All of the desirable properties above are obtained at the expense of a reduction in gain. It will be shown that the gain-reduction factor, called the **amount of feedback**, is the factor by which the circuit is desensitized, by which the input resistance of a voltage amplifier is increased, by which the bandwidth is extended, and so on. In short, *the basic idea of negative feedback is to trade off gain for other desirable properties*. This chapter is devoted to the study of negative-feedback amplifiers: their analysis, design, and characteristics.

Under certain conditions, the negative feedback in an amplifier can become positive and of such a magnitude as to cause oscillation. In fact, in Chapter 18 we will study the use of positive feedback in the design of oscillators and bistable circuits. Here, in this chapter, however, we are interested in the design of stable amplifiers. We shall therefore study the stability problem of negative-feedback amplifiers and their potential for oscillation.

It should not be implied, however, that positive feedback always leads to instability. In fact, positive feedback is quite useful in a number of nonregenerative applications, such as the design of active filters, which are studied in Chapter 17.

Before we begin our study of negative feedback, we wish to remind the reader that we have already encountered negative feedback in a number of applications. Almost all op-amp circuits (Chapter 2) employ negative feedback. Another popular application of negative feedback is the use of the emitter resistance R_E to stabilize the bias point of bipolar transistors and to increase the input resistance, bandwidth, and linearity of a BJT amplifier. In addition, the source follower and the emitter follower both employ a large amount of negative feedback. The question then arises about the need for a formal study of negative feedback. As will be appreciated by the end of this chapter, the formal study of feedback provides an invaluable tool for the analysis and design of electronic circuits. Also, the insight gained by thinking in terms of feedback can be extremely profitable.

11.1 The General Feedback Structure

11.1.1 Signal-Flow Diagram

Figure 11.1 shows the basic structure of a feedback amplifier. Rather than showing voltages and currents, Fig. 11.1 is a signal-flow diagram, where each of the quantities x can represent either a voltage or a current signal. The basic amplifier is unilateral and has a gain A, known as the **open-loop gain**; thus its output x_o is related to the input x_i by

$$x_o = Ax_i \tag{11.1}$$

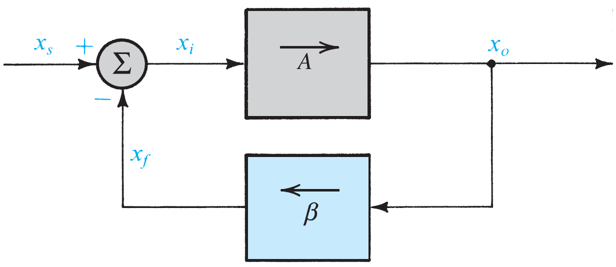

Figure 11.1 General structure of the feedback amplifier. This is a signal-flow diagram, and the quantities x represent either voltage or current signals.

The *feedback network* measures or samples the output signal x_o and provides a *feedback signal* x_f that is related to x_o by the **feedback factor** β,

$$x_f = \beta x_o \tag{11.2}$$

It is assumed that connecting the feedback network to the amplifier output does not change the gain A or the value of x_o; that is, *the feedback network does not load the amplifier output*. Also, the feedback network is unilateral.

The feedback signal x_f is *subtracted* from the source signal x_s, which is the input to the complete feedback amplifier,[1] to produce the signal x_i, which is the input to the basic amplifier,

$$x_i = x_s - x_f \tag{11.3}$$

Here we note that it is this subtraction that makes the feedback negative. In essence, *negative feedback reduces the signal that appears at the input of the basic amplifier*. Here, too, we assume that connecting the output of the feedback network to the amplifier input, through the subtractor or differencing circuit, does not change the gain A; that is, *the feedback network does not load the amplifier input.*

11.1.2 The Closed-Loop Gain

The gain of the feedback amplifier, known as the closed-loop gain or the **gain-with-feedback** and denoted A_f, is defined as

$$A_f \equiv \frac{x_o}{x_s}$$

Combining Eqs. (11.1) through (11.3) provides the following expression for A_f:

$$A_f = \frac{A}{1 + A\beta} \tag{11.4}$$

The quantity $A\beta$ is called the **loop gain**, a name that follows from Fig. 11.1. For the feedback to be negative, the loop gain $A\beta$ must be positive; that is, the feedback signal x_f should have the same sign as x_s, thus resulting in a smaller difference signal x_i. Equation (11.4) indicates that for positive $A\beta$ the gain with feedback A_f will be smaller than the open-loop gain A by a factor equal to $1 + A\beta$, which is called the **amount of feedback**.

If, as is the case in many circuits, the loop gain $A\beta$ is large, $A\beta \gg 1$, then from Eq. (11.4) it follows that

$$A_f \simeq \frac{1}{\beta} \tag{11.5}$$

which is a very interesting result: *When the loop gain is large, the gain of the feedback amplifier is almost entirely determined by the feedback network*. Since the feedback network usually consists of passive components, which usually can be chosen to be as accurate as one wishes, the advantage of negative feedback in obtaining accurate, predictable, and stable gain

[1] In earlier chapters, we used the subscript "sig" for quantities associated with the signal source (e.g., v_{sig} and R_{sig}). We did that to avoid confusion with the subscript "*s*," which is usually used with FETs to denote quantities associated with the source terminal of the transistor. At this point, however, it is expected that readers have become sufficiently familiar with the subject that the possibility of confusion is minimal. Therefore, we will revert to using the simpler subscript *s* for signal-source quantities.

should be apparent. In other words, the overall gain will have very little dependence on the gain of the basic amplifier, A, a desirable property because the gain A is usually a function of many manufacturing and application parameters, some of which might have wide tolerances. We have seen a dramatic illustration of all of these effects in op-amp circuits in Chapter 2, where the closed-loop gain is almost entirely determined by the feedback elements. Generally, we will consider $(1/\beta)$ to be the ideal value of A_f.

Equations (11.1) through (11.3) can be combined to obtain the following expression for the feedback signal x_f:

$$x_f = \frac{A\beta}{1+A\beta}x_s \tag{11.6}$$

Thus for $A\beta \gg 1$ we see that $x_f \simeq x_s$, which implies that the signal x_i at the input of the basic amplifier is reduced to almost zero. Thus if a large amount of negative feedback is employed, the feedback signal x_f becomes an almost identical replica of the input signal x_s. The difference between x_s and x_f, which is x_i, is sometimes referred to as the **error signal**.[2] Accordingly, the **input differencing circuit** is often also called a **comparison circuit**. (It is also known as a **mixer**.) An expression for x_i can be easily determined as

$$x_i = \frac{1}{1+A\beta}x_s \tag{11.7}$$

from which we can verify that for $A\beta \gg 1$, x_i becomes very small. An outcome of this property is the tracking of the two input terminals of an op amp. Observe that negative feedback reduces the signal that appears at the input terminals of the basic amplifier by the amount of feedback $(1 + A\beta)$. As will be seen later, it is this reduction of input signal that results in the increased linearity of the feedback amplifier.[3]

11.1.3 The Loop Gain

From the discussion above we see that the loop gain $A\beta$ is a very important—in fact, the most important—characteristic parameter of a feedback amplifier:

1. The sign of $A\beta$ determines the polarity of the feedback; the loop gain $A\beta$ must be positive for the feedback to be negative.
2. The magnitude of $A\beta$ determines how close the closed-loop gain A_f is to the ideal value of $1/\beta$.
3. The magnitude of $A\beta$ determines the amount of feedback $(1+A\beta)$ and hence, as we shall see in the next section, the magnitude of the various improvements in amplifier performance resulting from the negative feedback.
4. As we shall see in later sections, the inevitable variation of $A\beta$ with frequency can cause $A\beta$ to become negative, which in turn can cause the feedback amplifier to become unstable. It follows that the design of a stable feedback amplifier may involve modifying the frequency behaviors of its loop gain $A\beta$ appropriately (Section 11.10).

[2]This terminology is more common in feedback control systems than in feedback amplifiers.

[3]We have in fact already seen examples of this: adding a resistance R_e in the emitter of a CE amplifier (or a resistance R_s in the source of a CS amplifier) increases the linearity of these amplifiers because for the same input signal as before, v_{be} and v_{gs} are now smaller (by the amount of feedback).