unity. This corresponds to designing the circuit so that the poles are in the right half of the s-plane. Thus as the power supply is turned on, oscillations will grow in amplitude. When the amplitude reaches the desired level, the nonlinear network comes into action and causes the loop gain to be reduced to exactly unity. In other words, the poles will be "pulled back" to the $j\omega$-axis. This action will cause the circuit to sustain oscillations at this desired amplitude. If, for some reason, the loop gain is reduced below unity, the amplitude of the sine wave will diminish. This will be detected by the nonlinear network, which will cause the loop gain to increase to exactly unity.

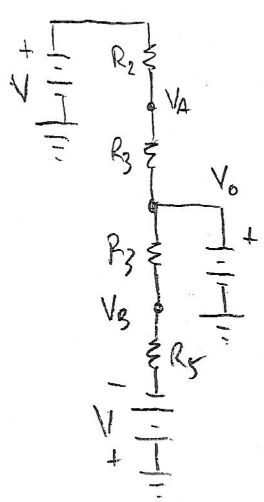
As will be seen, there are two basic approaches to the implementation of the nonlinear amplitude-stabilization mechanism. The first approach makes use of a limiter circuit (see Chapter 3). Oscillations are allowed to grow until the amplitude reaches the level to which the limiter is set. Once the limiter comes into operation, the amplitude remains constant. Obviously, the limiter should be "soft" in order to minimize nonlinear distortion. Such distortion, however, is reduced by the filtering action of the frequency-selective network in the feedback loop. In fact, in one of the oscillator circuits studied in Section 12.2, the sine waves are hard-limited, and the resulting square waves are applied to a bandpass filter present in the feedback loop. The "purity" of the output sine waves will be a function of the selectivity of this filter. That is, the higher the Q of the filter, the less the harmonic content of the sine-wave output.

The other mechanism for amplitude control utilizes an element whose resistance can be controlled by the amplitude of the output sinusoid. By placing this element in the feedback circuit so that its resistance determines the loop gain, the circuit can be designed so that the loop gain reaches unity at the desired output amplitude. Diodes, or JFETs operated in the triode region, are commonly employed to implement the controlled-resistance element.

A Popular Limiter Circuit for Amplitude Control

We conclude this section by presenting a limiter circuit that is frequently employed for the amplitude control of op amp oscillators, as well as in a variety of other applications. The circuit is more precise and versatile than those presented in Chapter 3.

The limiter circuit is shown in Fig. 12.3(a), and its transfer characteristic is depicted in Fig. 12.3(b). To see how the transfer characteristic is obtained, consider first the case (1) when the input signal v_I is small (close to zero) and the output voltage v_O is also small, so that v_A is positive and v_B is negative. It can be easily seen that both diodes D_1 and D_2 will be off. Thus all of the input current v_I/R_1 flows through the feedback resistance R_f, and the output voltage is given by

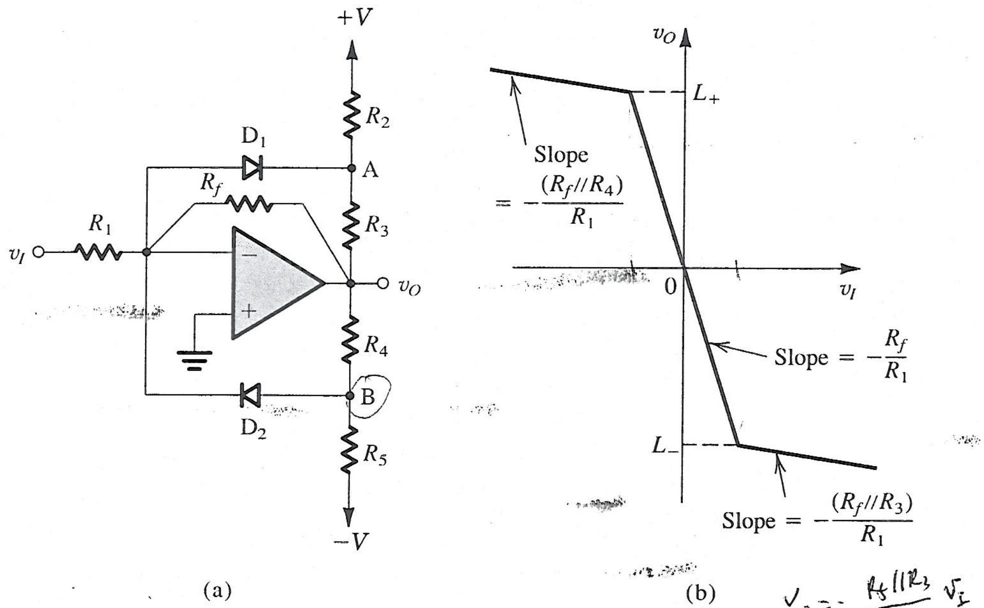


$$v_O = -(R_f/R_1)v_I \tag{12.5}$$

This is the linear portion of the limiter transfer characteristic in Fig. 12.3(b). We now can use superposition to find the voltages at nodes A and B in terms of $\pm V$ and v_O as

$$v_A = V\frac{R_3}{R_2 + R_3} + v_O\frac{R_2}{R_2 + R_3} \tag{12.6}$$

$$v_B = -V\frac{R_4}{R_4 + R_5} + v_O\frac{R_5}{R_4 + R_5} \tag{12.7}$$



$V_o = -\frac{R_f \| R_3}{R_1} v_I$

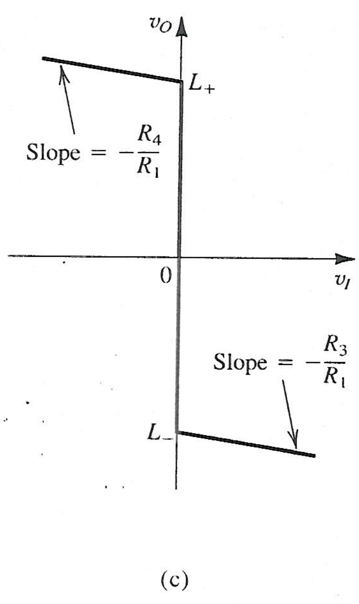


Fig. 12.3 (a) A popular limiter circuit. **(b)** Transfer characteristic of the limiter circuit; L_- and L_+ are given by Eqs. (12.8) and (12.9), respectively. **(c)** When R_f is removed the limiter turns into a comparator with the characteristics shown.

2 As v_I goes positive, v_O goes negative (Eq. 12.5), and we see from Eq. (12.7) that v_B will become more negative, thus keeping D_2 off. Equation (12.6) shows, however, that v_A becomes less positive. Then if we continue to increase v_I, a negative value of v_O will be reached at which v_A becomes −0.7 V or so and diode D_1 conducts. If we use the constant-voltage-drop model for D_1 and denote the voltage drop V_D, the value of v_O at which D_1

$V_A = -V_D$

In equation 12.6) set $V_A = -V_D$ and solve for V_0:

$$-V_D \frac{R_2+R_3}{R_2} = V\frac{R_3}{R_2} + V_0$$

$$\Rightarrow V_0 = -V\frac{R_3}{R_2} - V_D\left(1+\frac{R_3}{R_2}\right)$$

conducts can be found from Eq. (12.6). This is the negative limiting level, which we denote L_-,

$$L_- = -V\frac{R_3}{R_2} - V_D\left(1 + \frac{R_3}{R_2}\right) \tag{12.8}$$

The corresponding value of v_I can be found by dividing L_- by the limiter gain $-R_f/R_1$. If v_I is increased beyond this value, more current is injected into D_1 and v_A remains at approximately $-V_D$. Thus the current through R_2 remains constant, and the additional diode current flows through R_3. Thus R_3 appears in effect in parallel with R_f, and the incremental gain (ignoring the diode resistance) is $-(R_f \,//\, R_3)/R_1$. To make the slope of the transfer characteristic small in the limiting region, a low value should be selected for R_3.

3 The transfer characteristic for negative v_I can be found in a manner identical to that employed above. It can be easily seen that for negative v_I, diode D_2 plays an identical role to that played by diode D_1 for positive v_I. The positive limiting level L_+ can be found to be

$$L_+ = V\frac{R_4}{R_5} + V_D\left(1 + \frac{R_4}{R_5}\right) \tag{12.9}$$

and the slope of the transfer characteristic in the positive-limiting region is $-(R_f \,//\, R_4)/R_1$. We thus see that the circuit of Fig. 12.3(a) functions as a soft limiter, with the limiting levels L_+ and L_- independently adjustable by the selection of appropriate resistor values.

4 Finally we note that increasing R_f results in a higher gain in the linear region while keeping L_+ and L_- unchanged. In the limit, removing R_f altogether results in the transfer characteristic of Fig. 12.3(c), which is that of a comparator. That is, the circuit compares v_I with the comparator reference value of 0 V; $v_I > 0$ results in $v_O \simeq L_-$, and $v_I < 0$ yields $v_O \simeq L_+$.

Exercise 12.2 For the circuit of Fig. 12.3(a) with $V = 15$ V, $R_1 = 30$ kΩ, $R_f = 60$ kΩ, $R_2 = R_5 = 9$ kΩ, and $R_3 = R_4 = 3$ kΩ, find the limiting levels and the value of v_I at which the limiting levels are reached. Also determine the limiter gain and the slope of the transfer characteristics in the positive and negative limiting regions. Assume that $V_D = 0.7$ V.

Ans. ±5.93 V; ±2.97 V; −2; −0.095

12.2 OP AMP–RC OSCILLATOR CIRCUITS

In this section we shall study some practical oscillator circuits utilizing op amps and RC networks.

The Wien-Bridge Oscillator

One of the simplest oscillator circuits is based on the Wien bridge. Figure 12.4 shows a Wien-bridge oscillator without the nonlinear gain-control network. The circuit consists of an op amp connected in the noninverting configuration, with a closed-loop gain of $1 + R_2/R_1$. In the feedback path of this positive-gain amplifier an RC network is connected.