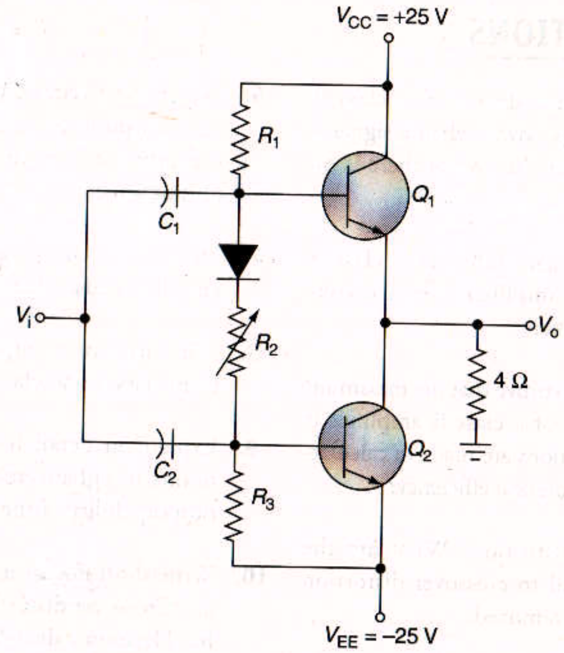


Figure 10.33 | Problem 4.

ANSWERS

Multiple-Choice Questions

1. (b)	**3.** (b)	**5.** (a)	**7.** (d)	**9.** (b)
2. (c)	**4.** (a)	**6.** (b)	**8.** (a)	**10.** (b)

Match the Following

Figure 10.31(a) – (f)
Figure 10.31(b) – (a)
Figure 10.31(c) – (c)
Figure 10.31(d) – (e)
Figure 10.31(e) – (b)
Figure 10.31(f) – (d)

Problems

1. 58.87%

2. D_2=8.33%, D_3=1.67%, D_4=0.67%, D=8.52%

3. 21.82%

4. Input power = 59.71 W; output power = 28.125 W; power handled by each transistor = 15.794 W; efficiency = 47.1%

CHAPTER 11

Feedback Amplifiers

Learning Objectives

After completing this chapter, you will learn the following:

- Classification of amplifiers based on input and output parameters of interest.
- Types of negative feedback.
- Examples of voltage-series, current-series, voltage-shunt and current-shunt feedback in amplifier circuits.
- Effect of negative feedback on input and output impedances.
- Effect of negative feedback on gain (or conversion) and bandwidth parameters.
- Effect of negative feedback on noise performance.

Practical amplifier circuits always have some kind of negative feedback inherent to their operation. As we will see during the course of our discussion, presence of negative feedback in amplifiers brings along with it many advantages. In this chapter are introduced the basic concepts of negative feedback in amplifiers. The chapter begins with a brief outline on the classification of amplifiers based on input (current or voltage) and output (current or voltage) parameters of interest. This is followed by different types of feedback encountered in amplifiers. The classification of types of feedback is based on the type of output signal (current or voltage) fed back to the input and also the mode in which it is fed back (series or shunt). Also, each of the different types of feedback enhances the performance of a particular type of amplifier circuit. Effect of different types of negative feedback on the performance parameters of the amplifier is also discussed in detail. The text is adequately illustrated with practical circuits and a large number of solved examples.

11.1 Classification of Amplifiers

On the basis of the input and output parameters of interest, amplifiers are classified as voltage amplifiers, current amplifiers, transresistance amplifiers and transconductance amplifiers. In the case of a voltage amplifier, a small change in the input voltage produces a large change in the output voltage. Voltage gain, which is the ratio of the change in the output voltage to change in the input voltage, is the gain parameter. The input and output circuits of a voltage amplifier are represented by Thevenin's equivalent circuits as shown in Figure 11.1. In order that the circuit of Figure 11.1 acts like a true voltage amplifier, the input resistance of the amplifier represented by R_i in Figure 11.1 should ideally be infinite so that the whole applied input voltage appears across the amplifier input irrespective of the value of source resistance R_s. In a practical voltage amplifier circuit, R_i is much larger than R_s. Also, the output resistance R_o should ideally be

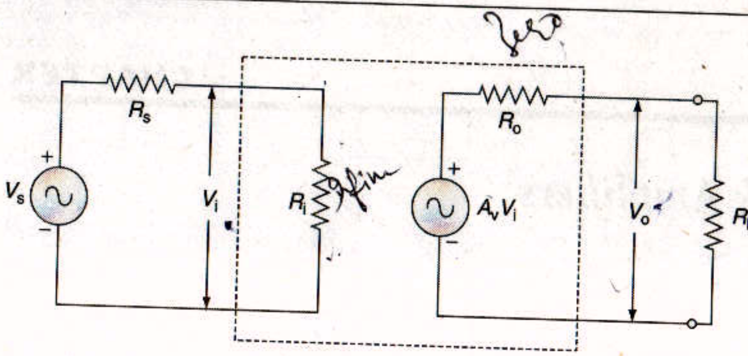


Figure 11.1 | Equivalent circuit of voltage amplifier.

zero so that whole of amplified input voltage appears across the load resistance R_L irrespective of the value of R_L. In a practical voltage amplifier circuit, R_o is much smaller than R_L.

In the case of a current amplifier, a small change in the input current produces a large change in the output current. Current gain, which is the ratio of change in the output current to the change in the input current, is the gain parameter. The input and output circuits of a current amplifier are represented by Norton's equivalent circuits as shown in Figure 11.2. In order that the circuit of Figure 11.2 acts like a true current amplifier, the input resistance of the amplifier represented by R_i in Figure 11.2 should ideally be zero so that the whole applied input current flows through the amplifier input irrespective of the value of source resistance R_s. In a practical current amplifier circuit, R_i is much smaller than R_s. Also, the output resistance R_o should ideally be infinite so that whole of amplified input current flows through the load resistance R_L irrespective of the value of R_L. In a practical current amplifier circuit, R_o is much larger than R_L.

In the case of a transresistance amplifier, a small change in the input current produces a large change in the output voltage. Ratio of the change in the output voltage to change in the input current is the gain parameter. The gain parameter has the units of resistance. The input and output circuits of a transresistance amplifier are, respectively, represented by Norton's and Thevenin's equivalent circuits as shown in Figure 11.3. For the circuit of Figure 11.3 to behave like a true transresistance amplifier, the input resistance of the amplifier represented by R_i in Figure 11.3 should ideally be zero so that the whole of applied input current flows through the amplifier input irrespective of the value of source resistance R_s. In a practical transresistance amplifier circuit, R_i is much smaller than R_s. Also, the output resistance R_o should ideally be zero so that the output voltage appears across the load resistance R_L irrespective of the value of R_L. In a practical circuit, R_o is much smaller than R_L.

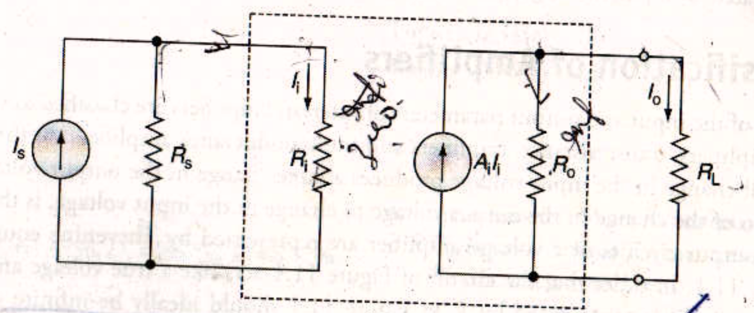


Figure 11.2 | Equivalent circuit of current amplifier.

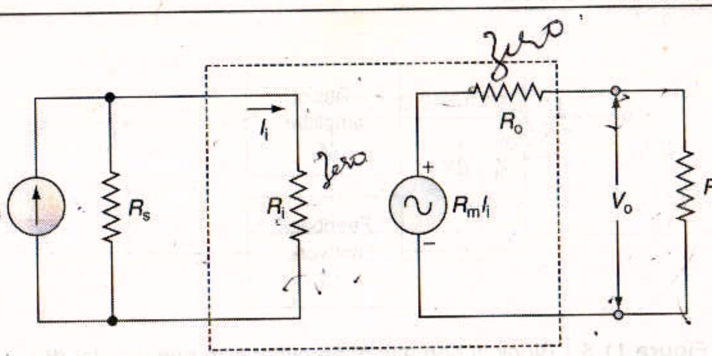


Figure 11.3 | Equivalent circuit of transresistance amplifier.

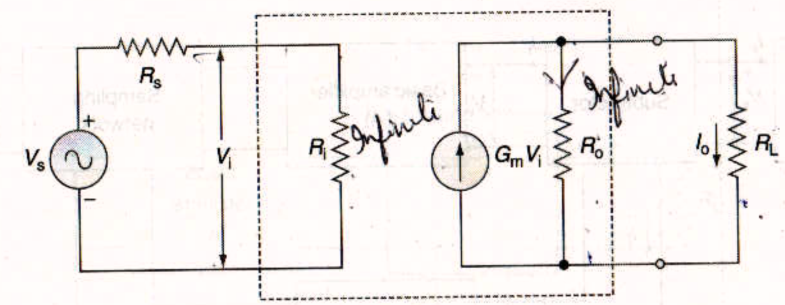


Figure 11.4 | Equivalent circuit of transconductance amplifier.

In the case of a transconductance amplifier, a small change in the input voltage produces a large change in the output current. Ratio of the change in the output current to the change in the input voltage is the gain parameter. The gain parameter has the units of conductance. The input and output circuits of a transconductance amplifier are, respectively, represented by Thevenin's and Norton's equivalent circuits as shown in Figure 11.4. For the circuit of Figure 11.4 to behave like a true transconductance amplifier, the input resistance of the amplifier represented by R_i in Figure 11.4 should ideally be infinite so that the whole of applied input voltage appears across the amplifier input irrespective of the value of source resistance R_s. In a practical transconductance amplifier circuit, R_i is much larger than R_s. Also, the output resistance R_o should ideally be infinite so that the output current flows through the load resistance R_L irrespective of the value of R_L. In a practical circuit, R_o is much larger than R_L.

11.2 Amplifier with Negative Feedback

In a negative-feedback amplifier, a sample of the output signal is fed back to the input and the feedback signal is combined with the externally applied input signal in a subtractor circuit as shown in Figure 11.5. As a result, the actual signal X_i applied to the basic amplifier is the difference of the externally applied input signal X_s and the feedback signal X_f. The generalized representation of input and output signals is intended to indicate that the signal could either be a current or a voltage signal.

Figure 11.6 shows a more elaborate schematic arrangement of an amplifier with negative feedback depicting different circuit blocks. The source of external input signal could either be a voltage source or a current source. The basic amplifier produces either an output current or voltage proportional to the input

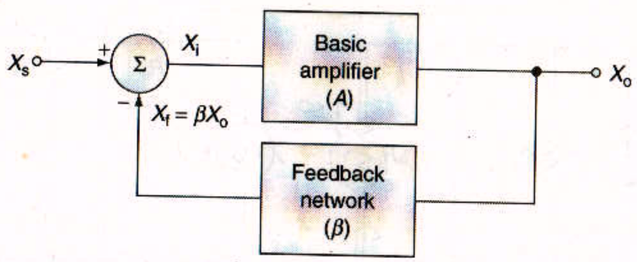


Figure 11.5 | Block schematic of amplifier with negative feedback.

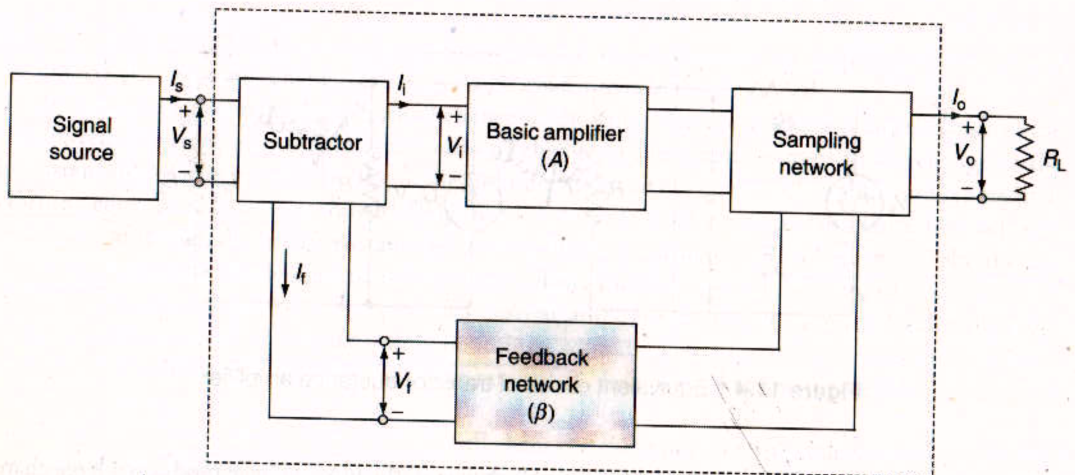


Figure 11.6 | Schematic arrangement of various building blocks of a negative-feedback amplifier.

current or voltage. The nature of input and output parameters decides the nature of gain parameter of the amplifier as outlined earlier in Section 11.1.

The sampling network samples either the output voltage by connecting the input side of the feedback network in shunt across the output [Figure 11.7(a)] or the output current where the input side of the feedback network is connected in series with the output [Figure 11.7(b)]. The two sampling techniques are, respectively, known as voltage and current sampling.

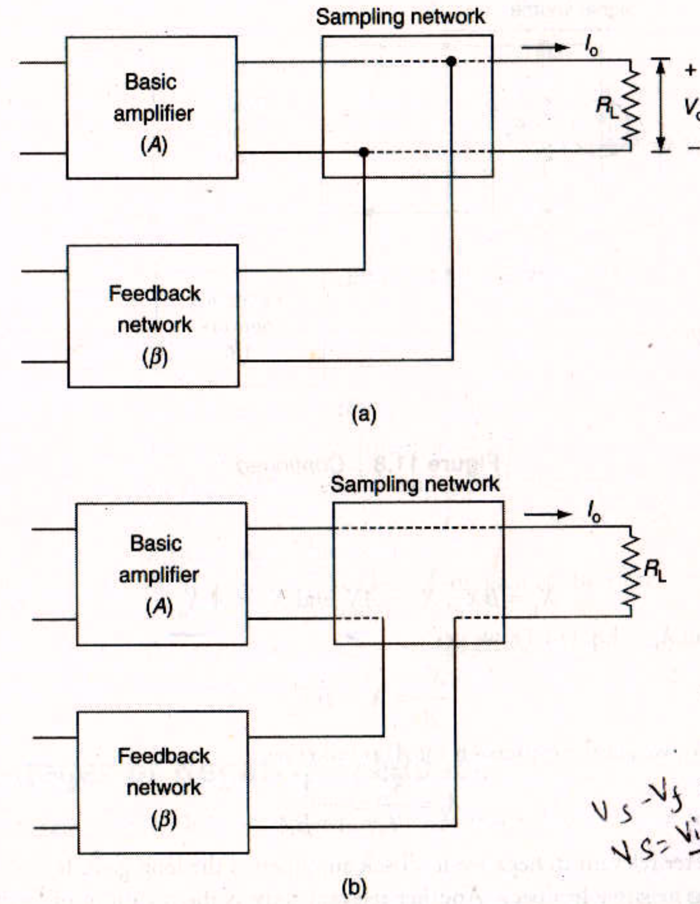
The combining operation of externally applied input signal and the feedback signal is carried out in a differential amplifier (or subtractor) circuit. It is done in either of the two ways, namely, series connection [Figure 11.8(a)] and shunt connection [Figure 11.8(b)].

The gain parameter – which could be a voltage gain, current gain, transresistance or transconductance – has two values, namely, the gain of the basic amplifier without feedback and the gain of the amplifier with feedback. With reference to Figure 11.5, gain values without and with feedback are, respectively, given by X_o/X_i and X_o/X_s.

Effect of Negative Feedback on Gain

We will now derive an expression for gain with feedback in terms of gain without feedback (open-loop gain) and the feedback factor for the negative-feedback amplifier of Figure 11.5. The actual signal applied to the amplifier input X_i is the difference of externally applied input signal X_s and the feedback signal X_f. It is given by

$$X_i = X_s - X_f \tag{11.1}$$



$V_s - V_f = V_i$
$V_s = V_i + V_f$

Figure 11.7 | Sampling in negative-feedback amplifiers: (a) Voltage sampling; (b) current sampling.

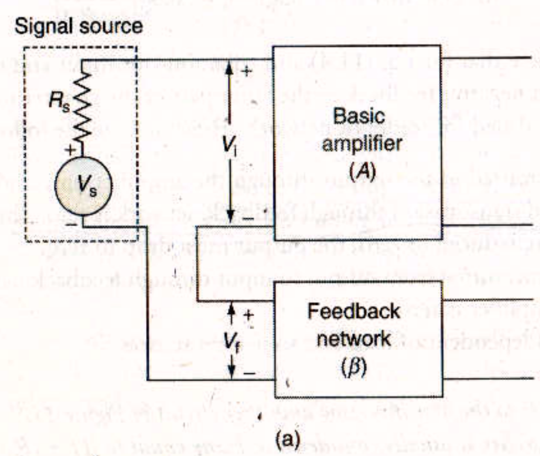


Figure 11.8 | Mixing operation in negative-feedback amplifiers: (a) Series input connection; (b) shunt input connection.

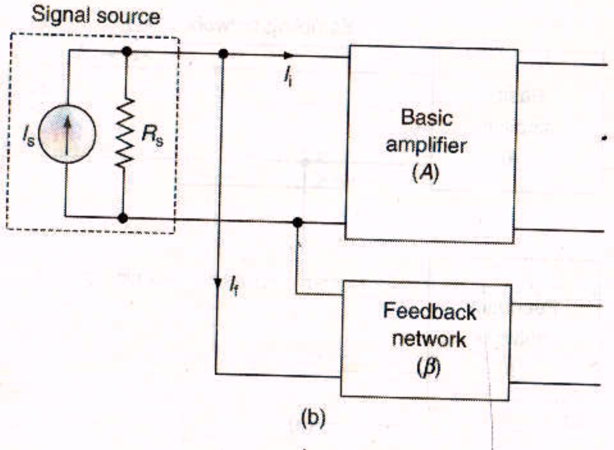


Figure 11.8 | *Continued.*

Also,

$$X_f = \beta X_o,\ X_o = AX_i \text{ and } X_o = A_f X_s \tag{11.2}$$

Substituting for X_i and X_f in Eq. (11.1), we get

$$\frac{X_o}{A} = X_s - \beta X_o \tag{11.3}$$

Simplifying Eq. (11.3), we get the expression for A_f as follows:

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

An important parameter relevant to negative-feedback amplifiers is the loop gain. It is given by $(-\beta A)$ with minus sign indicating negative feedback. Another relevant term is the quantum of feedback expressed in decibels. It is given by

$$\text{dB of feedback} = 20\log\left|\frac{A_f}{A}\right| = 20\log\left|\frac{1}{1+\beta A}\right| \tag{11.5}$$

It may be mentioned here that for Eq. (11.4) and equations for input and output impedances derived in the case of amplifiers with negative feedback in the latter part of the chapter to be valid, three fundamental assumptions should be satisfied for feedback network. These include the following:

1. The input signal is transmitted to the output through the amplifier only and not through the feedback network. That is, forward transmission through feedback network is zero. This further implies that if the gain of the amplifier were reduced to zero, the output must drop to zero.
2. The feedback signal is transmitted from output to input through feedback network only. That is, reverse transmission through amplifier is zero.
3. The feedback factor is independent of load and source resistances.

EXAMPLE 11.1 *Refer to the non-inverting amplifier circuit of Figure 11.9. The closed-loop gain of this amplifier is usually considered as being equal to $[(1 + (R_2/R_1)]$. Given that the open-loop gain of the opamp is 10,000, values of R_1 and R_2 are 10 kΩ and 100 kΩ, respectively, and the value of the applied input voltage V_i is 1 V, determine the percentage error incurred in computing the output voltage by using this expression.*

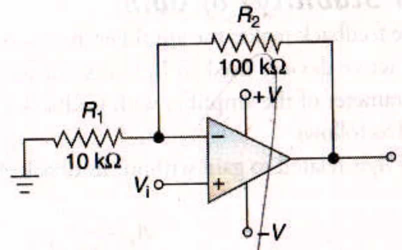


Figure 11.9 | Example 11.1.

Solution

1. Closed-loop gain ignoring the effect of finite value of open loop gain = $1 + (R_2/R_1)$.
2. Substituting for R_1 and R_2, it comes out to be 11.
3. The output voltage is, therefore, 11 V.
4. The true value of closed-loop gain is given by $[A/(1 + \beta A)]$. A is the open-loop gain and is equal to 10,000. β is the feedback factor and is given by $[R_1/(R_1 + R_2)]$. This equals 1/11.
5. The true value of the closed-loop gain is, therefore, given by [10,000/{(1 + 10,000)/11}] = 10.988.
6. The true value of output voltage is, therefore, 10.988 V.
7. Percentage error = [(11 − 10.988)/10.988] × 100 = 0.11%.

11.3 Advantages of Negative Feedback

Introduction of negative feedback in amplifiers gives them many desirable features, which include the following:

1. It desensitizes the gain parameter to variation in values of components used in building the basic amplifier.
2. It increases the bandwidth.
3. It reduces distortion and increases linearity. It may be mentioned here that fundamentally all electronic devices (bipolar transistors, MOSFETs, etc.) that provide power gain are non-linear. Negative feedback allows the gain to be traded for higher linearity.
4. It reduces noise.
5. It can decrease or increase the input resistance depending upon the feedback topology. To be more specific, it depends upon how the feedback signal is mixed with the externally applied input signal. Series and shunt mixing, respectively, increase and decrease the input resistance.
6. It can decrease or increase the output resistance depending upon the feedback topology. More precisely, it depends upon how the output signal is sampled. Voltage sampling decreases the output resistance while current sampling increases it.

Most of the above-mentioned advantages (increased linearity, increased bandwidth, etc.) come at the cost of reduced gain. Closed-loop gain is smaller than the open-loop gain and the quantum of reduction depends upon the open-loop gain and the feedback factor. It, in fact, depends upon the product of the two called the loop gain.

Second disadvantage is the sensitivity of the input and output impedances to variation in open-loop gain. Third, negative feedback may sometimes lead to instability. But this can be taken care of in a carefully designed amplifier. Each one of these features is discussed in detail in the following sections.

Desensitivity (or Stability) of Gain

Introduction of negative feedback makes the amplifier insensitive to variations in the values of the components and parameters of the active devices used in building the amplifier. The expression that relates percentage variation in the gain parameter of the amplifier with feedback to the percentage variation in the same without feedback can be derived as follows.

Gain with feedback A_f is related to gain without feedback A by Eq. (11.4) and the equation is reproduced as follows:

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

Differentiating the above equation with respect to A, we get

$$\frac{dA_f}{dA} = \frac{d}{dA}\left[\frac{A}{1+\beta A}\right] = \frac{(1+\beta A)-\beta A}{(1+\beta A)^2} = \frac{1}{(1+\beta A)^2}$$

$$dA_f = \frac{dA}{(1+\beta A)^2} = \left(\frac{dA}{A}\right)\times\left[\frac{A}{(1+\beta A)^2}\right] = \left(\frac{dA}{A}\right)\times\left[\frac{A_f}{1+\beta A}\right]$$

$$\frac{dA_f}{A_f} = \left[\frac{1}{1+\beta A}\right]\times\left(\frac{dA}{A}\right)$$

$$\left|\frac{dA_f}{A_f}\right| = \left|\frac{1}{1+\beta A}\right|\times\left|\frac{dA}{A}\right| \tag{11.6}$$

$|(1+\beta A)|$ is called the desensitivity parameter D. Thus, percentage variation in gain with feedback is equal to the percentage variation in gain without feedback divided by the desensitivity parameter D. As a special case, when $\beta A >> 1$, A_f equals $1/\beta$ and therefore becomes independent of the open-loop gain of the amplifier. In that case, the stability of the gain parameter depends only on the stability of the components used in the feedback network. By using stable passive components in the feedback network, it is indeed possible to have a stable amplifier that is immune to variations in parametric values of the amplifier. Remember that all this comes at the cost of reduced gain. This implies that the gain without feedback needs to be much larger than the desired value of the gain with feedback. If increase in instability of the amplifier on account of having a larger gain without feedback is not significantly higher than the instability of the amplifier without feedback at a lower gain value, then introduction of negative feedback certainly improves the stability by a significant margin.

Effect on Bandwidth

Bandwidth increases with introduction of negative feedback. Increase in bandwidth results from the fact that amplifiers exhibit a constant gain-bandwidth product. Reduction in gain is, therefore, accompanied by increase in bandwidth. Bandwidth increases by the same desensitivity factor $D = 1 + \beta A$ by which the gain reduces. Bandwidth of amplifier with feedback is given by

$$(BW)_f = BW \times (1+\beta A) \tag{11.7}$$

Figure 11.10 shows the gain-bandwidth curve of a typical operational amplifier. The gain-bandwidth product is given by the unity gain crossover frequency. We can see how bandwidth can be traded for closed-loop gain. Increase in bandwidth with introduction of negative feedback can also be explained as follows. As the gain rolls off with increase in frequency, reduced output signal amplitude means reduced feedback. Reduced negative feedback means increase in the magnitude of effective input signal which increases the output. In other words, output remains at its mid-band value up to a higher frequency.

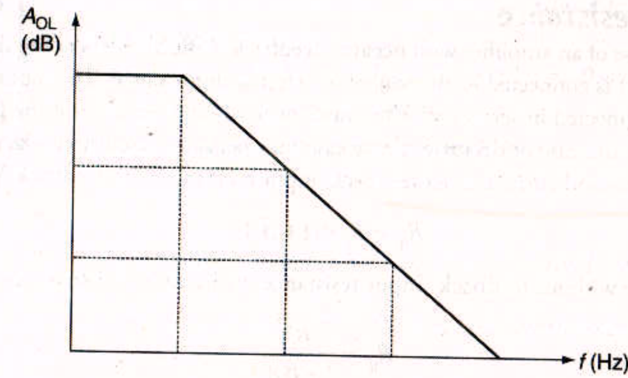


Figure 11.10 | Effect of negative feedback on bandwidth.

Effect on Non-Linear Distortion

As discussed in Chapter 10 on large signal amplifiers, non-linear distortion arises from the existence of non-linear transfer characteristics of the active device and large input and output signal swings that are large enough to drive the active device to operate in the non-linear region of its characteristics. Non-linear distortion can be assumed to be predominantly second harmonic distortion. Introduction of negative feedback reduces distortion provided that reduction in gain caused by negative feedback is compensated by increased gain in the preamplifier stages rather than introducing an additional gain stage. Remember that the non-linear distortion mainly occurs in the last stage of amplification and increasing the gain of previous stages does not add significantly to the overall distortion level.

It can be proved that non-linear distortion decreases by the desensitivity factor $D = 1 + \beta A$. Let us assume that the distortion levels without and with negative feedback are D_2 and D_{2f}, respectively. Suffix "2" implies second harmonic distortion. D_2 is the distortion contributed by the active device. In the presence of feedback, D_{2f} appears as $-\beta AD_{2f}$ at the input of the amplifier. The following gives the expression for D_{2f}:

$$D_2 - \beta AD_{2f} = D_{2f} \tag{11.8}$$

$$D_{2f} = \frac{D_2}{1+\beta A} \tag{11.9}$$

Derivation of above expression makes use of superposition principle. Equation (11.9) is, therefore, valid only when the active device operates close to the linear region. This further means that the above expression is valid for small distortion levels. Also, small amount of additional distortion arising out of small fraction of distortion present at the output being fed back to the input is assumed to be negligible in deriving the above expression.

Effect on Noise

Introduction of negative feedback acts on the noise generated in the amplifier in the same manner as it does on the non-linear distortion. Reduction in noise is governed by

$$N_f = \frac{N}{1+\beta A} \tag{11.10}$$

N_f and N are, respectively, the noise levels with and without negative feedback. However, if reduction in gain resulting from introduction of negative feedback is compensated by adding an amplifier stage, the overall system may turn out to be noisier than before. In order to benefit from the positive effect of negative feedback on noise, it is important that the reduced gain is compensated by readjustment of amplifier parameters for a higher gain without feedback so that the amplifier with feedback gives the desired gain.