11.5 Introduction to Oscillator

An oscillator is a nonlinear electronic device consisting of active and passive circuit elements which can generate sinusoidal or other periodic waves at a desired frequency. In addition the frequency may be variable. It delivers an output voltage without any external input signal. In this sense, it is a regenerative circuit of infinite gain. It converts the d.c. power from the supply source to the output a.c. power. Oscillators form the basic element of all signal generators. They are widely used in different communication systems and laboratory test equipments.

A great variety of oscillator circuits have been developed. If the output waveform is sinusoidal then it is called *sinusoidal oscillator*. On the other hand, a *non-sinusoidal* (*or relaxation*) oscillator produces square waves, triangular waves, sawtooth waves, pulses etc. The circuits which generate square waves or pulses are usually called *multivibrators*. Oscillators may also be classified according to the particular active device that makes oscillation possible. Thus we have *negative-resistance oscillators* and *feedback oscillators*. The negative resistance arises due to negative slope of the current-voltage characteristic of the active element. Unlike ordinary resistance, it does not absorb but delivers power. In feedback oscillators a feedback voltage of proper magnitude and phase is used as input such that it can sustain the output voltage. Depending on the frequency range of operations oscillators may also be classified as *audio frequency* (*AF*) *oscillators*, *radio frequency* (*RF*) *oscillators* etc. Sinusoidal oscillators may also be classified according to the frequency determining linear passive networks used in the oscillator. Thus we have *tuned circuit* (*LC*) *oscillators*, *RC oscillators* and *crystal oscillators*.

Regardless of its type and designation every oscillator must have the following basic constituents :

(1) an internal amplifier

(2) either a positive feedback network or a suitable negative resistance effect

(3) amplitude limiting device and

(4) frequency selective network.

Since an oscillator may be considered as an amplifier of infinite gain, an amplifier forms an essential component of any oscillator. A feedback loop (either external or internal) enables the amplifier to get its input signal from its own output. Thus the system becomes self-sustaining. In a practical oscillator, oscillation starts with small amplitude and goes on increasing until the nonlinearities of the active elements limit the amplitude of oscillation and a steady state is reached. Since the amplifier and feedback network may contain reactive elements the overall phase shift is a function of frequency. For oscillation to occur there is a precise phase requirement and hence the oscillator operates at a frequency satisfying the phase requirement. No external signal is applied to an oscillator but the assumed input signal is provided by the circuit noise having a broad frequency spectrum. For this we require a frequency selective network which picks up the correct frequency component satisfying the phase requirement.

7-11-2 Oscillator Types

Because of their widespread use, many different types of oscillators are available. These oscillator types are summarized in Table 7–6.

TABLE 7–6 Oscillator Types.

Types of components used	*Frequency of oscillation*	*Types of waveform generated*
RC oscillator	Audio frequency (AF)	Sinusoidal
LC oscillator	Radio frequency (RF)	Square wave
Crystal oscillator		Triangular wave
		Sawtooth wave, etc.

7-11-3 Frequency Stability

The ability of the oscillator circuit to oscillate at one exact frequency is called *frequency stability*. Although a number of factors may cause changes in oscillator frequency, the primary factors are temperature changes and changes in the dc power supply. Temperature and power supply changes cause variations in the op-amp's gain, in junction capacitances and resistances of the transistors in an op-amp, and in external circuit components. In most cases these variations can be kept small by careful design, by using regulated power supplies, and by temperature control.

Another important factor that determines frequency stability is the *figure of merit Q* of the circuit. The higher the Q, the greater the stability. For this reason, crystal oscillators are far more stable than *RC* or *LC* oscillators, especially at higher frequencies. *LC* circuits and crystals are generally used for the generation of high-frequency signals, while *RC* components are most suitable for audio-frequency applications. Here we discuss audio-frequency *RC* oscillators only. We begin with the sinusoidal oscillators.

7-12 PHASE SHIFT OSCILLATOR

Figure 7–18 shows a phase shift oscillator, which consists of an op-amp as the amplifying stage and three *RC* cascaded networks as the feedback circuit. The feedback circuit provides feedback voltage from the output back to the input of the amplifier. The op-amp is used in the inverting mode; therefore, any signal that appears at the inverting terminal is shifted by 180° at the output. An additional 180° phase shift required for oscillation is provided by the cascaded *RC* networks. Thus the total phase shift around the loop is 360° (or 0°). At some specific frequency when the phase shift of the cascaded *RC* networks is exactly 180° and the gain of the amplifier is sufficiently large, the circuit will oscillate at that frequency. This frequency is called the frequency of oscillation, f_o, and is given by

$$f_o = \frac{1}{2\pi\sqrt{6}RC} = \frac{0.065}{RC} \tag{7–22a}$$

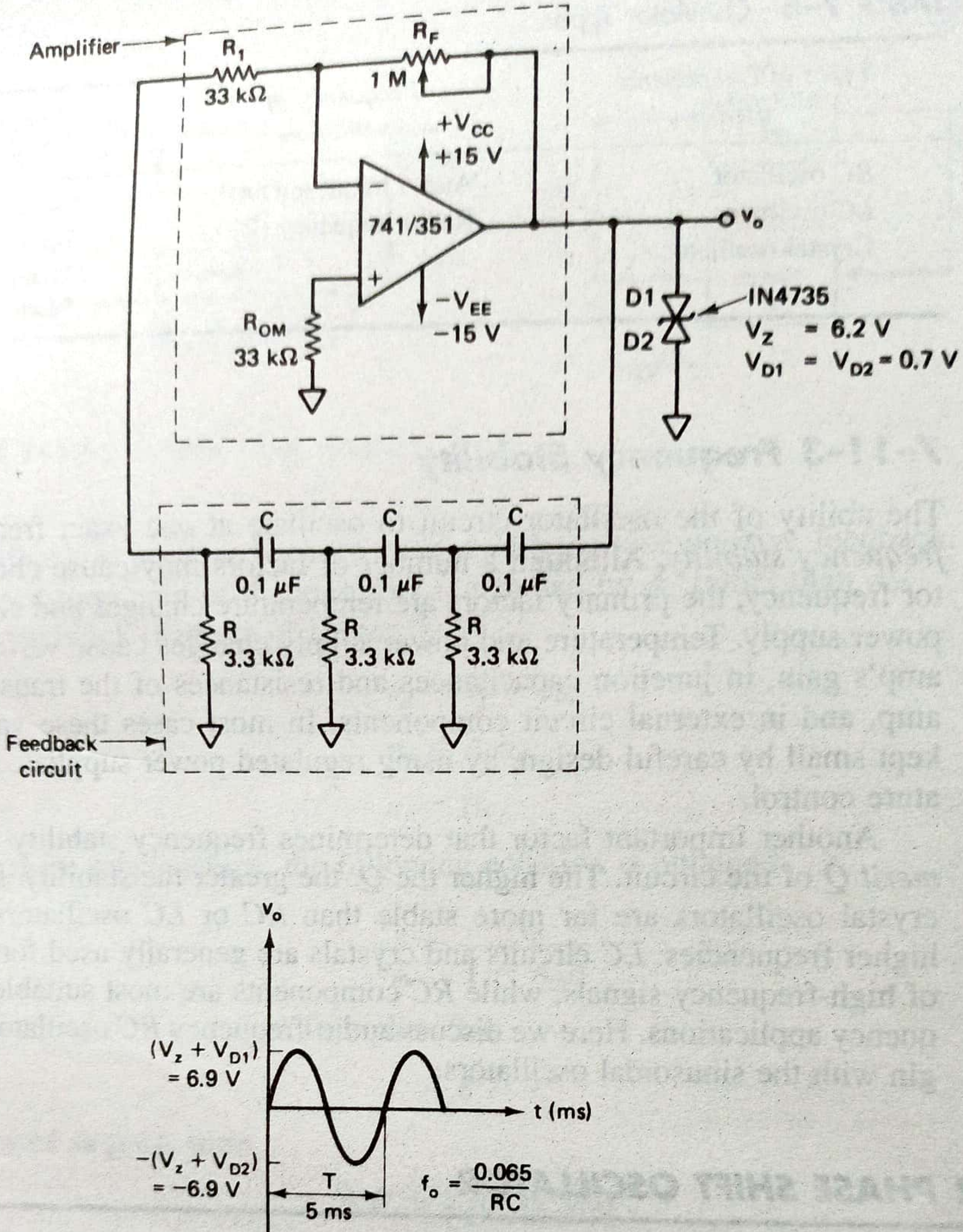

FIGURE 7–18 Phase shift oscillator and its output waveform.

At this frequency, the gain A_v must be *at least* 29. That is,

$$\left|\frac{R_F}{R_1}\right| = 29$$

or

$$R_F = 29R_1 \tag{7–22b}$$

For the derivation of Equation (7–22a) and (7–22b), refer to Appendix C. Thus the circuit will produce a sinusoidal waveform of frequency f_o if the gain is 29 and the total phase shift around the circuit is exactly 360°. For a desired frequency of oscillation, choose a capacitor C, and then calculate the value of R from Equation (7–22a). A desired output amplitude, however, can be obtained with back-to-back zeners connected at the output terminal.

EXAMPLE 7–12

Design the phase shift oscillator of Figure 7–18 so that $f_o = 200$ Hz.

SOLUTION

Let $C = 0.1\ \mu F$. Then, from Equation (7–22a),

$$R = \frac{0.065}{(200)(10^{-7})} = 3.25\ k\Omega$$

(Use $R = 3.3\ k\Omega$.)

To prevent the loading of the amplifier because of *RC* networks, it is necessary that $R_1 \geq 10\,R$. Therefore, let $R_1 = 10R = 33\ k\Omega$. Then, from Equation (7–22b),

$$R_F = 29(33\ k\Omega) = 957\ k\Omega$$

(Use $R_F = 1\text{-}M\Omega$ potentiometer.)

When choosing an op-amp, type 741 can be used at lower frequencies (<1 kHz); however, at higher frequencies, an op-amp such as the LM318 or LF351 is recommended because of its increased slew rate.

7-13 WIEN BRIDGE OSCILLATOR

Because of its simplicity and stability, one of the most commonly used audio-frequency oscillators is the Wien bridge. Figure 7–19 shows the Wien bridge oscillator in which the Wien bridge circuit is connected between the amplifier input terminals and the output terminal. The bridge has a series *RC* network in one arm and a parallel *RC* network in the adjoining arm. In the remaining two arms of the bridge, resistors R_1 and R_F are connected (see Figure 7–19).

The phase angle criterion for oscillation is that the total phase shift around the circuit must be 0°. This condition occurs only when the bridge is balanced, that is, *at resonance.* The frequency of oscillation f_o is exactly the resonant frequency of the balanced Wien bridge and is given by

$$f_o = \frac{1}{2\pi RC} = \frac{0.159}{RC} \quad \textbf{(7–23a)}$$

assuming that the resistors are equal in value, and the capacitors are equal in value in the reactive leg of the Wien bridge. At this frequency the gain required for sustained oscillation is given by

$$A_v = \frac{1}{B} = 3$$

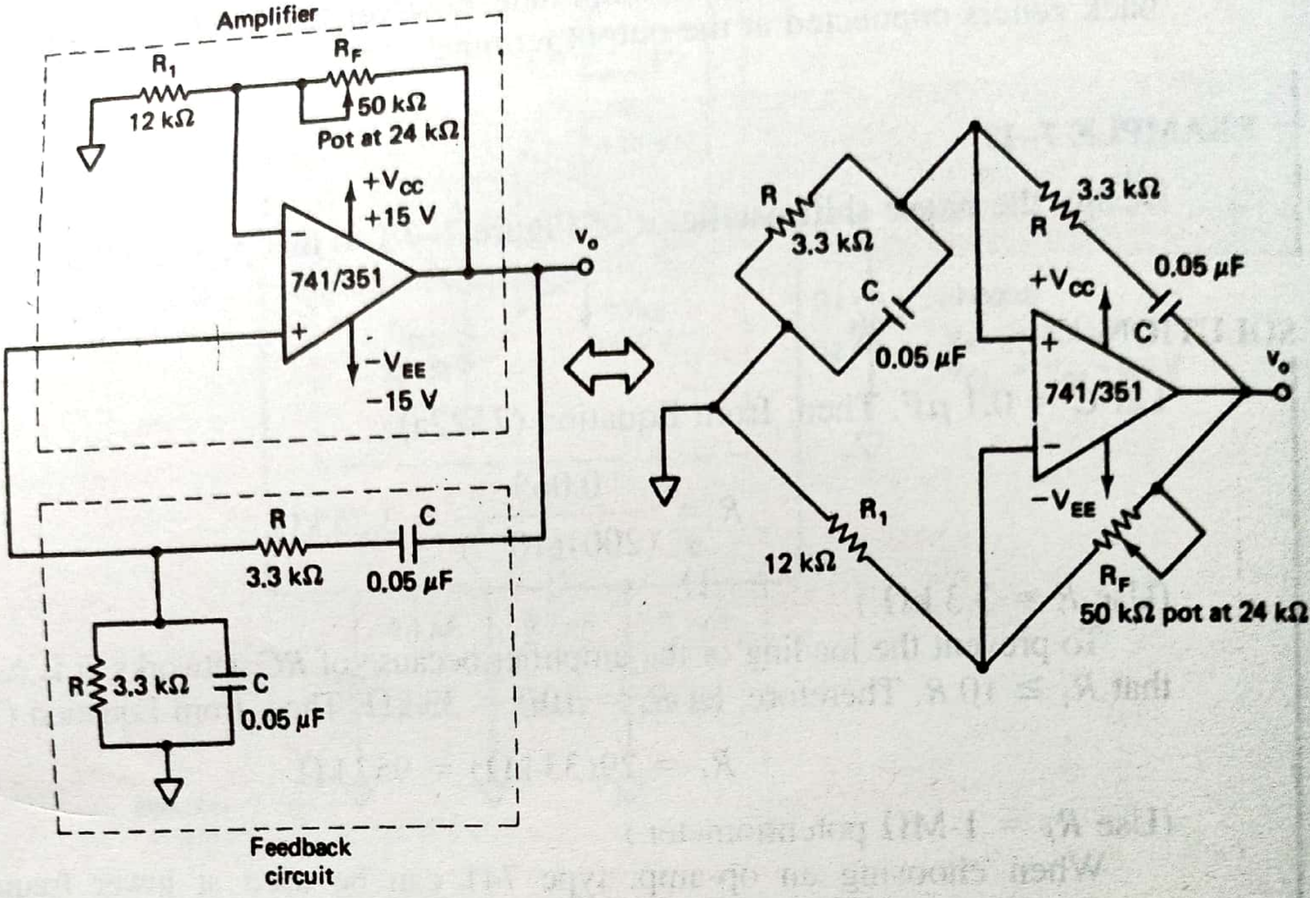

FIGURE 7–19 Wien bridge oscillator.

That is,

$$1 + \frac{R_F}{R_1} = 3$$

or

$$R_F = 2R_1 \qquad \textbf{(7–23b)}$$

For the derivation of Equations (7–23a) and (7–23b), refer to Appendix C. The Wien bridge oscillator is designed using Equations (7–23a) and (7–23b), as illustrated in Example 7–13.

EXAMPLE 7–13

Design the Wien bridge oscillator of Figure 7–19 so that $f_o = 965$ Hz.

SOLUTION

Let $C = 0.05\ \mu$F. Therefore, from Equation (7–23a),

$$R = \frac{0.159}{(5)(10^{-8})(965)} = 3.3\ \text{k}\Omega$$

Now, let $R_1 = 12\ \text{k}\Omega$. Then, from Equation (7–23b),

$$R_F = (2)(12\ \text{k}\Omega) = 24\ \text{k}\Omega$$

(Use $R_F = 50\ \text{k}\Omega$ potentiometer.)

7-15 SQUARE WAVE GENERATOR

In contrast to sine wave oscillators, square wave outputs are generated when the op-amp is forced to operate in the saturated region. That is, the output of the op-amp is forced to swing repetitively between positive saturation $+V_{sat}$ ($\cong +V_{CC}$) and negative saturation $-V_{sat}(\cong -V_{EE})$, resulting in the square-wave output. One such circuit is shown in Figure 7–21(a). This square wave generator is also called a *free-running* or *astable* multivibrator. The output of the op-amp in this circuit will be in positive or negative saturation, depending on whether the differential voltage v_{id} is negative or positive, respectively.

Assume that the voltage across capacitor C is zero volts at the instant the dc supply voltages $+V_{CC}$ and $-V_{EE}$ are applied. This means that the voltage at the inverting terminal is zero initially. At the same instant, however, the voltage v_1 at the noninverting terminal is a very small finite value that is a function of the output offset voltage V_{ooT} and the values of resistors R_1 and R_2. Thus the differential input voltage v_{id} is equal to the voltage v_1 at the noninverting terminal. Although very small, voltage v_1 will start to drive the op-amp into saturation. For example, suppose that the output offset voltage V_{ooT} is positive and that, therefore, voltage v_1 is also positive. Since initially the capacitor C acts as a short circuit, the gain of the op-amp is very large (A); hence v_1 drives the output of the op-amp to its positive saturation $+V_{sat}$. With the output voltage of the op-amp at $+V_{sat}$, the capacitor C starts charging toward $+V_{sat}$ through resistor R. However, as soon as

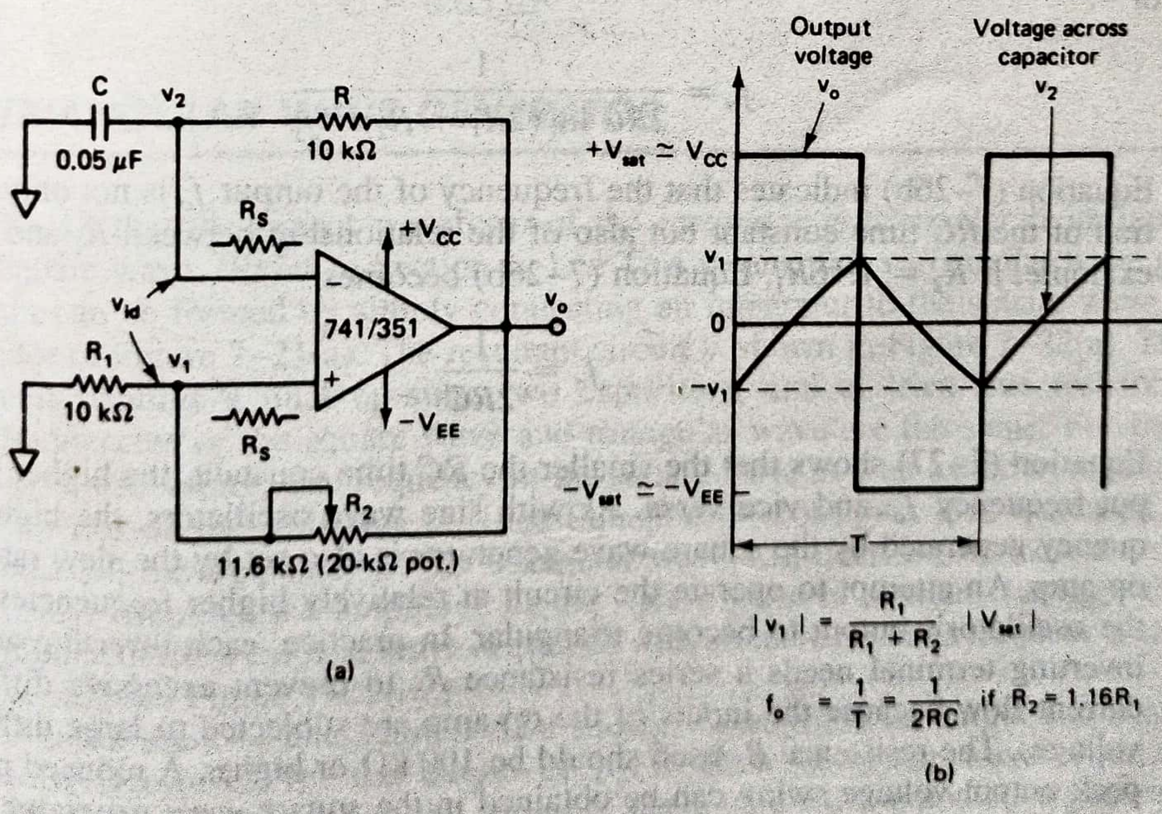

FIGURE 7–21 (a) Square wave generator. (b) Waveforms of output voltage v_o and capacitor voltage v_2 of the square-wave generator.

the voltage v_2 across capacitor C is slightly more positive than v_1, the output of the op-amp is forced to switch to a negative saturation, $-V_{sat}$. With the op-amp's output voltage at negative saturation, $-V_{sat}$, the voltage v_1 across R_1 is also negative, since

$$v_1 = \frac{R_1}{R_1 + R_2}(-V_{sat}) \tag{7–25a}$$

Thus the net differential voltage $v_{id} = v_1 - v_2$ is negative, which holds the output of the op-amp in negative saturation. The output remains in negative saturation until the capacitor C discharges and then recharges to a negative voltage slightly higher than $-v_1$. [See Figure 7–21(b).] Now, as soon as the capacitor's voltage v_2 becomes more negative than $-v_1$, the net differential voltage v_{id} becomes positive and hence drives the output of the op-amp back to its positive saturation $+V_{sat}$. This completes one cycle. With output at $+V_{sat}$, voltage v_1 at the noninverting input is

$$v_1 = \frac{R_1}{R_1 + R_2}(+V_{sat}) \tag{7–25b}$$

The time period T of the output waveform is given by

$$T = 2RC \ln\left(\frac{2R_1 + R_2}{R_2}\right) \tag{7–26a}$$

or

$$f_o = \frac{1}{2RC \ln[(2R_1 + R_2)/R_2]} \tag{7–26b}$$

Equation (7–26b) indicates that the frequency of the output f_o is not only a function of the RC time constant but also of the relationship between R_1 and R_2. For example, if $R_2 = 1.16R_1$, Equation (7–26b) becomes

$$f_o = \frac{1}{2RC} \tag{7–27}$$

Equation (7–27) shows that the smaller the RC time constant, the higher the output frequency f_o, and vice versa. As with sine wave oscillators, the highest frequency generated by the square wave generator is also set by the slew rate of the op-amp. An attempt to operate the circuit at relatively higher frequencies causes the oscillator's output to become triangular. In practice, each inverting and noninverting terminal needs a series resistance R_S to prevent excessive differential current flow because the inputs of the op-amp are subjected to large differential voltages. The resistance R_S used should be 100 kΩ or higher. A reduced peak-to-peak output voltage swing can be obtained in the square-wave generator of Figure 7–21(a) by using back-to-back zeners at the output terminal.

EXAMPLE 7–15

Design the square-wave oscillator of Figure 7–21(a) so that f_o = 1 kHz. The op-amp is a 741 with dc supply voltages = ±15 V.

SOLUTION

Use $R_2 = 1.16\,R_1$ so that the simplified frequency Equation (7–27) can be applied. Let $R_1 = 10\ \text{k}\Omega$. Then

$$R_2 = (1.16)(10\ \text{k}\Omega) = 11.6\ \text{k}\Omega$$

(Use R_2 = 20-kΩ potentiometer.)

Next, choose a value of C and calculate the value of R from Equation (7–27). Hence let $C = 0.05\ \mu\text{F}$. By Equation (7–27),

$$R = \frac{1}{(10)(10^{-8})(10^{3})} = 10\ \text{k}\Omega$$

Thus

$$R_1 = 10\ \text{k}\Omega$$

$$R_2 = 11.6\ \text{k}\Omega \quad \text{(20-k}\Omega\text{ potentiometer)}$$

$$R = 10\ \text{k}\Omega$$

$$C = 0.05\ \mu\text{F}$$

7-16 TRIANGULAR WAVE GENERATOR

Recall that the output waveform of the integrator is triangular if its input is a square wave. (Refer to Section 6–12.) This means that a triangular wave generator can be formed by simply connecting an integrator to the square wave generator of Figure 7–21(a). The resultant circuit is shown in Figure 7–22(a). This circuit requires a dual op-amp, two capacitors, and at least five resistors. The frequencies of the square wave and triangular wave are the same. For fixed R_1, R_2, and C values, the frequency of the square wave as well as the triangular wave depends on the resistance R. [See Equation (7–26b).] As R is increased or decreased, the frequency of the triangular wave will decrease or increase, respectively. Although the amplitude of the square wave is constant ($\pm V_{sat}$), the amplitude of the triangular wave decreases with an increase in its frequency, and vice versa. [See Figure 7–22(b).]

The input of integrator A_2 is a square wave, while its output is a triangular wave. However, for the output of A_2 to be a triangular wave requires that $5R_3C_2 > T/2$, where T is the period of the square wave input. As a general rule, R_3C_2 should be equal to T. To obtain a stable triangular wave, it may also be

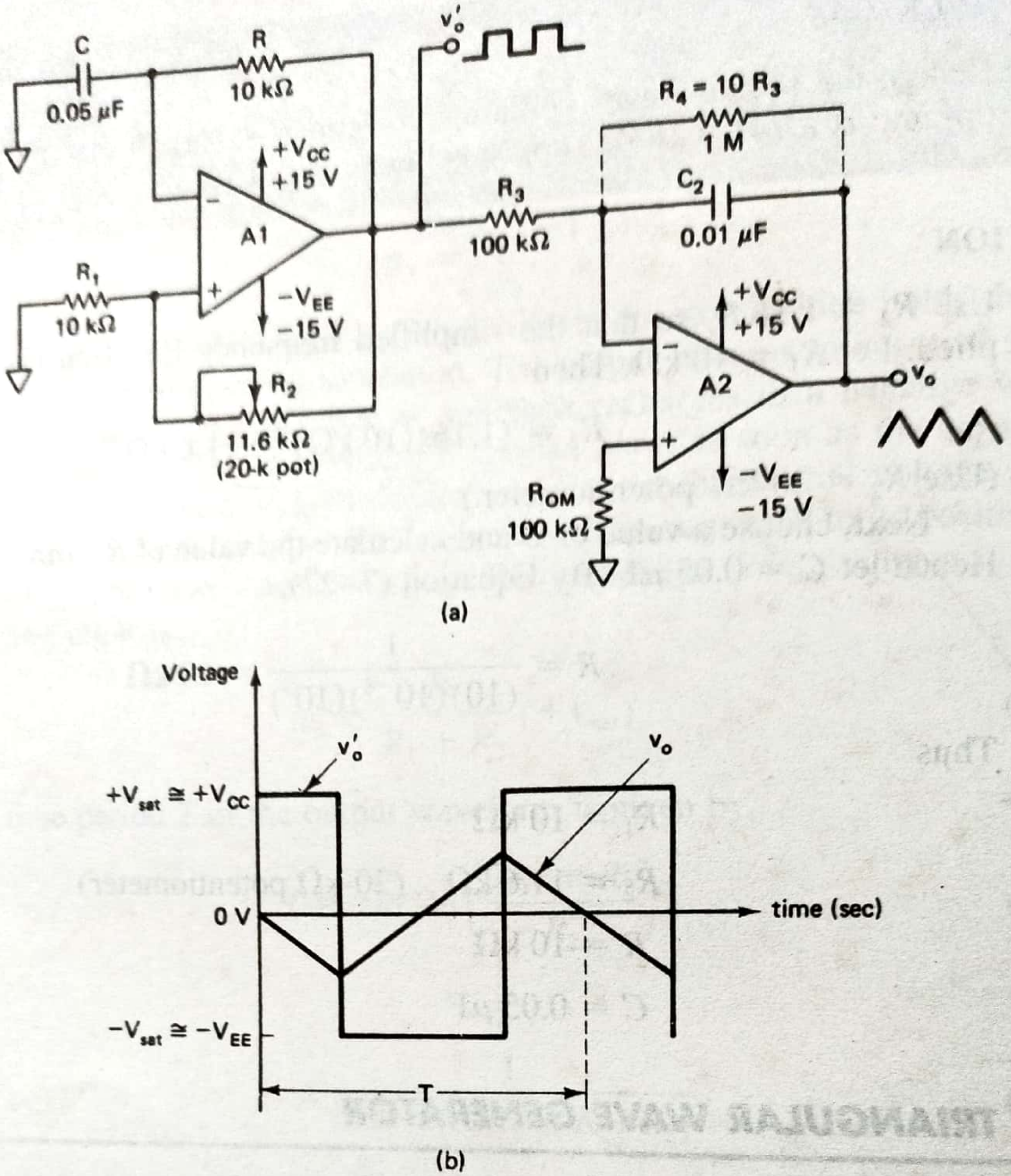

FIGURE 7–22 Triangular wave generator. (a) Circuit. (b) Its output waveform. A_1 and A_2 dual op-amp: 1458/353.

necessary to shunt the capacitor C_2 with resistance $R_4 = 10R_3$ and connect an offset voltage-compensating network at the noninverting terminal of A_2. As with any other oscillator, the frequency of the triangular wave generator is limited by the slew rate of the op-amp. Therefore, a high-slew-rate op-amp such as LM301 should be used for the generation of relatively higher frequencies.

Another triangular wave generator, which requires fewer components, is shown in Figure 7–23(a). The generator consists of a *comparator* A_1 and an *integrator* A_2. The comparator A_1 compares the voltage at point P continuously with the inverting input that is at 0 V. When the voltage at P goes slightly below or above 0 V, the output of A_1 is at the negative or positive saturation level, respectively.

To illustrate the circuit's operation, let us set the output of A_1 at positive saturation $+V_{sat}$ ($\cong +V_{CC}$). This $+V_{sat}$ is an input of the integrator A_2. The output of

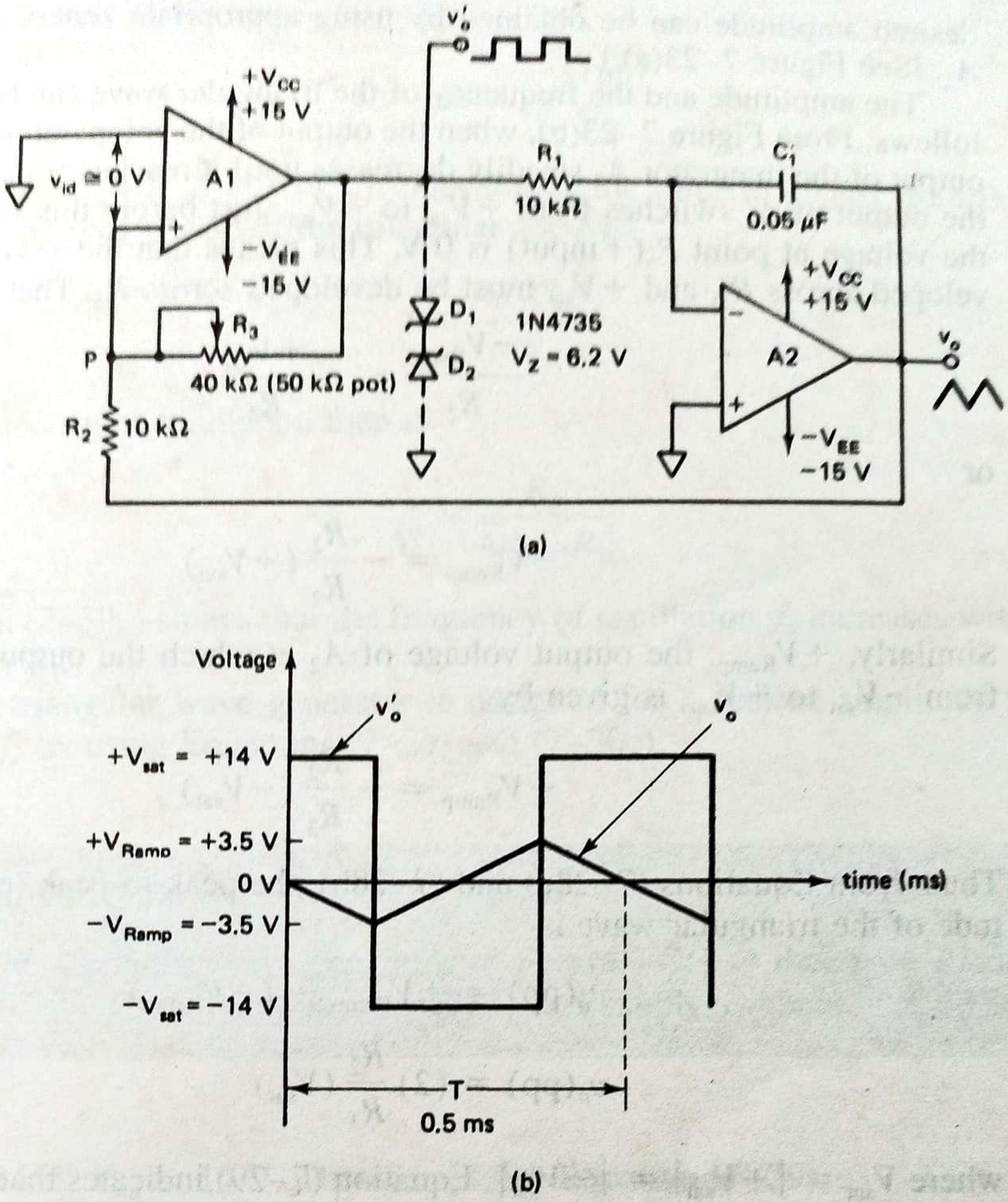

FIGURE 7–23 Triangular wave generator. (a) Circuit. (b) Its waveforms. A_1 and A_2 dual op-amp: 1458/353.

A_2, therefore, will be a negative-going ramp. Thus one end of the voltage-divider R_2–R_3 is the positive saturation voltage $+V_{sat}$ of A_1 and the other is the negative-going ramp of A_2. When the negative-going ramp attains a certain value $-V_{Ramp}$, point P is slightly below 0 V; hence the output of A_1 will switch from positive saturation to negative saturation $-V_{sat}$ ($\cong -V_{EE}$). This means that the output of A_2 will now stop going negatively and will begin to go positively. The output of A_2 will continue to increase until it reaches $+V_{Ramp}$. At this time the point P is slightly above 0 V; therefore, the output of A_1 is switched back to the positive saturation level $+V_{sat}$. The sequence then repeats. The output waveform is as shown in Figure 7–23(b).

The frequencies of the square wave and the triangular wave are the same. The amplitude of the square wave is a function of the dc supply voltages. However, a desired amplitude can be obtained by using appropriate zeners at the output of A_1. [See Figure 7–23(a).]

The amplitude and the frequency of the triangular wave can be determined as follows: From Figure 7–23(b), when the output of the comparator A_1 is $+V_{sat}$, the output of the integrator A_2 steadily decreases until it reaches $-V_{Ramp}$. At this time the output of A_1 switches from $+V_{sat}$ to $-V_{sat}$. Just before this switching occurs, the voltage at point P (+input) is 0 V. This means that the $-V_{Ramp}$ must be developed across R_2, and $+V_{sat}$ must be developed across R_3. That is,

$$\frac{-V_{Ramp}}{R_2} = -\frac{+V_{sat}}{R_3}$$

or

$$-V_{Ramp} = -\frac{R_2}{R_3}(+V_{sat}) \tag{7–28a}$$

Similarly, $+V_{Ramp}$, the output voltage of A_2 at which the output of A_1 switches from $-V_{sat}$ to $+V_{sat}$, is given by

$$+V_{Ramp} = -\frac{R_2}{R_3}(-V_{sat}) \tag{7–28b}$$

Thus, from Equations (7–28a) and (7–28b), the peak-to-peak (pp) output amplitude of the triangular wave is

$$v_o(\text{pp}) = +V_{Ramp} - (-V_{Ramp}) \tag{7–29}$$

$$v_o(\text{pp}) = (2)\frac{R_2}{R_3}(V_{sat})$$

where $V_{sat} = |+V_{sat}| = |-V_{sat}|$. Equation (7–29) indicates that the amplitude of the triangular wave decreases with an increase in R_3.

The time it takes for the output waveform to swing from $-V_{Ramp}$ to $+V_{Ramp}$ (or from $+V_{Ramp}$ to $-V_{Ramp}$) is equal to half the time period $T/2$. [See Figure 7–23(b).] This time can be calculated from the integrator output equation, (6–23), by substituting $v_i = -V_{sat}$, $v_o = v_o(\text{pp})$, and $C = 0$.

$$v_o(\text{pp}) = -\frac{1}{R_1C_1}\int_0^{T/2}(-V_{sat})\,dt \tag{6–23}$$

$$= \left(\frac{V_{sat}}{R_1C_1}\right)\left(\frac{T}{2}\right)$$

Hence

$$\frac{T}{2} = \frac{v_o(\text{pp})}{V_{sat}}(R_1C_1)$$

or

$$T = (2R_1C_1)\frac{v_o(\text{pp})}{V_{sat}} \tag{7-30a}$$

where $V_{sat} = |+V_{sat}| = |-V_{sat}|$. Substituting the value of $v_o(\text{pp})$ from Equation (7–29), the time period of the triangular wave is

$$T = \frac{4R_1C_1R_2}{R_3} \tag{7-30b}$$

The frequency of oscillation then is

$$f_o = \frac{R_3}{4R_1C_1R_2} \tag{7-30c}$$

Equation (7–30c) shows that the frequency of oscillation f_o increases with an increase in R_3.

The triangular wave generator is designed for a desired amplitude and frequency f_o by using Equations (7–29) and (7–30c).

EXAMPLE 7–16

Design the triangular wave generator of Figure 7–23 so that $f_o = 2$ kHz and $v_o(\text{pp}) = 7$ V. The op-amp is a 1458/772 and supply voltages = ± 15 V.

SOLUTION

For the 1458, $V_{sat} = 14$ V. Therefore, from Equation (7–29),

$$\frac{R_2}{R_3} = \frac{7}{(2)(14)}$$

$$R_2 = \frac{R_3}{4}$$

Let $R_2 = 10\ \text{k}\Omega$; then $R_3 = 40\ \text{k}\Omega$. (Use a 50-kΩ potentiometer.)

Now, from Equation (7–30c),

$$2\ \text{kHz} = \frac{40\ \text{k}\Omega}{(4)(R_1C_1)(10\ \text{k}\Omega)}$$

Therefore, $R_1C_1 = 0.5$ ms. Let $C_1 = 0.05\ \mu\text{F}$; then $R_1 = 10\ \text{k}\Omega$. *Thus* $R_1 = R_2 = 10\ \text{k}\Omega$, $C_1 = 0.05\ \mu\text{F}$, and $R_3 = 40\ \text{k}\Omega$ (50-kΩ potentiometer). [See Figure 7–23(a).]

7-17 SAWTOOTH WAVE GENERATOR

The difference between the triangular and sawtooth waveforms is that the rise time of the triangular wave is always equal to its fall time. That is, the same amount of time is required for the triangular wave to swing from $-V_{Ramp}$ to $+V_{Ramp}$ as from $+V_{Ramp}$ to $-V_{Ramp}$. [See Figure 7–23(b).] On the other hand, the sawtooth waveform has unequal rise and fall times. That is, it may rise positively many times faster than it falls negatively, or vice versa. The triangular wave generator of Figure 7–23(a) can be converted into a sawtooth wave generator by injecting a variable dc voltage into the noninverting terminal of the integrator A_2. This can be accomplished by using the potentiometer and connecting it to $+V_{CC}$ and $-V_{EE}$ as shown in Figure 7–24(a). Depending on the R_4 setting, a certain dc level is inserted in the output of A_2. Now, suppose that the output of A_1 is a square wave and the potentiometer R_4 is adjusted for a certain dc level. This means that the output of A_2 will be a triangular wave, riding on some dc level that is a function of the R_4 setting. The duty cycle of the square wave will be determined by the polarity and amplitude of this dc level. A duty cycle less than 50% will then cause the output of A_2 to be a sawtooth. [See Figure 7–24(b).] With the wiper at the center of R_4, the output of A_2 is a triangular wave. For any other position of the R_4 wiper, the output is a sawtooth waveform. Specifically as the R_4 wiper is moved toward $-V_{EE}$, the rise time of the sawtooth wave becomes longer than the fall time, as shown in Figure 7–24(b). On the other hand, as the wiper is moved toward $+V_{CC}$, the fall time becomes longer than the rise time. Also, the frequency of the sawtooth wave decreases as R_4 is adjusted toward $+V_{CC}$ or $-V_{EE}$. However, the amplitude of the sawtooth wave is independent of the R_4 setting.

7-18 VOLTAGE-CONTROLLED OSCILLATOR

In all the preceding oscillators, the frequency is determined by the *RC* time constant. However, there are applications, such as *frequency modulation* (FM), *tone generators*, and *frequency shift keying* (FSK), where the frequency needs to be controlled by means of an input voltage called *control voltage*. This function is achieved in the *voltage-controlled oscillator* (VCO), also called a *voltage-to-frequency converter*. A typical example is the Signetics NE/SE 566 VCO, which provides simultaneous square wave and triangular wave outputs as a function of input voltage. Figure 7–25(b) is a block diagram of the 566. The frequency of oscillation is determined by an external resistor R_1, capacitor C_1, and the voltage V_C applied to the control terminal 5. [See Figure 7–25(c).] The triangular wave is generated by alternately charging the external capacitor C_1 by one current source and then linearly discharging it by another. [See Figure 7–25(b).] The charge–discharge levels are determined by Schmitt trigger action. The Schmitt trigger also provides the square wave output. Both the output waveforms are buffered so that

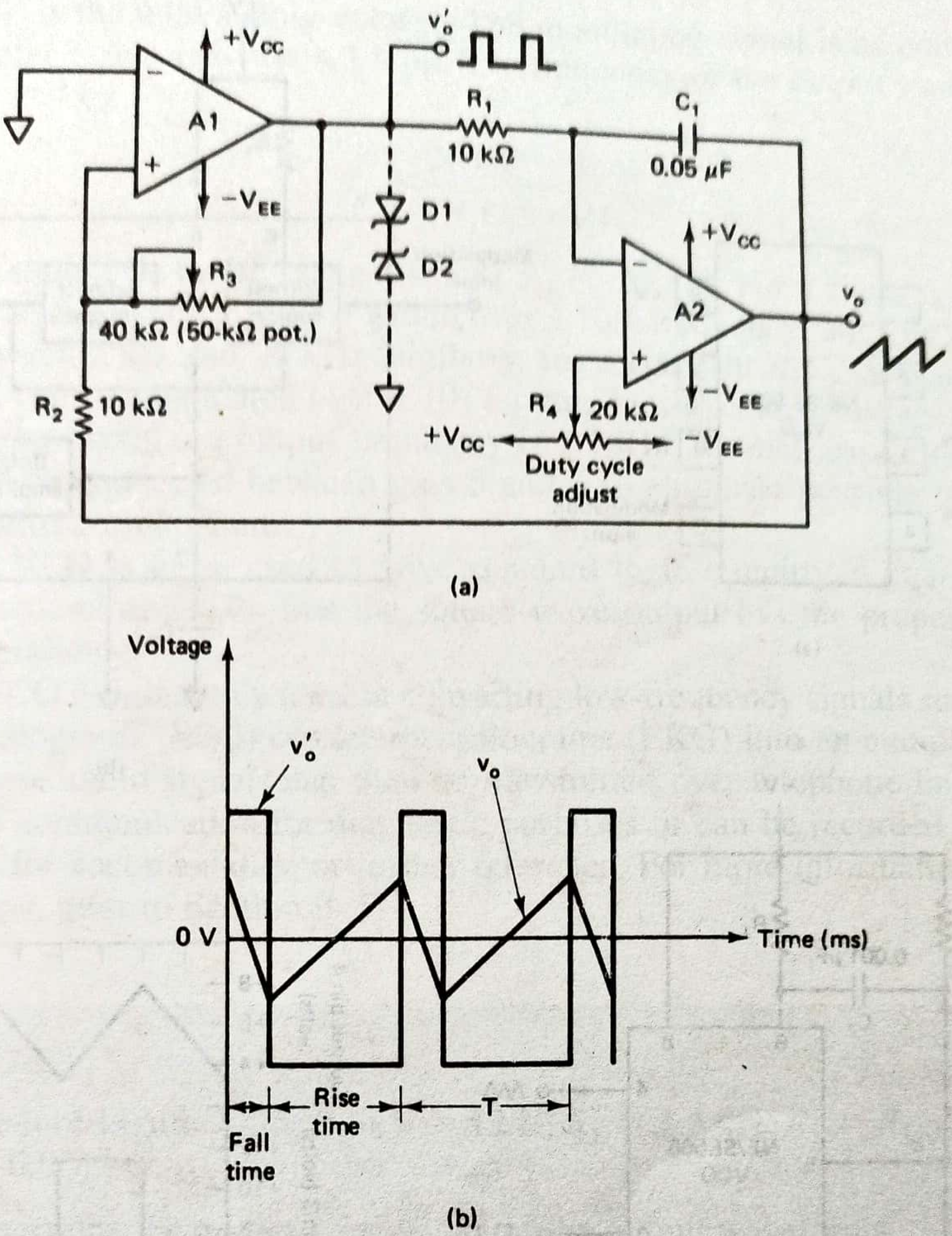

FIGURE 7–24 Sawtooth wave generator. (a) Circuit. A_1 and A_2 dual op-amp: 1458/353. D_1 and D_2: IN4735 with $V_Z = 6.2$ V. (b) Output waveform when noninverting input of A_2 is at some negative dc level.

the output impedance of each is 50 Ω. The typical amplitude of the triangular wave is 2.4 V pp and that of the square wave is 5.4 V pp.

Figure 7–25(c) is a typical connection diagram. In this arrangement, the R_1C_1 combination determines the free-running frequency, and the control voltage V_C at terminal 5 is set by the voltage divider formed with R_2 and R_3. The initial voltage V_C at terminal 5 must be in the range

$$\frac{3}{4}(+V) \leq V_C \leq +V \qquad \text{(7–31a)}$$

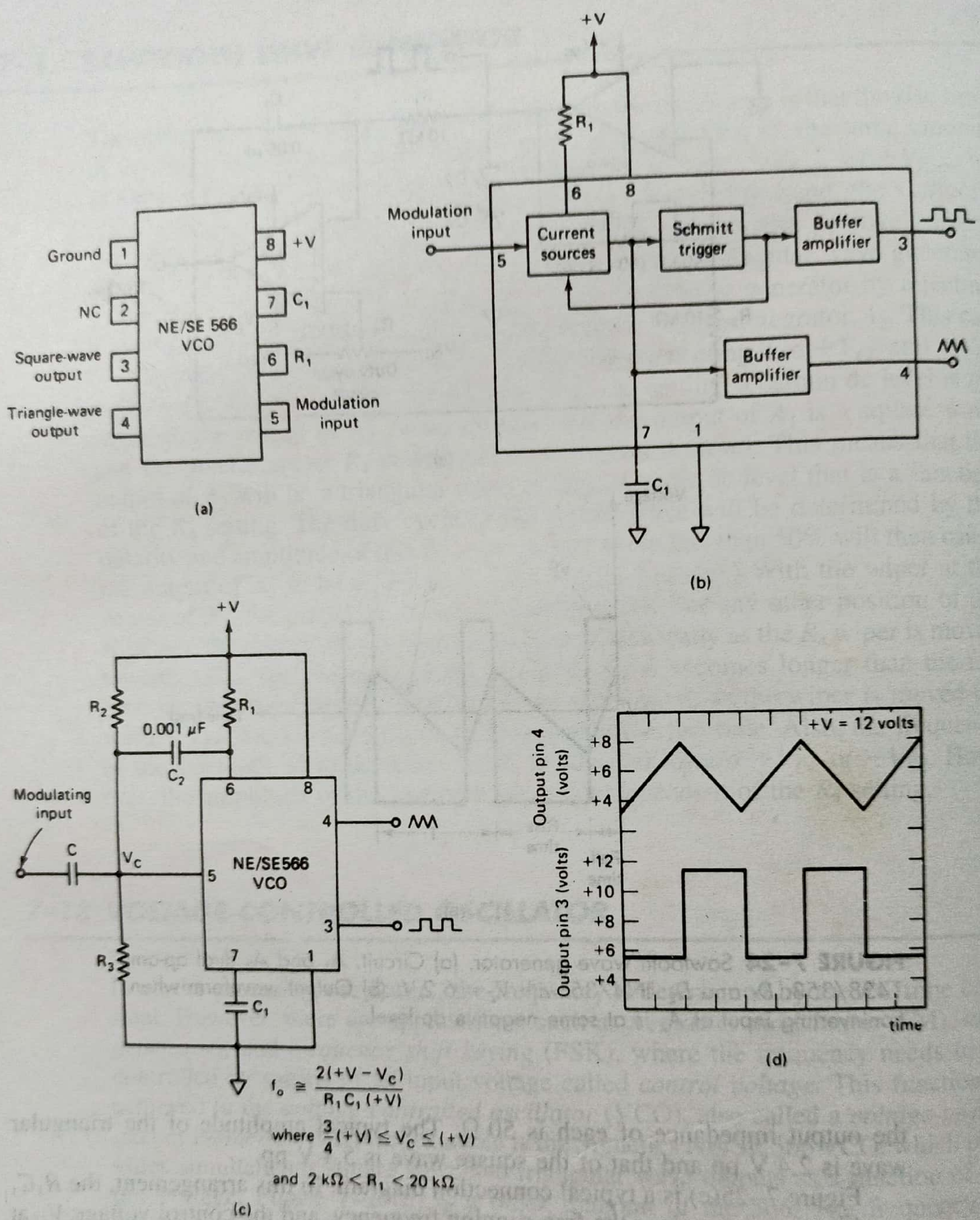

FIGURE 7–25 Voltage-controlled oscillator 566. (a) Pin configuration. (b) Block diagram. (c) Typical connection diagram. (d) Output waveforms. (Courtesy of Signetics Corporation.)

where $+V$ is the total supply voltage. The modulating signal is ac coupled with the capacitor C and must be $<3\ V$ pp. The frequency of the output waveforms is approximated by

$$f_o \cong \frac{2(+V - V_C)}{R_1 C_1 (+V)} \tag{7–31b}$$

where R_1 should be in the range $2\ \text{k}\Omega < R_1 < 20\ \text{k}\Omega$. For a fixed V_C and constant C_1, the frequency f_o can be varied over a 10:1 frequency range by the choice of R_1 between 2 kΩ and 20 kΩ. Similarly, for a constant R_1C_1 product, the frequency f_o can be modulated over a 10 : 1 range by the control voltage V_C. In either case the maximum output frequency is 1 MHz. A small capacitor of 0.001 μF should be connected between pins 5 and 6 to eliminate possible oscillations in the control current source.

If the VCO is to be used to drive standard logic circuitry, a dual supply of ±5 V is recommended so that the square wave output has the proper dc levels for logic circuitry.

The VCO is commonly used in converting low-frequency signals such as electroencephalograms (EEG) or electrocardiograms (EKG) into an audio-frequency range. These audio signals can then be transmitted over telephone lines or two-way radio communication for diagnostic purposes or can be recorded on a magnetic tape for documentation or further reference. For more information on VCO applications, refer to Section 9–5.

EXAMPLE 7–17

In the circuit of Figure 7–25(c), $+V = 12$ V, $R_2 = 1.5\ \text{k}\Omega$, $R_1 = R_3 = 10\ \text{k}\Omega$, and $C_1 = 0.001\ \mu\text{F}$.

a. Determine the nominal frequency of the output waveforms.
b. Compute the modulation in the output frequencies if V_C is varied between 9.5 V and 11.5 V.
c. Draw the square wave output waveform if the modulating input is a sine wave, as shown in Figure 7–26.

SOLUTION

a. Using the voltage-divider rule, the initial control voltage V_C at terminal 5 is

$$V_C = \frac{(10\ \text{k})(12)}{11.5\ \text{k}} = 10.43\ \text{V}$$

From Equation (7–31b), the approximate nominal frequency f_o is

$$f_o \cong \frac{(2)(12 - 10.43)}{(10^4)(10^{-9})(12)} = 26.17\ \text{kHz}$$

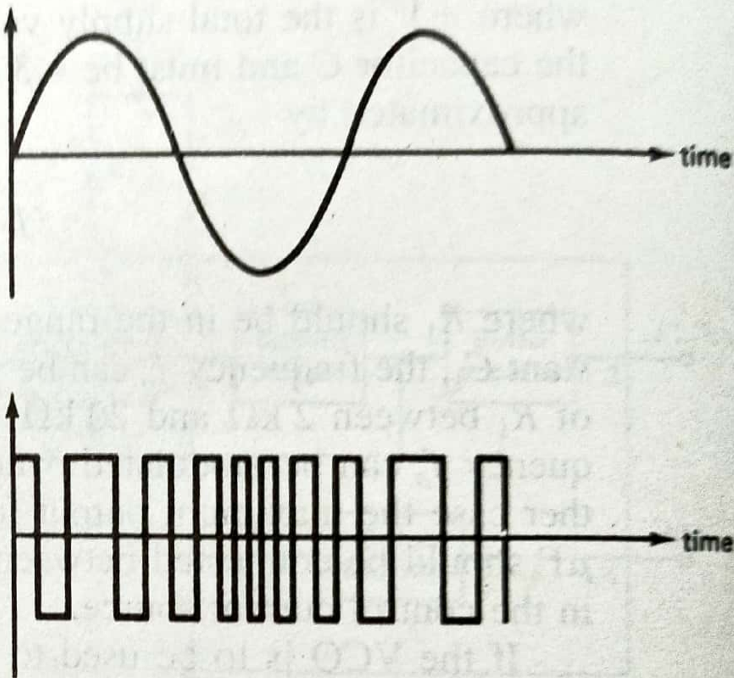

FIGURE 7–26 Input and output waveforms for Example 7–17.

b. The modulation in the output frequencies can be calculated from Equation (7–31b) by substituting for V_C, first 9.5 V and then 11.5 V, as follows:

$$f_o \cong \frac{(2)(12 - 9.5)}{(10^4)(10^{-9})(12)} = 41.67 \text{ kHz}$$

$$f_o \cong \frac{(2)(12 - 11.5)}{(10^4)(10^{-9})(12)} = 8.33 \text{ kHz}$$

Thus the change in the output frequency is

$$41.67 \text{ kHz} - 8.33 \text{ kHz} = 33.34 \text{ kHz}$$

c. During the positive half-cycle of the sine wave input, the control voltage V_C will increase. Therefore, according to Equation (7–31b), the frequency of the output waveform will decrease and the time period will increase. Exactly the opposite action will take place during the negative half-cycle of the input, as shown in Figure 7–26.