Appendix D

New Products Appendix to the RMS to DC Conversion Application Guide

INTRODUCTION*

Since the last printing of this Applications Guide in 1986, Analog Devices has introduced four new rms products. These devices supplement ADI's original rms products: the AD536A, AD636, and AD637.

The AD736 and AD737 are low power, low cost rms converters designed for use in portable instruments.

The AD8361 and AD8362 TruPwr™ RF power detectors are designed for accurate control of radiated power levels in cellular, broadband, CATV, MMDS, and LMDS communications equipment.

HOW TO SELECT AN RMS-TO-DC CONVERTER

Selecting an rms-to-dc converter means picking the product whose attributes best match the requirements of the application. Unfortunately, no one converter fits every situation so trade-offs must be made between accuracy, bandwidth, power consumption, input signal level, crest factor, settling time, and cost.

The AD637 accepts input voltages as high as 7 V rms and is Analog Devices' most accurate and widest bandwidth rms-to-dc converter. Its –3 dB bandwidth is 8 MHz for a 1 V rms input. It has an auxiliary dB output and a power-down feature that reduces its quiescent current from 3 mA to 450 µA.

The AD536A and its 200 mV companion product, the AD636, are designed for low cost, general-purpose applications. These converters offer true rms conversion accuracy and will accurately process input signals with high crest factors. The AD536A has a 2 V rms full-scale range, while that of the AD636 is 200 mV rms. Both products consume only about 1 mA of power supply current. They also offer a dB output feature with an output that is proportional to the logarithm of the rms input signal.

Both the AD736 and AD737 are optimized for use in portable instruments; they consume less than 200 µA of quiescent current and accept signal levels from 0 mV rms to 200 mV rms. The AD737 also has a power-down input that allows the user to reduce its quiescent current from 160 µA to 40 µA in portable applications.

The AD637 should be chosen if the application requires high accuracy and a quick response for large, abrupt changes in signal level. The AD637's settling time is independent of signal level, while for a given value of averaging capacitor, the settling times of the AD536A, AD636, AD736, and AD737 will be longer for low level signals and shorter for high level signals.

Some monolithic rms converters use a sigma-delta computational technique. This method can provide wide bandwidth while operating at low supply current levels but suffers from a very serious low frequency "rumble." In effect, as the input signal frequency increases, a larger percentage of the input signal is aliased down to dc, producing a low frequency modulation at the output of the converter. This rumble is a low frequency error that increases both with rms signal level and signal frequency. When this type of rms converter is used in a DVM, the lower digits on the display will flicker and, as the rms level or frequency increases, more and more display digits will become erratic. Attempts to minimize this problem using a low-pass "rumble filter" after the converter will result in longer settling times between readings and will, in any case, be generally ineffective in removing the flicker. In contrast, the AD736/AD737 architecture is continuous-time and not subject to this type of unstable behavior.

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*Portions of this appendix are excerpts from Application Note AN-268, *RMS to DC Converters Ease Measurement Tasks*, by Bob Clarke, Mark Fazio, and Dave Scott: Analog Devices Publication.
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Table I provides a quick performance comparison between Analog Devices' rms products.

Table I. RMS Converter Comparison Table

	AD536AJ	AD637J	AD636J	AD736J	AD737J
Input Dynamic Range	7 V rms	7 V rms	1 V rms	1 V rms*	1 V rms*
Nominal RMS Full Scale	2 V	2 V	200 mV	200 mV	200 mV
Peak Trans. Input	±20 V	±15 V	±2.8 V	±2.7 V	±2.7 V
Max Total Error	5 mV	1 mV	0.5 mV	0.5 mV	0.4 mV
No Ext. Trim	±0.5% rdg	±0.5% rdg	±1% rdg	±0.5% rdg	±0.5% rdg
–3 dB Bandwidth					
Full Scale	2 MHz	8 MHz	1.3 MHz	190 kHz	190 kHz
0.1 V rms	300 kHz	600 kHz	800 kHz	170 kHz	170 kHz
Error at Crest					
Factor of 5	–0.3%	±0.15%	–0.5%	±2.5%	±2.5%
For V rms	@1 V	@1 V	@200 mV	@200 mV	@200 mV
Power Supply					
Volts	±13 V	±13 V	+2 V, –2.5V	+2.8, –3.2 V	+2.8, –3.2 V
	to ±18 V	to ±18 V	to ±12 V	to ±16.5 V	to ±16.5 V
Current	1 mA	2 mA	800 µA	230 µA	170 µA

*±5 V to ±16.5 V dual-supply operation only. 200 mV rms under +5 V, –3 V single-supply conditions.

THE AD736 AND AD737 LOW COST RMS CONVERTERS

As shown in Figures 1 and 2, the AD736 and AD737 architectures are very similar. The major difference between these two products is that the AD736 includes an output buffer amplifier for general-purpose applications, while the AD737 is unbuffered for low power operation. The AD737 also includes a power-down feature that further reduces its standby current consumption to a mere 25 µA. Both products can be operated either as a true rms converter or as an average responding (MAD) rectifier. The AD736 and AD737 converters are optimized for low power operation, and their averaging capacitor appears directly across a diode in the rms core. Because of this, the averaging time constant will increase as the rms input level decreases. Consequently, lower input levels allow the circuit to perform better (due to increased averaging) but result in longer settling times, requiring more time between readings.
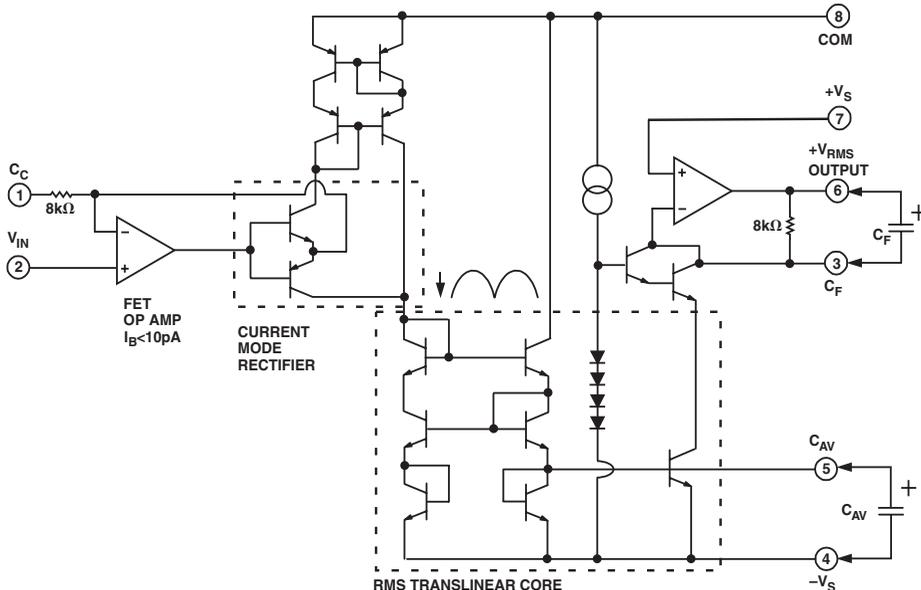
Figure 1. Simplified Schematic of the AD736

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The input to the AD736 and AD737 is through a FET input op amp connected as a unity-gain buffer. This amplifier allows both a high impedance, buffered input (Pin 2) or a low impedance input (Pin 1) that provides a wider dynamic range. The high impedance input, with its low input bias current, is well suited for use with high impedance input attenuators.

The output of the buffer drives a current mode rectifier (absolute value circuit) that in turn drives an rms core.

In the AD736 (Figure 1), the output of the rms core drives the summing node of an inverting op amp connected as a current-to-voltage converter. Pin 3 gives access to this node to connect a filter capacitor, C_F, in parallel with the 8 kΩ feedback resistor, to form a one-pole low-pass filter.

The design of the AD737 is very similar to that of the AD736. In order to reduce power consumption, the AD737 does not have an output buffer amplifier. Instead, it uses an NPN transistor to drive an 8 kΩ internal load resistor.

The converter develops its output voltage by sinking current through this resistor. The external averaging capacitor (C_{AV}) for the AD736 and AD737 is connected between Pins 4 (–V_S) and 5 (C_{AV}), which places C_{AV} across a transistor's base-emitter junction in the rms core. This means that a diode is in parallel with the averaging capacitor; the resulting time constant is therefore *inversely proportional* to the rms value.
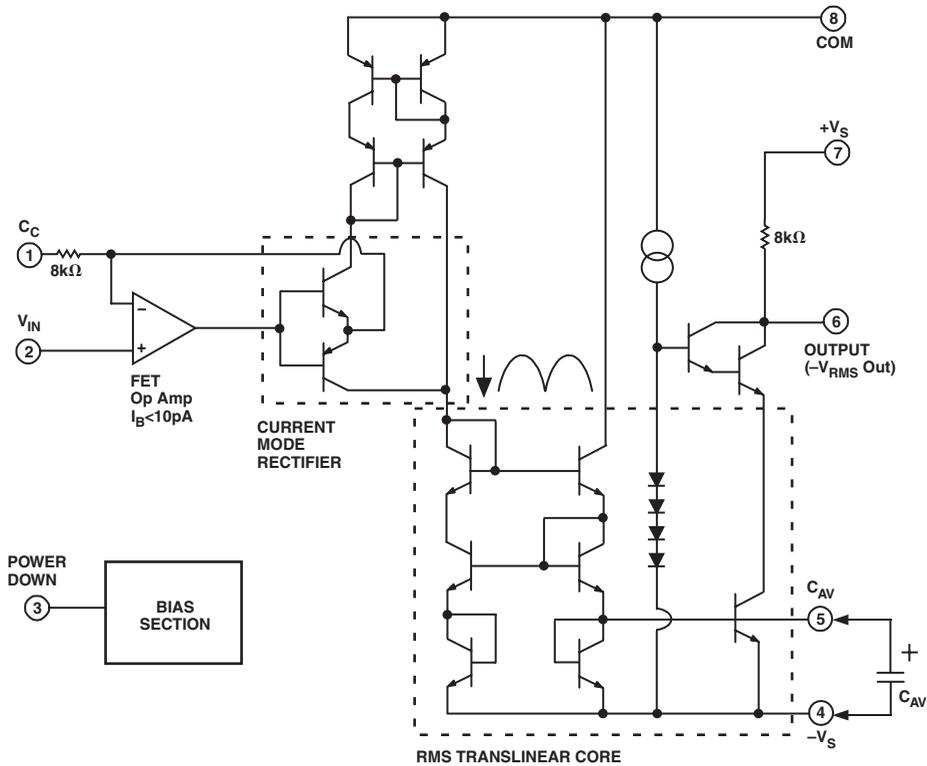
Figure 2. Simplified Schematic of the AD737

Because the external averaging capacitor, C_{AV}, "holds" the rectified input signal during rms computation, its value directly affects the accuracy of the measurement—especially at low frequencies. (The larger the value of C_{AV}, the lower the error.) Also, because the averaging capacitor appears across a base-emitter junction in the squarer/divider, the averaging time constant will *increase linearly* as the input signal is reduced.

AD736/AD737 settling time versus rms input level and C_{AV} is shown in Figure 3.

Due to the varying time constant, as the input level decreases, errors due to nonideal averaging will decrease, 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, because the capacitor takes longer to charge or discharge. Thus, a trade-off between computational accuracy and settling time is required.

Table II provides practical values of C_{AV} and C_F for several common applications.
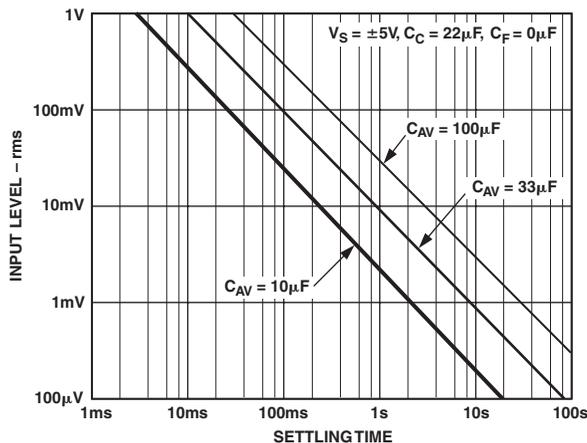
Figure 3. Settling Time vs. RMS Input Level of the AD736 and AD737 for Various Values of C_{AV}

CALCULATING AD737 SETTLING TIME
The graph of Figure 3 may be used to approximate the time required for the AD736 or AD737 to settle when its input level is reduced in amplitude. The total time required for the rms converter to settle will be the difference between two settling times extracted from the graph—the initial settling time minus the final settling time.

Table II. Practical Values for C_{AV} and C_F for AD736 and AD737

Application	RMS Input Level	Low Frequency Cutoff (–3 dB)	Max Crest Factor	C_{AV}	C_F	Settling Time* to 1%
General-Purpose RMS Computation	0 V–1 V	20 Hz	5	150 µF	10 µF	360 ms
		200 Hz	5	15 µF	1 µF	36 ms
	0 mV–200 mV	20 Hz	5	33 µF	10 µF	360 ms
		200 Hz	5	3.3 µF	1 µF	36 ms
General-Purpose Average Responding	0 V–1 V	20 Hz			33 µF	1.2 sec
		200 Hz			3.3 µF	120 ms
	0 mV–200 mV	20 Hz			33 µF	1.2 sec
		200 Hz			3.3 µF	120 ms
SCR Waveform Measurement	0 mV–200 mV	50 Hz	5	100 µF	33 µF	1.2 sec
		60 Hz	5	82 µF	27 µF	1.0 sec
	0 mV–100 mV	50 Hz	5	50 µF	33 µF	1.2 sec
		60 Hz	5	47 µF	27 µF	1.0 sec
Audio Applications Speech	0 mV–200 mV	300 Hz	3	1.5 µF	0.5 µF	18 ms
Music	0 mV–100 mV	20 Hz	10	100 µF	68 µF	2.4 sec

*Settling time is specified over the stated rms input level with the input signal increasing from zero. Settling times will be greater for decreasing amplitude input.

As an example, consider the following conditions: a 33 µF averaging capacitor an initial rms input level of 100 mV and a final (reduced) input level of 1 mV. From Figure 3, the initial settling time (where the 100 mV line intersects the 33 µF line) is around 80 ms. The settling time corresponding to the new or final input level of 1 mV is about 8 seconds. Therefore, the net time for the circuit to settle to its new value will be dominated by the final settling time. Figure 4 shows the additional error versus the crest factor of the AD736 and AD737 for various values of C_{AV}.
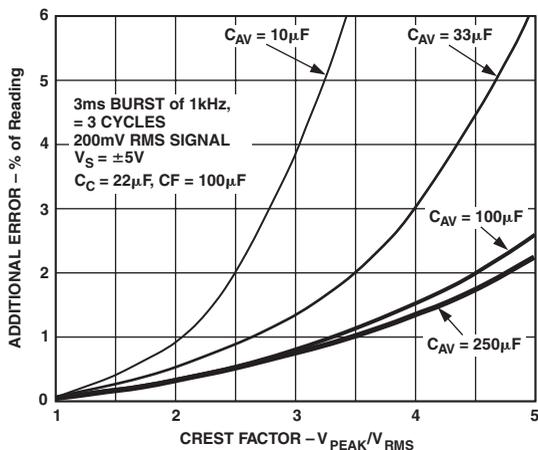
Figure 4. Additional Error vs. Crest Factor of the AD736 and AD737 for Various Values of C_{AV}

AC Coupling Design Considerations
The AD736 and AD737 rms converters offer the designer the option of ac coupling both the input signal and the dc offset voltages on the rms converter's input stage.
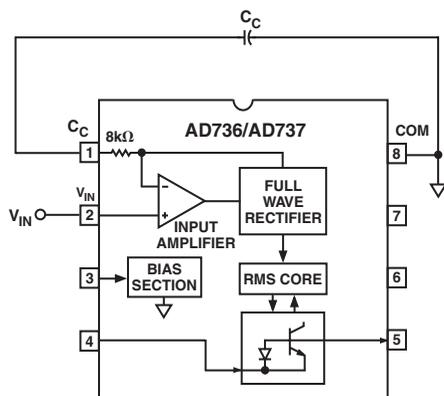
Figure 5. Using Capacitor C_C to Block Internal Offset Voltage Errors

Normally, the input offset errors in the traditional monolithic rms converter will create a region of diode nonconduction at low level input voltages. That is, any input voltages that are smaller than the input offset voltage will not be rectified and a "dead zone" is created.

However, the AD736 and AD737 are specifically designed to eliminate this problem. The maximum input offset voltage of these rms converters is 3 mV. If Pin 1 is directly grounded, this offset voltage will limit the converter's low level resolution. However, as shown in Figure 5, the use of capacitor C_C between Pin 1 and ground will ac couple the low impedance input pin and "float" this input above ground. This prevents any dc currents from flowing through the 8 kΩ internal resistor and creating an input voltage offset. Capacitor C_C should be chosen to provide a low frequency cutoff substantially below the lowest signal input frequency.

The 3 db roll-off frequency of C_C =

$$\frac{1}{2\,\pi\,(8{,}000\,\Omega)\left(C_C \ in \ Farads\right)}$$

For most applications, a value of 10 µF (F_{CUTOFF} = 2 Hz) will suffice. A good rule of thumb is to use a value of C_C approximately equal to one-third that of C_{AV}.
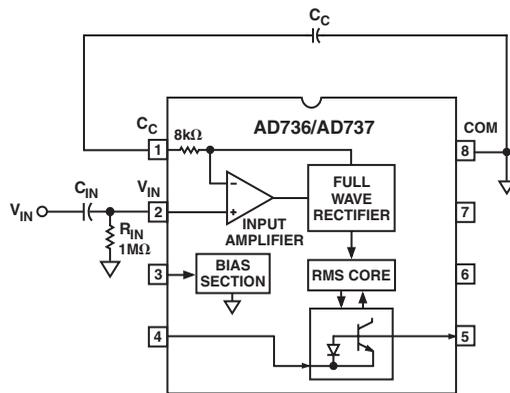
Figure 6. AC Coupling Using Capacitor C_{IN}

Figure 6 shows ac input coupling for Pin 2. Capacitor C_{IN} is necessary if the input signal is an ac waveform riding on a dc voltage, or if the rms converter is operating from a single-supply voltage. In this case, Pin 1 will be "floating" above ground and C_{IN} is needed to prevent the rms converter from full-wave rectifying the differential voltage between Pins 1 and 2, which often will result in input overload. A resistor is needed between Pin 2 of the rms converter and ground to provide a dc return path for input bias currents. Note that capacitor C_C is still needed to prevent input offset voltage errors.

APPLICATIONS OF THE AD736 AND AD737
AD736 as Precision Rectifier

Building a precision rectifier from discrete components requires two op amps, two diodes, and a handful of matched resistors. An easy way to replace all these parts and save some board space is to use an rms-to-dc converter IC. Just omit the averaging capacitor and disconnect the feedback; this uses only the converter's internal precision rectifier (Figure 7), which, being monolithic, has inherently matched diodes.
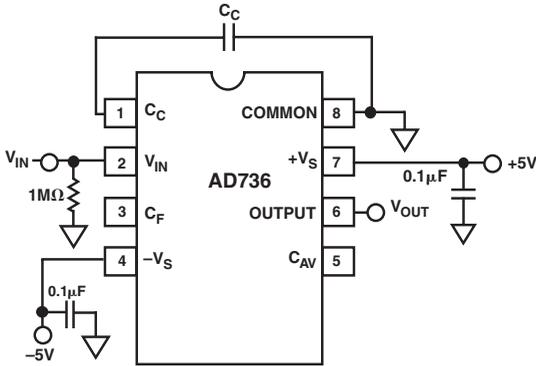
Figure 7. AD736 Connected as a Precision Rectifier

A precision rectifier circuit must provide enough gain to forward bias its rectifier diodes. So, as the input signal gets smaller in amplitude, more gain is needed. The traditional circuit uses an op amp to provide this gain. However, it will usually have a fixed gain/bandwidth product, which means that the rectifier's bandwidth will change with the input signal level. In contrast to a discrete circuit, the internally trimmed, monolithic design of the AD736 and AD737 greatly helps to minimize this effect.

Figure 8 shows the AD736's performance as a precision rectifier.
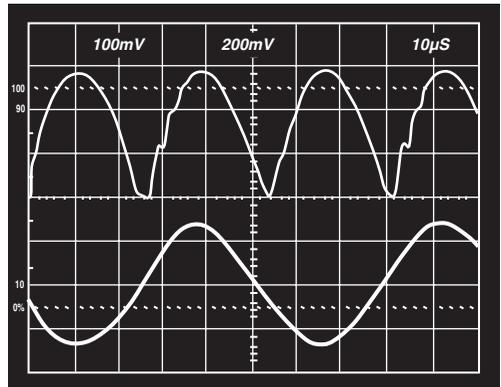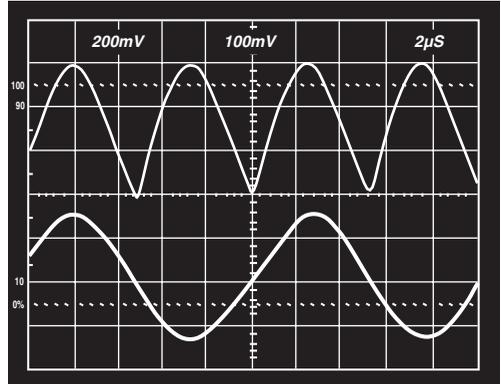
Figure 8. Performance of AD736 Precision Rectifier at 1 kHz (Top) and 19 kHz (Bottom)

True RMS and Average Value Circuit

Figure 9 shows a circuit that measures *both* the true rms value and the rectified average value of an ac signal. This design uses two low cost ICs in SOIC packages and consumes only 180 µA quiescent current. Operating from a 5 V single supply, this circuit has an input dynamic range from below 30 mV to greater than 3 V rms. Sine wave accuracy is quite good (see performance data below) and bandwidth is approximately 100 kHz, depending on the input level. The circuit can also measure a 1 V rms, crest factor of 5 pulse train with less than 1% of reading error.

Average responding measurements and rms have traditionally used different circuits. However, in some cases, it may be extremely useful to know both the rms and rectified average value of an ac waveform. The ratio of rms to rectified average value is one way to determine the characteristics of a particular waveform without actually seeing it on an oscilloscope. For example, the rms/average value ratio for a 1 V peak *undistorted* sine wave is 0.707 V/0.636 V or 1.11, a symmetrical square wave is 1.0, a triangular wave is 1.155, and Gaussian noise is 1.253.

Circuit Operation

As shown in Figure 9, an AD737 rms converter IC drives an AD8541AR micropower op amp. Resistors

R7 and R8 form a voltage divider to allow operation from a single-supply voltage or battery. Capacitors C4 and C5 bypass any signal currents on V_S or $V_S/2$ to ground.

The rms converter IC has two inputs: a high impedance ($10^{12}\ \Omega$) input (at Pin 2) and an 8 kΩ, wide dynamic range input via Pin 1. The rms converter's full-scale input range is normally 200 mV. This can be greatly increased by adding an external resistance, in this case resistor R1 and trimpot R2, between the signal input and Pin 1. This has the added advantage of increasing the circuit's input impedance.

The AD737JR measures the true rms value when switch SW1 connects its averaging capacitor, C_{AV}, to Pin 5. The averaging capacitor performs the "mean" portion of the rms (root-mean-square) function. Removing C_{AV}, by opening SW1, converts the circuit to rectified average value operation. Resistor R6 allows a small leakage current to flow past the switch, keeping the capacitor charged and preventing any large surge currents from flowing into or out of C_{AV} when the switch is closed.

The rms value of a sine wave is 0.707 V peak while the rectified average value is 0.636 V peak. This ratio of 0.707 V/0.636 V is equivalent to an 11% scale factor difference between the two measurement methods. If it is

–3dB BW	C_{AV}	C_F*
10Hz	68µF	0.82µF
20Hz	33µF	0.47µF
100Hz	6.8µF	0.1µF

*C_{AV} IS DISCONNECTED IN THE AVERAGE VALUE MODE. THEREFORE, THE OUTPUT RIPPLE WILL BE NOTICEABLY HIGHER AT VERY LOW FREQUENCIES. SIMPLY INCREASE THE VALUE OF C_F TO REDUCE RIPPLE TO THE DESIRED LEVEL.
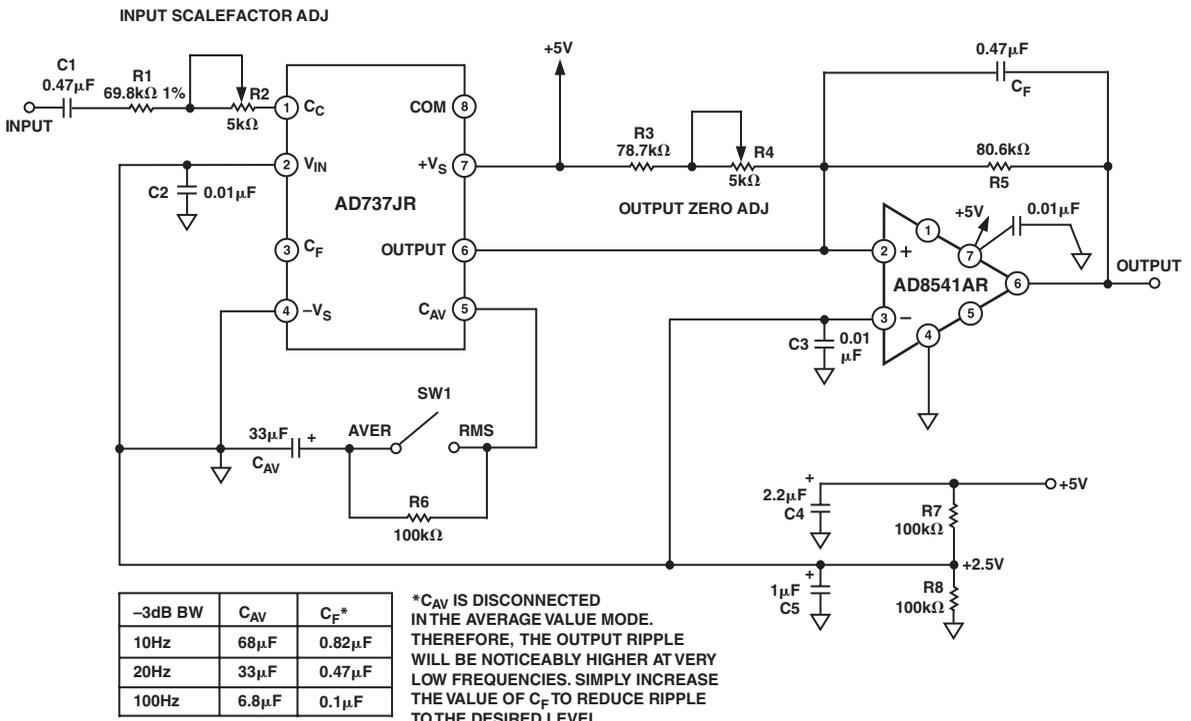
Figure 9. An RMS/Average Rectified Value Measurement Circuit

desired to have this circuit accurately read the rms value for sine waves in the rectified average value mode, SW1 can be a two-pole switch. The second pole can connect a 523 kΩ 1% resistor in parallel with R1 to increase the scale factor by 11% in the average value mode.

The AD737JR drives the AD8541AR op amp with a negative flowing output current. The op amp operates as a current-to-voltage converter and also inverts the signal, providing an output voltage that swings more positive with increasing input level. Resistor R5's value of 80 kΩ matches the effective input resistance of the AD737 (R1 + R2 + 8 kΩ) so that input/output scaling is 1:1. Resistor R3 and trimpot R4 cause a current to flow from the supply to the op amp summing junction. This offsets the op amp output such that the circuit's output is approximately zero with no voltage applied. Note that this circuit has a maximum supply voltage limit of 5.5 V; operation may be extended up to 12 V by substituting an OP-196GS op amp for the AD8541AR.

Circuit calibration:

1. Adjust trimpot R4 to midscale and set SW1 for rms.

2. Apply a 2.000 V rms, 1 kHz sine wave input signal.

3. Adjust R2 until the circuit's output voltage is 2.000 V dc.

4. Reduce the input to 100 mV rms and adjust offset trimpot R4 for a reading of 100 mV dc.

5. Repeat Step 3.

As the dc offset circuitry is ratiometric, it will remain calibrated with modest variations in supply voltage. The measured PSRR of this circuit (over a 4.5 V to 5.5 V supply range) is approximately 61 dB.

Measured Performance Data
1 kHz Sine Wave Accuracy
V_{IN} is in ac volts rms as monitored by Keithley 191 DVM in ac mode. 5 VDC supply.

V_{IN}	V_{OUT} rms	V_{OUT} Rectified Average Value
3 V	2.9999	2.6762
1 V	1.0027	0.8947
0.3 V	0.30201	0.2698
0.1 V	0.10082	0.09947
0.03 V	0.02960	0.02956

Error versus Crest Factor. +5 VDC Supply, 1 V rms, 100 µs pulse.

Duty Cycle Varied for Desired Crest Factor.

Crest Factor	% of Reading Error
3	0.67%
5	0.98%
10	4.7%

Extending the AD736 and AD737 Full–Scale Input Ranges
The high impedance input (Pin 2) of the AD736 and AD737 allows simple resistive attenuators (Figure 10) to be used to extend their input range. Without input attenuation, both the AD736 and AD737 can accurately measure input signals as large as 200 mV rms with crest factors of 1 to 3.
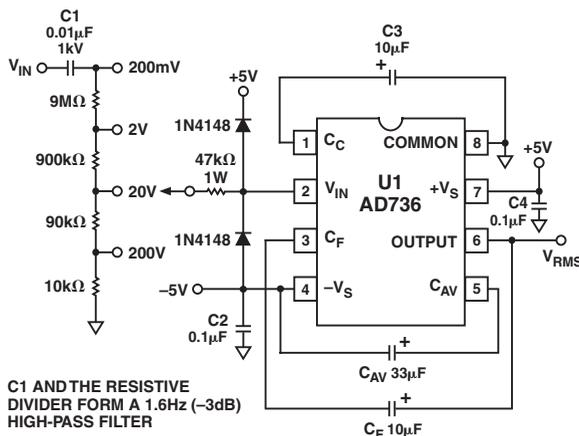
Figure 10. By Using an External Input Attenuator, the Measurement Range of the AD736 and AD737 Can be Extended

The external attenuator simply reduces the full-scale input to the 200 mV rms input range of the AD736 or AD737. For a maximum 7 V rms input (10 V peak), for example, the attenuator should be a 35:1 (7 V/200 mV) voltage divider. The reading of the converter should be scaled by the factor of attenuation used. An external attenuator can also be used with the converter's low impedance input (Pin 1), as shown in Figure 10.

Figures 11 and 12 show the recommended connections for external offset and scale factor.
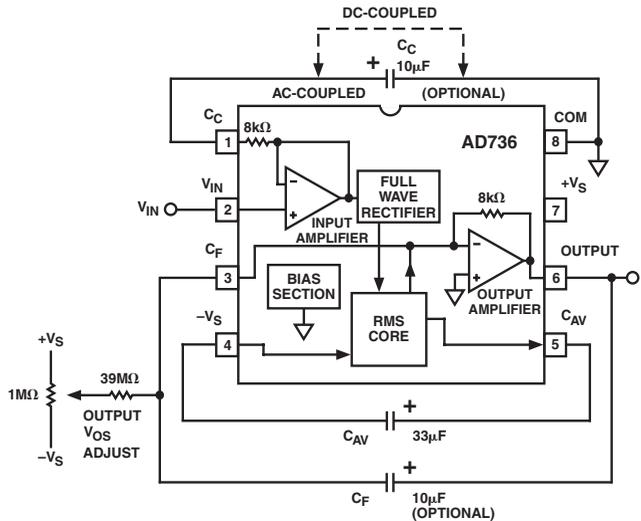
Figure 11. AD736 External VOS Adjustment
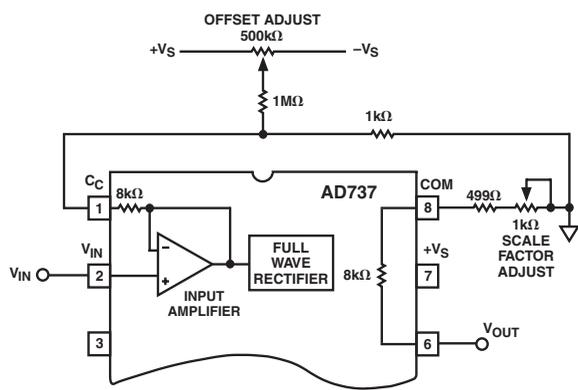
Figure 12. AD737 DC-Coupled V_{OS} and Scale Factor Adjustments