CHAPTER 6

Signal Generators

LEARNING OBJECTIVES

Upon completion of this chapter on signal generators, you will be able to:

- Explain the operation of a multivibrator circuit, sketch its output voltage waveshapes, and calculate its frequency of oscillation.
- Make a one-shot multivibrator and explain the purpose of this circuit.
- Show how two op amps, three resistors, and one capacitor can be connected to form an inexpensive triangle/square-wave generator.
- Predict the frequency of oscillation and amplitude of the voltages in a bipolar or unipolar triangle-wave generator and identify its disadvantages.
- Build a sawtooth wave generator and tell how it can be used as a voltage-to-frequency converter, frequency modulator, or frequency shift key circuit.
- Connect an AD630 balanced modulator/demodulator to operate as a switched gain amplifier.

- Connect the AD630 to an op amp circuit to make a *precision* triangle-wave generator whose output voltage amplitude can be adjusted independently of the oscillating frequency, and vice versa.
- Build, test, measure, and explain the operation of an AD639 universal trigonometric function generator when it is wired to generate sine functions.
- Connect the AD639 to the triangle-wave generator to make a superb *precision* sine-wave generator. Its oscillating frequency can be adjusted over a wide frequency range by a *single* resistor, without changing amplitude.
- Know about the operation of a single IC function generator.

6-0 INTRODUCTION

Up to now our main concern has been to use the op amp in circuits that process signals. In this chapter we concentrate on op amp circuits that *generate* signals. Four of the most common and useful signals are described by their shape when viewed on an oscilloscope. They are the square wave, triangular wave, sawtooth wave, and sine wave. Accordingly, the signal generator is classified by the shape of the wave it generates. Some circuits are so widely used that they have been assigned a special name. For example, the first circuit presented in Section 6-1 is a multivibrator that generates primarily square waves and exponential waves. Some ICs that generate these waveforms from a single IC are available. However, you may need a waveform quickly and not have on hand one of these function generator ICs.

6-1 FREE-RUNNING MULTIVIBRATOR

6-1.1 Multivibrator Action

A *free-running* or *astable multivibrator* is a square-wave generator. The circuit of Fig. 6-1 is a multivibrator circuit and looks something like a comparator with hysteresis (Chapter 4), except that the input voltage is replaced by a capacitor. Resistors R_1 and R_2 form a voltage divider to feed back a fraction of the output to the (+) input. When V_o is at $+V_{sat}$, as shown in Fig. 6-1(a), the feedback voltage is called the upper-threshold voltage V_{UT}. V_{UT} is given in Eq. (4-1) and repeated here for convenience:

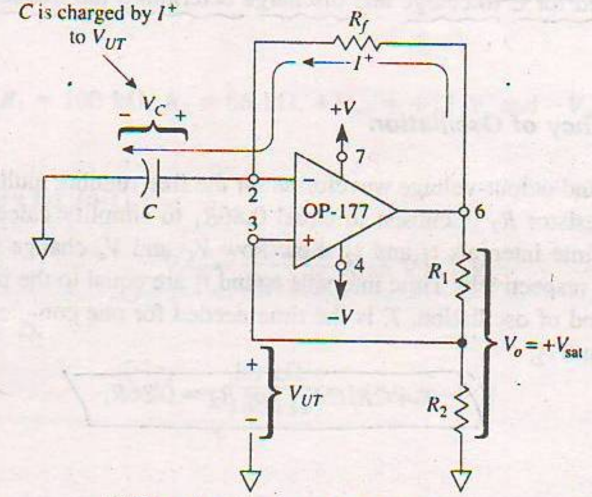
$$V_{UT} = \frac{R_2}{R_1 + R_2}(+V_{sat}) \tag{6-1}$$

Resistor R_f provides a feedback path to the (−) input. When V_o is at $+V_{sat}$, current I^+ flows through R_f to charge capacitor C toward V_{UT}. As long as the capacitor voltage V_C is less than V_{UT}, the output voltage remains at $+V_{sat}$.

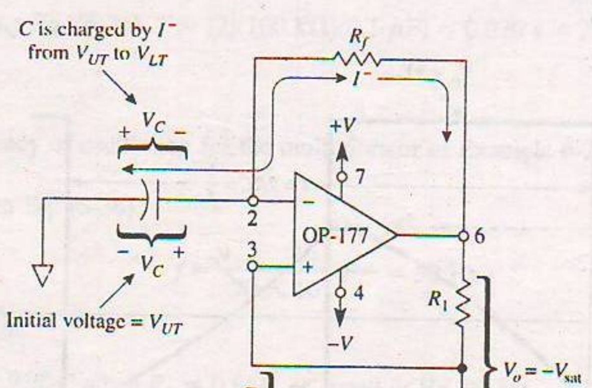
When V_C charges to a value slightly greater than V_{UT}, the (−) input goes positive with respect to the (+) input. This switches the output from $+V_{sat}$ to $-V_{sat}$. The (+) input is now held negative with respect to ground because the feedback voltage is negative and given by

$$V_{LT} = \frac{R_2}{R_1 + R_2}(-V_{sat}) \tag{6-2}$$

Equation (6-2) is the same as Eq. (4-2). Just after V_o switches to $-V_{sat}$, the capacitor has an initial voltage equal to V_{UT} [see Fig. 6-1(b)]. Now current I^- discharges C to 0 V and recharges C to V_{LT}. When V_C becomes slightly more negative than the feedback voltage V_{LT}, output voltage V_o switches back to $+V_{sat}$. The condition in Fig. 6-1(a) is reestab-



(a) When $V_o = +V_{sat}$, V_C charges toward V_{UT}.



(a) When $V_o = -V_{sat}$, V_C charges toward V_{LT}.

FIGURE 6-1 Free-running multivibrator ($R_1 = 100\,\text{k}\Omega$, $R_2 = 86\,\text{k}\Omega$). Output-voltage waveforms shown in Fig. 6-2.

lished except that C now has an initial charge equal to V_{LT}. The capacitor will discharge from V_{LT} to 0 V and then recharge to V_{UT}, and the process is repeating. Free-running multivibrator action is summarized as follows:

1. When $V_o = -V_{sat}$, C discharges from V_{UT} to V_{LT} and switches V_o to $+V_{sat}$.
2. When $V_o = +V_{sat}$, C charges from V_{LT} to V_{UT} and switches V_o to $-V_{sat}$.

The time needed for C to charge and discharge determines the frequency of the multivibrator.

6-1.2 Frequency of Oscillation

The capacitor and output-voltage waveforms for the free-running multivibrator are shown in Fig. 6-2. Resistor R_2 is chosen to equal $0.86R_1$ to simplify calculation of capacitor charge time. Time intervals t_1 and t_2 show how V_C and V_o change with time for Figs. 6-1(a) and (b), respectively. Time intervals t_1 and t_2 are equal to the product of R_f and C.

The period of oscillation, T, is the time needed for one complete cycle. Since T is the sum of t_1 and t_2,

$$\boxed{T = 2R_fC \qquad \text{for } R_2 = 0.86R_1} \tag{6-3a}$$

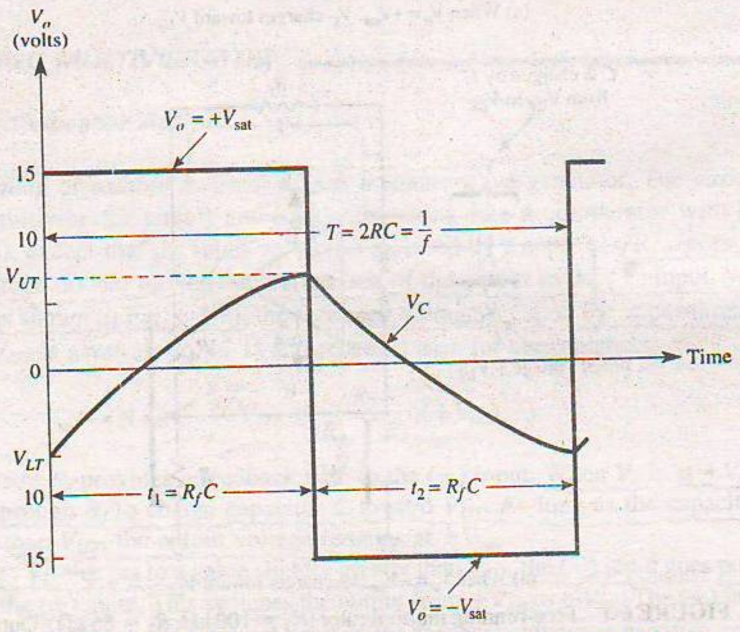


FIGURE 6-2 Voltage waveshapes for the multivibrator of Fig. 6-1.

The frequency of oscillation f is the reciprocal of period T and is expressed by

$$f = \frac{1}{T} = \frac{1}{2R_fC} \tag{6-3b}$$

where T is in seconds, f in hertz, R_f in ohms, and C in farads.

Example 6-1

In Fig. 6-1, if $R_1 = 100\ \text{k}\Omega$, $R_2 = 86\ \text{k}\Omega$, $+V_{sat} = +15$ V, and $-V_{sat} = -15$ V, find (a) V_{UT}; (b) V_{LT}.

Solution (a) By Eq. (6-1),

$$V_{UT} = \frac{86\ \text{k}\Omega}{186\ \text{k}\Omega} \times 15\ \text{V} \cong 7\ \text{V}$$

(b) By Eq. (6-2),

$$V_{LT} = \frac{86\ \text{k}\Omega}{186\ \text{k}\Omega}(-15\ \text{V}) \cong -7\ \text{V}$$

Example 6-2

Find the period of the multivibrator in Example 6-1 if $R_f = 100\ \text{k}\Omega$ and $C = 0.1\ \mu\text{F}$.

Solution Using Eq. (6-3a), $T = (2)(100\ \text{k}\Omega)(0.1\ \mu\text{F}) = 0.020\ \text{s} = 20$ ms.

Example 6-3

Find the frequency of oscillation for the multivibrator of Example 6-2.

Solution From Eq. (6-3b),

$$f = \frac{1}{20 \times 10^{-3}\ \text{s}} = 50\ \text{Hz}$$

Example 6-4

Show why $T = 2\,R_fC$ when $R_2 = 0.86R$, as stated in Eq. (6-3a).

Solution The time required for a capacitor C to charge through a resistor R_f from some *starting* capacitor voltage toward some *aiming* voltage to a *stop* voltage is expressed generally as

$$t = R_fC \ln\left(\frac{\text{aim} - \text{start}}{\text{aim} - \text{stop}}\right)$$

Applying the equation to Fig. 6-2 yields

$$t_1 = R_f C \ln\left(\frac{+V_{sat} - V_{LT}}{+V_{sat} - V_{UT}}\right)$$

If the magnitudes of $+V_{sat}$ and $-V_{sat}$ are equal, the term in parentheses simplifies to

$$\ln\left[\frac{+V_{sat} - \dfrac{R_2}{R_1 + R_2}(-V_{sat})}{+V_{sat} - \dfrac{R_2}{R_1 + R_2}(+V_{sat})}\right] = \ln\left(\frac{R_1 + 2\,R_2}{R_1}\right)$$

Since $\ln 2.718 = 1$, the ln term can be reduced to 1 if

$$\frac{R_1 + 2R_2}{R_1} = 2.718 \qquad \text{or} \qquad R_2 = 0.86R_1$$

Now $t_1 = R_f C$ and $t_2 = R_f C$ if $R_2 = 0.86R_1$. Therefore, $T = t_1 + t_2 = 2R_f C$.

6-2 ONE-SHOT MULTIVIBRATOR

6-2.1 Introduction

A *one-shot multivibrator* generates a single output pulse in response to an input signal. The length of the output pulse depends only on external components (resistors and capacitors) connected to the op amp. As shown in Fig. 6-3, the one-shot generates a single output pulse on the negative-going edge of E_i. The duration of the input pulse can be longer or shorter than the expected output pulse. The duration of the output pulse is represented by τ in Fig. 6-3. Since τ can be changed only by changing resistors or capacitors, the one-shot can be considered a *pulse stretcher*. This is because the width of the pulse can be longer than the input pulse. Moreover, the one-shot introduces an idea of an adjustable delay, that is, the delay between the time when E_i goes negative and the time for V_o to go positive again. Operation of the one-shot will be studied in three parts: (1) the stable state, (2) transition to the timing state, and (3) the timing state.

6-2.2 Stable State

In Fig. 6-4(a), V_o is at $+V_{sat}$. Voltage divider R_1 and R_2 feeds back V_{UT} to the (+) input. V_{UT} is given by Eq. (6-1). The diode D_1 clamps the (−) input at approximately +0.5 V. The (+) input is positive with respect to the (−) input, and the high open-loop gain times the differential input voltage ($E_d = 2.1 - 0.5 = 1.6$ V) holds V_o at $+V_{sat}$.

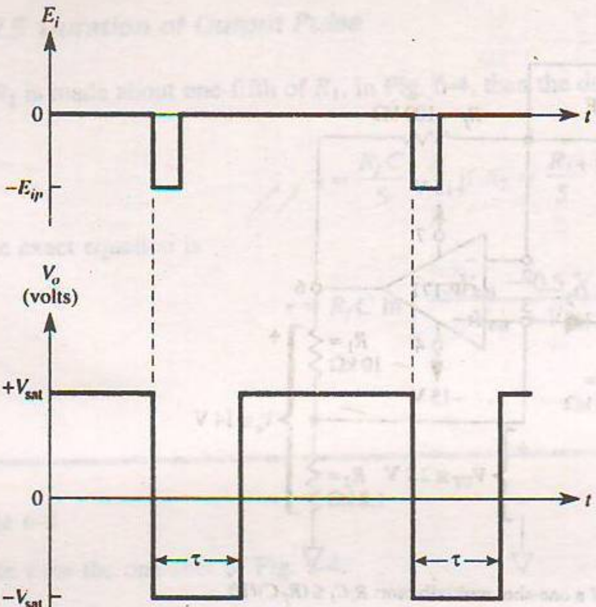


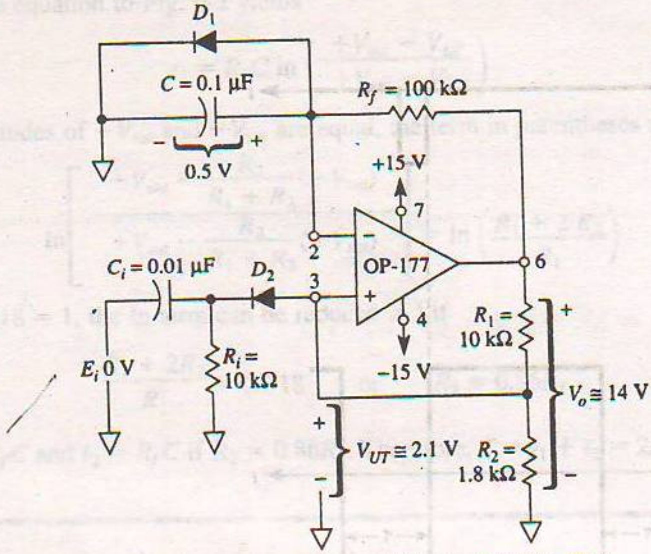
FIGURE 6-3 Input signal E_i and output pulse of a one-shot multivibrator.

6-2.3 Transition to the Timing State

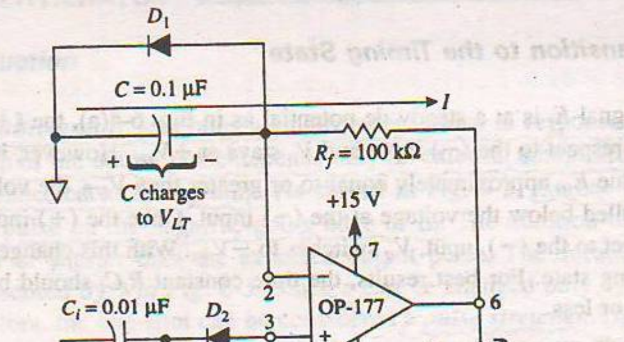
If input signal E_i is at a steady dc potential as in Fig. 6-4(a), the (+) input remains positive with respect to the (−) input and V_o stays at $+V_{sat}$. However, if E_i goes negative by a peak value E_{ip} approximately equal to or greater than V_{UT}, the voltage at the (+) input will be pulled below the voltage at the (−) input. Once the (+) input becomes negative with respect to the (−) input, V_o switches to $-V_{sat}$. With this change, the one-shot is now in its timing state. For best results, the time constant R_iC_i should be 1/10 the time constant R_fC or less.

6-2.4 Timing State

The timing state is an unstable state; that is, the one-shot cannot remain very long in this state for the following reasons. Resistors R_1 and R_2 in Fig. 6-4(b) feed back a negative voltage ($V_{LT} = -2.1$ V) to the (+) input. The diode D_1 is now reverse biased by $-V_{sat}$ and is essentially an open circuit. Capacitor C discharges to 0 and then recharges with a polarity opposite to that in Fig. 6-4(a) [see Fig. 6-4(b)]. As C recharges, the (−) input becomes more and more negative with respect to ground. When the capacitor voltage is slightly more negative than V_{LT}, V_o switches to $+V_{sat}$. The one-shot has now completed its output pulse and is back to the stable state in Fig. 6-4(a). Since the one-shot has only one stable state, it is also called a *monostable multivibrator.*



(a) Stable state of a one-shot multivibrator: $R_iC_i \leq (R_fC)/10$.



(b) Timing state: When E_i goes negative, V_o goes negative for 2 ms.

FIGURE 6-4 Monostable or one-shot multivibrator.

6-2.5 Duration of Output Pulse

If R_2 is made about one-fifth of R_1, in Fig. 6-4, then the duration of output pulse is given by

$$\tau = \frac{R_f C}{5} \qquad \text{if } R_2 = \frac{R_1}{5} \tag{6-4a}$$

The exact equation is

$$\tau = R_f C \ln \left[\frac{-V_{sat} - 0.5\text{ V}}{-V_{sat} - V_{UT}} \right] \tag{6-4b}$$

Example 6-5

Calculate τ for the one-shot of Fig. 6-4.

Solution By Eq. (6-4a),

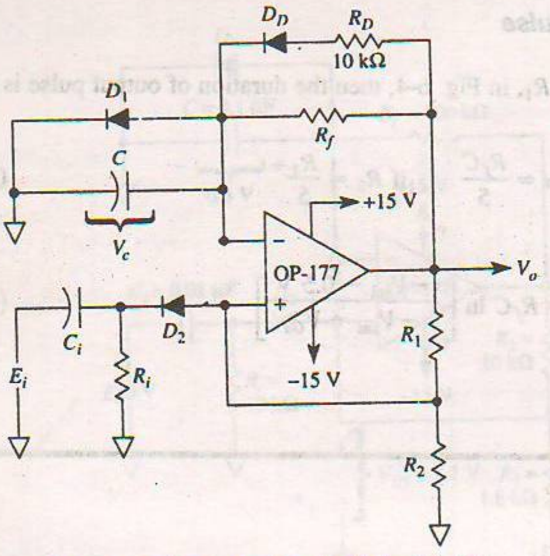
$$\tau = \frac{(100\text{ k}\Omega)(0.1\ \mu\text{F})}{5} = 2\text{ ms}$$

For test purposes, E_i can be obtained from a square-wave or pulse generator. Diode D_2 prevents the one-shot from coming out of the timing state on positive transitions of E_i. To build a one-shot that has a positive output pulse for a positive input signal, simply reverse the diodes.

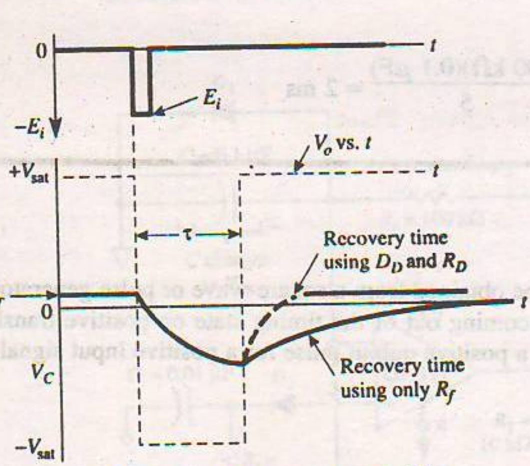
6-2.6 Recovery Time

After the timing state is completed, the output returns to $+V_{sat}$. However, the circuit is not ready to be retriggered reliably until C returns to its initial state of 0.5 V because it takes time for C to be discharged from $V_{LT} = -2.1$ V in Fig. 6-4(b) to 0.5 V in Fig. 6-4(a). This time interval is called *recovery time* and is shown in Fig. 6-5(b). Recovery time is approximately τ.

Normally, C is charged back to its initial state by a current through R_f. By adding a discharge resistor R_D in parallel with R_f, as in Fig. 6-5(a), the recovery time is reduced. Typically, if $R_D = 0.1R_f$, recovery time is reduced to one-tenth. Diode D_D prevents R_D from affecting the timing-cycle interval τ.



(a) Discharge diode D_D and R_D are added to Fig. 6-4.



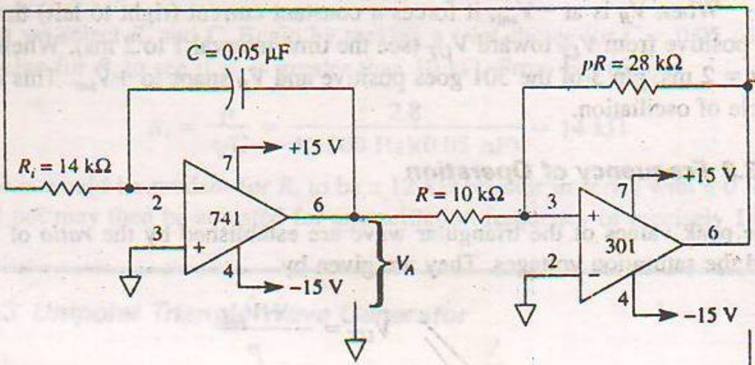
(b) Recovery time is reduced by D_D and R_D.

FIGURE 6-5 The recovery time of a one-shot multivibrator is reduced by adding discharge diode D_D and R_D. R_D should be about one-tenth of R_f to reduce recovery time to one-tenth.

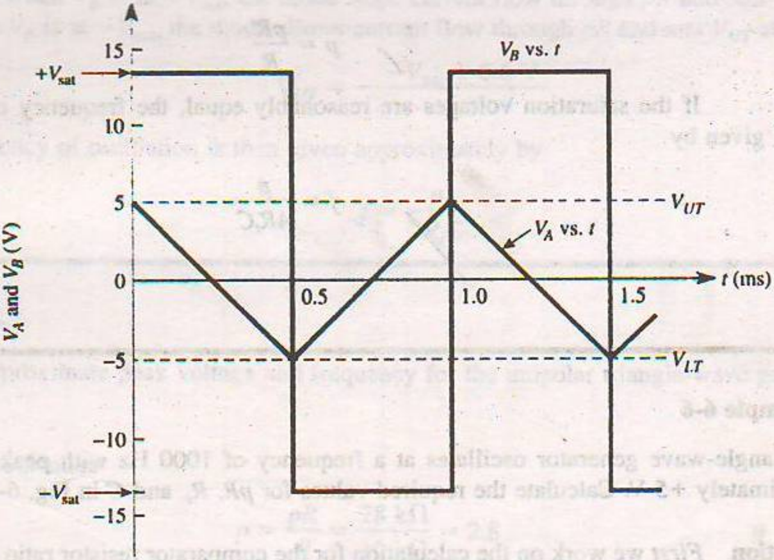
6-3 TRIANGLE-WAVE GENERATORS

6-3.1 Theory of Operation

A basic bipolar triangle-wave generator circuit is presented in Fig. 6-6. The triangle wave, V_A, is available at the output of the 741 integrator circuit. An additional square-wave signal, V_B, is available at the output of the 301 comparator.



(a) The 741 integrator circuit and 301 comparator circuit are wired to make a triangle-wave generator.



(b) Waveshapes.

FIGURE 6-6 The bipolar triangle-wave generator circuit in (a) generates triangle-wave and square-wave oscillator signals as in (b). (a) Basic bipolar triangle-wave generator oscillator frequency for 1000 Hz; (b) output-voltage waveshapes.

To understand circuit operation, refer to time interval 0 to 1 ms in Fig. 6-6. Assume that V_B is high at $+V_{sat}$. This forces a constant current (V_{sat}/R_i) through C (left to right) to drive V_A negative from V_{UT} to V_{LT}. When V_A reaches V_{LT}, pin 3 of the 301 goes negative, and V_B snaps to $-V_{sat}$, and $t = 1$ ms.

When V_B is at $-V_{sat}$, it forces a constant current (right to left) through C to drive V_A positive from V_{LT} toward V_{UT} (see the time interval 1 to 2 ms). When V_A reaches V_{UT} at $t = 2$ ms, pin 3 of the 301 goes positive and V_B snaps to $+V_{sat}$. This initiates the next cycle of oscillation.

6-3.2 Frequency of Operation

The peak values of the triangular wave are established by the *ratio* of resistor pR to R and the saturation voltages. They are given by

$$V_{UT} = -\frac{-V_{sat}}{p} \tag{6-5a}$$

$$V_{LT} = -\frac{+V_{sat}}{p} \tag{6-5b}$$

where

$$p = \frac{pR}{R} \tag{6-5c}$$

If the saturation voltages are reasonably equal, the frequency of oscillation, f, is given by

$$f = \frac{p}{4R_iC} \tag{6-6}$$

Example 6-6

A triangle-wave generator oscillates at a frequency of 1000 Hz with peak values of approximately +5 V. Calculate the required values for pR, R_i, and C in Fig. 6-6.

Solution *First* we work on the calculation for the comparator resistor ratio p that controls peak triangle-wave output voltages, V_{UT} and V_{LT}. $+V_{sat}$ is practically +14.2 V and $-V_{sat}$ is typically −13.8 V for a ±15-V supply. This observation points out one deficiency in our low-cost triangle-wave generator. It does *not* have *precisely* equal positive and negative peak outputs. (We will remedy this problem, at a higher cost, in Section 6-6.) From Eq. (6-5a), solve for p:

$$p = -\frac{-V_{sat}}{V_{UT}} = -\frac{-13.8\text{ V}}{5\text{ V}} = +2.76 \approx 2.8$$

Choose $R = 10\text{ k}\Omega$. Then from Eq. (6-5c) we solve for pR as

$$pR = 2.8(10\text{ k}\Omega) = 28\text{ k}\Omega$$

Next we select R_i and C. Begin by making a *trial* choice for $C = 0.05\ \mu F$. Then calculate a value for R_i to see if R_i is greater than 10 kΩ. From Eq. (6-6),

$$R_i = \frac{p}{4fC} = \frac{2.8}{4(1000\text{ Hz})(0.05\ \mu\text{F})} = 14\text{ k}\Omega$$

In practice it would be prudent for R_i to be a 12-kΩ resistor in series with a 0 to 5-kΩ pot. The 5-kΩ pot may then be adjusted for an oscillation frequency of precisely 1.00 kHz.

6-3.3 Unipolar Triangle-Wave Generator

The bipolar triangle-wave generator circuit of Fig. 6-6 can be changed to produce a unipolar triangle wave output. Simply add a diode in series with pR as shown in Fig. 6-7. Circuit operation is studied by reference to the waveshapes in Fig. 6-7(b).

When V_B is at $+V_{sat}$, the diode stops current flow through pR and sets V_{LT} at 0 V. When V_B is at $-V_{sat}$, the diode allows current flow through pR and sets V_{UT} at a value of

$$V_{UT} = -\frac{-V_{sat} + 0.6\text{ V}}{p} \tag{6-7a}$$

Frequency of oscillation is then given approximately by

$$f \simeq \frac{p}{2R_iC} \tag{6-7b}$$

Example 6-7

Find the approximate peak voltage and frequency for the unipolar triangle-wave generator in Fig. 6-7.

Solution Calculate

$$p = \frac{pR}{R} = \frac{28\text{ k}\Omega}{10\text{ k}\Omega} = 2.8$$

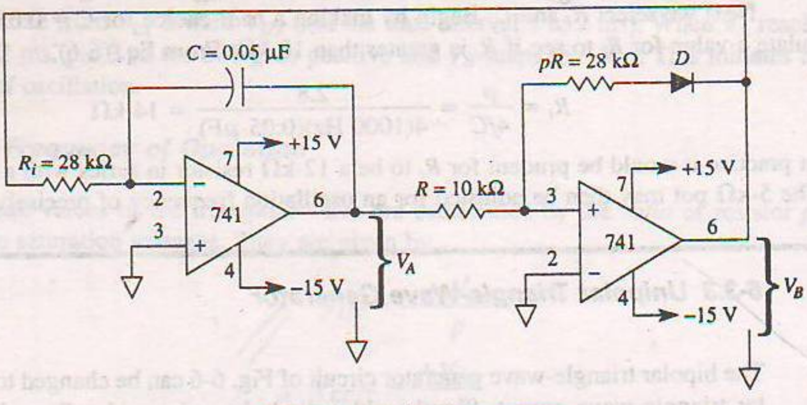
Find the peak value of V_A from Eq. (6-7a):

$$V_{UT} = -\left(\frac{-V_{sat} + 0.6\text{ V}}{p}\right) = -\left(\frac{-13.8\text{ V} + 0.6\text{ V}}{2.8}\right) \simeq 4.7\text{ V}$$

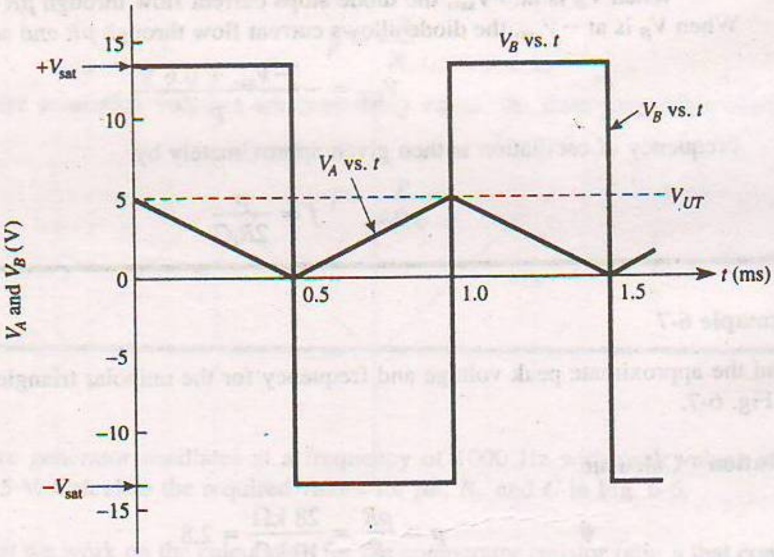
From Eq. (6-7b),

$$f = \frac{p}{2R_iC} = \frac{2.8}{2(28\text{ k}\Omega)(0.05\ \mu\text{F})} = 1000\text{ Hz}$$

Note the change in R_i value from Fig. 6-6(a) to Fig. 6-7(a).



(a) Unipolar triangle-wave generator.



(b) Waveshapes.

FIGURE 6-7 Diode D in (a) converts the bipolar triangle-wave generator into a unipolar triangle-wave generator. Waveshapes are shown in (b). (a) Basic unipolar triangle-wave generator; oscillating frequency is 1000 Hz. (b) Output-voltage waveshapes.

6-4 SAWTOOTH-WAVE GENERATOR

6-4.1 Circuit Operation

A low-parts-count sawtooth-wave generator circuit is shown in Fig. 6-8(a). Op amp A is a ramp generator. Since E_i is negative, $V_{o\,\text{ramp}}$ can only ramp up. The rate of rise of the ramp voltage is constant at

$$\frac{V_{o\,\text{ramp}}}{t} = \frac{E_i}{R_i C} \tag{6-8}$$

The ramp voltage is monitored by the (+) input of comparator 301B. If $V_{o\,\text{ramp}}$ is below V_{ref}, the comparator's output is negative. Diodes protect the transistors against excessive reverse bias.

When $V_{o\,\text{ramp}}$ rises to just exceed V_{ref}, the output $V_{o\,\text{comp}}$ goes to positive saturation. This forward biases "dump" transistor Q_D into saturation. The saturated transistor acts as a short circuit across the integrating capacitor C. C discharges quickly through Q_D to essentially 0 V. When $V_{o\,\text{comp}}$ goes positive, it turns on Q_1 to short-circuit the 10-kΩ potentiometer. This drops V_{ref} to almost zero volts.

As C discharges toward 0 V, it drives $V_{o\,\text{ramp}}$ rapidly toward 0 V. $V_{o\,\text{ramp}}$ drops below V_{ref}, causing $V_{o\text{comp}}$ to go negative and turn off Q_D. C begins charging linearly, and generation of a new sawtooth wave begins.

6-4.2 Sawtooth Waveshape Analysis

The ramp voltage rises at a rate of 1 V per millisecond in Fig. 6-8(b). Meanwhile, $V_{o\,\text{comp}}$ is shown to be negative. When the ramp crosses V_{ref}, $V_{o\,\text{comp}}$ snaps positive to drive the ramp voltage quickly toward 0 V. As $V_{o\,\text{ramp}}$ snaps to 0 V, the comparator's output is reset to negative saturation. Ramp operation is summarized in Fig. 6-8(c).

6-4.3 Design Procedure

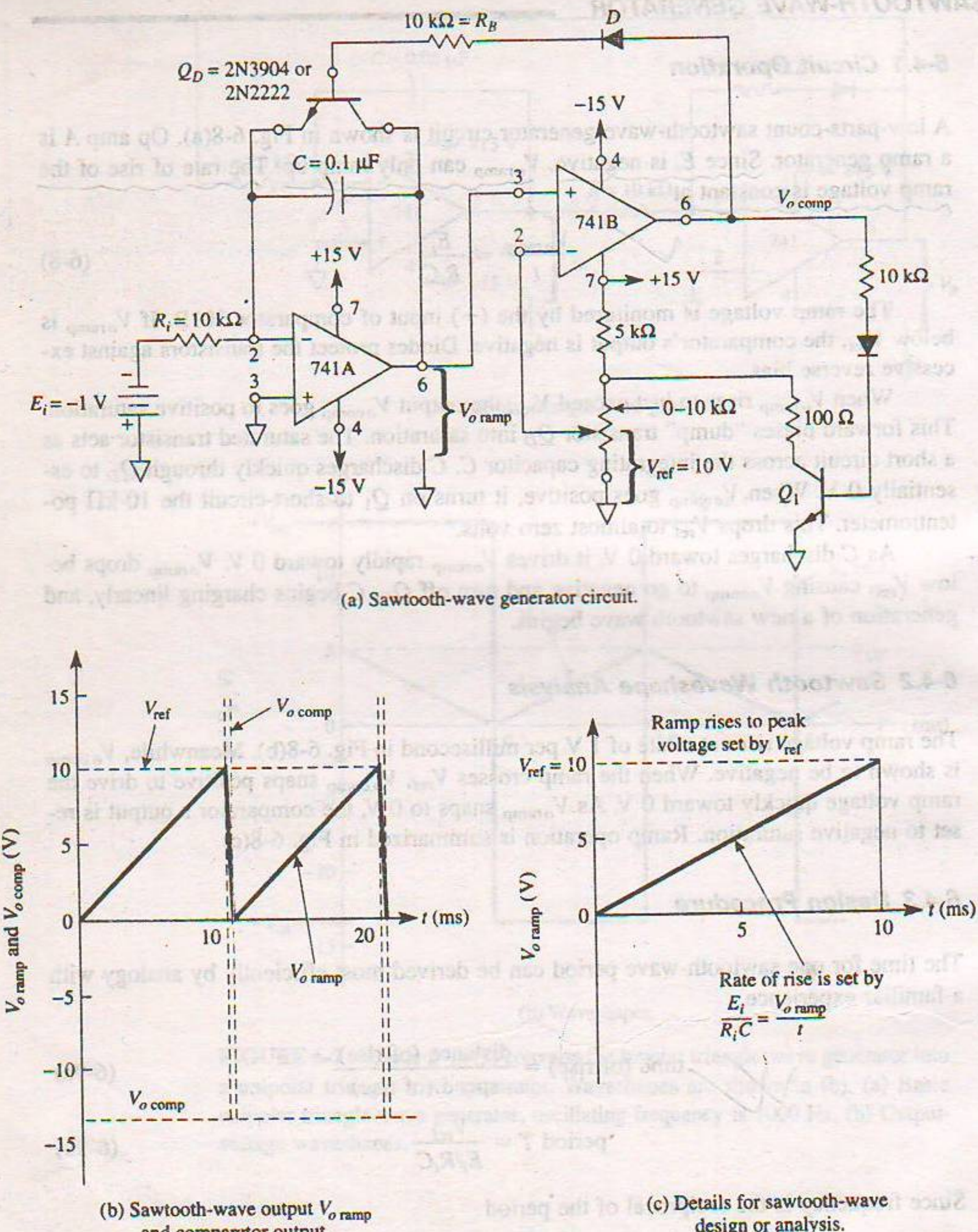
The time for one sawtooth-wave period can be derived most efficiently by analogy with a familiar experience.

$$\text{time (of rise)} = \frac{\text{distance (of rise)}}{\text{speed (of rise)}} \tag{6-9a}$$

$$\text{period } T = \frac{V_{\text{ref}}}{E_i/R_i C} \tag{6-9b}$$

Since frequency is the reciprocal of the period

$$f = \left(\frac{1}{R_i C}\right)\frac{E_i}{V_{\text{ref}}} \tag{6-9c}$$



(a) Sawtooth-wave generator circuit.

(b) Sawtooth-wave output $V_{o\,ramp}$ and comparator output.

(c) Details for sawtooth-wave design or analysis.

FIGURE 6-8 The sawtooth-wave generator circuit in (a) has the waveshapes shown in (b) and (c). Oscillating frequency is 100 Hz or $f = (1/R_iC)(E_i/V_{ref})$.

Design Example 6-8

Design a sawtooth-wave generator to have a 10-V peak output and a frequency of 100 Hz. Let $E_i = 1$ V.

Design Procedure

1. Design a voltage divider to give a reference voltage $V_{ref} = +10$ V for op amp B in Fig. 6-8(a).
2. Let's select a ramp rate rise of 1 V/ms. Pick any R_iC combination to give 1.0 ms. Therefore, let's select $R_i = 10\ \text{k}\Omega$ and $C = 0.1\ \mu\text{F}$.
3. The resulting circuit is shown in Fig. 6-8(a).
4. E_i may be made from a voltage divider and voltage follower to make an ideal voltage source (see Section 3.7).
5. Alternatively, you could pick a trial value for R_iC and solve for E_i in Eq. (6-9b).
6. Check the design values in Eq. 6-9c.

$$f = \frac{1}{(10\ \text{k}\Omega)(0.1\ \mu\text{F})}\left(\frac{1\ \text{V}}{10\ \text{V}}\right) = 100\ \text{Hz}$$

6-4.4 Voltage-to-Frequency Converter

There are two ways to change or modulate the oscillating frequency of Fig. 6-8. We see from Eq. (6-9c) that the frequency is directly proportional to E_i and inversely proportional to V_{ref}. The advantages and disadvantages of each method are examined with an example.

This type of frequency modulation by V_{ref} has two disadvantages with respect to control of frequency by E_i. First, the relationship between input voltage V_{ref} and output frequency is *not* linear. Second, the sawtooth's peak output voltage is not constant, since it varies directly with V_{ref}.

6-4.5 Frequency Modulation and Frequency Shift Keying

Examples 6-9 and 6-10 indicate one way of achieving *frequency modulation* (FM). Thus, if the amplitude of E_i varies, the frequency of the sawtooth oscillator will be changed or modulated. If E_i is keyed between two voltage levels, the sawtooth oscillator changes frequencies. This type of application is called *frequency shift keying* (FSK) and is used for data transmission. These two preset frequencies correspond to "0" and "1" states (commonly called *space* and *mark*) in binary.

Example 6-9

If E_i is doubled to -2 V in Fig. 6-8, find the new frequency of oscillation.

Solution In Eq. (6−9c) use $|E_i|$

$$f = \left(\frac{1}{R_iC}\right)\frac{E_i}{V_{\text{ref}}} = \frac{1}{(10 \times 10^3\ \Omega)(0.1 \times 10^{-6}\ \text{F})}\frac{E_i}{10\ \text{V}}$$

$$= \frac{1}{1.0 \times 10^{-3}\ \text{s}} = \frac{E_i}{10\ \text{V}} = \left(\frac{100\ \text{Hz}}{\text{V}}\right)E_i$$

For $E_i = -2$ V, $f = (2\ \text{V})(100\ \text{Hz/V}) = 200$ Hz. Thus as E_i changes from 0 V to -10 V, frequency changes from 0 Hz to 1 kHz. The peak amplitude of the sawtooth wave remains equal to V_{ref} (10 V) for all frequencies.

Example 6-10

Keep E_i, R_i, and C at their value shown in Fig. 6-8(a). Reduce V_{ref} by one-half to 5 V. Is the frequency doubled or halved?

Solution From Example 6-8 and Eq. (6-9c),

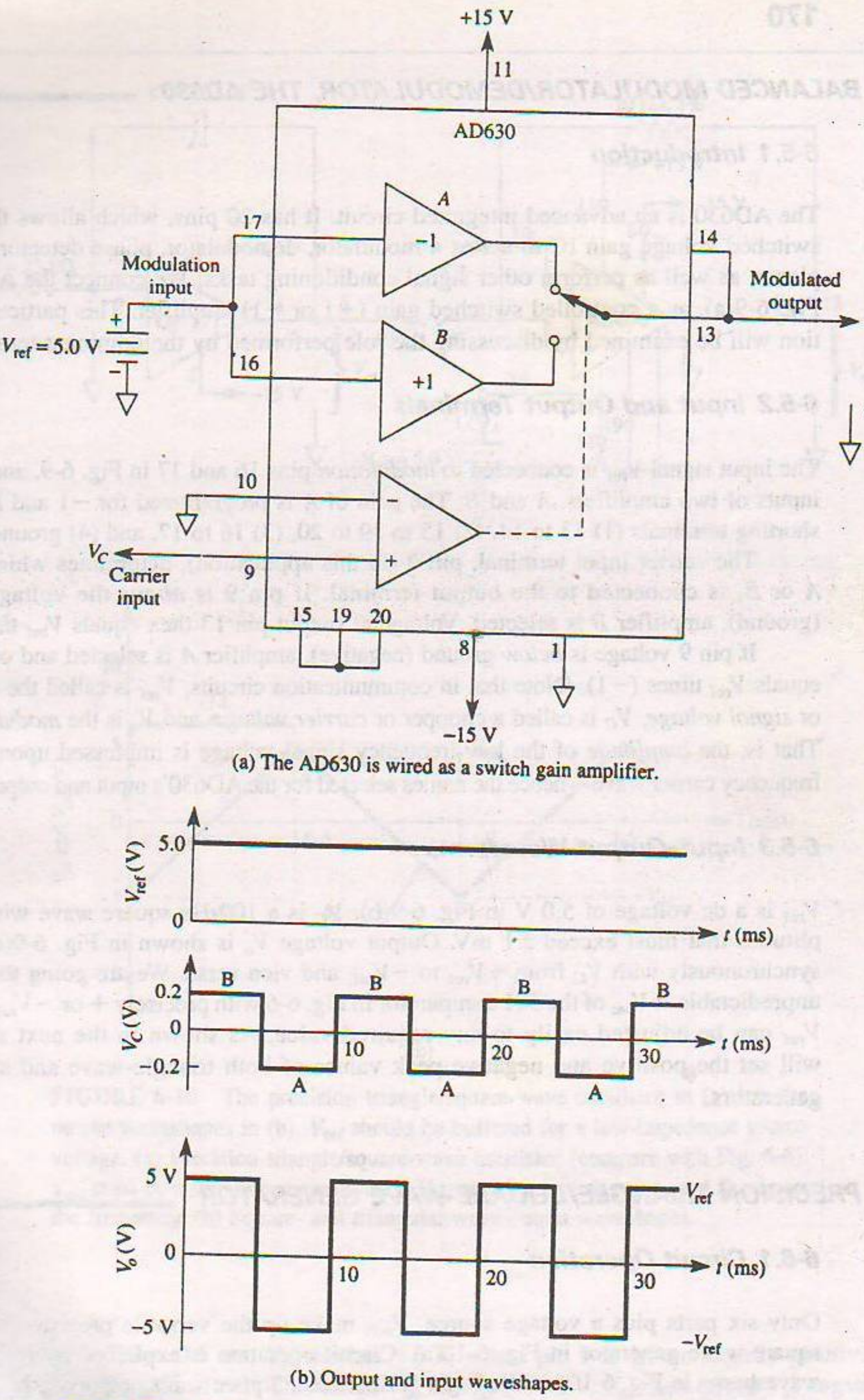
$$f = \frac{1\ \text{V}}{(\text{ms})V_{\text{ref}}} = \frac{(1000\ \text{Hz})/\text{V}}{V_{\text{ref}}}$$

For $V_{\text{ref}} = 10$ V, $f = 100$ Hz. For $V_{\text{ref}} = 5$ V the frequency is doubled to 200 Hz. As V_{ref} is *reduced* from 10 V to 0 V, the frequency is increased from 100 Hz to a very high value.

6-4.6 Disadvantages

The triangle-wave generators of Section 6-3 are inexpensive and reliable. However, they have two disadvantages. The rates of rise and fall of the triangle wave are unequal. Also, the peak values of both triangle-wave and square-wave outputs are unequal, because the magnitudes of $+V_{\text{sat}}$ and $-V_{\text{sat}}$ are unequal.

In the next section we substitute an AD630 for the comparator. This will give the equivalent of precisely equal square-wave ± voltages that will *also* be equal to the ± peak values of triangle-wave voltage. Once we have made a precision triangle-wave generator, we will use it to drive a new state-of-the-art trigonometric function generator to make a precision sine-wave generator.



(a) The AD630 is wired as a switch gain amplifier.

(b) Output and input waveshapes.

FIGURE 6-9 Operation of the AD630 balanced modulator/demodulator as a switched gain amplifier. (a) Wiring for switched gains of +1 or −1; (b) carrier V_C selects gains of +1 or −1 for input V_{ref}. Output V_o is equal to precisely V_{ref} or $-V_{ref}$.

6-5 BALANCED MODULATOR/DEMODULATOR, THE AD630

6-5.1 Introduction

The AD630 is an advanced integrated circuit. It has 20 pins, which allows this versatile switched voltage gain IC to act as a modulator, demodulator, phase detector, and multiplexer, as well as perform other signal conditioning tasks. We connect the AD630, as in Fig. 6-9(a), as a controlled switched gain (+1 or −1) amplifier. This particular application will be examined by discussing the role performed by the dominant terminals.

6-5.2 Input and Output Terminals

The input signal V_{ref} is connected to *modulation* pins 16 and 17 in Fig. 6-9, and thus to the inputs of two amplifiers, A and B. The gain of A is programmed for −1 and B for +1 by shorting terminals (1) 13 to 14, (2) 15 to 19 to 20, (3) 16 to 17, and (4) grounding pin 1.

The carrier input terminal, pin 9 (in this application), determines which amplifier, A or B, is connected to the output terminal. If pin 9 is *above* the voltage at pin 10 (ground), amplifier B is selected. Voltage at output pin 13 then equals V_{ref} times (+1).

If pin 9 voltage is *below* ground (negative), amplifier A is selected and output pin 13 equals V_{ref} times (−1). (Note that in communication circuits, V_{ref} is called the *analog data* or *signal voltage*, V_C is called a chopper or *carrier voltage*, and V_o is the *modulated* output. That is, the *amplitude* of the low-frequency signal voltage is impressed upon the higher-frequency carrier wave—hence the names selected for the AD630's input and output terminals.)

6-5.3 Input–Output Waveforms

V_{ref} is a dc voltage of 5.0 V in Fig. 6-9(b). V_C is a 100-Hz square wave with peak amplitudes that must exceed ±1 mV. Output voltage V_o is shown in Fig. 6-9(c) to switch synchronously with V_C from $+V_{ref}$ to $-V_{ref}$, and vice versa. We are going to replace the unpredictable $\pm V_{sat}$ of the 301 comparator in Fig. 6-6 with precisely + or $-V_{ref}$. Moreover, V_{ref} can be adjusted easily to any required value. As shown in the next section, V_{ref} will set the positive and negative peak values of both triangle-wave and square-wave generators.

6-6 PRECISION TRIANGLE/SQUARE-WAVE GENERATOR

6-6.1 Circuit Operation

Only six parts plus a voltage source, V_{ref}, make up the versatile precision triangle- and square-wave generator in Fig. 6-10(a). Circuit operation is explained by referencing the waveshapes in Fig. 6-10(b). We begin at time zero. Square-wave output V_{os} begins at $-V_{ref}$ or −5 V. This forces the triangle wave V_{ot} to go positive from a starting point of $-V_{ref} = -5$ V. During this time, pin 9 is below ground to select an AD630 gain of −1 and holds V_{os} at

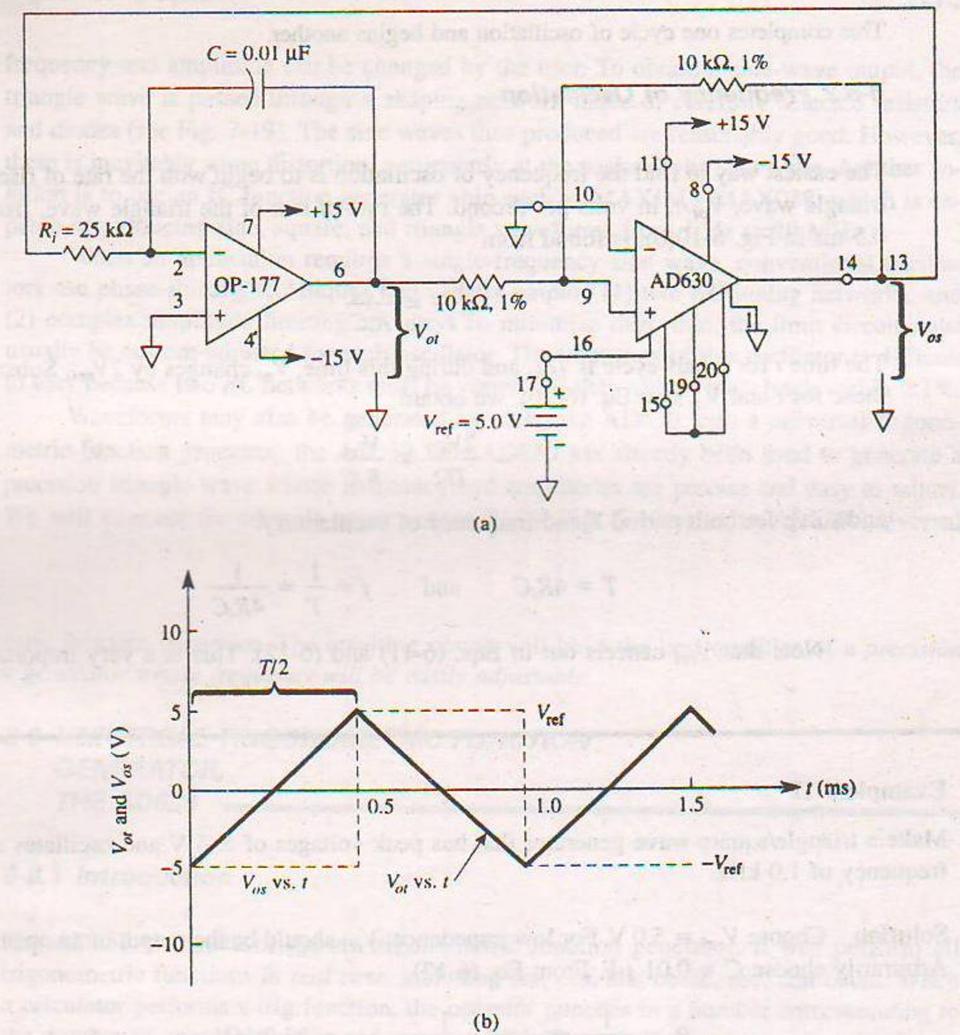


FIGURE 6-10 The precision triangle/square-wave oscillator in (a) has the output waveshapes in (b). V_{ref} should be buffered for a low-impedance source voltage. (a) Precision triangle/square-wave oscillator (compare with Fig. 6-6). V_{ref} must be a low-impedance source. V_{ref} sets the ± peak values and R_i adjusts the frequency. (b) Square- and triangular-wave output waveshapes.

−5 V.

At time $T/2 = 0.5$ ms, V_{ot} reaches +5 V, where pin 9 is driven slightly positive to select an AD630 gain of +1. This snaps V_{os} to $V_{ref} = +5$ V. V_{os} then drives V_{ot} negative. When V_{ot} reaches −5 V, pin 9 goes negative at $T = 1.0$ ms and snaps V_{os} negative to −5 V.

This completes one cycle of oscillation and begins another.

6-6.2 Frequency of Oscillation

The easiest way to find the frequency of oscillation is to begin with the rate of rise of the triangle wave, V_{ot}/t, in volts per second. The rate of rise of the triangle wave, from 0 to 0.5 ms in Fig. 6-10(b), is found from

$$\frac{V_{ot}}{t} = \frac{V_{\text{ref}}}{R_iC} \tag{6-10}$$

The time t for a half-cycle is $T/2$, and during this time, V_{ot} changes by $2V_{\text{ref}}$. Substituting these for t and V_{ot} into Eq. (6-10), we obtain

$$\frac{2V_{\text{ref}}}{T/2} = \frac{V_{\text{ref}}}{R_iC} \tag{6-11}$$

and solve for both period T and frequency of oscillation f:

$$T = 4R_iC \qquad \text{and} \qquad f = \frac{1}{T} = \frac{1}{4R_iC} \tag{6-12}$$

Note that V_{ref} cancels out in Eqs. (6-11) and (6-12). This is a very important ad-

Example 6-11

Make a triangle/square-wave generator that has peak voltages of $\pm$ 5 V and oscillates at a frequency of 1.0 kHz.

Solution Choose V_{ref} = 5.0 V. For low impedance, V_{ref} should be the output of an op amp. Arbitrarily choose C = 0.01 μF. From Eq. (6-12),

$$R_i = \frac{1}{4\,fC} = \frac{1}{4(1000)(0.01\ \mu F)} = 25.0\ k\Omega$$

For a fine adjustment of the output frequency, make R_i from a 22-kΩ resistor in series with a 5- or 10-kΩ variable resistor.

vantage. The peak output voltages of both square- and triangle-wave signals are set by $+V_{\text{ref}}$. As V_{ref} is adjusted, the frequency of oscillation does *not* change.

6-7 SINE-WAVE GENERATION SURVEY

Commercial function generators produce triangular, square, and sinusoidal signals whose