$T_2 \ll T_1$. The only limit on reset time T_2 is the output current rating of A_1 and A_2, and so very fast resetting is possible.

10.2.3 Diode-bridge triangle-wave generator A final circuit for generating a triangle wave is shown in Fig. 10.10. It is referred to as a diode-bridge triangle-wave generator. This circuit does not have quite the high-frequency capability of the three-operational-amplifier triangle generator, but it is somewhat more economical and is an excellent circuit for many applications. For best results, the diodes in the bridges should all be of the same type. Potentiometer P_1 adjusts the amplitude of the triangle wave. This also affects the frequency.

In analyzing this circuit it should be noted that the diode bridges act as current gates; when e_1 is positive, D_2 and D_4 are blocking and current flows through both D_3's into the summing junctions. The voltage waveforms at e_1 and e_o, assuming all diode drops to be 0.6 V, are shown in Fig. 10.11. Typical circuit values for the components shown in Fig. 10.10

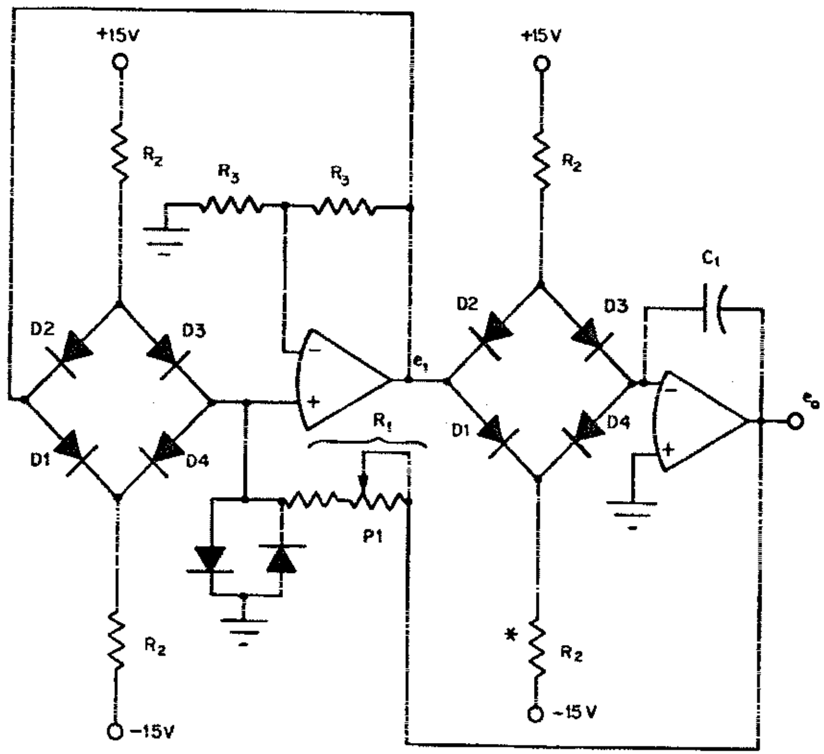


Fig. 10.10 Triangle-wave generator using diode bridges.

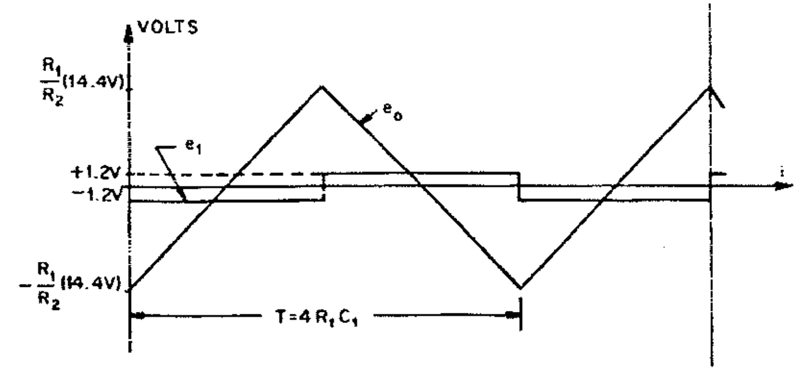


Fig. 10.11 Triangle generator waveforms.

would be $R_2 = 10\ k\Omega$, $R_1 = 5\ k\Omega$, $R_3 = 100\ k\Omega$, $C_1 = 0.1\ \mu F$. These values will provide a triangle wave of approximately $+7.2$ to -7.2 V swing at a frequency of 500 Hz.

10.3 Sine-wave Generators[3-5]

One of the most important waveforms that an engineer may be called upon to generate is the sinusoidal waveform. In this section we shall treat a variety of techniques which may be used to perform this task. Specifically we shall investigate the use of Wien-bridge oscillators, quadrature oscillators, and phase-shift oscillators. For the Wien-bridge and the quadrature oscillator case several different circuits are considered. These may be applied to different special requirements as indicated in the discussion of the circuits.

10.3.1 Wien-bridge oscillator—general description A Wien bridge may be combined with an operational amplifier to form an excellent sine-wave generator. Some sort of automatic gain control is generally used to stabilize the magnitude of the output sinusoid. A general schematic of a Wien-bridge oscillator is shown in Fig. 10.12. To see how this circuit operates let us assume that the output e_o is a sinusoid; then the feedback ratio of the bridge is given by

$$\frac{Z_2}{Z_1 + Z_2} = \frac{R_2}{R_1 + R_2(1 + C_2/C_1) + j(\omega R_1 R_2 C_2 - 1/\omega C_1)}$$

where $Z_1 = R_1 + 1/j\omega C_1$ and $Z_2 = R_2/(1 + j\omega R_2 C_2)$. The operational amplifier will maintain 0 V between its input terminals; thus,

$$\beta \hat{E}_o = \frac{Z_2}{Z_1 + Z_2} \hat{E}_o$$

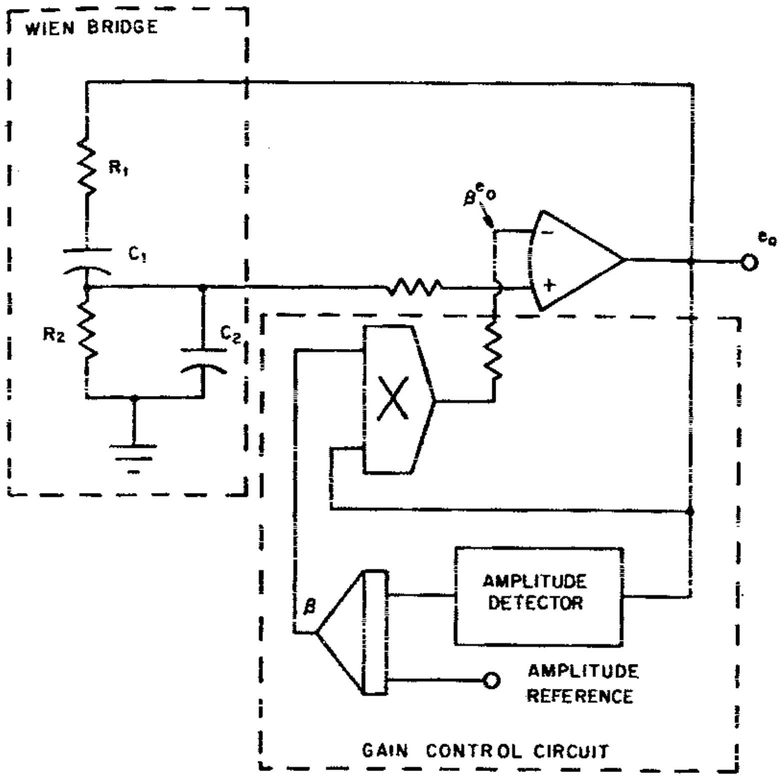


Fig. 10.12 Wien-bridge oscillator.

where $\hat{E}_o$ is a phasor representing the voltage $e_o(t)$. The condition for oscillation is

$$\omega_o R_1 R_2 C_2 - \frac{1}{\omega_o C_1} = 0$$

$$\omega_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

If we make $R_1 = R_2$ and $C_1 = C_2$, then

$$\omega_o = \frac{1}{R_1 C_1} \qquad \text{and} \qquad \beta = \frac{1}{3}$$

If $\beta = 1/3$ and the condition of $R_1 = R_2$ and $C_1 = C_2$ is met, then the output will be a sinusoid of frequency $1/2\pi RC$.

It should be noted that, so long as β is $1/3$, the circuit will oscillate at any amplitude. Also, if β is less than $1/3$, the oscillation will diverge and if β is more than $1/3$ the oscillation will converge. Thus it is common practice to provide some sort of automatic amplitude control. This is usually

done by varying the negative feedback gain (β) to stabilize the oscillator. Incandescent lamps, thermistors, FETs, diode bridges, or general-purpose multipliers can all be used for such gain control purposes.

10.3.2 Precise Wien-bridge oscillator[4,5] As a typical implementation of the general Wien-bridge oscillator diagram shown in Fig. 10.12, consider the circuit shown in Fig. 10.13. The actual Wien bridge is formed by R_1, C_1, R_2, and C_2. The oscillatory output of amplifier A_1 is amplified by A_2, and the output level is sensed by the absolute-value circuit of A_3 and A_4. The amplifier A_4 acts as an error integrator and will stabilize only when the absolute value of the input equals the reference amplitude. A diode bridge is used for varying the negative feedback of A_1. An FET can be used for gain control rather than the diode bridge if desired.

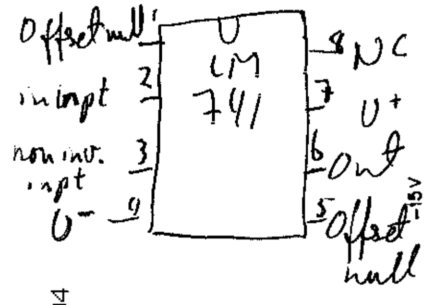
The integrator gain is set by capacitor C_3. The choice of C_3 is a tradeoff between response time and distortion. Small values of C_3 will allow the circuit to reach its stable value very rapidly. Also, response to any disturbance is rapid. On the other hand, making C_3 large will minimize distortion. The frequency of oscillation, as discussed previously, will be

$$f_o = \frac{1}{2\pi R_1 C_1}$$

where $R_1 = R_2$ and $C_1 = C_2$. Frequencies in the range of 10 Hz to 10 kHz are practical for this circuit. Distortion of less than 0.1 percent and excellent frequency stability are readily achieved. The circuit will operate at frequencies above 10 kHz, but the type of operational amplifier must be carefully chosen and stray capacitances should be considered.

Although, in the circuit shown in Fig. 10.13, five operational amplifiers are used, similar circuits are available in miniature encapsulated packages. In such packages, integrated-circuit operational amplifiers are usually used to minimize the size.

10.3.3 Low-cost Wien-bridge oscillator The Wien-bridge oscillator circuit presented in the preceding paragraphs has the disadvantage of requiring five operational amplifiers. In Fig. 10.14 a circuit diagram for a Wien-bridge oscillator which requires only one operational amplifier is given. The primary virtue of this circuit is that very few components are required. Distortion will be greater than with the previously discussed Wien bridge. But, depending upon care of adjustment, distortion will be in the range of 1 to 5 percent. This circuit has high output impedance, and any loading at e_o will shift the operating point of the diodes, which will in turn change the amplitude. Thus this circuit *must* be used with either a fixed load at e_o or a buffer must be added. As with



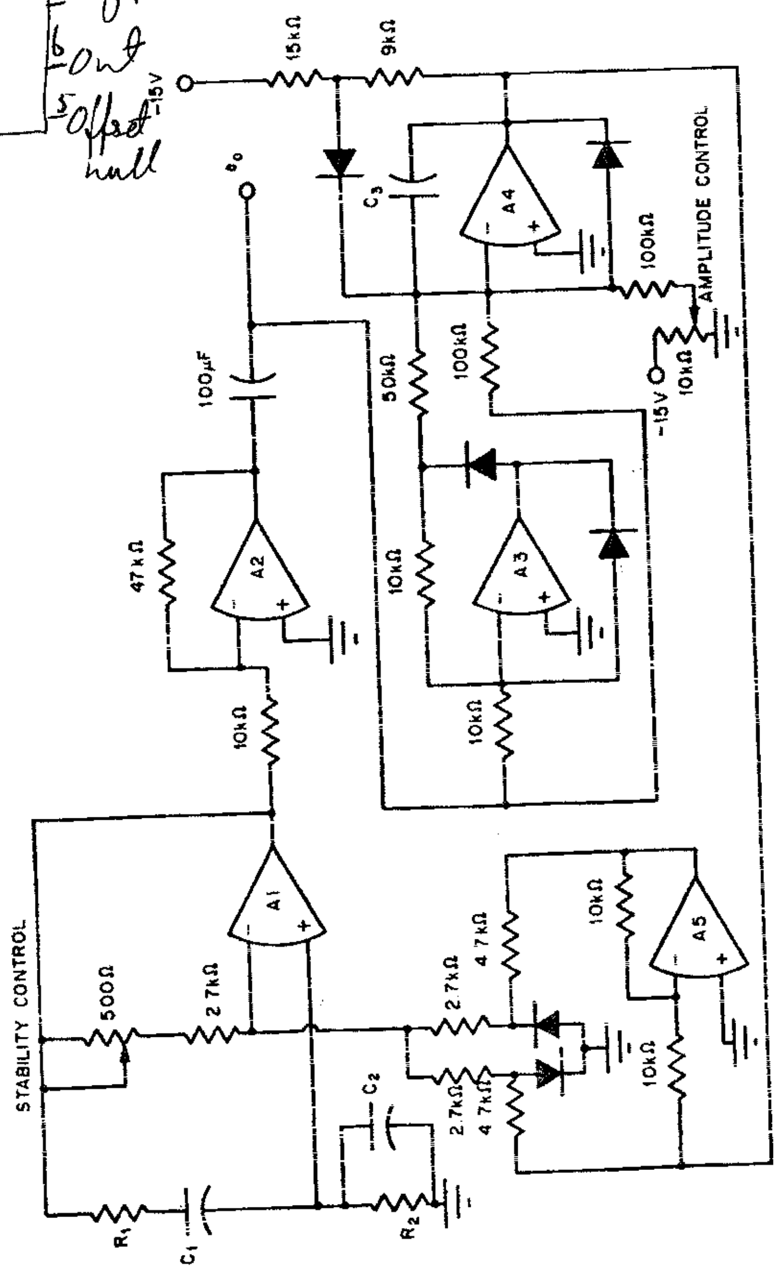


Fig. 10.13 Wien-bridge oscillator, diode gain control.

C: 100 nF
f: 1 kHz
R: 1,6k

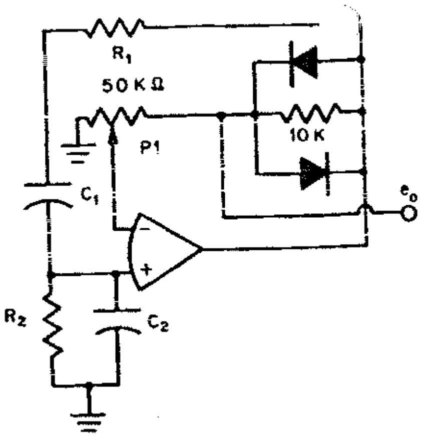


Fig. 10.14 Low-cost Wien-bridge oscillator.

the previous Wien-bridge circuit, R_1 is set equal to R_2 and C_1 is set equal to C_2. Then

$$f_o = \frac{1}{2\pi R_1 C_1}$$

Potentiometer P_1 is adjusted until the oscillations just start to diverge. At that condition, the inverting input to the operational amplifier will be about $\frac{1}{3}e_o$. As the oscillations grow, the diodes start to conduct and the impedance across the diodes lowers. This raises the amount of negative (or degenerative) feedback. Adjustment of P_1 will vary the output amplitude at which amplitude stability occurs. Unlike the circuit shown in Fig. 10.13, the amplitude, amplitude stability, and distortion of this circuit all interact somewhat. The control over amplitude is indirect since P_1 must be set so that distortion is minimized. Distortion is lower as amplitude is made greater. Also, using matched diodes will minimize distortion. Frequency stability depends primarily on the quality of the Wien-bridge components, and so good frequency stability is easily obtained with this simple circuit.

Much lower distortion may be obtained by using amplitude limiting circuits which are thermally limited. The limiting elements of such circuits may be thermistors or incandescent lamps.

10.3.4 Quadrature oscillators The sine-wave generator circuits presented so far in this section have been based on Wien-bridge techniques. In the following paragraphs we present a quite different technique for generating sinusoidal waves, namely, the use of a quadrature oscillator. The quadrature oscillator has two important advantages over the Wien-bridge oscillator:

1. A cosine and sine term are simultaneously available as outputs.