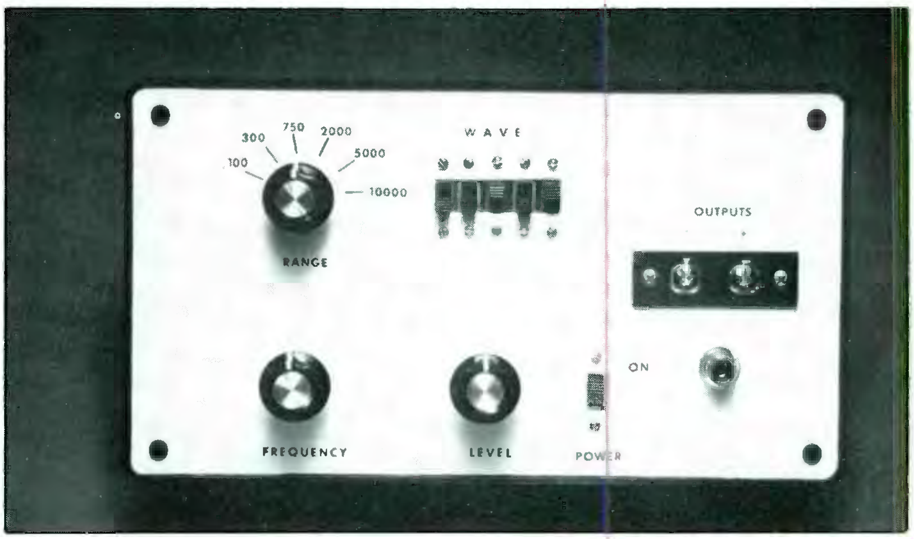
A Programmable Waveform Generator

An audio-frequency test instrument that generates up to 32 different waveforms at frequencies up to 10 kHz

By Paul Renton



Audio frequency generators made their mark as a signal source for audio trouble-shooting, design and setup work. A typical generator provides sine waves, but some function generators, which many people use instead of a sine-wave-only generator, also provide square and triangular waves. The programmable waveform generator described here goes far beyond this by allowing you to select up to 32 different waveforms to suit a wide variety of testing needs.

Three main characteristics can be used to describe a repetitive waveform: frequency (repetition rate), amplitude and the shape of the waveform (sine, square, triangle, etc.). To make a waveform generator useful, each of these characteristics must be alterable independently without affecting the other two. This criterion is met in our programmable waveform generator by separate frequency, amplitude and waveform controls.

Though our programmable waveform generator is extremely flexible, it is relatively easy to build at only moderate cost for components. In fact, your parts cost should be just about $50, including the enclosure in which to house the project. Part of the reason for the simplicity is that the circuitry—mainly readily available and low-cost ICs— wires together on a printed-circuit board. The only specialty device used in the project is an erasable programmable read-only memory (EPROM) in which the waveform parameters are stored for recall by front-panel switches.

About the Circuit

In operation, the programmable waveform generator repetitively "reads" digital values from the EPROM and uses a digital-to-analog (D/A) converter to change these values into the selected output waveform. Varying the rate at which new values are read from the EPROM changes the output frequency (repetition rate) of the generator without affecting the type of waveform being generated. Waveform selection is a function of the program stored in the EPROM and the settings of five switches. Finally, by adjusting the gain of the output stage, the amplitude of the output wave can be varied.

As shown in Part 1 of Fig. 1, eight-bit counter *IC2* generates addresses that call the data stored in EPROM *IC3*. The rate at which the counter is clocked is determined by the rate at which new values are read out from *IC3* and, thus, determines the frequency of the waveform being generated. Since 256 different addresses can be generated by the eight address lines of an 8-bit counter, the wave will repeat every 256 clock inputs to the counter. Therefore, the output wave will have a frequency equal to *IC2*'s clock rate divided by 256.

The oscillator used to generate the clock pulses for the *IC2* counter is *IC1*. In this dual multivibrator, one section uses FREQUENCY control potentiometer *R2* and any one of capacitors *C2* through *C7* selected by section A of RANGE switch *S1* to set the period of its output pulse. Using a six-position switch for *S1* conveniently divides the audio frequency range into segments that make it easy for *IC1* to tune. The output pulse from the first multivibrator drives the second multivibrator in *IC1*.

In the output multivibrator of *IC1*, the pulse length is held to about 40 nanoseconds by *R3*, which needs no timing capacitor. The not-Q output from the second multivibrator, at pin 12, is fed back to pin 2 of the first multivibrator to retrigger the first stage and cause oscillation. The Q output at pin 5 from the second stage is used to clock the *IC2* counter.

An 8K × 8-bit EPROM used for *IC3* holds the data to generate 32 different waveforms, each consisting of 256 bytes. To select the desired waveform, switches *S2* through *S6* are selectively connected to the five higher-order address lines (A8 through A12) of *IC3*. Single in-line package (SIP) resistor *R4* contains five 10,000-ohm resistors that are individually used to pull these address lines high when the switches are open. Closing any *S2* through *S6* switch grounds the selected address line and brings it low. Chip select at pin 20 and output enable at pin 22 of *IC3* are both permanently grounded.

Access time of the *IC3* EPROM is important to proper operation of the circuit. If a slow version of this EPROM were to be used, one with an access time of 450 nanoseconds, output values could not be expected to reliably change at a rate greater than about 2.22 MHz. Since output frequency will be 1/256 of the counter's clock rate, this is equivalent to an output frequency from the generator of 2.22 MHz/256, or only 8680 Hz. Though this might be sufficient in some applications, to ensure that the generator will operate out to a full 10 kHz, an EPROM with a 350-nanosecond or faster access time is needed.

After data for the selected waveform exits from *IC3* on data output pins 11, 12, 13 and 15 through 19, it is latched by octal flip-flop *IC4* (see Part 2 of Fig. 1). Inputs to *IC4* are directly connected to the data output lines of *IC3* in the proper sequence. In turn, the outputs from *IC4* become the inputs to digital-to-analog converter *IC5*.

Output data from *IC4* must be latched to hold the output data from one location in *IC3* while the next location is being addressed. Otherwise, the data sent to *IC5* will change while *IC3* is reading the next memory location, causing noise and random errors to occur in the waveforms.

As shown in Part 1 of Fig. 1, the clock input at pin 11 of *IC4* is the same as that used to increment *IC2*. The counter increments on the falling edge of this clock pulse, generating a new address for the EPROM to read. Data on the rising edge of the clock pulse is latched by *IC4* (Part 2). Since the output from *IC1* is a pulse with a rising edge followed by a falling edge about 40 nanoseconds later, *IC4* will latch the data output from *IC3* just before the EPROM is given a new address from which to read. This prevents any errors from being generated as a result of the changing of the EPROM address.

Digital-to-analog converter *IC5* (Part 2 of Fig. 1) is fed reference currents by grounding pin 15 through *R7* and fixing pin 14 at 2.8 volts above ground potential with the zener diode *D1* and resistor *R5* arrangement. By using the same value for *R5* and *R7*, the currents cancel to assure that errors do not occur. Capacitor *C9* connected from pin 16 to ground provides compensation for *IC5*.

The eight digital inputs from *IC4* are converted by *IC5* to an output current. This output current is normally available at pins 2 and 4. However, in this project, the negative current at pin 2 is connected to ground, and the output at pin 4 is used to drive one of the four operational amplifiers in *IC6*, which is used here as a current-to-voltage converter. (Details of what input data is converted to what output voltage are covered under "Programming Waveforms.")

Since slew rate determines how fast the output signal of an op amp can change and a fast slew rate is needed in this generator, a fast-slew-rate TL084 quad op amp was chosen for *IC6*. A second reason for choosing a TL084 is that it has four independent op amps in a single package. Since three op amps were required in the programmable waveform generator, only a single TL084 takes the place of three independently packaged devices.

One op amp in *IC6* converts the output from *IC5* to a voltage. A generated waveform may contain some sharp edges at the points where the signal changes voltage levels, due to reconstruction of a sampled signal, rather than a continuous waveform. These sharp edges produce a waveform that is not continuous unless the residue of the sampling is removed. This is done in the generator's circuit with the low-pass filter made up of a second op amp in *IC6*.

The low-pass filter should be set at about 80 to 200 times the output frequency so that only the unwanted components are filtered out. RANGE switch *S1B* is used to select which of capacitors *C11* through *C16* will be used in the low-pass filter. This allows the filter to maintain a proper frequency relationship as the frequency is stepped from range to range.

A third op amp in *IC6* serves as the output amplifier that delivers the generated signal to the device under test through OUTPUT jack *J1*. The output signal from the second op amp (at pin 8) is ac coupled through *C17* to the output op amp so that the output signal will be centered about circuit ground.

AMPLITUDE control *R14* provides a means for adjusting output signal level as needed by controlling the gain of the output op amp. Resis-

PARTS LIST

Semiconductors

D1—1N5224B or other 2.8-volt zener diode

D2,D3—1N4001 silicon rectifier diode

IC1—74LS123 dual multivibrator

IC2—74HCT393 or 74LS393 counter (see text)

IC3—2768 (8K × 8) EPROM (see text)

IC4—74HCT374 or 72LS374 octal flip-flop (see text)

IC5—DAC-08 digital-to-analog converter

IC6—TL086 quad op amp

IC7—7805 +5-volt regulator

Capacitors

C1,C8,C9—0.1-μF disc

C2—0.02-μF disc

C3,C11—0.01-μF disc

C4,C12—0.033-μF disc

C5,C13—0.001-μF disc

C6—270-pF disc

C7,C10,C16—100-pF disc

C14—470-pF disc

C15—220-pF disc

C17—22-μF, 15-volt electrolytic

C18,C19—1,000-μF, 25-volt electrolytic

C20—220-μF, 15-volt electrolytic

Resistors (¼-watt, 5% tolerance)

R1—3,300 ohms

R3,R10,R11,R12—2,200 ohms

R5,R7,R9—1,000 ohms

R6—470 ohms

R8—220 ohms

R13—10,000 ohms

R4—10,000-ohm × 5 SIP resistor assembly (see text)

R2—10,000-ohm, linear-taper, panel-mount potentiometer

R14—100,000-ohm, linear-taper, panel-mount potentiometer

Miscellaneous

J1—Panel-mount phono jack

J2—Power jack (see text)

S1—2-pole, 6-position nonshorting rotary switch (Radio Shack Cat. No. 275-1386 or similar)

S2 thru S7—Spst slide or toggle switch (see text)

9- to 10-volt ac power transformer or plug-in adapter; printed-circuit board; sockets for IC1 through IC6; suitable enclosure (Radio Shack Cat. No. 270-232 or similar); small TO-220 heat sink for IC7; knobs for R2 and R14; ⅜″ or ½″ spacers (4); lettering kit; color-coded ribbon cable; machine hardware; hookup wire; solder; etc.

Note: The following are available from Paul Renton, P.O. Box 1525, Mercer Island, WA 98040: Etched and drilled pc board and programmed EPROM for $24; kit containing pc board, programmed EPROM and all board-mounted components (does not include power supply, enclosure and front-panel controls) for $44. Prices include shipping in U.S. Washington residents, please add state sales tax.

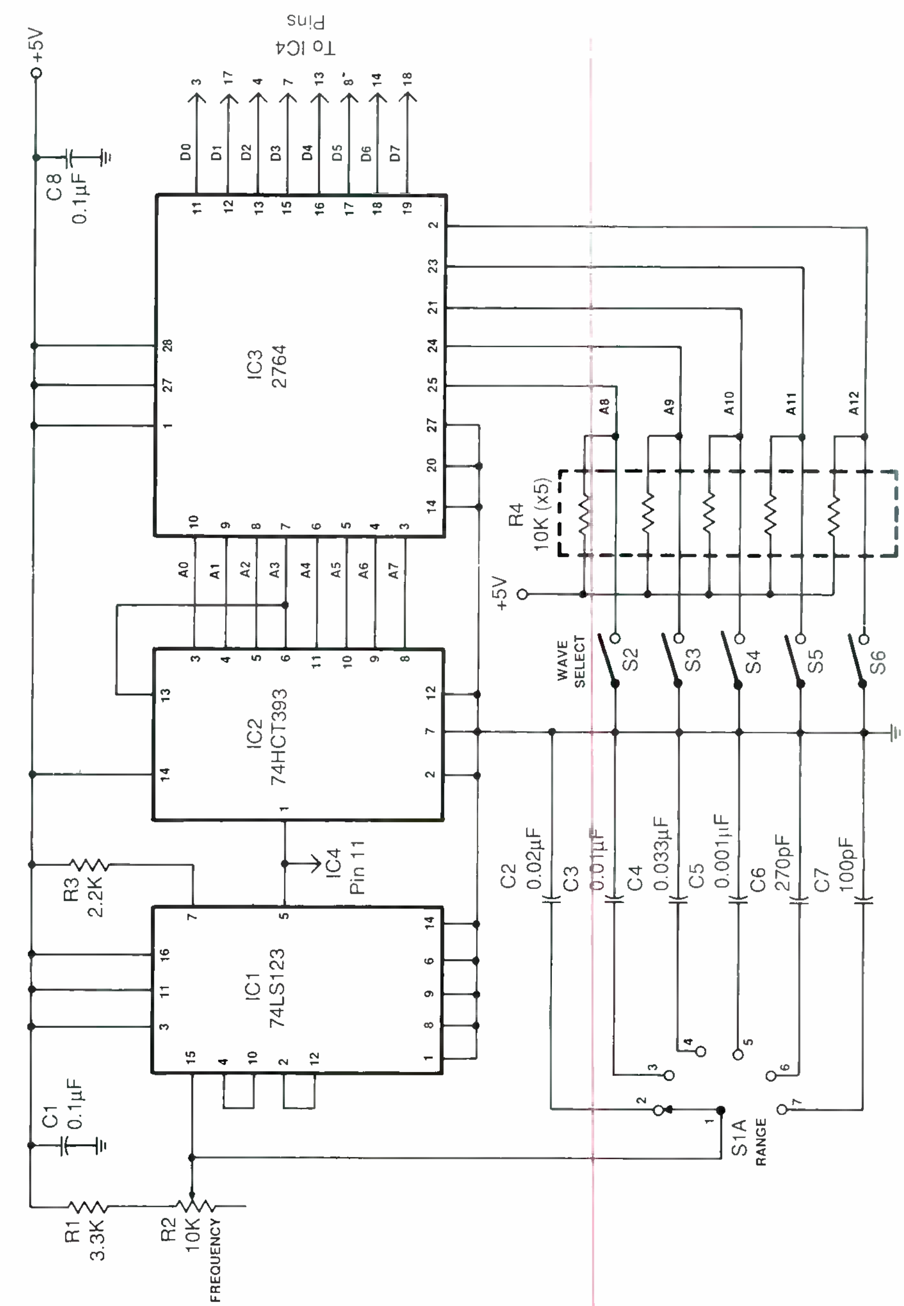
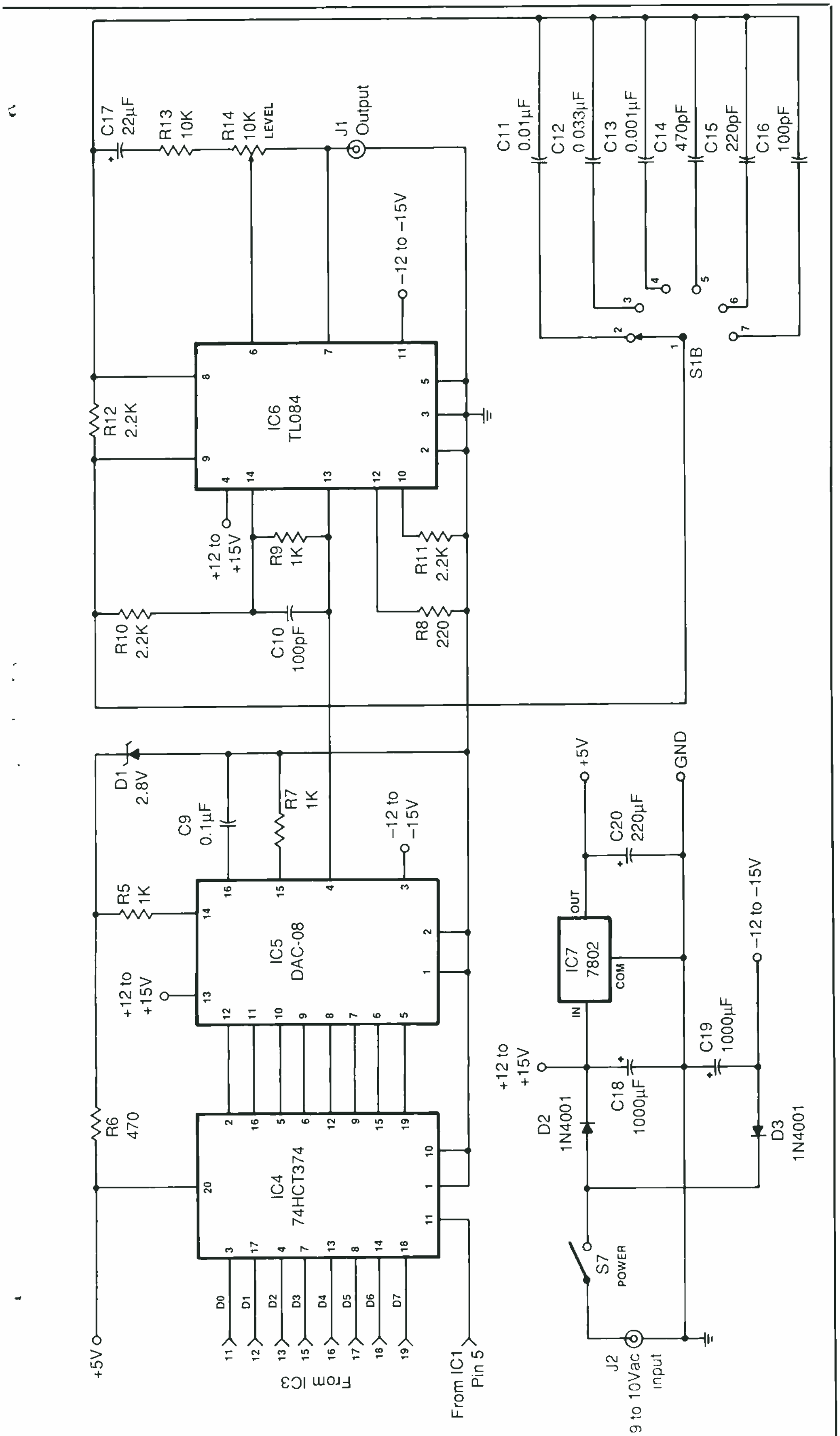


Fig. 1 Complete schematic diagram of programmable waveform generator, including power supply but not power transformer.



tor *R13* in series with *C17* prevents the signal delivered to the output op amp from being over-amplified and clipping.

Although high-speed CMOS ("HCT") devices are specified for *IC2* and *IC4* in Fig. 1, standard low-power Schottky ("LS") devices can be used instead. The CMOS versions require less operating current, resulting in cooler operation of the voltage regulator in the power supply. No circuit changes are needed if you use the LS devices.

Shown below the main circuit in Part 2 of Fig. 1 is the power supply that operates the generator circuit. This is a standard full-wave supply, with rectification provided by *D2* and *D3* and main filtering provided by *C18* and *C19*. The +12- to +15-volt output from the rectifier/filter arrangement is regulated to +5 volts (which is further filtered by *C20*) to power *IC1* through *IC5*. Note also that a pair of unregulated bipolar supply lines (at +12 to +15 and −12 to −15 volts) are provided for powering *IC6*. Input power for the supply is provided by any 9-to-10-volt ac source, including a plug-in transformer if you should have one lying about.

Construction

Assembly of the programmable waveform generator is best done on a printed-circuit board. You can fabricate your own pc board using the actual-size etching-and-drilling guide shown in Fig. 2. Alternatively, you can purchase a ready-to-wire pc board from the source given in the Note at the end of the Parts List.

Installation of the components on the pc board is fairly straightforward. Use sockets for *IC1* through *IC6* only. As shown in Fig. 3, begin populating the board by installing and soldering into place the IC sockets—*not* the ICs themselves. Then install the diodes (observe polarity), resistors and smaller capacitors. Leave the large electrolytic capaci-

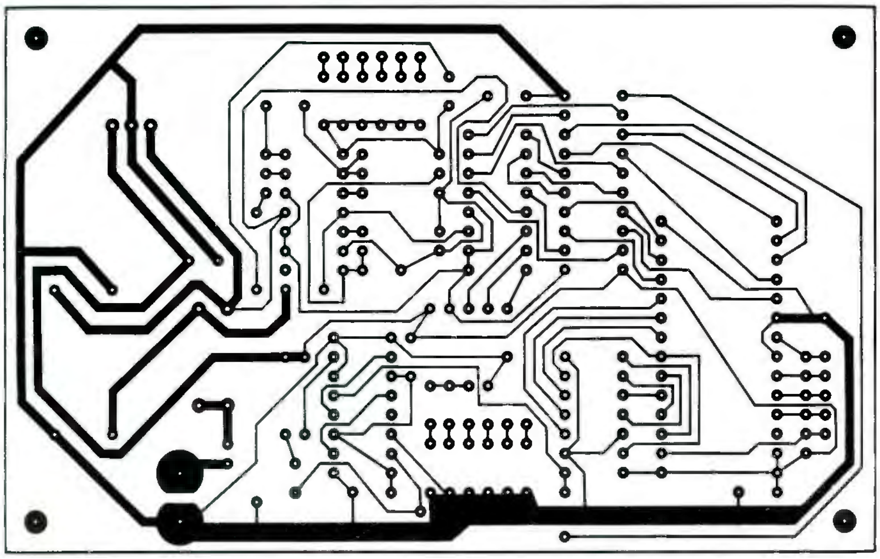


Fig. 2. Actual-size etching-and-drilling guide to be used for fabricating printed-circuit board.

tors and *IC7* for last. Work carefully to avoid creating solder bridges between the closely spaced solder pads and conductor traces.

There are several choices with regard to bringing power to the circuit board. You can mount a pc-type connector that is compatible with the connector on the 9-to-10-volt ac input source directly on the board. You can mount a panel-mount version of the same type of connector off the board. Or you can dispense with a connector arrangement altogether by using a 9-to-10-volt transformer that mounts inside the selected project enclosure and use a permanent ac line cord and appropriately rated fuse in its holder in place of an external transformer.

Once the other discrete components have been soldered into place on the board, install the electrolytic capacitors (observe polarity) and

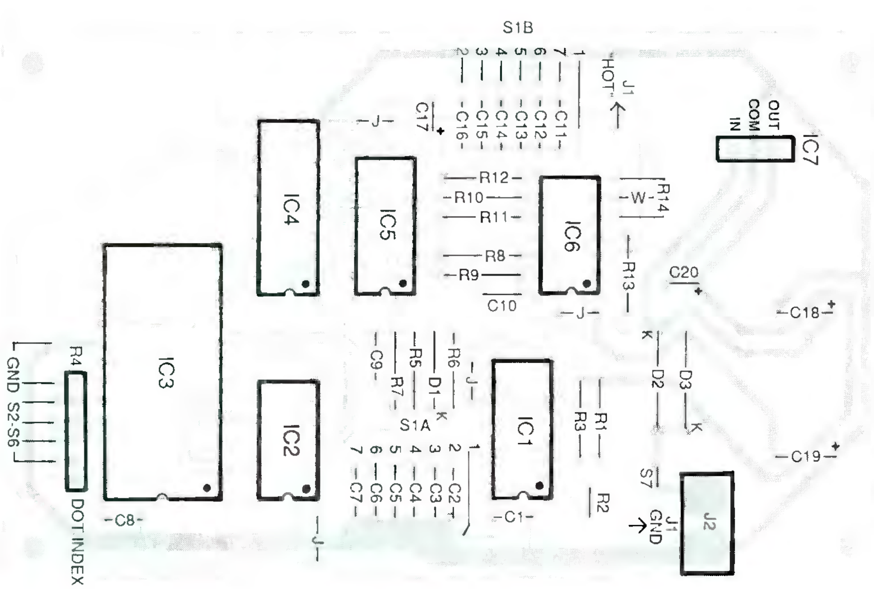


Fig. 3. Wiring guide for pc board.

IC7, after bolting to the latter a small TO-220 heat sink. At this point, *IC1* through *IC6* should still not be installed in their sockets; they will be installed after voltage checks have been made. Install and solder into place the four wire jumpers on the board. For these, you can use bare or insulated solid hookup wire or even cut-off resistor or capacitor leads.

Place the circuit-board assembly on the floor of the enclosure in which the project is to be housed and mark the locations of the four mounting holes. Remove and set aside the circuit board and then drill the holes in the marked locations. Using ⅜" or ½" spacers and machine hardware, loosely mount the circuit board with POWER jack *J2* toward the rear wall of the enclosure. Carefully mark the outline of the jack on the rear wall. Once again, remove and set aside the circuit board.

Drill a ¼" hole in the marked location for the power jack. Then use a small file, nibbler or other suitable tool to carefully trim the cutout to appropriate size and shape. Test fit the jack occasionally to check your work. If you opt for the panel-mount jack or an internal power transformer, you need drill only a single round hole in which to mount the jack or pass through the line cord.

Preparation of the front panel will require a little more effort. Start by accurately marking the mounting locations for the switches, controls and INPUT jack *J1*. Make sure before you do any drilling or cutting that the controls and switches will not interfere with each other or the circuit-board assembly when mounted in place. When you are sure of the locations, drill the holes for mounting *J1, R2, R14* and *S1*.

Ordinarily, use of slide-type switches makes mounting a major operation because they require rectangular slots for their toggles plus two mounting holes for each. In the case of *S2* through *S6*, which mount side by side in this project, all you need is a single long slot for the five toggles, though you must still drill 10 small holes for their mounting screws. (If you prefer not to have to cut a slot, you can substitute miniature toggle switches, in which case all you need is a single mounting hole for each switch.)

Assuming you have decided to use slide-type switches, you will find the slot to be relatively easy to cut. Start by accurately measuring the size of the slot, leaving about a 1/16" leeway all around, and transferring the dimensions to the front panel. Drill a hole at each end of the slot within the drawn rectangle and use a nibbling tool to cut away the unwanted material. If you do not have a nibbler, drill a 1/8" hole in each of the four corners of the drawn rectangle and then a series of holes spaced about one drill bit diameter apart all around the drawn slot shape. Then use a coping saw, Moto Tool or other suitable tool to cut through the material between the holes to remove the unwanted material. Any ragged edges or rounded corners can be dealt with using a small flat file or a Moto tool.

Once the slot is cut, test fit all five switches to make sure that enough material has been removed to assure smooth switch toggle operation. Mark the locations and drill the holes for the mounting screws. Then cut the slot or drill the hole for the POWER switch, depending on whether you are using a slide-type or miniature toggle switch.

Note in the lead photo that a two-contact screw-type terminal strip OUTPUT connector was also included in the prototype of the project. This is an option that is not really needed, though its inclusion will allow you to connect to the generator's output cables other than the usual phono type. If you decide to incorporate this option into the project, simply cut an appropriately sized slot for its solder lugs and drill the two holes for the mounting hardware.

Once the front panel has been prepared, temporarily mount the rotary switch and potentiometer controls in their respective holes and slip the control knobs onto their shafts. Use a pencil to very faintly draw the outlines of the knobs onto the front panel. Then rotate the knob on the range switch stop to stop in both directions and note the position of the pointer in both cases. Remove the knob and adjust the orientation of the switch to balance the locations of the stops. Then, after tightening the mounting nut and replacing the knob, rotate the latter to each position and mark this on the panel.

Remove the switch and controls and set them aside. Now, using a dry-transfer lettering kit, label the various controls, switches and OUTPUT jack (and identify the + and − contacts of the OUTPUT terminal strip if you have decided to incorporate it) as shown in the lead photo. If you wish, you can punch and cut appropriate-size holes and slots in and do all your labeling on a heavy white sheet of cardboard that then goes in front of the aluminum panel that comes with the enclosure. This done, spray on two or three *light* coats of clear acrylic to protect the lettering. Allow each coat to completely dry before spraying on the next.

When the acrylic spray has completely dried, mount the OUTPUT connector(s), rotary switch and potentiometer controls. Then use an ohmmeter or continuity tester to determine which position the toggles of the slide or toggle switches must be in to be on. Connect the probes of the meter or tester to the lugs of the switches and move the toggles to their alternate positions. Leave each toggle in the "on" position, as indicated by a short circuit, which will be zero ohm on the meter or will light an indicator or sound a buzzer on the continuity tester.

Without disturbing the toggles, install the five WAVE switches in the long rectangular slot for slide-type switches or in individual round holes for toggle switches so that all toggles are facing toward the *bottom* of the panel. Then install the POWER switch so that its toggle is toward the *top* of the panel. Rotate the knob on the RANGE switch stop to stop and note the pointer's position in each case. If the pointer does not align with the panel markings, reposition the switch until it does.

An easy way to make connections to the rotary RANGE and individual WAVE switches and the potentiometer controls is to use color-coded ribbon cable to provide a means for keeping track of wiring. Trim the cable to the length needed, separate the conductors at opposite ends a distance of 1" and 1/2" and strip 1/4" of insulation from all conductors at both ends. A length of 25-conductor ribbon cable is all that is needed. Separate this into bundles of seven, seven, six, three and two conductors.

At the circuit-board end, use the 1/2" separated ends of the cables. Plug the two-conductor cable into the *R2* holes in the circuit board and solder into place. Similarly, plug the three-conductor cable into the *R14* holes and solder them into place. The six-conductor cable goes to the holes labeled A8 through A12 and GND near R14. Finally, the seven-conductor cables go to the S1A and S1B holes on the circuit board.

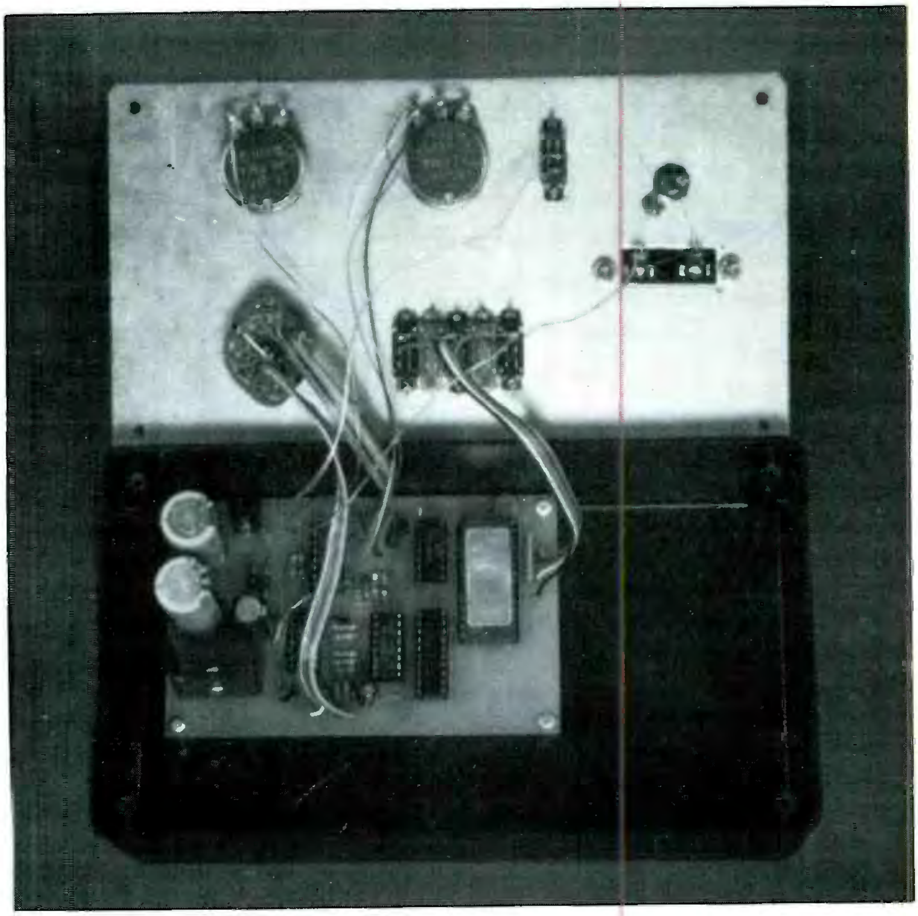
Connect and solder the free end of the two-conductor cable to the lugs on the FREQUENCY control. Similarly, connect and solder the three-conductor cable to the lugs on the LEVEL control (center conductor goes to wiper lug on control). Referring back to Fig. 3, connect and solder all but the GND wire of the six-conductor cable to the lower lugs of the appropriate WAVE switches. Run a bare solid wire through the upper lug holes of all five switches to tie them in common with each other, hook the GND wire of the six-conductor cable through one of these lugs, and solder all six connections.

Use an ohmmeter to figure out

which conductors in the S1A and S1B groups correspond to the different positions of the RANGE switch (identified by number on Figs. 1 and 3) and connect and solder the free ends of the two seven-conductor cables to the appropriate lugs of the rotary switch.

Use ordinary hookup wire to interconnect the appropriate points on the board with the POWER switch and OUTPUT connectors. Then, if you are using an internal power transformer, drill the holes for it through the floor of the enclosure in an area where it will not interfere with the circuit-board assembly or controls and an entry hole for the ac line cord through the rear wall. Mount the transformer with machine hardware, sandwiching the mounting tab of a two-lug terminal strip (both lugs isolated from the tab) between the head of one mounting screw and the transformer mounting tab. Route the free end of the ac line cord through the entry hole and tie a knot about 4″ from the free end inside the enclosure to serve as a strain relief.

Connect and solder one transformer primary wire and one conductor of the line cord to one lug of the terminal strip. Connect the other line-cord conductor and one end of a 4″ hookup wire to the other lug of the terminal strip and solder the connection. Connect and solder the other end of the 4″ wire to one lug of the POWER switch. Then connect and solder the other primary lead to the other lug of the POWER switch and wire the transformer's secondary directly into the circuit in place of *J2*.



Interior view of project shows panel-mounted controls, switches and output connectors and floor-mounted circuit-board assembly. Note how pc-mount power jack fits into cutout on rear wall of enclosure.

Checkout

Before installing *IC1* through *IC6* in their sockets, power up the circuit and use a dc voltmeter set to measure 20 volts dc or so to check for proper voltages at key points in the circuit. With the meter's common probe connected to circuit ground at all times, touching the following socket pins should give you a +5 volt reading: *IC1* pins 3, 11 and 16; *IC2* pin 14; *IC3* pins 1, 27 and 28; *IC4* pin 20; and *IC7* pin 3 (output). At *IC5* pin 13, *IC6* pin 4 and *IC7* pin 1 (input), the reading should be between +12 and +15 volts, while at *IC5* pin 3, *IC6* pin 11 and the anode of *D3*, the reading should be between −12 and −15 volts. Though some variation in the +12- to +15-volt and −12- to −15-volt lines is permitted, in no case should these potentials exceed +/− 18 volts.

Once you have verified that the proper potentials exist at the above key points in the circuit (or have rectified the problem if they did not), power down the circuit and allow the charges to bleed off the electrolytic capacitors. Then, exercising care in handling and orientation, install the ICs in their respective sockets. Make sure that no pins overhang the sockets or fold under between sockets and IC bodies.

Testing of the generator is fairly simple. Connect an oscilloscope to the generator's output via either *J1* or the terminal strip and turn on both the generator and the scope to view the waveform being generated on the latter's screen. Rotate the FREQUENCY control's knob and note that the frequency displayed increases as the control knob is rotated clockwise and decreases in the counterclockwise direction. Rotating the LEVEL control should cause the amplitude of the displayed waveform to increase and decrease in the clockwise and counterclockwise directions, respectively. If you note just the opposite results in either case, power down the project and rewire the offending control(s).

Setting the WAVE switches in different combinations of on and off should cause the waveform being displayed to change to another shape. If the generator does not appear to be working as it should, check components for proper placement, identification and polarity. If everything seems to be okay here, check for clock pulses at pin 1 of *IC2* and pin 11 of *IC4*. Also check to make sure that the address lines to *IC3* and the inputs to *IC5* (pins 5 through 12) are changing.

If clock pulses are being generated but *IC3*'s address lines are not changing, *IC2* is bad and must be replaced or is improperly connected. If the output data from *IC3* is changing but the inputs to *IC5* never do, *IC4* is the problem.

Waveform Programming

Generation of waveforms with the programmable waveform generator requires programming of the EPROM. This is best accomplished with a simple computer program that can generate the values to be stored in the EPROM for each of the desired waveforms. The *IC5* DAC-08 accepts data inputs in the 0-to-255 range and will produce a larger negative current for larger values of data inputs. A value of 255, for example, generates the largest negative current, while a value of 0 generates the largest positive current. Data values between 0 and 255 produce intermediate currents.

Since the *IC6* TL084 quad op amp has three stages operated as inverters, an input value of 255 to *IC5* will produce the largest output voltage swing. This makes it easier to generate EPROM programming data because the greater the voltage desired, the larger the value to program into a given EPROM byte.

Each waveform has 256 samples, meaning that the waveform must be broken down into 256 distinct sample values. For a 50-percent-duty cycle square wave, there will be 128 samples with a value of 0 followed by 128 samples with a value of 255. A pulse with a 25-percent duty cycle would have 192 samples with a value of 0 followed by 64 samples with a value of 255.

For waveforms that contain rounded curves, the procedure is more complex. The sine wave, for example, must complete one cycle in 256 samples. With one cycle consisting of 360 degrees (2π radians), each sample is 360/256, or 1.41 degrees. Since most computers calculate the sine function in radians, this is also $2\pi/256$, or 0.0245 radian.

The computer program used must calculate the value of the sine function 256 times, with 0.0245 radian between each value. The values must then be converted into integers between 1 and 255. With 1 representing a sine value of −1 and 255 representing a value of +1, 128 would represent a value of 0. A 1-to-255 range is used to give the wave 127 values above and below 0 volt. If a 0-to-255 range were to be used, the signal generated would not be symmetrical about the ground reference of 0 volt because there would be 128 values above but only 127 values below below 0 volt.

Program 1 both sets the 1-to-255 range and saves the values in memory using the Poke command. (The EPROM programmer I use requires the data to be sitting in memory to be programmed into the EPROM, which is why I "poked" it into memory.) The computed values could be stored in an array, sent out a serial port or saved on a disk, depending on how your EPROM programmer requires the data to be sent to it.

Program 2 is an example in which proper values are calculated for the function sin(X) + sin(2X), where X goes from 0 to 2π. This program generates a sine wave plus its second harmonic that has the same amplitude as the fundamental. A similar approach could be used to generate other functions that are a fundamental sine wave plus harmonics by changing the function calculated.

For a waveform that is not a simple function, you may have to use several program steps to generate the function. Or you may have to draw the waveform on graph paper and calculate the values by hand—a tedious task at best.

Waveforms Programmed Into EPROM

Waveform Number	Type of Waveform
0	sine
1	square
2	triangle
3	sawtooth (slow rise)
4	sawtooth (slow fall)
5	sin(X) + sin(2X)
6	sin(X) + sin(2X) + sin(4X)
7	sin(X) + ⅓sin(3X)
8	sin(X) + ⅓sin(3X) + ⅕sin(5X)
9	pulse (10% duty cycle)
10	pulse (20% duty cycle)
11	pulse (30% duty cycle)
12	pulse (40% duty cycle)
13	pulse (50% duty cycle)
14	pulse (60% duty cycle)
15	pulse (70% duty cycle)
16	pulse (80% duty cycle)
17	pulse (90% duty cycle)
18	absolute value of sin (X)
19	ringing (exponential decay, slow)
20	ringing (exponential decay, medium
21	ringing (exponential decay, fast)
22	staircase (eight steps up)
23	staircase (16 steps up)
24	spare waveforms
.	.
.	.
.	.
31	spare waveforms

Note: Ringing waveforms are at four times generator frequency and repeat at generator frequency rate.

Program 1. Sets 1-to-255 Range & Saves Values in Memory

```
5 REM GENERATE VALUES FOR SIN WAVE
6 REM AND PLACE IN MEMORY FROM $6000 TO $60FF
10 PI=3.14159
20 FOR T=0 TO 255
30 X=(2*PI)*(T/256): REM COMPUTE X IN RADIANS
40 Y=SIN(X):REM COMPUTE SIN VALUE
50 W=(Y*127):REM FIND OFFSET FROM ZERO IN RANGE +-127
60 Z=ABS(W):R=Z-(INT(Z)):REM DO ROUNDOFF
70 IF R<.5 THEN Z=INT(Z):GOTO 90
80 Z=INT(Z+1)
90 IF W<0 THEN P=128-Z:GOTO110:REM IF SIN<0 THEN NEG. VOLTAGE
100 P=128+Z:REM IF SIN POSITIVE THEN POS. VOLTAGE
110 POKE 24576+T,P
120 PRINT T,P
130 NEXT
140 END
```

Each waveform is 256 bytes in length and must begin with an address that is either 0 or a multiple of 256. The first waveform will be from bytes 0 to 255, the second from 256 to 511, and so forth. The generator's WAVE switches select a waveform by changing the higher-order address lines (A8 through A12). If all *S2* through *S6* switches are open (all higher-order address lines low), the waveform will start at address 256 × 0 = 0. With the A8 switch (*S2*) closed and all other switches open, the waveform will be read starting at address 256 × 1 = 256. Other combinations will result with different settings of the switches.

The starting and ending bytes for a waveform should be very close to each other in value; otherwise, the waveform will have a sharp edge generated each time the address counter starts over at 0. For sine waves generated as mentioned above, the starting and ending values for the waveform make a smooth transition. The waveform starts at 128 and ends at 125. For the square wave, the waveform starts at 0 and ends at 255, and it should have a sharp falling edge at the end of the wave.

Uses for this programmable waveform generator and the waveforms it can generate are limited only by the imagination of the user and the restriction of the 256 samples per waveform. Considering that each of the 256 samples can have different values, there are more than 10 to the 256 different possible waveforms that could be generated. This should be enough for even the most imaginative user. **ME**

Program 2. Calculates Function Sin(X) + Sin(2X)

```
5 REM GENERATE VALUES FOR SIN(X)+SIN(2X)
6 REM AND PLACE IN MEMORY FROM $6000 TO $60FF
10 PI=3.14159
20 FOR T=0 TO 255
30 X=(2*PI)*(T/256): REM COMPUTE X IN RADIANS
40 Y=SIN(X)+SIN(2*X):REM COMPUTE SIN VALUE
50 Y=Y/2:REM KEEP IN RANGE OF -1 TO +1
60 W=(Y*127):REM FIND OFFSET FROM ZERO IN RANGE +-127
70 Z=ABS(W):R=Z-(INT(Z)):REM DO ROUNDOFF
80 IF R<.5 THEN Z=INT(Z):GOTO 100
90 Z=INT(Z+1)
100 IF W<0 THEN P=128-Z:GOTO120:REM IF <0 THEN NEG.  VOLTAGE
110 P=128+Z:REM IF SIN POSITIVE THEN POS.  VOLTAGE
120 POKE 24576+T,P
130 PRINT T,P
140 NEXT
150 END
```