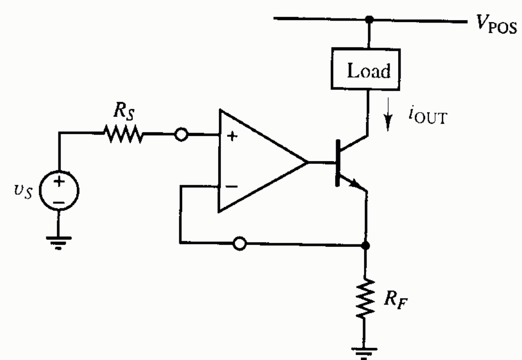


Fig. P10.57

10.58 Design a simple modification to the circuit of **Fig. P10.57** that will permit currents of both positive and negative polarities to be produced by v_S.

10.7.3 Single-Transistor Transresistance Amplifier (Shunt/Shunt Feedback)

10.59 The op-amp inverting amplifier of Chapter 2 is really a feedback amplifier in which shunt mixing is employed at the input and shunt sampling at the output. Use feedback analysis to determine the feedback factor, input resistance, output resistance, and closed-loop gain of an inverting amplifier with $r_{in} = 10\,\text{M}\Omega$, $r_{out} = 10\,\Omega$, $R_1 = 10\,\text{k}\Omega$, and $R_2 = 100\,\text{k}\Omega$, where R_2 is the feedback resistor.

10.60 The current-to-voltage converter of **Fig. P10.60** is made from an op-amp with open-loop parameters $A_o = 2 \times 10^5$, $r_{in} = 2\,\text{M}\Omega$, and $r_{out} = 75\,\Omega$. Suppose that $R_F = 1\,\text{M}\Omega$, and that the circuit drives an $R_L = 10\,\text{k}\Omega$ load resistor to ground. Find the transresistance gain, input resistance, and output resistance of the amplifier with feedback.

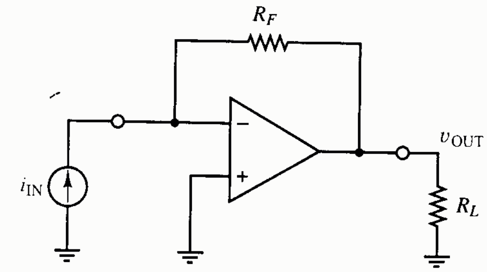


Fig. P10.60

10.61 The simple op-amp circuit of **Fig. P10.60** functions as a transresistance amplifier that converts a current signal into a voltage signal. If the op-amp has parameters $A_o = 500{,}000$, $r_{in} = 1\,\text{M}\Omega$, and $r_{out} = 25\,\Omega$, find the values of the closed-loop A_r, R_{in}, and R_{out}.

10.62 Draw the feedback-loop block diagram of an op-amp integrator made from one feedback capacitor and one input resistor. This circuit incorporates shunt/shunt feedback with an op-amp. Find an expression for the frequency-dependent feedback function β in the sinusoidal steady state. Model the open-loop op-amp gain as a constant A_o. Show that the feedback function (10.6) approaches the integrator transfer function $\mathbf{V}_{out}/\mathbf{V}_{in} = -1/j\omega RC$ in the limit of large open-loop op-amp gain.

10.63 Repeat Problem 10.62 if a resistor R_F is connected in parallel with the feedback capacitor, so as to make a modified op-amp integrator, or low-pass filter.

10.64 Draw the feedback-loop block diagram of an op-amp differentiator made from one input capacitor and one feedback resistor. Find an expression for the frequency-dependent feedback function β in the sinusoidal steady state. Show that the feedback function (10.6) approaches the differentiator transfer function $\mathbf{V}_{out}/\mathbf{V}_{in} = -j\omega RC$ in the limit of large open-loop op-amp gain.

10.65 Consider the analysis of the BJT transresistance amplifier of Figs. 10.24 to 10.26. Transform the output port of the feedback circuit in Fig. 10.26 into its Thévenin equivalent circuit. Use this new representation of the circuit to derive the open-loop gain A_r, the feedback function $\beta = i_F/v_{OUT}$, and the amplifier input and output resistances.

10.66 The transresistance amplifier of Fig. 10.24 is made with $R_C = 5\,\text{k}\Omega$, $R_F = 10\,\text{k}\Omega$, $\beta_o = 100$, and $I_C = 1\,\text{mA}$. Find the transresistance gain A_r, input resistance R_{in}, and output resistance R_{out}.

10.67 ○ Design a circuit based on the BJT transresistance amplifier of Fig. 10.24 that has a gain magnitude of 5 V/mA, an input resistance smaller than 500 Ω, and an output resistance smaller than 20 Ω. The circuit should operate from a single 15-V supply and be biased so that Q_1 operates well into the constant-current region. For the purpose of this problem, assume a BJT with $\beta_F = \beta_o = 200$ and $V_f = 0.7$ V.

10.68 ○ Use feedback analysis to find an expression for the closed-loop gain of the shunt/shunt circuit of Fig. 10.24 if a MOSFET is substituted for the BJT and if i_S is replaced by a voltage source v_S in series with a resistance R_S. Your answer can be confirmed by direct calculation.

10.69 A piezoelectric pressure transducer with a peak output voltage of 10 V and a series output resistance of 10 MΩ can be modeled as a current source that provides a peak short-circuit current of 1 μA. It is desired to use the sensor output to drive a 10-kΩ load.

(a) Compute the peak power delivered to the load if the sensor is connected directly to it.

(b) Compute the peak power delivered to the load if the sensor feeds a transresistance amplifier that has parameters $R_{in} = 10\,\text{k}\Omega$, $A_r = 10$ V/A, and $R_{out} = 10\,\text{k}\Omega$.

10.70 Consider the current-to-voltage converter of **Fig. P10.70**. For the condition $R_F \ll r_{in}$, find the following:

(a) The open-loop gain A_r with the op-amp input and output ports loaded by the resistance R_F.

(b) The feedback factor $\beta = i_F/v_{OUT}$.

(c) The closed-loop gain of the overall circuit.

(d) The overall input resistance R_{in} seen by the i_{IN} source.

(e) Derive the gain v_{OUT}/i_{IN} using circuit theory principles and the ideal op-amp approximation of Chapter 2. Compare the result with the closed-loop gain derived from the reciprocal of the β found in part (c).

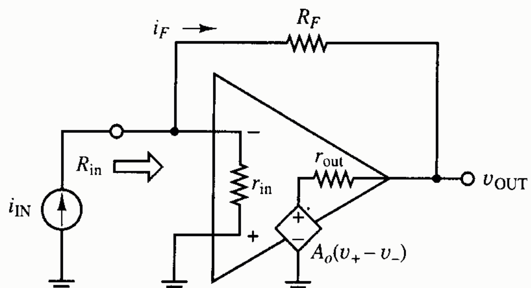


Fig. P10.70

10.71 ◐ Consider the three-stage feedback amplifier of **Fig. P10.71** with $R_{C1} = R_{C2} = R_{C3} = 5\,\text{k}\Omega$ and $R_B = 1\,\text{k}\Omega$. Identify the feedback function β, then find the closed-loop gain A_r, the input resistance R_{in}, and output resistance R_{out}.

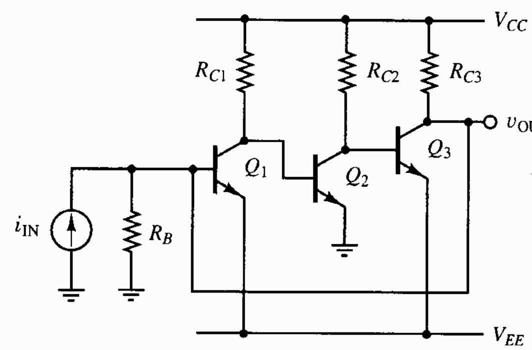


Fig. P10.71

10.7.4 BJT Current Amplifier with Feedback (Shunt/Series Feedback)

10.72 Find the gain of the circuit of Fig. 10.27 if $\beta_F = \beta_o = 75$ for both transistors, $r_{\pi 1} = r_{\pi 2} = 5\,\text{k}\Omega$, $R_E = 220\,\Omega$, $R_F = 4.7\,\text{k}\Omega$, and $R_C = 1.5\,\text{k}\Omega$.

10.73 ○ Design a practical bias network for the current amplifier of Fig. 10.27 such that Q_1 and Q_2 are both biased in the active region when $V_{CC} = 12$ V, $R_C = 1\,\text{k}\Omega$, and an approximate feedback factor of $\beta = -0.02$ is desired. For the purpose of this problem, assume that $\beta = 75$ for both transistors.

10.74 Consider the circuit of Fig. 10.27. This circuit was analyzed in Example 10.6 assuming $\beta_1 = \beta_2 = 200$. Suppose that component variations results in beta values in the range $50 < \beta < 250$. Find the minimum and maximum possible closed-loop gain of the circuit.

10.75 Consider the two-stage BJT circuit shown in Fig. 10.27. Suppose that a collector resistor R_C is connected between Q_2 and the V_{CC} supply bus, and that the right-hand side of R_F is connected to the collector of Q_2, rather than to the emitter of Q_2.

(a) Show that the feedback for this new configuration is positive.

(b) Design a modification to the new circuit that will allow negative feedback to be successfully implemented.

10.8 Feedback-Loop Stability

10.8.1 Amplifier Phase Shift

10.76 The measured open-loop transfer function of a particular op-amp can be approximated by the expression $A(j\omega) = 10^3/[(1 + j\omega/\omega_1)(1 + j\omega/\omega_2)^2]$, where $\omega_1 = 10^4$ rad/s and $\omega_2 = 10^5$ rad/s. The op-amp is connected as a noninverting amplifier with a feedback function β that is not a function of frequency.

(a) Find the value of ω at which the loop gain undergoes a $-180°$ phase shift, thereby creating positive feedback.

(b) Find the maximum value of β before the circuit begins to oscillate.

(c) If the circuit does become unstable due to an overly large value of β, what will be the frequency of oscillation?

10.8.3 Bode-Plot Analysis of Feedback Stability

10.77 A particular op-amp has an open-loop dc gain of 80 dB and open-loop poles at 1, 10^5, and 10^7 Hz. If the op-amp is connected as a unity-gain follower, the circuit will be stable. Find the gain and phase margins.

10.78 Consider an op-amp with an open-loop dc gain of 80 dB and open-loop poles at 1, 10^5, and 10^7 Hz. The internal circuitry of the op-amp is redesigned so that the open-loop dc gain is increased to 160 dB without changing the pole frequencies.

(a) How small must the feedback function β be if a circuit made from the op-amp is to be stable?

(b) Implement a negative-feedback circuit with a gain margin of +10 dB using the inverting-amplifier configuration.

10.79 An amplifier with a dc gain of 100 dB and poles at $f_1 = 10^5$ Hz, $f_2 = 10^6$ Hz, and $f_3 = 10^7$ Hz is connected in the inverting-amplifier configuration. What is the minimum inverter gain required to ensure circuit stability?

10.80 An op-amp with a dc gain of 80 dB and poles at $f_1 = 10^4$ Hz, $f_2 = 10^5$ Hz, and $f_3 = 10^6$ Hz is connected as an inverting amplifier with a gain of -100. The resulting circuit meets the stability condition. What are its gain and phase margins?

10.81 An op-amp with a dc gain of 80 dB has poles at $f_1 = 10^5$ Hz, $f_2 = 10^6$ Hz, and $f_3 = 10^7$ Hz. As designed, this op-amp is not stable in all feedback configurations. It is desired to stabilize the op-amp in the *inverting-amplifier* configuration by the addition of a simple *RC* filter cascaded with the v_{out} terminal, as in Fig. 10.35.

(a) Suppose the values of R_1, R_2, and R_C are chosen so that the voltage-divider relation can be approximately applied to R_C and C_C. Under such conditions, derive an expression for the open-loop gain of the op-amp with R_C and C_C included but with R_1 and R_2 of the inverting-amplifier feedback network disconnected.

(b) Find the minimum value of C_C that will guarantee the stability of the circuit if $R_C = 1\,k\Omega$ when $R_1 = R_2$.

10.82 Design a series cascade of amplifiers that has an overall cascade gain of +30 dB and a bandwidth of at least 500 Hz. Each stage is to be built using the op-amp described in Problem 10.81. The overall circuit must be stable.

10.8.4 Frequency Compensation

10.83 An amplifier with a dc gain of 80 dB and a dominant pole at 2 MHz must be compensated for all possible closed-loop gains. Discuss the constraints that will determine the frequency at which a compensation pole should be placed.

10.84 Consider the amplifier described by the open-loop response of Fig. 10.33. By how much must the gain at ω_{90} be reduced if the amplifier is to be stable for feedback factors in the range $0.1 < \beta < 0$? Below what frequency must ω_c be located?

10.85 Choose the value of C in Example 10.11 if the amplifier must have a closed-loop gain of -15 and a phase margin of 50°.

10.86 Find the bandwidth in hertz of the compensated amplifier of Example 10.11 if $A_{fb} = 300$ and $A_o = 10^5$.

10.87 An amplifier with a dc gain of 75 dB and three open-loop poles at 2×10^4, 10^5, and 3×10^6 Hz is connected in a negative feedback configuration.

(a) Find the maximum allowed β and minimum A_{fb} that will ensure stability.

(b) Determine the placement of a fourth pole f_c such that the amplifier will be stable for all values of β.

10.88 An amplifier with a dc gain of 60 dB and four open-loop poles at 10^3, 5×10^4, 2×10^5, and 10^7 Hz is connected in a negative feedback configuration.

(a) What are the maximum β and minimum A_{fb} that will ensure stability?

(b) How might this amplifier be modified if it is to be stable for gains between 50 and 200 with a gain margin of at least 5 dB?

10.89 An inverting amplifier with a dc gain of −20 is to be constructed from an op-amp. In order to ensure stability, a compensation pole at $f_c = 5\,\text{Hz}$ is required.

(a) Choose suitable resistor values, and use the arrangement of Fig. 10.36 to implement the required compensation pole.

(b) Design an alternative compensation network that does not make use of scheme shown in Fig. 10.36. You might try adding a capacitor in parallel with the feedback resistor R_F of the inverting amplifier to introduce the required pole.

10.90 An op-amp has the open-loop frequency response shown in Fig. 10.33. Design a noninverting amplifier with a closed-loop gain of 40 dB. Find the location of the compensation pole ω_c required to guarantee stability with a phase margin of 45°. Implement ω_c using an external compensation capacitor.

10.91 An inverting amplifier with a dc gain of −10 is to be made from a particular op-amp. Design the circuit such that a compensation pole at $\omega_c = 10\,\text{rad/s}$ is added to the closed-loop response.

◆ SPICE PROBLEMS

10.92 Use SPICE to find the exact value of the input resistance of a noninverting amplifier with a gain of 31 ($R_2 = 30\,\text{k}\Omega$, $R_1 = 1\,\text{k}\Omega$) made from an op-amp having parameters $r_{\text{in}} = 10\,\text{M}\Omega$, $r_{\text{out}} = 10\,\Omega$, and $A_o = 10^6$.

10.93 Use SPICE to find the exact value of the output resistance of an inverting amplifier with a gain of −20 ($R_2 = 200\,\text{k}\Omega$, $R_1 = 10\,\text{k}\Omega$) made from an op-amp having parameters $r_{\text{in}} = 10\,\text{M}\Omega$, $r_{\text{out}} = 10\,\Omega$, and $A_o = 10^6$.

10.94 Use SPICE to simulate a noninverting amplifier with $R_1 = 10\,\text{k}\Omega$ and $R_2 = 100\,\text{k}\Omega$, where R_2 is the feedback resistor. Assume the op-amp to have internal parameters $r_{\text{in}} = 10\,\text{M}\Omega$, $r_{\text{out}} = 10\,\Omega$, and $A_o = 10^6$. Find the closed-loop parameters A_{fb} , R_{in}, and R_{out}.

10.95 Use SPICE to find the gain, input resistance, and output resistance of the closed-loop amplifier of Fig. 10.24 if $R_F = 220\,\text{k}\Omega$, $R_C = 3.9\,\text{k}\Omega$, and $\beta_o = 175$.

10.96 A voltage amplifier with open-loop parameters $A_v = 3 \times 10^4$, $r_{\text{in}} = 2\,\text{k}\Omega$, and $r_{\text{out}} = 200\,\Omega$ is connected in a negative feedback loop with $\beta = 0.1$. Use SPICE to determine the resulting closed-loop parameters A_{fb}, R_{in}, and R_{out}.

10.97 A current amplifier with $A_i = 1000$, $r_{\text{in}} = 25\,\Omega$, and $r_{\text{out}} = 500\,\text{k}\Omega$ is connected in a feedback loop with $\beta = 0.05$. Use SPICE to determine the resulting closed-loop parameters A_{fb}, R_{in}, and R_{out}.

10.98 Confirm the results of Example 10.6 by simulating the circuit's small-signal model on SPICE.

10.99 Simulate the circuit of **Fig. P10.51** on SPICE with $V_{CC} = 10\,\text{V}$, $V_{EE} = -10\,\text{V}$, $I_o = 1\,\text{mA}$, $R_1 = R_2 = 5\,\text{k}\Omega$, $R_3 = 1\,\text{k}\Omega$, $R_4 = 5\,\text{k}\Omega$, $R_A = 100\,\text{k}\Omega$, and $R_B = 820\,\text{k}\Omega$. Find the resulting closed-loop gain, input resistance, and output resistance.

10.100 Simulate the series/series triple of **Fig. P10.56** on SPICE with $V_{CC} = 7\,\text{V}$, $R_{C1} = 9\,\text{k}\Omega$, $R_{C2} = 5\,\text{k}\Omega$, $R_{C3} = 600\,\Omega$, $R_{E1} = R_{E2} = 100\,\Omega$, and $R_F = 640\,\Omega$. Find the resulting closed-loop gain.

10.101 Simulate the MOSFET transconductance amplifier of Fig. 10.23 on SPICE with $K = 0.5\,\text{mA/V}^2$, $V_{TR} = 1.5\,\text{V}$, $V_A = 35\,\text{V}$, $V_{SS} = -6\,\text{V}$, $R_S = 50\,\Omega$, and $R_F = 560\,\Omega$. Find the resulting transconductance gain i_{OUT}/v_S, where i_{OUT} is the current i_D flowing into the MOSFET.

10.102 The purpose of this problem is to construct a subcircuit definition for use in SPICE that will represent an op-amp with the magnitude response of Fig. 10.33

(a) Specify a subcircuit op-amp definition that has an open-loop dc gain of 100 dB, as in Fig. 10.33.

(b) Modify the subcircuit so that it has the configuration shown in **Fig. P10.102(a)**. Set the parameters of this new model so that the op-amp has the same dc gain as that of part (a).

(c) Add a simple capacitor to the circuit, as in Fig. **P10.102(b)** so as to create a simple RC filter. The values of R_1 and C_1 should be chosen so that the modified op-amp has a single dominant pole at 10^5 Hz.

(d) Now add two more cascaded dependent sources and RC filters to the model so that the op-amp response has the three poles shown in Fig. 10.33. Test your op-amp model by plotting its magnitude response using SPICE.

10.103 Use the op-amp subcircuit developed in Problem 10.102 to test the circuit of Fig. 10.36 on SPICE (see