Using new low-cost RMS converter chips

The latest generation of monolithic RMS converter chips offers true RMS measurement capability, at op-amp prices. This article discusses the operation and applications of the new Analog Devices AD736 and AD737 chips, which are laser trimmed for high accuracy.

Precision rectifiers, or average responding circuits, have long been popular for RMS measurement in low-cost portable meters. Their inherent disadvantages have been tolerated because of their simplicity and very low cost.

As its name implies, an average responding circuit directly follows the *average* value of an AC voltage or current. First, the circuit rectifies the signal and then low pass filters it. In the precision rectifier shown in Fig.1 amplifier A1 half-wave rectifies the input signal. Amplifier A2, operating as a summing amplifier, supplies a gain of 2 for the half-wave rectified signal, but only a gain of 1 for the raw input signal. Since the 2X amplitude half-wave rectified output of A1 is 180° out of phase with the raw input waveform, A2 subtracts the negative half cycle, resulting in a full-wave rectified output voltage.

The 2.2uF capacitor between A2's output and the summing junction averages the rectified signal. The resulting DC voltage is then scaled by adding gain; the chosen scale factor converts the DC average reading to an RMS equivalent value for a sine wave form. For example, if the average absolute value of a sinewave voltage is 0.636 that of Vpeak, then the corresponding RMS value is 0.707 times Vpeak. Therefore, for sinewave voltages, the required scale factor (or gain) is 1.11 (0.707 divided by 0.636).

There are several obvious problems with the average rectified approach to AC measurement. First, the circuit requires several trims: symmetry and scale factor, plus an offset adjustment for each amplifier. Second, precision rectifiers also exhibit low typical bandwidths while measuring low-amplitude input signals. Last, and perhaps the least obvious, are the inherent difficulties in trying to measure signals that differ from the pre-calibrated waveform. Errors can easily exceed 30%, for waveforms other than that used for calibration.

In contrast to the "average" value of an AC signal, true RMS is a "universal language" among waveforms. RMS-to-DC conversion permits the magnitudes of all types of waveforms to be compared among one another and to their respective "DC" equivalents.

In reality, RMS is a direct measure of the power or heating value of an AC voltage, compared to that of DC; a 1 volt RMS signal will produce the same amount of heat in a resistor as a 1 volt DC signal. Mathematically, the RMS value of a voltage is defined as:

$$V_{rms} = \sqrt{Avg\,(V^2)}$$

In actual circuit practice, RMS computation involves squaring the signal, taking the average, and then obtaining the square root. Computation techniques based on the logarithmic Vbe relationship of a transistor calculate the square and square root. A capacitor or low-pass filter performs the averaging. So, true RMS converters are "smart rectifiers," since they provide an accurate RMS reading regardless of the type of waveform being measured.

Table 1 compares the performance of true RMS to that of average responding methods. As shown, if an average responding circuit is calibrated to determine the RMS value of sinewave voltages, and then used to measure either symmetrical square waves (or DC volt-

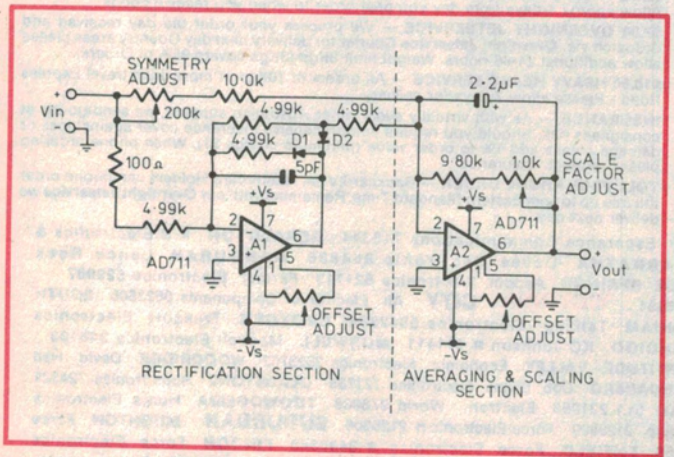
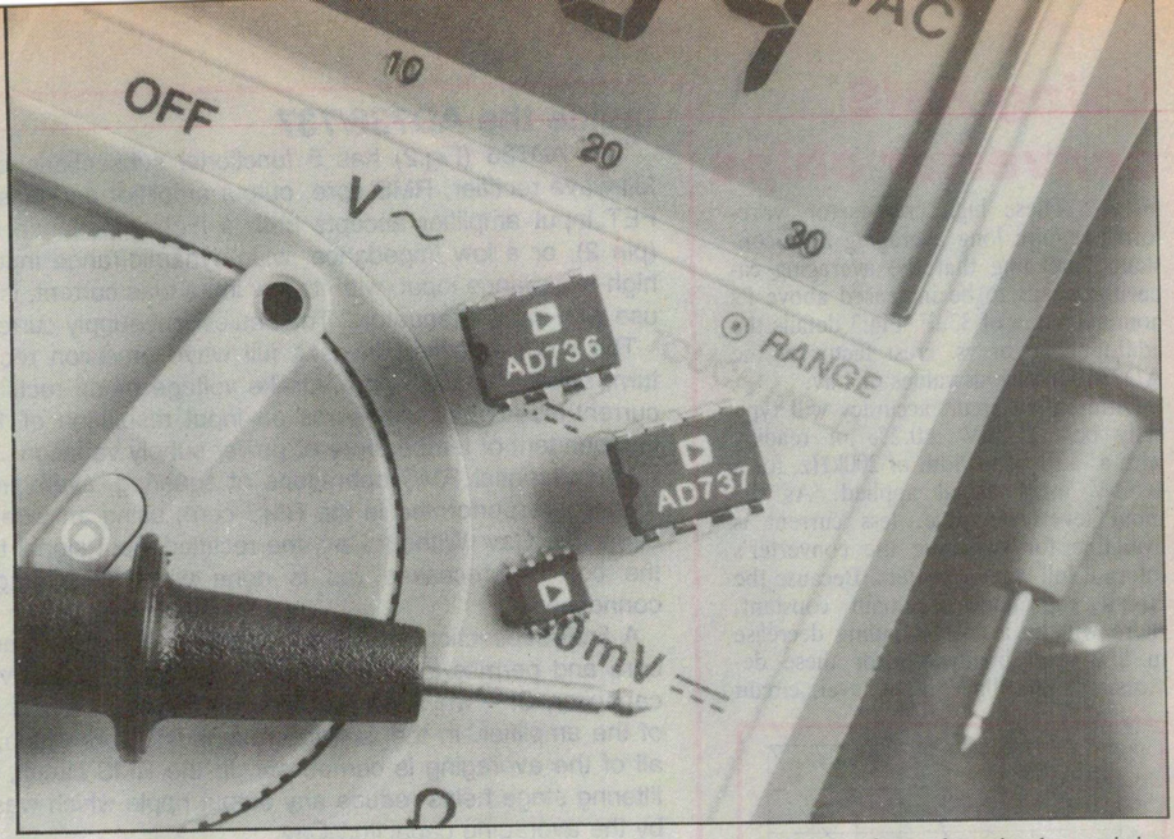


Fig.1: A standard average-reading precision rectifier circuit, as discussed in the text.

Waveform Type 1 Volt Peak Amplitude	Crest Factor (Vpeak/Vrms)	True rms Value	Average Responding Circuit Calibrated to Read rms Value of Sinewaves will Read	% of Reading Error* Average Responding
Undistorted Sinewave	1.414	0.707 V	0.707V	0%
Symmetrical Squarewave	1.00	1.00V	1.11V	+11.0%
Undistorted Trianglewave	1.73	0.580V	0.555V	-2.1%
Gaussian Noise (98% of Peaks < 1 V)	3	0.333	0.266	-20.2%
Rectangular Pulse Train	2	0.5V	0.25V	-50%
	10	0.1V	0.01V	-99%
SCR Waveforms 50% Duty Cycle	2	0.495V	0.354V	-28%
25% Duty Cycle	4.7	0.212V	0.150V	-30%

* % of Reading Error = $\frac{\text{Aver.Resp. Value - True rms Value}}{\text{True rms Value}} \times 100\%$

Table 1 (right): Average and true RMS measurements compared for different waveforms.



Analog Devices' new AD736 and AD737 laser trimmed RMS converter chips are well suited for use in digital multimeters.

ages), then the circuit will exhibit a 11% computational error.

As is the case with many things in the real world, there is no all round "best measurement" technique. Rather, each method has its own virtues. Average responding detectors are simple, quick to respond to changes in amplitude, and exhibit low errors when measuring a pre-calibrated waveform. RMS devices will measure a wide variety of waveforms, but are slow to respond (or settle) when input amplitudes vary.

The circuit shown in Fig.2 improves low-level RMS measurement by accepting a differential input voltage. This differential connection breaks up ground loops typically found in the unbalanced input signals. The user may connect the differential input voltage to pins 1 and 2, or use input coupling capacitors to eliminate the typical 2mV input offset of the AD736.

Most RMS circuits employing the AD736 or AD737 require only two external components: an averaging capacitor, Cav and an input-coupling capacitor. Cc. An optional filtering capacitor, Cf, can reduce output ripple. With single-ended input signals, the designer can reduce the required parts count by omitting input AC coupling capacitor Cc and connecting pin 1 directly to the common terminal at pin 8.

Since the averaging capacitor, Cav, "holds" the rectified input signal during RMS computation, its value directly effects the accuracy of the RMS measurement, especially at low frequencies. Furthermore, because Cav appears across a diode in the RMS core circuit of the AD736, the averaging time constant will increase exponentially as the input signal decreases. As a result, as the input level decreases, errors due to non-ideal averaging will *decline*, while the time it takes for the circuit to settle to the new RMS level will *increase*. Therefore, lower input levels allow the circuit to perform better (due to increased averaging) but increase the waiting time between measurements. Obviously, users must accept a trade-off between computational accuracy and settling time.

The differential circuit may be set to respond to the average value of a differential waveform by simply omitting Cav. Because the average responding connection does not use an averaging capacitor, its settling time does not vary with input signal level; it is determined solely by the RC time constant of Cf and the internal 8kΩ resistor in the output amplifier's feedback path.

The *crest factor* of the input waveform should be considered when designing a low-error RMS circuit. Crest factor is the ratio of the peak signal amplitude to the RMS amplitude (CF = Vpeak / Vrms). Many common waveforms, such as sine and triangle waves, have crest factors less then two. Other waveforms – low duty cycle pulse trains or SCR waveforms – have high crest

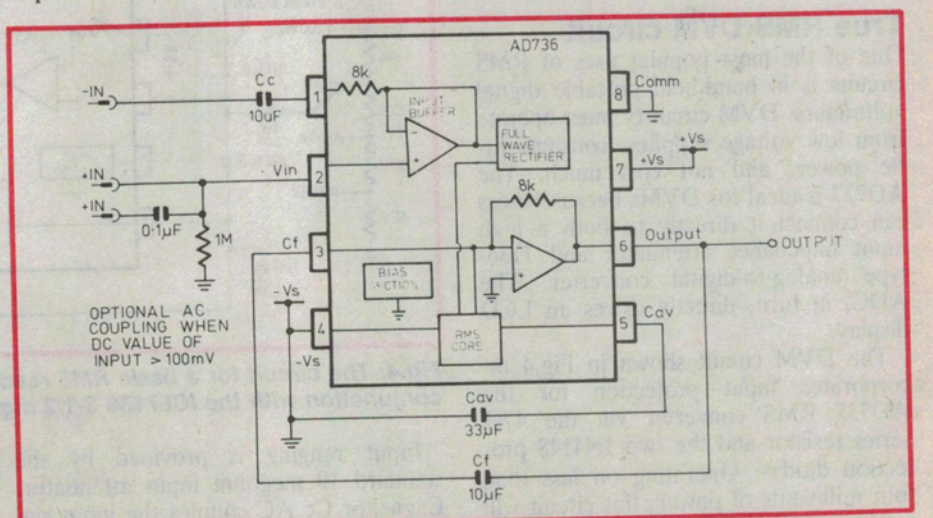


Fig.2: A true-RMS measuring circuit using the AD736 chip, with the ability to accept differential input voltages.

Using RMS converter chips

factors. These high crest-factor waveforms require long averaging time constants, meaning that the averaging capacitor needs to be increased above its nominal value of 33uF. Fig.3 details the additional error vs. crest factor of the AD736 for various values of Cav.

Differential circuit accuracy will typically be ±0.2mV ±0.2% of reading with a -3dB bandwidth of 200kHz, for a 100mV input signal applied. As the input levels decrease, less current is available for switching the converter's internal full wave rectifiers. Because the circuit capacitances remain constant, there will be a corresponding decrease in low level bandwidth for these devices. At the 10mV input level, circuit

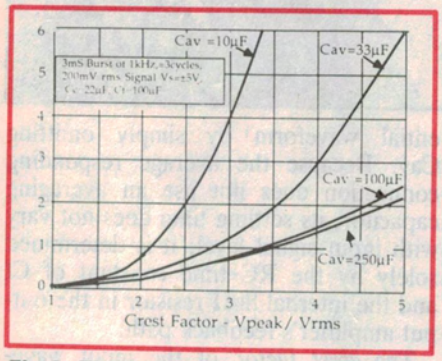


Fig.3: The additional error vs crest factor for the AD736, for various values of Cav.

bandwidth is approximately 50kHz; at 1mV it drops to 5kHz. The circuit will handle input voltages as low as 10uV (with ac coupled inputs). However, the device's bandwidth will not exceed 100Hz.

True RMS DVM circuit

One of the most popular uses of RMS circuits is in hand-held portable digital voltmeters. DVM circuitry must operate from low voltage supplies, consume little power, and not cost much. The AD737 is ideal for DVMs because users can connect it directly to both a high input impedance attenuator and 7136-type analog-to-digital converter. The ADC, in turn, directly drives an LCD display.

The DVM circuit shown in Fig.4 incorporates input protection for the AD737 RMS converter via the 47Ω series resistor and the two 1N4148 protection diodes. Operating on less than four milliwatts of power, this circuit will work even if the 9V battery decays to six volts.

Inside the AD736/737

The AD736 (Fig.2) has 5 functional subsections: input amplifier, full-wave rectifier, RMS core, output amplifier and bias sections. The FET input amplifier accepts both a high impedance, buffered input (pin 2), or a low impedance, wide-dynamic-range input (pin 1). The high-impedance input, with its low input bias current, is well suited for use with input attenuators. Total quiescent supply current is 180uA.

The input amplifier drives a full wave precision rectifier, which in turn, drives the RMS core. Unlike voltage mode rectifier circuits, the current-mode rectifier insures an input resolution of 100uV or less, independent of temperature or power supply variations.

The essential RMS operations of squaring, averaging and square rooting are performed in the RMS core, using an external averaging capacitor, Cav. Without Cav, the rectified input signal travels through the core unprocessed (as is done with the average responding connection).

A final subsection, an output amplifier, buffers the output from the core and permits low pass filtering to be performed via an external capacitor, Cf – which should be connected across the feedback path of the amplifier. In the average responding connection, this is where all of the averaging is carried out. In the RMS circuit, this additional filtering stage helps reduce any output ripple which was not removed by the averaging capacitor, Cav.

The AD737 (Fig.4) differs somewhat from that of the AD736. Since it omits an output buffer amplifier, it has 4 functional subsections rather than 5. This significantly reduces DC offset errors at the device's output, allowing the device to be highly compatible with high input impedance A/D converters.

Requiring only 160uA of power supply current, the AD737 is optimized for portable multimeters and other battery powered applications. The converter also offers a "power down" feature, reducing the power supply standby current from 160uA down to a mere 30uA. The power-down is turned on by tying pin 3 to the +Vs terminal.

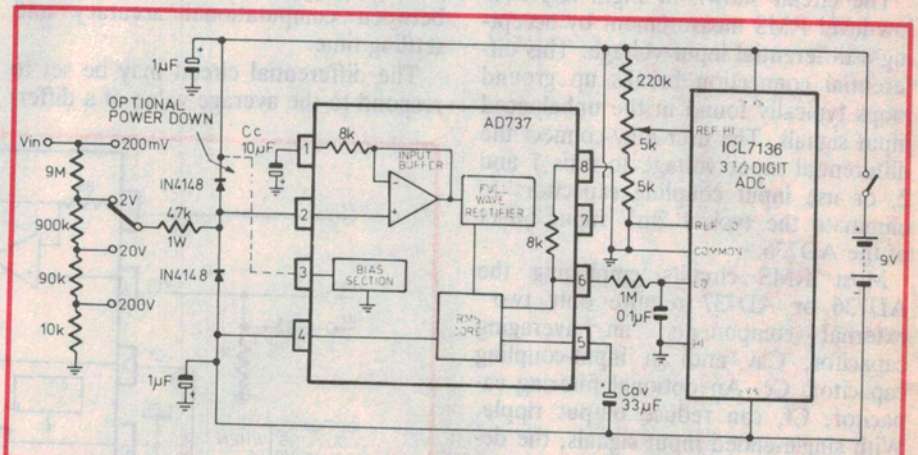


Fig.4: The circuit for a basic RMS reading digital voltmeter using the AD737 in conjunction with the ICL7136 3-1/2 digit ADC chip.

Input ranging is provided by the standard 10 megohm input attenuator. Capacitor Cc AC couples the input signal to the AD737. A large value capacitor connected between pins 6 and 8 of the AD737 delivers post filtering. Because the A/D has a high input impedance, a user can employ an RC network using a large value resistor and a 0.1uF capacitor to save valuable board space.

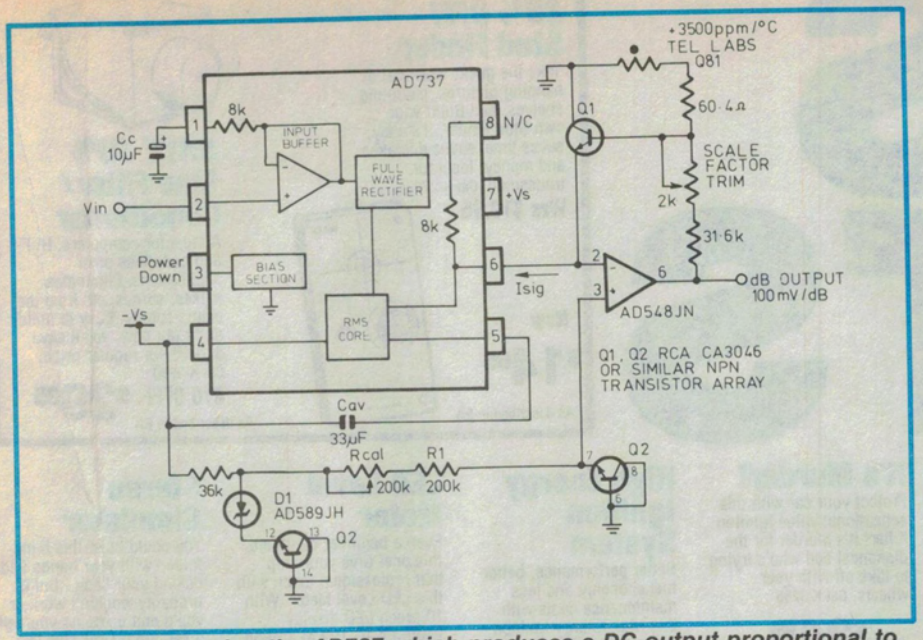


Fig.5: A circuit using the AD737 which produces a DC output proportional to dB, over a +/-30dB range.

Wide range dB circuit

With the help of a few external components, an AD737 can determine the RMS level of an input voltage over a ±30dB range (relative to a preset 0dB level of 30mV). Typical accuracy for the circuit in Fig.5 is ±0.5dB from 1mV to 300mV, and ±1dB from 300mV to 1V. The current Iref, which flows through resistors Rcal and R1 to transistor Q2 sets the zero dB reference level. Bandgap reference D1 and transistor Q3 establish a reference voltage that minimizes effects of negative supply and temperature variations. The current output at pin 6 of the AD 737 drives one input of a log ratio circuit. Iref drives the other input, which is set by resistors Rcal and R1.

The +3500ppm/°C thermistor, together with a 60.4Ω metal film resistor, compensate for the gain temperature coefficient (TC), and set the amplifier's gain to 33.3 at room temperature. This scales the output voltage to a more convienent 100mV/dB level from the approximately 3mV/dB value of Q1's emitter/base voltage.

The calibration procedure for this circuit is:

1) Apply a 30mV RMS, 1kHz, sinewave voltage to Vin.
2) Adjust Rcal for Vout = OV
3) Reduce the input sinewave voltage to 3mV. Adjust scale factor trim for -2.00 volts Vout.

Editor's Note: Analog Devices' AD736 and AD737 RMS converter chips are available in Australia from Parameters, the local distributor, with offices in Melbourne (03) 575 0222, Sydney (02) 888 8777 and Perth (09) 242 2000. The price for both chips (JN package) in one-off quantities is $7.45 plus 20% sales tax, if applicable.