Construction Project

A True-rms Adapter

This inexpensive accessory lets you use a standard 3½-digit DMM to measure true-rms voltages

By John T. Bailey

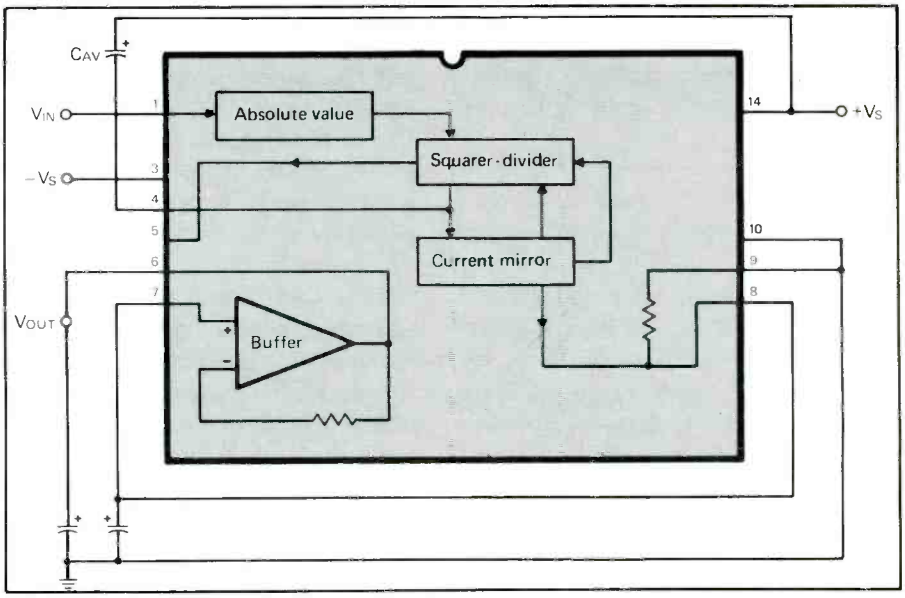
Most digital multimeters (DMMs) are dedicated to measuring sine-wave inputs, displaying "average" values. However, it's often important to know the true-rms value of a complex waveform to determine its actual heating effect on a component. After all, square waves, sawtooths, pulses of various duty cycles, distorted shapes from SCRs or flyback transformers, among other waveshapes are non-sinusoidal.

You can indeed buy a costly DMM to read true-rms volts. An alternative is presented here, however, in the form of a modest-cost adapter that will convert your garden-variety DMM into a true-rms-reading meter that offers reasonably good measuring accuracy. About $50 in newly bought parts will do it. Taking this route, here's how to enhance your ordinary 3½-digit DMM.

About The Circuit

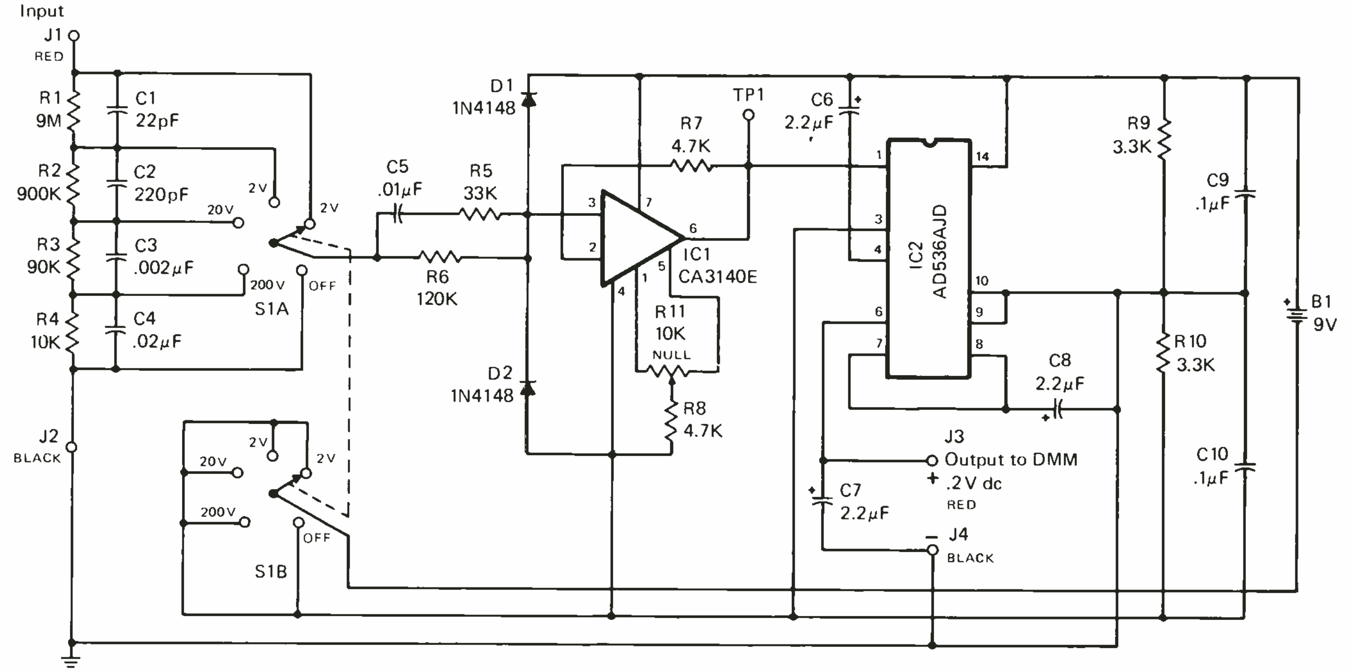
This adapter is built around an Analog Devices AD536AJD monolithic IC that directly computes the true-rms value of complex and sine waveforms and outputs their dc equivalent values. A simplified block diagram, with pinout information, of this IC is shown in Fig. 1. This diagram shows the IC's internal buffer being used as an output filter.

Fig. 1. Block diagram of the AD536AJD IC that computes true-rms voltages.



For this project, a basic design option had to be chosen at the outset. The AD536AJD can be connected, externally, to "read" ac-only or ac-plus-dc inputs, each option having its own advantages and disadvantages. To be most practical for modern electronics needs, it was decided that the

"About $50 in parts will do it"



PARTS LIST

Semiconductors
D1,D2—1N4148 diode
IC1—CA3140E op amp
IC2—AD536AJD (Analog Devices)
Capacitors
C1—22-pF disc
C2—220-pF disc
C3—0.002-μF disc
C4—0.02-μF disc
C5—0.01-μF disc
C6,C7,C8—2.2-μF, 35-volt tantalum
C9,C10—0.1-μF, 50-volt ceramic with radial leads

Resistors
R1—9 megohms, 1%, ¼-watt
R2—900,000 ohms, 1%, ¼-watt
R3—90,000 ohms, 1%, ¼-watt
R4—10,000 ohms, 1%, ¼-watt
R5—33,000 ohms, 5%, ½-watt
R6—120,000 ohms, 5%, 2-watt
R7,R8—4700 ohms, 5%, ¼-watt
R9,R10—3300 ohms, 5%, ¼-watt
R11—10,000-ohm, linear-taper miniature pc-type potentiometer

Miscellaneous
B1—9-volt transistor battery
J1,J2—Banana jack (one red, one black)
J3,J4—Phone jack (one red, one black)
S1—2p6t nonshorting rotary switch (Centralab No. PSA-203 or similar)
Printed-circuit board: one 14- and one 8-pin low-profile IC sockets; connector and holder for B1; ¾"-diameter pointer-type control knob; suitable size metal enclosure; lettering kit; test leads; machine hardware; etc.

Fig. 2. Shown here is the complete schematic diagram of the battery-powered true-rms adapter circuit.

adapter be direct coupled. This allows the adapter to measure ac as well as dc and any combination of ac and dc. Since an rms value, by definition, produces the same heating effect as the same dc value, it was deemed more appropriate for the adapter to provide rms readings that include any dc component.

Shown in Fig. 2 is the full schematic diagram of the adapter. Input resistance is 10 megohms, provided by the voltage divider composed of *R1* through *R4*. This is the same input resistance presented by most 3½-digit DMMs. The adapter's voltage divider is frequency compensated by *C1* through *C4* to enhance bandwidth.

Full-scale output from the adapter is 0.2 volt (200 mV) dc on all ranges. Therefore, the DMM with which the adapter is used should be set to its 200-mV range for all ranges selected on the adpater.

There is a slight problem with decimal point location in the DMM's display when using the adapter. A 3½-digit DMM's 200-mV full-scale display goes to 199.9, with the decimal point fixed as indicated. Consequently, the decimal point is correct only for the adapter's 200-volt range. For the other three ranges, the decimal point must be mentally moved to the left by multiplying by the proper factor pointed to by the adapter's RANGE switch knob (see *S1* in Fig. 2 and lead photo). For example, if the adapter is set to its 2-volt range, an rms input signal of 1.5 volts amplitude will display 150.0 on the DMM. Applying the DMM factor of 0.01 gives the correct reading of 1.500 volts.

From the range divider network, the input signal goes to a filter and protection network. Filtering is provided by the *C5/R5/R6* network. This network limits current through the diodes when input overload occurs. In conjunction with the stray input capacitance of the buffer amplifier, it also serves as a low-pass filter that attenuates frequencies above 100 kHz to prevent input overloading by high frequencies.

An undedicated buffer amplifier is provided internally in the AD-536AJD's chip. This amplifier can be used as a buffer input stage or as an output filter to secure a clean dc output. In our adapter, the latter function is used. Because of this, an additional buffer state is required to present a high impedance to the voltage divider and to buffer *IC2*'s input. A CA3140E op amp (*IC1*) is used for this purpose. Because its input is about 1.5×10^{12} ohms, it presents negligible loading on the 10-megohm input divider. Also, the CA3140E can be nulled without requiring regulated voltage sources.

Averaging time-constant capacitor *C6* (C_{AV} in Fig. 1) determines such things as limits on handling crest factors (C.F.); limits on low-duty-cycle; low-frequency pulse trains; noise spikes; settling time for a step change in input level; and ripple in the output. The 2.2-μF value specified is a compromise that satisfies reasonable trade-offs without seriously sacrificing instrument accuracy.

Power for the project is supplied by a single 9-volt battery (*B1*). Notice in Fig. 3 that *B1* is referenced to ground at midpoint by *R9* and *R10* to provide equal positive and negative supplies for the circuit. Battery output can run down to 6 volts before erratic circuit operations sets in. Current drawn by the circuit is minimal, amounting to only 5 mA. Power to the circuitry is controlled by one section of *S1*, as shown in Fig. 2.

Construction

The true-rms adapter is best assembled on a printed-circuit board (see Fig. 3 for actual-size etching-and-drilling guide and component-placement diagram). It can be housed inside any metal box large enough to accommondate the circuit board, range switch, and 9-volt battery in its holder. The box shown in the photos was custom-made by the author for his prototype.

All components, except *B1* and its holder, mount directly on the board. Sockets are recommended for mounting the ICs on the board. Before installing the sockets, cut off the pins that are not used. These are pin 8 of the *IC1* socket and pins 2, 5, 11, 12 and 13 of the *IC2* socket. (Cut away the specified pin of only the sockets—not the pins on the ICs themselves.)

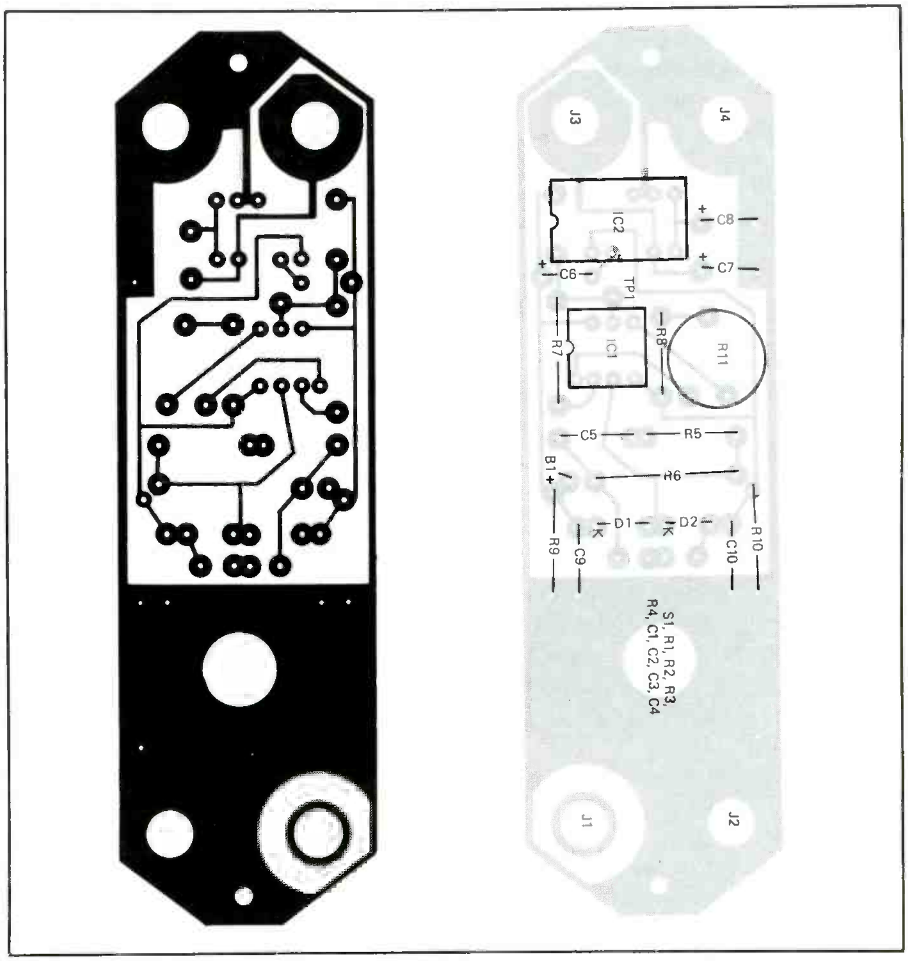
When wiring the board according to Fig. 3, make sure that you install all components in their correct loca-

DELINEATING THE SINE WAVE

There are three significant values for any waveform, whether sinusoid or complex. These are peak, average and rms. For the sine wave, peak is obviously the maximum instantaneous value the waveform reaches; the average value is the average of its absolute values; and the rms value is the square root of the mean of the squares of all instantaneous values. In mathematical terms, the sine wave's values at the three points are 100%, 73.7% and 70.7% of the zero-to-peak value for peak, average and rms.

For an ideal 117-volt ac power-line waveform, with no distortion due to harmonics or noise or spikes, the peak value is 165.5 volts, the average value is 105.3 volts, and the rms value is 117 volts. Peak-to-peak value is two times the peak value, or 331 volts. The ratio of rms to average value is 1.11.

Fig. 3. Etching-and-drilling guide and components-placement diagram.



tions and orientations. Also, when soldering, use heat and solder judiciously. Pay particular attention when soldering to closely spaced pads, such as around the IC leads, to avoid creating solder bridges.

Although the switch specified for *S1* (see Parts List) is a six-position rotary type, it has an adjustable stop for fixing it to five positions, as required in this project. Voltage-divider resistors *R1* through *R4* and capacitors *C1* through *C4* solder directly to the lugs of this switch.

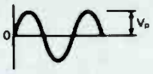
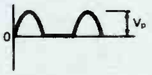
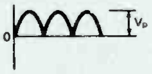
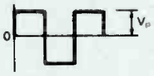
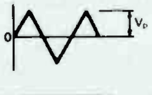
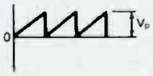
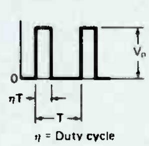
Once the pc-board assembly has been wired, machine the metal box in which it will be installed by drilling the various holes for the jack, rotary switch and mounting hardware for the battery clip. After deburring all holes, spray one or two coats of enamel paint (you choose the color) on all exterior surfaces of the box.

When the paint has completely dried, mount the battery clip on the floor of the box with machine hardware. Set the circuit board assembly into the top of the box and fasten in place with the lockwasher and hex nut that came with the rotary switch. Be careful not to scratch the paint. Place the control knob on the shaft of the switch and tighten. Turn the knob in both directions to establish the pointer's limits from position 1 to position 5. If necessary, loosen the knob and readjust its position so that it points straight up when the switch is set to position 5.

Next, use a dry-transfer lettering kit to carefully letter the identifying legends for the jacks and switch positions. This done, remove the knob from the switch shaft to free the top of the box from the rest of the project. Spray two or three very light coats of clear lacquer over the top of the box to protect the lettering from damage. Let each coat completely dry before spraying the next.

Finally, install the battery in its holder, reattach the top to the shaft of the switch, slide the control knob onto the switch shaft, index it properly and tighten the setscrew. Rotate the knob to OFF at this time.

WAVEFORMS QUALIFIED

Remainder		I V_{avg}	II V_{rms}	III C.F. = (V_p/II)	IV II/I	V (I × 1.111)/II
		half cycle =0.637 V_p full cycle =0	0.707 V_p	1.414	1.111	1
		0.318 V_p	0.5 V_p	2	1.571	0.707
		0.637 V_p	0.707 V_p	1.414	1.111	1
		half cycle =0 V_p full cycle =0	V_p	1	1	1.111
		0.5 V_p	0.707 V_p	1.414	1.414	0.786
		half cycle =0.5 V_p	0.577 V_p	1.733	1.154	0.936
		full cycle =0	0.577 V_p	1.733	1.154	0.936
		0.5 V_p	0.577 V_p	1.733	1.154	0.936
	η	ηV_p	$\sqrt{\eta}\ V_p$	C.F. = V_p/II	II/I	(I × 1.111)/II
	1	V_p	V_p	1	1	1.111
	0.5	0.5 V_p	0.707 V_p	1.414	1.414	0.786
	0.25	0.25 V_p	0.5 V_p	2	2	0.556
	0.0625	0.0625 V_p	0.25 V_p	4	4	0.278
	0.0156	0.0156 V_p	0.125 V_p	8	8	0.139
	0.01	0.01 V_p	0.1 V_p	10	10	0.111

This chart shows the tabulation of the average, rms and crest factor (C.F.) values of commonly encounterd values and the ratios of readings of average-responding, rms-calibrated VOMs, VTVMs and DMMs to true-rms-reading meters (column V).

Significant is the column that shows the ratio of rms to average values. Of even more significance is column V, which reveals the errors that occur when an average-responding, rms-calibrated (garden-variety) VOM, VTVM or DMM is used to measure the rms values of various waveforms.

Of the 13 waveforms listed, only two are without error. Using ratios, the reading errors vary between 1.111 and 0.111. Such diversity clearly substantiates the need for true-rms readings, especially if they can be accomplished accurately, simply and inexpensively.

Using The Adapter

Only one adjustment must be made before you can use the adapter with your DMM. That is to null the CA3140E op amp (*IC1*). To do this, set the RANGE switch (*S1*) to the 0.2-volt position, short the input jacks, connect your DMM (set to the

DEMONSTRATION TESTS

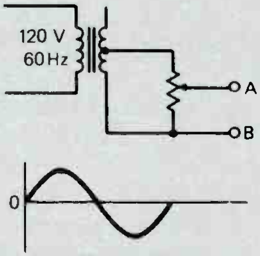
Several simple tests can be made to demonstrate the performance of the true-rms adapter. To peform them, no test equipment beyond your DMM itself is required. Results obtained from these tests reflect minor errors due chiefly to less-than-ideal waveforms used.

Basically, these tests are of several of the waveforms listed in the table shown elsewhere in this article. You will be using your DMM on its dc range (except in Test 2, which uses the DMM's ac range) to measure the magnitude parameters of the waveforms at the adaptor's input. With such measurements, true-rms values can be determined from the relationships given in the table and then the adapter's true-rms readings can be compared with the anticipated figures to reveal any deviations.

In spite of the less-than-ideal waveforms used for the tests, accuracy of the adapter is remarkably good. Tests on the other waveforms in the table were not included here because they require use of an oscilloscope, which may not be available to you at this time.

Test 1. This is a direct-current measuring test. Set the adapter's range switch to 2 volts. Connect a nominal 1.5-volt dry cell to the input. The reading obtained on your DMM, when connected directly across the cell, might be 1.514 volts. Transferring the DMM on its 0.2-volt dc range to the adapter's output might now provide a reading of 151.1 which, after applying the range factor of 0.01 would give a reading of 1.511 volts (regardless of polarity of the cell at the input, the DMM reading at the output of the adapter will always be positive). The 3-mV discrepancy in this test represents an error of −0.2%.

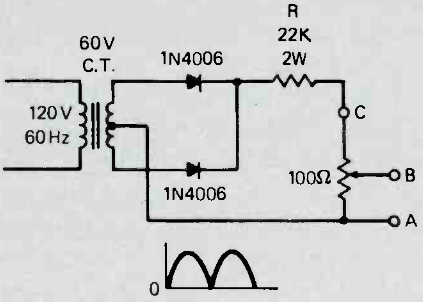
Test 2. In this test you will measure the true-rms value of a sine wave taken from the ac line, as shown in the drawing. Connect a 1000-ohm potentiometer across half the secondary winding of a 6.3-volt transformer and the test probes of your meter to points A and B. Make sure the meter's range switch is on 2 volts ac. Adjust the pot for a meter reading of about 1.8 volts. Select a reading of 1.801 volts.



WAVEFORM AT A–B

Set the adapter's range switch to 2 volts and the range switch of your DMM to the 0.2-volt dc range. Now, without disturbing the setting of the pot, plug the adapter into your DMM and touch the adapter's test probes to points A and B in the circuit. The meter might now read 1.792 volts (179.2×0.01), which calculates out to an error of −0.5%. This error is probably due mostly to inaccuracy of the DMM's ac function.

Test 3. In this test, you will be measuring the full-sine voltage from the full-wave rectifier circuit shown. Select a combination of *R* and transformer secondary voltage that will provide a drop of about 0.25 volt across the pot, as measured by your DMM when set to its 2-volt dc range and measuring between points B and C. The values shown are for example only.



WAVEFORM AT A–B

Set your DMM to its 0.2-volt dc range and connect the test probes to points A and B. Adjust the pot for a meter reading of 170 mV. Set the adapter's range switch to 0.2 volt. Now connect the adapter's input to points A and B in the circuit and the meter's input to the output of the adapter. In our test, we obtained a reading of 189.8×0.001, or 0.1898 volt, as the rms value of the full-sine waveform's amplitude. The average value of the waveform is the 170-mV measurement taken at the start of the test. For an ideal full-sine waveform, the rms value is 1.111 times the average value. In this case, the ratio was 0.1898 to 0.1700, or 1.1165.

Test 4. For our final test, you will be measuring the half-square and square waveform, as shown in the drawing. Begin by connecting a 555 timer in its astable configuration as shown. With

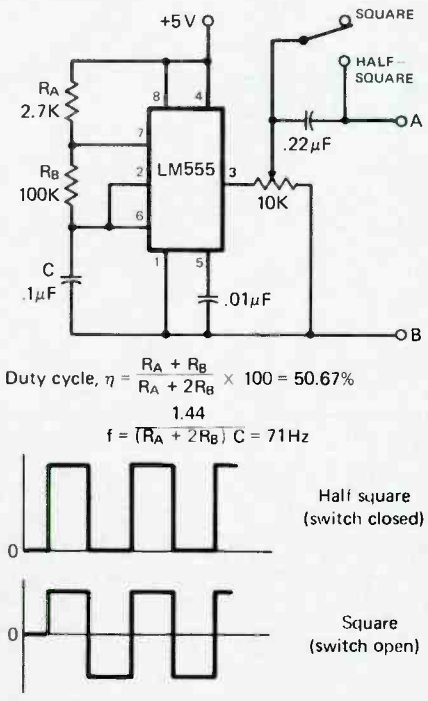
0.2-volt dc range) to *TP1* (see Fig. 3) and ground, and adjust *R11* for a zero reading on your meter.

Measuring rms values with the adapter is relatively simple, but certain limitations must be understood at the outset. One of these is that bandwidth is proportional to signal input. That is, greater bandwidths are achieved with higher-amplitude inputs. The manufacturer's curves for frequency-versus-input for the AD536AJD IC show the following:

input	−3 dB	10%	1%
0.2 V	600 kHz	350 kHz	60 kHz
0.1 V	300 kHz	200 kHz	40 kHz
0.01 V	45 kHz	30 kHz	6 kHz

This data pertains to the AD536ADJ itself, without regard to the effects of associated circuitry. For this adapter, these effects were minimized but were not measured for lack of suitable instruments.

Another performance error pertains to the crest factor (C.F.), which is defined as the ratio of the peak to the rms values. It is never less than 1



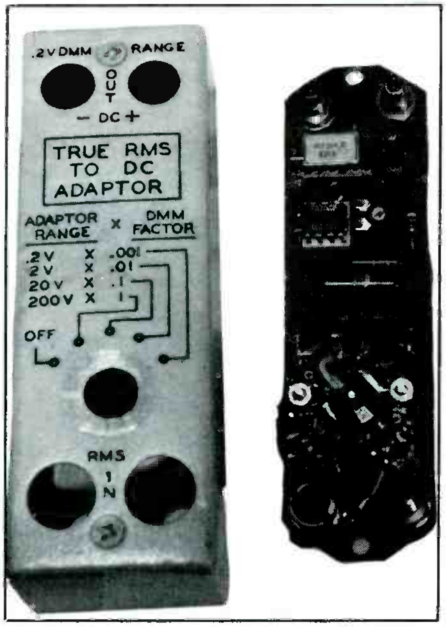
WAVEFORMS AT A–B

this arrangement and the component values shown, duty cycle of the circuit will be close to 50%, frequency will be about 70 Hz, and zero-to-peak voltage at pin 3 of the 555 will be close to the 5 volts of the supply.

For a half-square waveform demonstration, close the switch across the 0.22-µF capacitor. Connect your DMM, set to its 0.2-volt dc range, to points A and B and adjust the pot for a reading of 140.0 mV. Then transfer the DMM, without changing its range setting, to the output of the adapter, the latter set to its 0.2-volt range. In our test, the reading obtained at this point was 197.3 × 0.001, or 0.1973 volt as the rms value of the half-square waveform. For an ideal half-square wave of 50% duty cycle, the ratio of rms to average values is 1.414. Here, the ratio was 0.1973 to 0.1400, or 1.409 average.

For the square waveform test, leave the pot setting as it was above and open the switch. The waveform will not be symmetrical about the zero baseline and its zero-to-peak voltage at pin 3 of the 555 will be close to half the supply voltage, or 2.5 volts. With the DMM and adapter both set to their 0.2-volt ranges (the DMM on the dc function), we obtained a reading of 139.7 × 0.001, or 0.1397 volt for the rms value of the square wave. From the table's relationships, the rms value of a square wave is equal to the zero-to-peak value. In this case, it was 0.1397 versus 0.1400, which calculates to an error of −0.2%.

The Test 4 circuit also provides the basis for demonstrating how a true-rms measurement of a nonsymmetrical waveform is made when using an ac-coupled true-rms DMM. With such an instrument, ac and dc values must be measured separately and be entered into a formula. In the Test 4 circuit, when the switch is open, you have the equivalent of a true-rms ac-coupled DMM. The reading would be the ac component (0.1397 volt in this case). To obtain the dc component, you close the switch and read the dc voltage at points A and B with the DMM set to 0.2 volt dc. This reading would be 0.1400 volt dc. Using the formula $V_{rms} = \sqrt{ac^2 + dc^2}$, the result would be $\sqrt{0.1397^2 + 0.1400^2} = 0.19777$ volt rms, which is very close to the 0.2000 ideal value.



Suggested panel legends for switch and jacks are shown at left. At right is the fully wired pc-board assembly.

and, for commonly encountered complex waveforms, may be as high as 10. For example, a rectagular pulse train with duty cycle η of 1%, C.F. is 10 (C.F. $= 1/\sqrt{\nu}$). The AD536ADJ will handle crest factors of about 3 or less with little error. For a C.F. of 7, the error is −3%, subject to increases as input and duty cycle are reduced.

Another error in measuring high-C.F. waveforms has to do with the fact that the waveform must not be clipped in the measuring process. Since all energy in a pulse train is in the pulses, any clipping will produce a decreased rms reading. This can be avoided merely by switching *S1* to the 2-volt range, thus lowering the crest value by a factor of 10. However, since the adapter is designed for a 0.1-volt full-scale input, clipping is not likely to occur.

Input resistance to the adapter, being 10 megohms on all ranges, is relatively high but will create substantial errors due to loading when source resistance is relatively high. On dc, the error formula is $\%_{error} = [(R_{source} \times 100)/(R_{source} + 10\text{ megohms})]$. For a source resistance of 10,000 ohms, the error is only −0.1%, while for a source resistance of 100,000 ohms, the error will be −1%.

On ac, input impedance is frequency dependent. This error is in addition to frequency errors in the rest of the adapter circuitry. Because the 10-megohm input resistive divider has about 50 pF of capacitance across it, input impedance at 60 Hz is about 9.8 megohms. At 1000 Hz, impedance is about 3 megohms, and at 10,000 Hz, it is only about 300,000 ohms. Obviously, unless source resistance is low, say, less than 1000 ohms, the error for frequencies beyond 10,000 Hz will be considerable. **ME**