IN THIS CHAPTER YOU WILL LEARN

1. That an oscillator circuit that generates sine waves can be implemented by connecting a frequency-selective network in the positive-feedback path of an amplifier.
2. The conditions under which sustained oscillations are obtained and the frequency of the oscillations.
3. How to design nonlinear circuits to control the amplitude of the sine wave obtained in a linear oscillator.
4. A variety of circuits for implementing a linear sine-wave oscillator.
5. How op amps can be combined with resistors and capacitors to implement precision multivibrator circuits.
6. How a bistable circuit can be connected in a feedback loop with an op-amp integrator to implement a generator of square and triangular waveforms.
7. The application of one of the most popular IC chips of all time, the 555 timer, in the design of generators of pulse and square waveforms.
8. How a triangular waveform can be shaped by a nonlinear circuit to provide a sine waveform.

Introduction

In the design of electronic systems, the need frequently arises for signals having prescribed standard waveforms, for example, sinusoidal, square, triangular, or pulse. Systems in which standard signals are required include computer and control systems where clock pulses are needed for, among other things, timing; communication systems where signals of a variety of waveforms are utilized as information carriers; and test and measurement systems where signals, again of a variety of waveforms, are employed for testing and characterizing electronic devices and circuits. In this chapter we study signal-generator circuits.

The signal-generator or oscillator circuits studied in this chapter are collectively capable of providing signals with frequencies in the range of hertz to hundreds of gigahertz. While some can be fabricated on chip, others utilize discrete components. Examples of commonly encountered oscillators include the microprocessor clock generator (fabricated on chip utilizing the ring oscillator studied in Section 16.4.4 with frequencies in the several-gigahertz range); the carrier-waveform generator in wireless transceivers (on chip, up to the hundreds-of-gigahertz range); the oscillator in an electronic watch (utilizing a quartz crystal with a frequency of 2^{15} Hz); and the variable-frequency function generator in the electronics lab (utilizing a discrete circuit with frequency in the hertz to megahertz range).

There are two distinctly different approaches for the generation of sinusoids, perhaps the most commonly used of the standard waveforms. The first approach, studied in Sections 18.1 to 18.3, employs a **positive-feedback loop** consisting of an amplifier and an RC or LC **frequency-selective network**. While the frequency of the generated sine wave is determined by the frequency-selective network, the amplitude is set using a nonlinear mechanism, implemented either with a separate circuit or using the nonlinearities of the amplifying device itself. In spite of this, these circuits, which generate sine waves utilizing resonance phenomena, are known as **linear oscillators**. The name clearly distinguishes them from the circuits that generate sinusoids by way of the second approach. In these circuits, a sine wave is obtained by appropriately shaping a triangular waveform. We study waveform-shaping circuits in Section 18.8, following the study of triangular-waveform generators.

Circuits that generate square, triangular, pulse (etc.) waveforms, called **nonlinear oscillators** or **function generators**, employ circuit building blocks known as **multivibrators**. There are three types of multivibrator: the **bistable** (Section 18.4), the **astable** (Section 18.5), and the **monostable** (Section 18.6). The multivibrator circuits presented in this chapter employ op amps and are intended for precision analog applications. Bistable and monostable multivibrator circuits using digital logic gates were studied in Chapter 16.

A general and versatile scheme for the generation of square and triangular waveforms is obtained by connecting a bistable multivibrator and an op-amp integrator in a feedback loop (Section 18.5). Similar results can be obtained using a commercially available versatile IC chip, the 555 timer (Section 18.7).

18.1 Basic Principles of Sinusoidal Oscillators

In this section, we study the basic principles of the design of linear sine-wave oscillators. In spite of the name *linear oscillator,* some form of nonlinearity has to be employed to provide control of the amplitude of the output sine wave. In fact, all oscillators are essentially nonlinear circuits. This complicates the task of analysis and design of oscillators: No longer is one able to apply transform (s-plane) methods directly. Nevertheless, techniques have been developed by which the design of sinusoidal oscillators can be performed in two steps: The first step is a linear one, and frequency-domain methods of feedback circuit analysis can be readily employed. Subsequently, in step 2, a nonlinear mechanism for amplitude control can be provided.

18.1.1 The Oscillator Feedback Loop

The basic structure of a sinusoidal oscillator consists of an amplifier and a frequency-selective network connected in a **positive-feedback loop**, such as that shown in block diagram form in Fig. 18.1. Although no input signal will be present in an actual oscillator circuit, we include an input signal here to help explain the principle of operation. It is important to note that unlike the negative-feedback loop of Fig. 11.1, here the feedback signal x_f is summed with a *positive* sign. Thus the gain-with-feedback is given by

$$A_f(s) = \frac{A(s)}{1 - A(s)\beta(s)} \tag{18.1}$$

where we note the negative sign in the denominator. The loop gain $L(s)$ is given by

$$L(s) \equiv A(s)\beta(s) \tag{18.2}$$

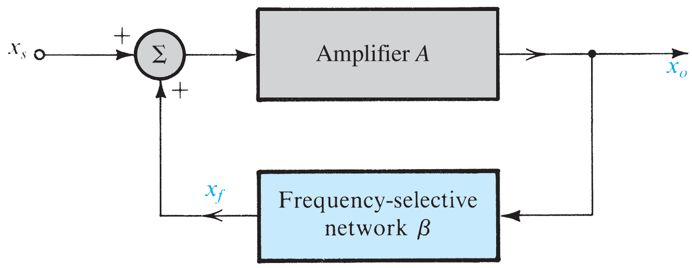

Figure 18.1 The basic structure of a sinusoidal oscillator. A positive-feedback loop is formed by an amplifier and a frequency-selective network. In an actual oscillator circuit, no input signal will be present; here an input signal x_s is employed to help explain the principle of operation.

and the characteristic equation is

$$1 - L(s) = 0 \tag{18.3}$$

18.1.2 The Oscillation Criterion

If at a specific frequency f_0 the loop gain $A\beta$ is equal to unity, it follows from Eq. (18.1) that A_f will be infinite. That is, at this frequency the circuit will have a finite output for zero input signal. Such a circuit is by definition an oscillator. Thus the condition for the feedback loop of Fig. 18.1 to provide sinusoidal oscillations of frequency ω_0 is

$$L(j\omega_0) \equiv A(j\omega_0)\beta(j\omega_0) = 1 \tag{18.4}$$

That is, *at ω_0 the phase of the loop gain should be zero and the magnitude of the loop gain should be unity*. This is known as the **Barkhausen criterion**. Note that for the circuit to oscillate at one frequency, the oscillation criterion should be satisfied only at one frequency (i.e., ω_0); otherwise the resulting waveform will not be a simple sinusoid.

An intuitive feeling for the Barkhausen criterion can be gained by considering once more the feedback loop of Fig. 18.1. For this loop to *produce* and *sustain* an output x_o with no input applied ($x_s = 0$), the feedback signal x_f,

$$x_f = \beta x_o$$

should be sufficiently large that when multiplied by A it produces x_o, that is,

$$Ax_f = x_o$$

that is,

$$A\beta x_o = x_o$$

which results in

$$A\beta = 1$$

It should be noted that the *frequency of oscillation* ω_0 is determined solely by the phase characteristics of the feedback loop; the loop oscillates at the frequency for which the phase is zero (or, equivalently, 360°). It follows that the stability of the frequency of oscillation will be determined by the manner in which the phase $\phi(\omega)$ of the feedback loop varies with frequency. A "steep" function $\phi(\omega)$ will result in a more stable frequency. This can be seen if one imagines a change in phase $\Delta\phi$ due to a change in one of the circuit components. If $d\phi/d\omega$ is large, the resulting change in ω_0 will be small, as illustrated in Fig. 18.2.

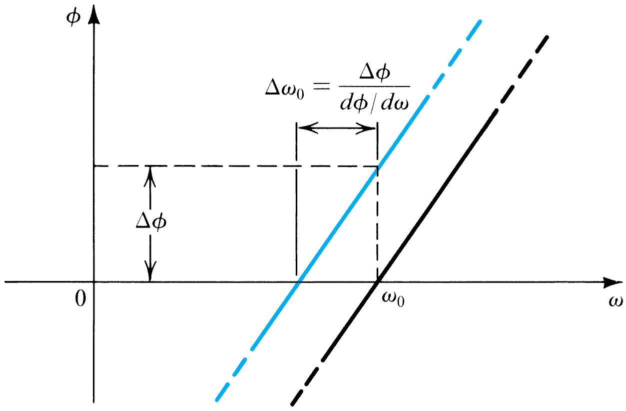

Figure 18.2 Dependence of the oscillator-frequency stability on the slope of the phase response. A steep phase response (i.e., large $d\phi/d\omega$) results in a small $\Delta\omega_0$ for a given change in phase $\Delta\phi$ [resulting from a change (due, for example, to temperature) in a circuit component].

An alternative approach to the study of oscillator circuits consists of examining the circuit poles, which are the roots of the **characteristic equation** (Eq. 18.3). For the circuit to produce **sustained oscillations** at a frequency ω_0 the characteristic equation has to have roots at $s = \pm j\omega_0$. Thus $1 - A(s)\beta(s)$ should have a factor of the form $s^2 + \omega_0^2$.

EXERCISE

18.1 Consider a sinusoidal oscillator formed by connecting an amplifier with a gain of 2 and a second-order bandpass filter in a feedback loop. Find the pole frequency and the center-frequency gain of the filter needed to produce sustained oscillations at 1 kHz.
Ans. 1 kHz; 0.5

18.1.3 Analysis of Oscillator Circuits

Analysis of a given oscillator circuit to determine the frequency of oscillation and the condition for the oscillations to start proceeds in three steps:

1. Break the feedback loop to determine the loop gain $A(s)\beta(s)$. This step is similar to that utilized in Section 11.2 in the analysis of negative-feedback amplifiers.
2. The oscillation frequency ω_0 is found as the frequency for which the phase angle of $A(j\omega)\ \beta(j\omega)$ is zero or, equivalently, 360°.
3. The condition for the oscillations to start is found from

$$|A(j\omega_0)\beta(j\omega_0)| \geq 1$$

Note that making the magnitude of the loop gain slightly greater than unity ensures that oscillations will start.

played by diode D_1 for positive v_I. We can use Eq. (18.7) to find the positive limiting level L_+

$$L_+ = V\frac{R_4}{R_5} + V_D\left(1 + \frac{R_4}{R_5}\right) \tag{18.9}$$

and the slope of the transfer characteristic in the positive limiting region is $-(R_f \parallel R_4)/R_1$. We thus see that the circuit of Fig. 18.4(a) functions as a soft limiter, with the limiting levels L_+ and L_-, and the limiting gains independently adjustable by the selection of appropriate resistor values.

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. 18.4(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

18.4 For the circuit of Fig. 18.4(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 characteristic in the positive and negative limiting regions. Assume that $V_D = 0.7$ V.
Ans. ±5.93 V; ±2.97 V; –2; –0.095

18.2 Op Amp–RC Oscillator Circuits

In this section we shall study some practical oscillator circuits utilizing op amps and RC networks. These circuits are usually assembled on printed-circuit boards; their frequency of operation extends from very low frequencies to at most 1 MHz.

18.2.1 The Wien-Bridge Oscillator

One of the simplest oscillator circuits is based on the Wien bridge. Figure 18.5 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. The loop gain can be easily obtained by multiplying the transfer function $V_a(s)/V_o(s)$ of the feedback network by the amplifier gain,

$$L(s) = \left[1 + \frac{R_2}{R_1}\right]\frac{Z_p}{Z_p + Z_s}$$

$$= \frac{1 + R_2/R_1}{1 + Z_s Y_p}$$

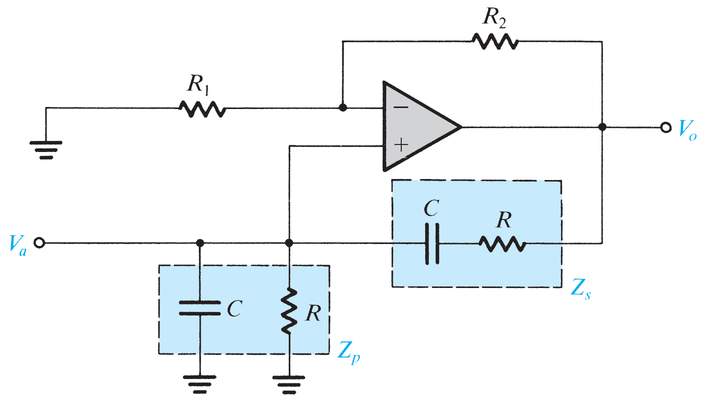

Figure 18.5 A Wien-bridge oscillator without amplitude stabilization.

Thus,

$$L(s) = \frac{1 + R_2/R_1}{3 + sCR + 1/sCR} \tag{18.10}$$

Substituting $s = j\omega$ results in

$$L(j\omega) = \frac{1 + R_2/R_1}{3 + j(\omega CR - 1/\omega CR)} \tag{18.11}$$

The loop gain will be a real number (i.e., the phase will be zero) at one frequency given by

$$\omega_0 CR = \frac{1}{\omega_0 CR}$$

That is,

$$\omega_0 = 1/CR \tag{18.12}$$

Oscillations will start at this frequency if the loop gain is at least unity. This can be achieved by selecting

$$R_2/R_1 = 2 \tag{18.13}$$

To ensure that oscillations will start, one chooses R_2/R_1 slightly greater than 2. The reader can easily verify that if $R_2/R_1 = 2 + \delta$, where δ is a small number, the roots of the characteristic equation $1 - L(s) = 0$ will be in the right half of the s plane.

The amplitude of oscillation can be determined and stabilized by using a nonlinear control network. Two different implementations of the amplitude-controlling function are shown in Figs. 18.6 and 18.7. The circuit in Fig. 18.6 employs a symmetrical feedback limiter of the type studied in Section 18.1.4. It is formed by diodes D_1 and D_2 together with resistors R_3, R_4, R_5, and R_6. The limiter operates in the following manner: At the positive peak of the output voltage v_O, the voltage at node b will exceed the voltage v_1 (which is about $\frac{1}{3}v_O$), and diode D_2 conducts. This will clamp the positive peak to a value determined by R_5, R_6, and the negative power supply. To be specific, the value of the positive output peak can be calculated by setting $v_b = v_1 + V_{D2}$ and writing a node equation at node b while neglecting the current through D_2. Similarly, the negative peak of the output sine wave will be clamped to the value that causes diode D_1 to conduct. The value of the negative peak can be determined by setting $v_a = v_1 - V_{D1}$

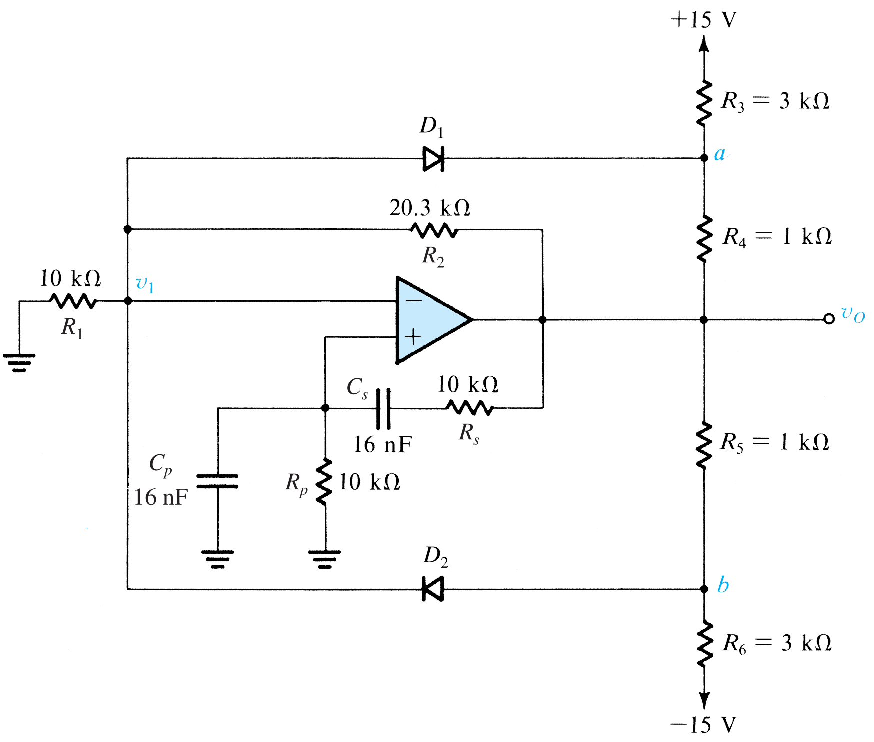

Figure 18.6 A Wien-bridge oscillator with a limiter used for amplitude control.

THE WIEN-BRIDGE OSCILLATOR:

The Wien bridge consisting of four resistors and two capacitors was invented in 1891 by Max Wien, a Prussian physicist, for inductance measurement. Much later, William Hewlett (cofounder in 1939 of Hewlett-Packard), while working toward his master's degree at Stanford University, realized the importance of placing part of the Wien bridge in a positive-feedback loop to form what was called the Wien-bridge oscillator. The first product in 1939 of the new Hewlett-Packard Company was the HP200A, a flexible, precision sine-wave generator using vacuum tubes to implement the amplifier and a tungsten lamp to control the loop gain and thus the amplitude of the sine wave.

EXERCISE

18.5 For the circuit in Fig. 18.6: (a) Disregarding the limiter circuit, find the location of the closed-loop poles. (b) Find the frequency of oscillation. (c) With the limiter in place, find the amplitude of the output sine wave (assume that the diode drop is 0.7 V).

Ans. (a) $(10^5/16)(0.015 \pm j)$; (b) 1 kHz; (c) 21.36 V (peak-to-peak)

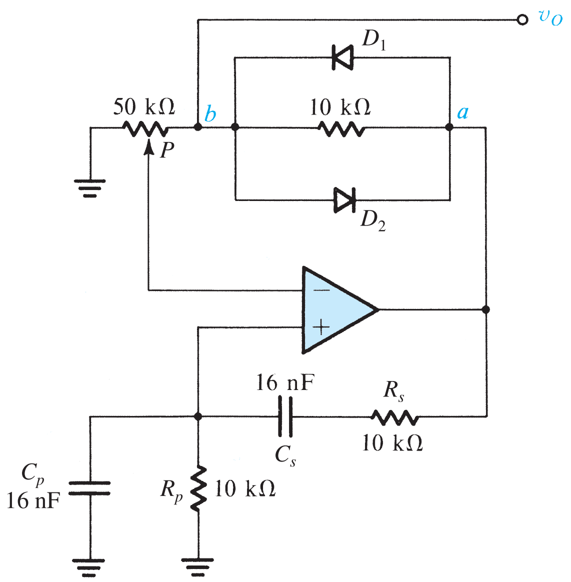

Figure 18.7 A Wien-bridge oscillator with an alternative method for amplitude stabilization.

and writing an equation at node a while neglecting the current through D_1. Finally, note that to obtain a symmetrical output waveform, R_3 is chosen equal to R_6, and R_4 equal to R_5.

The circuit of Fig. 18.7 employs an inexpensive implementation of the parameter-variation mechanism of amplitude control. Potentiometer P is adjusted until oscillations just start to grow. As the oscillations grow, the diodes start to conduct, causing the effective resistance between a and b to decrease. Equilibrium will be reached at the output amplitude that causes the loop gain to be exactly unity. The output amplitude can be varied by adjusting potentiometer P.

As indicated in Fig. 18.7, the output is taken at point b rather than at the op-amp output terminal because the signal at b has lower distortion than that at a. To appreciate this point, note that the voltage at b is proportional to the voltage at the op-amp input terminals and that the latter is a filtered (by the RC network) version of the voltage at node a. Node b, however, is a high-impedance node, and a buffer will be needed if a load is to be connected.

EXERCISE

18.6 For the circuit in Fig. 18.7, find the following: (a) the setting of potentiometer P at which oscillations just start; (b) the frequency of oscillation.
Ans. (a) 20 kΩ to ground; (b) 1 kHz

18.2.2 The Phase-Shift Oscillator

The basic structure of the phase-shift oscillator is shown in Fig. 18.8. It consists of a negative-gain amplifier ($-K$) with a three-section (third-order) RC ladder network in the feedback. The circuit will oscillate at the frequency for which the phase shift of the RC

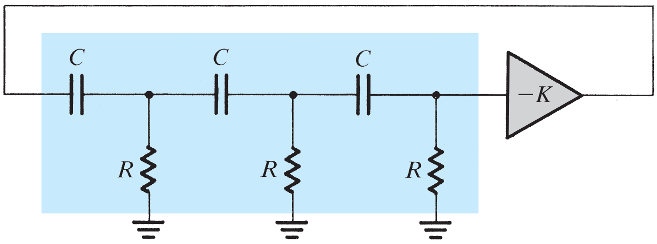

Figure 18.8 A phase-shift oscillator.

network is 180°. Only at this frequency will the total phase shift around the loop be 0° or 360°. Here we should note that the reason for using a three-section RC network is that three is the minimum number of sections (i.e., lowest order) that is capable of producing a 180° phase shift at a finite frequency.

For oscillations to be sustained, the value of K should be equal to the inverse of the magnitude of the RC network transfer function at the frequency of oscillation. However, to ensure that oscillations start, the value of K has to be chosen slightly higher than the value that satisfies the unity-loop-gain condition. Oscillations will then grow in magnitude until limited by some nonlinear control mechanism.

Figure 18.9 shows a practical phase-shift oscillator with a feedback limiter, consisting of diodes D_1 and D_2 and resistors R_1, R_2, R_3, and R_4 for amplitude stabilization. To start oscillations, R_f has to be made slightly greater than the minimum required value. Although the circuit stabilizes more rapidly and provides sine waves with more stable amplitude, if R_f is made much larger than this minimum, the price paid is an increased output distortion.

EXERCISES

18.7 Consider the circuit of Fig. 18.9 *without* the limiter. Break the feedback loop at X and find the loop gain $A\beta \equiv V_o(j\omega)/V_x(j\omega)$ in symbolic form (i.e., do not substitute the numerical values given). To do this, it is easier to start at the output and work backward, finding the various currents and voltages, and eventually V_x in terms of V_o.

Ans. $$\frac{\omega^2 C^2 R R_f}{4 + j(3\omega CR - 1/\omega CR)}$$

18.8 Use the expression derived in Exercise 18.7 to find the frequency of oscillation f_0 and the minimum required value of R_f for oscillations to start in the circuit of Fig. 18.9.

Ans. $\omega_0 = 1/\sqrt{3}CR; R_f \geq 12R; f_0 = 574.3\,\text{Hz}; R_f = 120\ \text{k}\Omega$

18.2.3 The Quadrature Oscillator

The **quadrature oscillator** is based on the two-integrator loop studied in Section 17.7. As an active filter, the loop is damped to locate the poles in the left half of the s plane. Here, no such