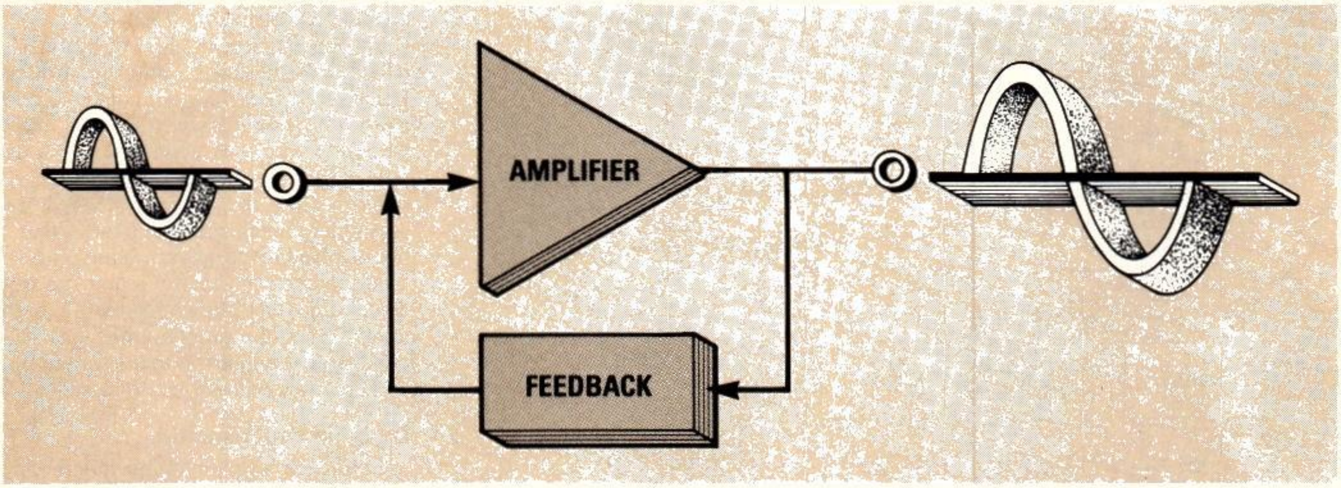
How to Design OSCILLATOR Circuits



JOSEPH J. CARR

Our series continues with a discussion of RC oscillators, ways of generating sinewaves from other waveforms, and other topics.

Part 3

IN THE PAST TWO INstallments of this series we discussed relaxation oscillators and feedback oscillators built from LC tank circuits. This time we'll look at RC oscillators. Some of our example circuits are built from FET's and bipolar transistors; others are built from operational amplifiers. But whatever components they're built from, all our circuits have one thing in common: The frequency at which a given circuit oscillates is determined by one or more RC time constants in the circuit.

The phase-shift oscillator

As we learned in a previous installment, a feedback oscillator works by feeding a portion of a circuit's output signal back to its input. The signal that is fed back must be applied in phase with the input signal. Since we usually use an inverting amplifier (which provides 180 degrees of phase shift) as the active element of a feedback oscillator, we must obtain an additional 180 degrees of phase shift from other circuit elements. In the three-leg RC phase-shift oscillator shown in Fig. 1, each leg provides 60 degrees of phase shift, for a total of 180 degrees. An op-amp version of the phase-shift oscillator is shown in Fig. 2. Both circuits produce a sinewave output signal.

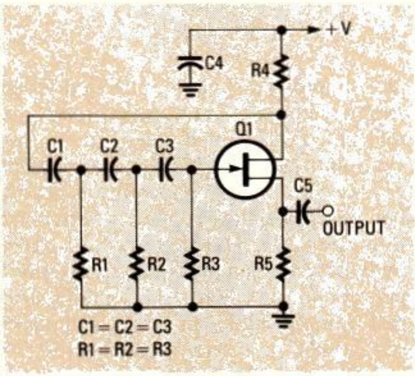


FIG. 1—EACH RC PAIR PROVIDES 60° of phase shift for a total of 180°; that phase shift combines with the 180° provided by the FET for a total of 360°.

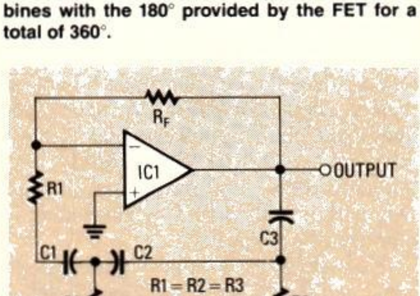


FIG. 2—A PHASE-SHIFT OSCILLATOR can also be built from an op-amp. R_F must be at least 30 times the value of R1 for the circuit to oscillate.

The frequency at which either circuit will oscillate is determined by the values of R1–R3 and C1–C3; to keep the mathematics simple, we usually give each resistor the same value; likewise with the capacitors. In Fig. 1, the other resistors (R4 and R5) serve to bias the FET, and capacitor C5 provides DC isolation. We'll discuss the function of the op-amp circuit's R_F below; first let's see how to calculate oscillating frequency.

Assuming that $R1 = R2 = R3$ and that $C1 = C2 = C3$, then

$$f = \frac{1}{2\pi\sqrt{6}\,RC}$$

In that equation, $R = R1$ and $C = C1$. If resistance is specified in ohms and capacitance in farads, then frequency will be given in hertz.

When the constant terms in that equation are combined, we can rewrite the equation as follows:

$$f = 1/(15.4\ RC)$$

or as

$$f = 0.408 / (2\pi\ RC)$$

When designing an oscillator we usually need to find a resistor/capacitor combination that will produce a desired frequency, so another form of the equation can also be useful. Since there are fewer standard capacitor values, we tend to select one and then plug it and the desired operating frequency into the equation to find the closest resistor value which will produce that frequency. So we rearrange the equation as follows:

$$R = 0.408/(2\pi fC)$$

Let's take an example: Find the resistance required to produce a 1000-Hz oscillator with a 0.01-μF capacitor.

$$R = \frac{0.408}{2 \times 3.14 \times 1000 \times .01 \times 10^{-6}}$$

$$R = 0.408/(6.28 \times 10^{-5})$$

$$R = 6497 \text{ ohms}$$

In any feedback oscillator we must ensure that the closed-loop gain is unity or more. The closed-loop gain of the circuit in Fig. 2 is the ratio R_F/R. Analysis reveals that the loss in the feedback circuit is $1/29$, so circuit gain must be greater than 29 in order to ensure oscillation. So R_F should be at least 30 times the value of R. For the 1000-Hz oscillator discussed previously, R_F should be $30 \times 6497 = 194{,}910$ ohms. You could use a 200K resistor, which is the closest standard value.

BASIC program

To ease the tedium of calculating the values of the frequency-determining components in a phase-shift oscillator, we wrote the simple BASIC program shown in Listing 1. The program was written in the dialect of BASIC that runs on the IBM-PC, but it will run on many machines unmodified, and it should be easy to translate into another dialect.

The program calculates component values for either three-leg phase-shift oscillator presented above; in addition, it will calculate minimum and maximum resistor values for a variable-frequency oscillator. To build a variable-frequency oscillator, you would have to use a triple-gang potentiometer or a triple-pole switch to select appropriate resistors.

When you run the program, it asks whether you want to calculate values for a fixed- or a variable-frequency oscillator. You must then type in the frequency (or the frequency range) you need. Then the program will request the value of the timing capacitor. Last, it calculates and displays the resistance (or range of resistance) that will be required.

It is possible to vary the frequency of a variable-frequency phase-shift oscillator over a range greater than 10:1 using just resistors, but it is impractical to do so. Circuit considerations aside, it becomes difficult to adjust the frequency accurately. Hence the program prints a warning if you enter high and low frequencies that are in a ratio greater than 10:1. If you really need a wide-range variable-frequency oscillator, be patient; we'll discuss a technique for designing one below.

LISTING 1

```
10 GOSUB 920
20 PRINT "This program calculates
30 PRINT "the component values
40 PRINT "for an RC phase-shift
50 PRINT "oscillator.
60 PRINT
70 PRINT
80 GOSUB 960
90 GOSUB 920
100 PRINT "CHOOSE one:
110 PRINT
120 PRINT "1. Fixed oscillator
130 PRINT "2. Variable oscillator
140 PRINT
150 INPUT "SELECTION?",A
160 IF A > 2, THEN GOTO 100
170 ON A GOTO 180, 480
180 GOSUB 880
190 PRINT "Fixed Frequency
200 PRINT "option selected
210 PRINT
220 INPUT "Frequency in Hz?",F
230 PRINT
240 PRINT
250 INPUT "Capacitance in uF",C
260 C = C/(10^6)
270 R = 1/(15.391*C*F)
280 R = INT(R)
290 R4 = 30*R
300 C = C*10^6
310 GOSUB 880
320 R4 = INT(R4)
330 PRINT "Component Values for
340 PRINT "fixed frequency version
350 PRINT
360 PRINT "Operating Frequency:";
370 PRINT F;" Hz
380 PRINT "Capacitors C1=C2=C3=";
390 PRINT C;" uF
400 PRINT "Resistors R1=R2=R3=";
410 PRINT R;" Ohms
420 PRINT "Feedback Resistor R4=";
430 PRINT R4;" Ohms
440 PRINT
450 PRINT
460 GOSUB 960
470 GOTO 1150
480 GOSUB 920
490 PRINT "Variable Frequency
500 PRINT "Option Selected
510 PRINT
520 PRINT "Set upper and lower
530 PRINT "frequency limits
540 PRINT
550 INPUT "Lower Limit in Hz?",FL
560 PRINT
570 INPUT "Upper Limit in Hz?",FH
580 PRINT
590 IF FH > 11*FL THEN GOSUB 990
600 GOSUB 880
610 PRINT "Value of capacitor:
620 PRINT
630 INPUT "Capacitance in uF?",C
640 C = C/10^6
650 RL = 1/(15.391*C*FL)
660 RL = INT(RL)
670 RH = 1/(15.391*C*FH)
680 RH = INT(RH)
690 R4 = 30*RH
700 R4 = INT(R4)
710 C = C*10^6
720 GOSUB 880
730 PRINT "Component Values for
740 PRINT "Variable Frequency
750 PRINT "Oscillator
760 PRINT
770 PRINT "Frequency Range:";
780 PRINT FL;" to ";FH;" Hz
790 PRINT "Capacitors C1=C2=C3=";
800 PRINT C;" uF
810 PRINT "Resistor Range";
820 PRINT RH;" to ";RL;" Ohms
830 PRINT "Feedback Resistor R4:"
840 PRINT R4;" Ohms
850 GOSUB 880
860 GOSUB 960
870 GOTO 1150
880 FOR I = 1 TO 5
890 PRINT
900 NEXT I
910 RETURN
920 FOR I = 1 TO 30
930 PRINT
940 NEXT I
950 RETURN
960 PRINT "Press any key . . .";
970 A$=INKEY$: IF A$="" THEN 970
980 RETURN
990 GOSUB 880
1000 PRINT "Frequency range is
1010 PRINT "greater than 10:1.
1020 PRINT "It would be better
1030 PRINT "to break the range
1040 PRINT "into two bands.
1050 PRINT "    You can:
1060 PRINT
1070 PRINT "1.  Continue anyway
1080 PRINT "    or
1090 PRINT "2.  Do something else
1100 PRINT
1110 INPUT "SELECTION?",W
1120 IF W > 2, THEN GOTO 990
1130 ON W GOTO 1140,90
1140 RETURN
1150 PRINT
1160 PRINT "What's Your Pleasure?
1170 PRINT
1180 PRINT "1. Repeat
1190 PRINT "2. Start over
1200 PRINT "3. All done
1210 PRINT
1220 INPUT L
1230 IF L > 3, THEN GOTO 1150
1240 ON L GOTO 170,100,1250
1250 GOSUB 920
1260 PRINT "PROGRAM ENDED
1270 END
```

Wien-bridge oscillator

Another common RC oscillator is called a Wien bridge; it is a bridge circuit that resembles a Wheatstone bridge. As you can see in Fig. 3, two arms of the Wien bridge are purely resistive, and the other two are RC networks. One of the RC networks is a series circuit, and the other is a parallel circuit. The feedback loop is degenerative (hence stable) at all frequencies other than the oscillating frequency, which is given by:

$$f = \frac{1}{2\pi \sqrt{R3 \times R4 \times C1 \times C2}}$$

If R3 = R4 and C1 = C2, then that equation can be simplified as follows:

$$f = 1/(2\pi \; R3 \times C1)$$

Like the phase-shift oscillator, the Wien-bridge oscillator produces a sinewave output, but its amplitude tends to be some-

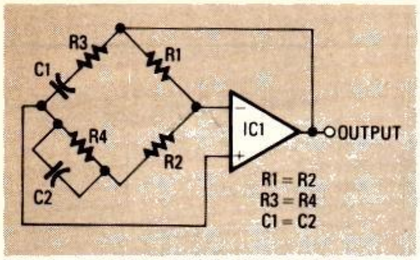


FIG. 3—A WIEN-BRIDGE OSCILLATOR resembles a Wheatstone bridge. Amplitude stability can be improved by substituting a low-current lamp for R2.

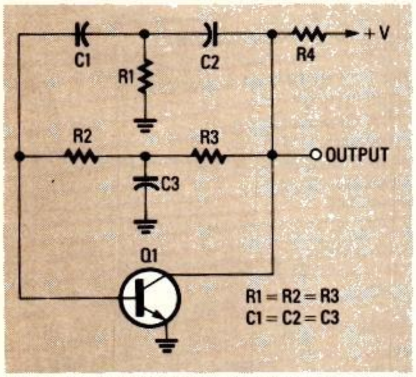


FIG. 4—TWIN-TEE OSCILLATOR is composed of two "T" shaped networks. One has series capacitors and a shunt resistor; the other has series resistors and a shunt capacitor.

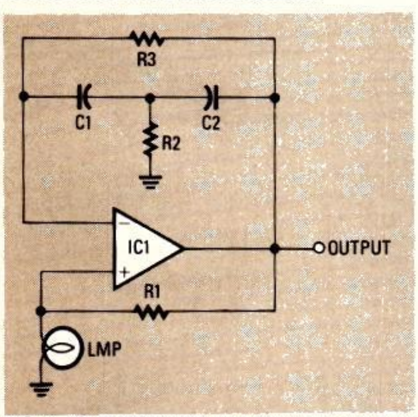


FIG. 5—THIS BRIDGED-TEE OSCILLATOR uses an incandescent lamp to increase amplitude stability of the output signal.

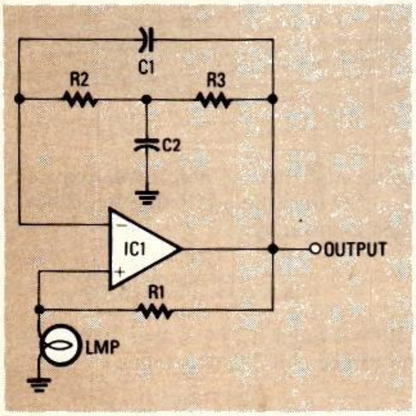


FIG. 6—ANOTHER BRIDGED-TEE OSCILLATOR; in both this circuit and the one shown in Fig. 5, the bridging component is the "opposite" of the T's series element.

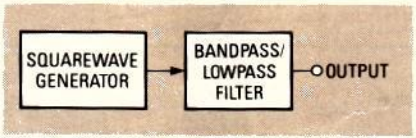


FIG. 7—LOWPASS OR BANDPASS FILTERS can clean up a squarewave source and provide a pure sinewave output.

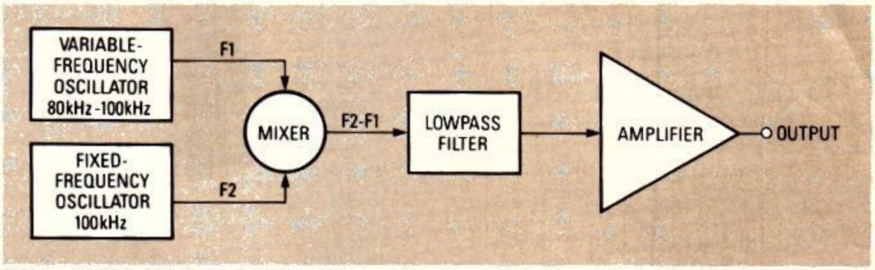


FIG. 8—A WIDE-RANGING OSCILLATOR can be built from a fixed- and a variable-frequency oscillator. Their outputs are mixed, the difference is taken, and that signal is then filtered and amplified for output.

what unstable, especially in a variable-frequency oscillator. It is possible to reduce that instability by replacing R2 with a low-current (40-mA) incandescent lamp. That type of lamp has a non-linear voltage-current characteristic that helps stabilize the output amplitude and prevent the amplifier from saturating. The lamp should be operated below incandescence.

Twin- and bridged-tee oscillators

There are several other types of sinewave oscillators based on RC networks. The circuit in Fig. 4 is called a twin-tee oscillator because its feedback network consists of two T-shaped networks. Note that those networks are, in a sense, opposites. One uses series resistors and a shunt capacitor, and the other uses series capacitors and a shunt resistor. If R1 = R2 = R3 and C1 = C2 = C3, the circuit's oscillating frequency is about:

$$f = 1/(2\pi\ RC)$$

A more useful form of that equation is:

$$R = 1/(2\pi\ fC)$$

For example, when each capacitor has a value of 0.01 µF, the resistance required for a 500-Hz twin-tee oscillator is:

$$R = 1/(2 \times 3.14 \times 500 \times 0.01 \times 10^{-6})$$

$$R = 1/(3.14 \times 10^{-5})$$

$$R = 31{,}831 \text{ ohms}$$

Another type of "tee" oscillator is called the bridged-tee oscillator. In that type of circuit, an RC tee-network is bridged by either a resistor or a capacitor. If the series elements of the tee-network are capacitors, then the bridging element will be a resistor (Fig. 5). If the series elements are resistors, then the bridging element will be a capacitor (Fig. 6).

Generating sinewaves

As we have seen, the output amplitude of many sinewave oscillators tends to be unstable. On the other hand, the output amplitude of a squarewave oscillator is inherently stable because it operates in a saturating mode wherein the output swings between two well-defined voltages. Therefore some designers prefer to use a squarewave or a triangle wave generator as the basic oscillator, and then shape its output into a sinewave.

Extracting a sinewave from a wave of some other shape is possible because all non-sinusoidal waveforms are composed of a number of sinewaves summed together. The squarewave and the triangle wave, for example, contain a sinewave at the fundamental frequency and a number of harmonics (multiples) of the fundamental frequency. For example, a squarewave with a fundamental frequency of 200 Hz would be composed of a 200-Hz sinewave, plus 400-Hz, 600-Hz, 800-Hz, . . . sinewaves.

If we filter out all of the harmonics, we'll be left with a sinewave at the fundamental frequency. The purity of the sinewave can be quite good, especially if a high order of filtering is used. As shown in Fig. 7, we can use a lowpass or bandpass filter.

Wide-range oscillators

Another way to bypass the limited frequency range of an RC oscillator is to use a dual-oscillator circuit; that type of circuit was popular in the 1950's. As shown in Fig. 8, the frequency of one oscillator is fixed (at 100 kHz); the other oscillates at a variable frequency (80–100 kHz) that is determined by the user. Both oscillators are LC types.

Their signals are fed to a non-linear mixer, the output of which is a new signal whose frequency is equal to the difference between the frequencies of the two input signals. That signal is sent through a lowpass filter to remove residual traces of f_1 and f_2, and then to an amplifier and the outside world.

For example, when f_1 is 100 kHz, the difference between f_1 and f_2 is 0 Hz, so there is no output. However, when f_1 is 80 kHz, the output frequency is 100 – 80 = 20 kHz. So the output frequency may vary from 0 to 20 kHz.

In our next installment we'll discuss RC triangle wave and squarewave oscillators; in addition we'll introduce the monostable multivibrator circuit. **R-E**