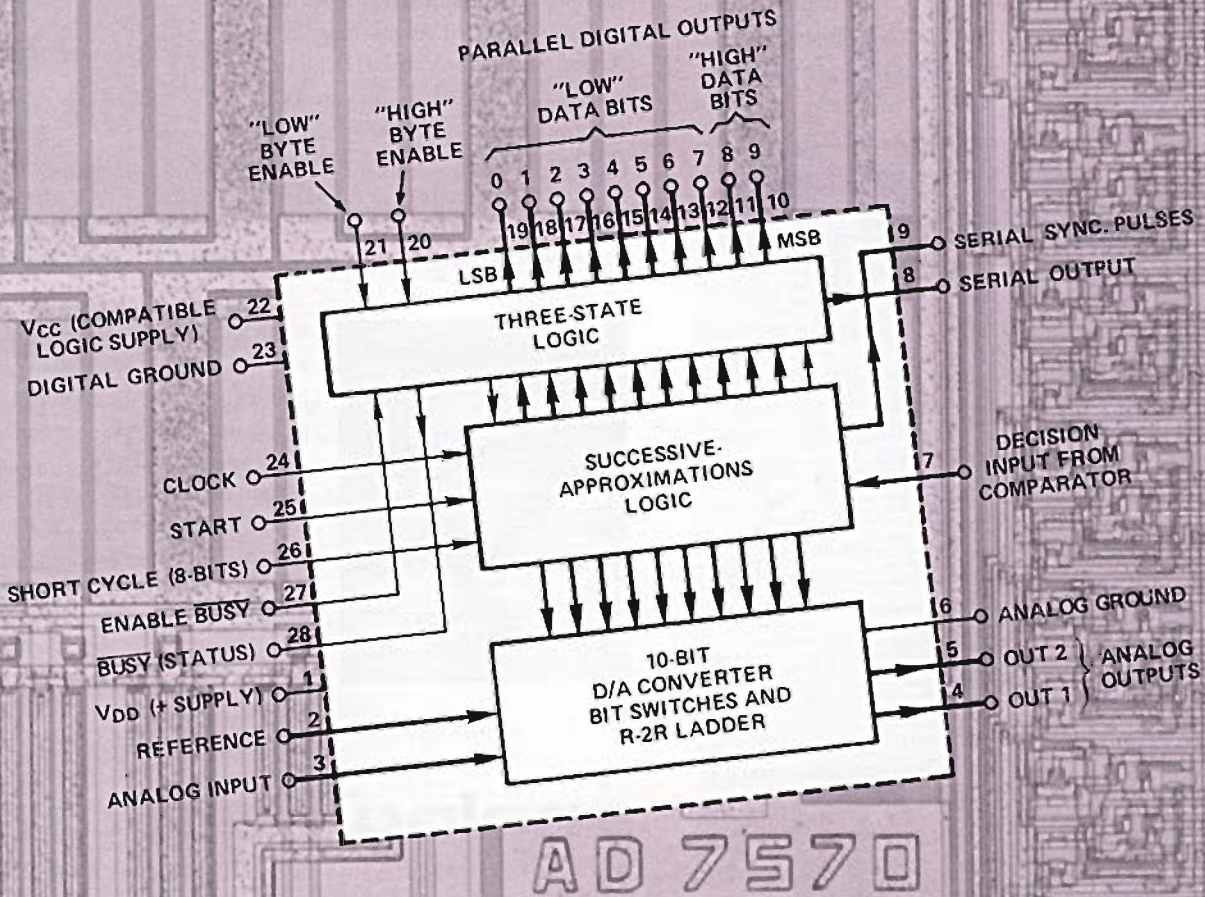


analog dialogue

A forum for the exchange of circuit technology: Analog and Digital, Monolithic and Discrete

10-BIT MONOLITHIC A/D CONVERTER (page 3)

Also in this issue:
True-RMS Digital Panel Meter
Isolation Amplifiers
12-Bit 4-Quadrant Multiplying DAC
Full contents on page 3



Editor's Notes

TRI-STATE vs. TERNARY

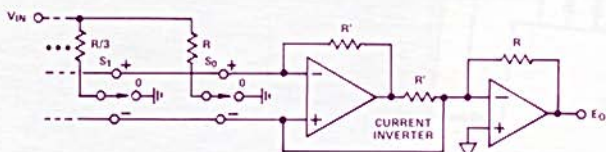
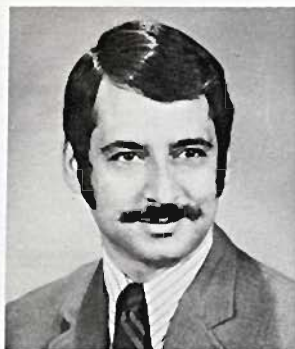
Like many of today's digital devices intended for processor bus applications, the AD7570 has "three-state" outputs. Their meaning, as you probably know, or as any digital aficionado can tell you, is that the output has three states, "1", "0", and "off".

Actually, *four* states are implied: "1", "0", "would-be 1", and "would-be 0", but the last two states are, like the sound made by the tree falling unheard in the forest, a nullity.

Our first exposure to the term "tri-state", a few years ago, reminded us of an older (and more-legitimate) use of the term (alas for the effects of "progress" on the language) in relation to the number of states corresponding to each digit of a ternary, or "base three", number (0, 1, 2). It further reminded us of a practical use of ternary number systems in setting gains of analog configurations.

It is well known that a binary resistance ladder uses the minimum number of resistors for setting a unipolar value of gain. It is far less well known that a *ternary* resistance ladder (R, R/3, R/9, etc.) with three-state switching (+, 0, -) and differential summing permits a much larger number of consecutive gain values, both positive and negative, for a given number of resistors: 3^n .

For example, in the circuit below, employing two weighting resistors, 9 gain values are possible; with 10 resistors, more than 59,000 values of gain would be achievable (in binary operation, nearly 16 resistors and switches would be required). If a factor of -1 corresponded to ternary 0, 0 to ternary 1, and +1 to ternary 2, the correspondence between gain and the "offset ternary" number would be as illustrated in the table.



$$\frac{E_O}{V_{IN}} = \sum_{i=0}^n S_i 3^i, \text{ where } S_i = +1, 0, \text{ or } -1$$

"2", "1", or "0"

GAIN	-4	-3	-2	-1	0	+1	+2	+3	+4
OFFSET-TERNARY NUMBER; 2-DIGIT	00	01	02	10	11	12	20	21	22

Actually, in the system we recall, the switching of gains was performed in what one might call sign-magnitude ternary-coded-decimal (TCD?), with three resistors per decade. Since 12-position ganged rotary switches were used, this permitted one step of overrange for each digit (i.e., 0 to 11).

In this day of 50¢ "commodity" op amps, the additional sign inversion required for the ternary system could well be worth the savings on resistors. On the other hand, colleagues in our Resistor Products Division might point out that, if networks are used instead of discrete resistors, the difference in cost might be negligible. What are *your* thoughts? ▶▶▶

Dan Sheingold

THE AUTHORS

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analog dialogue

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10-BIT MONOLITHIC CMOS ANALOG-TO-DIGITAL CONVERTER:

Uses Fast Successive-Approximation Circuitry, is Compatible With Microprocessors and TTL/DTL/CMOS

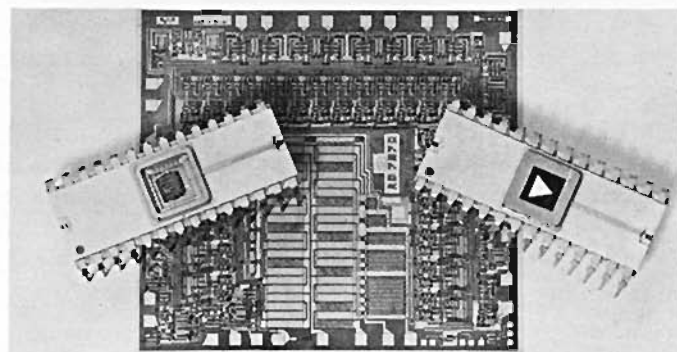
by J. Whitmore, and R. Van Aken

Monolithic circuits with A/D-conversion pretensions are still new and few. The 10-bit converter described here is the only one that is low-power CMOS, uses successive approximations, includes both DAC and logic, and is 8-bit data-bus compatible to boot. The small amount of external operational circuitry required is restricted to those items for which engineering judgment may in any case be desirable because of the nature of the application (for example, reference magnitude and polarity, clock rate, comparator resolution and speed, etc.)

The AD7570* is a 10-bit Analog-to-Digital converter on a single 120 x 135 mil (3 x 3.4mm) chip, packaged in a 28-pin dual in-line hermetically-sealed ceramic enclosure. It consists (Figure 1) of a 10-bit D/A converter and the associated logic circuitry required to perform a conversion using the successive-approximations technique. Its analog inputs can be either single-ended (of either polarity) or bipolar using an external inverting op amp. It interfaces with DTL/TTL or CMOS logic and has both serial and parallel outputs, with a number of interesting features designed to make it readily usable in complex data-acquisition systems (for example, with 8-bit microprocessor busses).

Its external operational requirements are 20mW of power (V_{DD} of +15V and V_{CC} of 5 to 15V), an external reference (which allows ratiometric operation and choice of input polarity), an external RC circuit to determine the internal clock frequency, or an external clock (for a wide range of conversion frequencies), and a comparator, such as the AD311 (for best tradeoff between accuracy conversion-speed, and cost). For bipolar operation, a low-cost external op amp preconditions the analog input.

The AD7570 will accurately digitize signals having full-scale ranges from $\pm 25V$ down to levels limited only by the comparator's ability to detect submillivolt changes. This is a direct consequence of the use of a highly-linear on-board multiplying D/A converter (closely-related to the AD7520†), which can accept a wide range of reference voltage. Normal operation is specified with 10V reference.



Available with 8- or 10-bit linearity (J or L versions, short-cycle-able to 8-bit resolution for increased speed), 40 μ s conversion time (10 bits), and $\pm 1/2$ LSB differential nonlinearity (over the temperature range), the AD7570 has a gain-temperature coefficient better than 10ppm/ $^{\circ}C$. Its price is \$52/69 (J/L) for 1-49 units.

MICROPROCESSOR CAPABILITY

As noted above, the AD7570 is specifically designed for ease of use in "data-bus" systems, where its three-state outputs are

(continued on page 4)

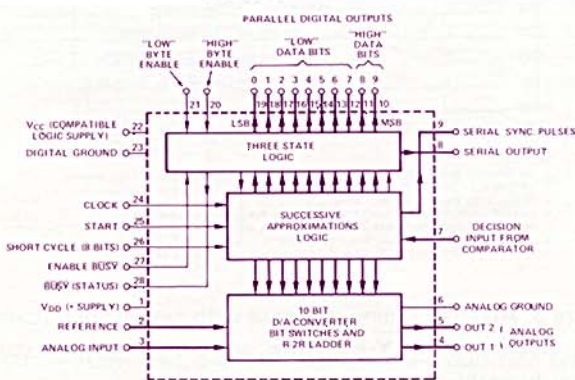


Figure 1. Functional diagram of the basic AD7570 analog-digital converter. Heavy lines denote major signal path.

*For data on the AD7570 A/D Converter, use the reply card.
†For data on the AD7520 D/A Converter, use the reply card.

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under external control. There are several features of especial interest:

- The parallel data outputs (bits 0-9) and the conversion status line are "three-state", that is, they are essentially disconnected from the common data bus until appropriate interrogation signals are received. (Data ready? High bits? Low bits?)
- The two most-significant bits and the 8 lower bits can be separately interrogated; this permits all 10 bits to be furnished on an 8-bit common data-bus in two "bytes".
- The serial output (non-return-to-zero) and an associated synchronized clock output are also provided with three-state outputs. The serial output is generated as the conversion proceeds; it and its associated SYNC output float at other times. To interrogate it, in bus applications, a conversion is started.
- The AD7570 can, of course, also be used with fully-committed connections, by connecting the three-state control inputs to the appropriate logic levels for the desired permanent mode of operation.

ADVANTAGES OF CMOS

The most-obvious reason for using complementary metal-oxide semiconductor (CMOS) construction is the low power dissipation. For example, an inverter consists of a stack of two complementary devices. When one is *on* (low voltage drop), the other is *off* (low leakage current). Since the output is always very near one or the other power-supply rail (except when switching), little continuous power is dissipated. The total power drain of the AD7570 is 20mW.

The low dissipation allows greater circuit density. Besides this, the CMOS process employed in the AD7570, which involves a two-layer metal-interconnect scheme, allows a 30% further reduction in chip size, to a reasonable, manufacturable 120 x 135 mils (3 x 3.4mm), with good yield.

The most important advantages of CMOS are realized in the D/A converter, which is the critical element in a successive-approximations converter. This topic has been covered in substantial detail in relation to the design of the AD7520¹, which the AD7570's DAC very much resembles. Briefly, the deposition of a thin-film high-precision R-2R ladder network on a

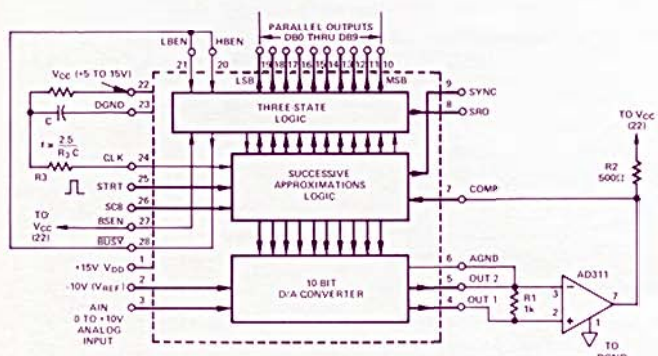


Figure 2. Operational connections for A/D conversion with positive (unipolar) analog input and internal clock. Parallel outputs are enabled when status (BUSY) goes high.

¹ *Analog Dialogue*, Vol. 8, No. 1, "A 10-Bit Monolithic CMOS D/A Converter That Can Be Used for 4-Quadrant Multiplication"

chip with low-dissipation CMOS switches eliminates problems caused by: finite transistor β and its variations, transistor V_{BE} and its variations, diffused-resistor matching and tracking, and drifts of gain and linearity caused by thermal gradients on the chip (as a result of sizeable dissipations). Though the absolute temperature coefficient of the silicon-chromium resistors used in the AD7570 is about $-150\text{ppm}/^\circ\text{C}$, they track to within $\pm 2\text{ppm}/^\circ\text{C}$; the result is an overall gain tempco better than $10\text{ppm}/^\circ\text{C}$.

HOW THE AD7570 WORKS

Figure 2 is a functional diagram of an AD7570, connected for 10-bit unipolar A/D conversion; Figure 3 is a typical timing diagram showing what happens at the various terminals, and the sequence. (If you are perplexed about the designation or function of any of the terminals, Figure 1 and the guide on the opposite page may be helpful.)

In the successive-approximations technique² the output of a D/A converter is compared against the analog input for a succession of combinations of digits. When the *start* signal is given, the MSB latch output (appearing at DB9, if enabled) goes high and causes the DAC to apply a current equal to one-half of full-scale to the input network, where it is compared with the current developed by the input voltage. If the input is less, the comparator output causes the MSB latch to go low at the 2nd clock pulse plus 200ns; if the input is greater, the MSB stays high, retaining the DAC output at one-half full scale. In either case, the decision initiates the trial of the second bit ($1/4$ full scale); it is compared and accepted (input $> 1/4$ or $> 3/4$) or rejected (input $< 1/4$ or $< 3/4$). The comparison proceeds until the LSB has been tried and accepted or rejected. The outputs DB9 through DB0, if all bits are enabled, will indicate a valid binary representation of the magnitude of the analog input, relative to the reference. This result will remain latched until another conversion is initiated.

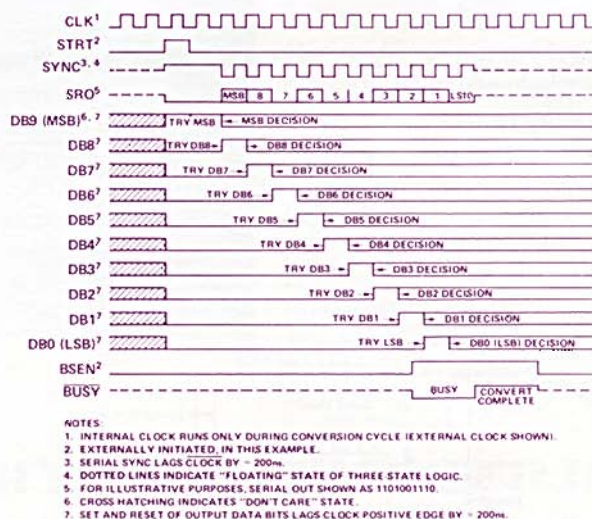


Figure 3. AD7570 timing sequence with externally-initiated start, clock, and BUSY-ENABLE, and parallel outputs continuously enabled.

² A good explanation of this — and much else about conversion — can be found in the 402-page *Analog-Digital Conversion Handbook*, available from ADI @ \$3.95.

From the timing diagram, it can be seen that when conversion start (STRT) goes high, DB9 is set while DB0 through DB8 are reset. Two-clock-pulses-plus-200ns after the STRT pulse returns to low the MSB (DB9) decision is made. Each succeeding trial and decision is made at $T_{clk} + 200ns$ (a fixed delay time designed into the AD7570 to ensure that data from the comparator is available at the "data" input of the output latch before clocking the latch). The output data lines (DB0 through DB9) are buffered from the output data latches by three-state drivers (similar to transmission gates in series with the outputs). The transmission gates are controlled by HBEN (High Byte Enable), which controls DB9 and DB8, the two most-significant bits, and LBEN (Low Byte Enable), which controls DB7 through DB0, the 8 least-significant bits.

The time relationship of the other signals is shown in Figure 3; their meaning and functions are explained in the adjacent column.

APPLICATION EXAMPLE — LOW-COST D.A.S.

Figure 4 shows how the AD7570 might be employed in an 8-channel data-acquisition system with 8-bit resolution. A single converter is used with an 8-channel multiplexer to perform time-division multiplexing of the eight 0 to +10V analog signals, in a sequential scan mode. It can provide 8 bits of data at a per-channel throughput rate of 3.8 kilobytes/s, or a total system throughput of 30.7 kilobytes/s, for less than \$70 parts cost (100's, and depending on choice of S/H amplifier).

The AD7501 multiplexer's *enable* line controls the sample-hold function. In *low*, the capacitor holds the previous charge ($5\mu V/\mu s$ leakage if the FET-input AD528 is used); in *high*, it samples the input that is connected. The follower-connected amplifier unloads the hold capacitor, and provides a low-impedance input signal to the A/D converter. The flip-flop applies a delayed negative spike to C_{COMP} to cancel the multiplexer's charge injection; R2 helps optimize the compensation.

Typical performance of the circuit is: Static accuracy, $\pm 0.2\% \pm 1/2LSB$; conversion time, $13.5\mu s$ (666kHz clock); sample/hold acquisition time ($\pm 0.1\%$), $4\mu s$; sample/hold aperture time, $1\mu s$.

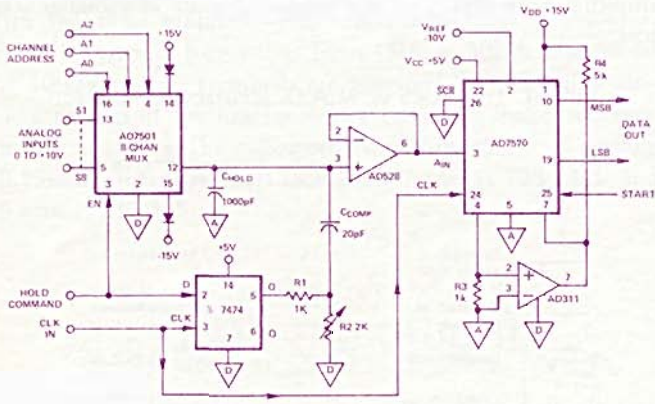


Figure 4. Low-cost, 8-bit, 8-channel data-acquisition system employing the AD7570.

*For information on the AD7501, use the reply card.

PERFORMANCE OF THE AD7570 A/D CONVERTER

Typical at $V_{DD} = +15V, V_{CC} = +5V, V_{REF} = \pm 10V$

(J, L temperature range $0^{\circ}C$ to $+75^{\circ}C$)

CHARACTERISTIC	$T_A = +25^{\circ}C$	Over-Specified Temperature Range
Accuracy		
Resolution, AD7570J, bits (SC8 = Logic 0)	8 min	8 min
Resolution, AD7570L, bits (SC8 = Logic 1)	10 min	10 min
Quantization error	$\pm 1/2LSB$ max	$\pm 1/2LSB$ max
Relative accuracy error (J, L versions only)	$\pm 1/2LSB$ max	$\pm 1/2LSB$ max
Differential nonlinearity	No Missing Codes ($\pm 1/2LSB$)	
Gain error	0.3%FS	
Gain-error temperature coefficient		10ppmFS/ $^{\circ}C$ max
Analog Input- and Reference- Resistance		
Analog Input- and Reference- Resistance	10k Ω	5k Ω min, 20k Ω max
Analog Output Leakage Current (I_{OUT1}, I_{OUT2})		
Analog Output Leakage Current (I_{OUT1}, I_{OUT2})	10nA	200nA max
Digital Inputs		
Low state	1.4V (0.8V max)	0.8V max
High state	1.4V (3.0V min)	3.0V min
Digital Outputs		
Low state ($I_{SNK} = 1.6mA, V_{CC} = 5V$)	0.5V max	0.8V max
High state ($I_{SOURCE} = 40\mu A, V_{CC} = 5V$)	2.4V min	2.4V min
Low state ($I_{SNK} = 3mA, V_{CC} = +15V$)	1.5V max	1.5V max
High state ($I_{SOURCE} = 1mA, V_{CC} = +15V$)	13.5V min	13.5V min
Dynamic Characteristics		
Conversion time (affected by external comparator)	20 μs , 8 bits	
Clock frequency	40 μs , 10 bits	
Standby Supply Current		
I_{SD} ($V_{DD} = +15V$)	0.5mA, 2mA max	
I_{CC} ($V_{CC} = +5V$)	0.5mA, 2mA max	
I_{CC} ($V_{CC} = +15V$)	0.5mA, 2mA max	
Absolute Maximum Voltage and Current Ratings		
All terminals, except Analog and Reference Inputs	0 $\leq V \leq V_{(DD)}$	
V_{DD} to GND	$+17V$ max	
V_{CC} to GND	$+17V$ max	
V_{REF} to GND	$\pm 25V$ max	
Analog Input to GND	$\pm 25V$ max	
I_{OUT1}, I_{OUT2}	$\pm 5mA$ max	

NOTES ON LOGIC FUNCTIONS

Inputs

- Convert Start (STRT-pin 25): When STRT goes high, the MSB data latch goes high, all other bits go low. Conversion begins when STRT goes low (at least 500ns later). If STRT is re-initiated during conversion, the conversion sequence starts over.
- High Byte Enable (HBEN-20): When HBEN is low, output lines for data bits 9 and 8 (MSB and 2nd bit) float. When HBEN is high, digital data from the latches appears on the data lines.
- Low Byte Enable (LBEN-21): Same function as HBEN, bits 0 (LSB) -7.
- Busy Enable (BSEN-27): When high, requests status of conversion (see "Busy" under Output functions).
- Short Cycle, 8 Bits (SC8-26): When low, conversion stops after 8 bits (essential for J); when high, conversion runs for 10 bits.
- Clock (CLK-24): External clock (TTL/DTL or CMOS) may be applied here. For internal clock, connect RC as shown in Figure 2 ($f \approx 2.5/RC$); clock begins with STRT, ceases at end of conversion.

- V_{DD} (VDD-1): Principle supply voltage, nominally +15V
- V_{CC} (VCC-22): Compatible-logic supply; +15V: CMOS, +5V: DTL/TTL

Outputs

- Busy (BUSY-pin 28): Indicates conversion status. Floats when BSEN-27 is low. When interrogated (BSEN high): goes high when conversion complete, stays low while conversion in process.
- Serial Output (SRO-8): Indicates state of each decision (non-return-to-zero) as conversion proceeds. Must be used with SYNC-9 for correct interpretation of data. Floats when no conversion.
- Serial Synchronization (SYNC-pin 9): Provides 10 positive edges when SRO data valid. Floats when no conversion.

ROOT-MEAN-SQUARE DIGITAL PANEL METER

Model AD2011 Reads True RMS of AC or (DC+AC) Signals

Has Opto-Isolated Input, 4 F.S. Ranges : 1V, 10V, 100V, 1kV

by Jim Hayes

The Analog Devices AD2011* is a 3-digit line-powered digital panel meter that computes and displays the true RMS value of any ac or dc input. Having four calibrated input ranges (1V, 10V, 100V, and 1kV full scale), it can be used for a wide variety of classes of measurement, from power-line voltage- and current-measurements to instrumentation of noise measurements (both electrical and audio), and the measurement of complex waveforms, such as those encountered in power-level control using SCR's. Its fully-floating opto-isolated input section permits accurate measurements to be made in the presence of common-mode voltages up to 300V rms. In addition to its highly-readable Beckman visual display, it has BCD and data outputs and is fully controllable to permit it to interface with data-logging or digital feedback-control systems, including the unique Analog Devices SERDEX† system.

DPM innovations: Three years ago, Analog Devices entered the digital panel meter marketplace with an innovation — a DPM that could be energized by +5V logic supplies. By removing the power supply from the DPM, the size of the DPM could be greatly reduced, allowing DPM's to be used in instruments that previously had too little space available for ac-powered DPM's § (Of course, we also make available line-powered DPM's, for applications where a system supply (or an extra +5V supply) is not necessarily desirable — and in fact, the AD2011's versatility is enhanced by being line-powered).

A little over a year ago, Analog Devices introduced a true-rms module, the 440,‡ the first such device combining low cost and high accuracy. Again, it was a timely innovation, because engineers were beginning to recognize that true-rms measurements (which had long been sidestepped because of cost or complexity) had important advantages of *validity*, both physical (rms measures the heating effect in a resistance, hence its dissipation, whatever the nature of the repetitive waveform applied) and statistical (the rms is equivalent to the standard deviation of a zero-mean stationary process).

It is high time for another innovation. Until now, most DPM's were designed to measure dc input voltages. To be sure, some ac-reading DPM's were available, but their averaging inputs (i.e., full-wave rectified, or mean absolute deviation — m.a.d. [sic]) were only good for monitoring sinusoidal ac lines. Any distortion of the input signal (or any nonsinusoidal input — square wave, pulse, random noise, unknown waveform) produced errors that made the n digits of precision useless. Now, to fill this need, a new type of DPM — the AD2011 — measures the *true rms* of the input voltage.

Use the reply card to request:

*a data sheet on the AD2011,

†information on the teletypewriter-compatible SERDEX SERIAL Data-EXchange modules (ask for "SERDEX"),

§information on the Analog Devices DPM line,

‡information on the model 440 true-RMS module.










TRUE RMS MEASUREMENTS

Unlike most ac meters (digital and otherwise), which display RMS but measure the rectified average of ac input signals, the AD2011 uses an implicit analog-computing technique to derive the actual rms value of ac signals. Its rms accuracy does not depend on the waveform. Pulse trains, triangular pulses, and SCR-chopped sine waves — even with high crest factors* — as well as pure or slightly-distorted sine waves, are all measured with high accuracy and no recalibration over a wide range of frequency content.

The computing technique† provides faster response than some thermal converters and permits the use of an externally-connected capacitor to extend the bandwidth at the low end. Since the input is dc-coupled, the AD2011 accepts (dc + ac) inputs, and will even serve "in a pinch" as a multirange dc meter. Naturally, one can easily ac-couple the input if it is desired to measure an ac signal riding on a constant dc voltage, as in measuring the ripple of a power supply, the noise of an amplifier with offset, or the output of some ac signal generators.

Table 1. True RMS vs. M.A.D. accuracy comparison

WAVEFORM	TYPICAL AD2011 ERROR	TYPICAL "AVERAGE" RESPONDING METER ERROR
 Sine wave	±0.2%	±X%
 Symmetrical Square Wave	±0.5%	±X% + 11% (High)
 Triangular or Sawtooth	±0.4%	±X% - 4% (Low)
 Gaussian Noise	±0.4%	±X% - 11.3% (Low)
 Pulse Train (10% Duty Cycle)	±0.9%	±X% - 30% to - 65% (Low)
 SCR'd Sine wave { 90° Firing	±0.9%	±X% - 14% to - 28% (Low)
 SCR'd Sine wave { 110° Firing	±0.9%	±X% - 20% to - 43% (Low)

*Crest factor: ratio of peak input signal to the rms value

†For a discussion of the nature, uses, and practical aspects of rms electronic circuits, the *Nonlinear Circuits Handbook* (Analog Devices, 1974, \$5.95) is an invaluable reference.

Table 1 compares the performance of a true-rms DPM, such as the AD2011, with the performance of comparable mean absolute-deviation (sine-wave calibrated full-wave-rectified averaging) meters, over a variety of commonly-encountered waveforms.

HOW IT WORKS

Figure 1 is a block diagram of the AD2011. It shows the interrelationship of the front-end attenuators, rms converter, A/D converter, opto-isolation, logic, decoder-drivers, display, and power supply. The key to its rms performance is the log-

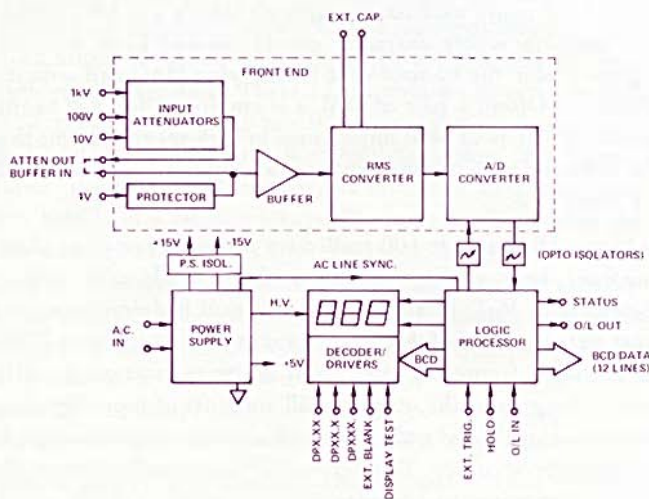


Figure 1. AD2011 block diagram

antilog rms-to-dc converter, shown in block-diagram form in Figure 2. Using the running average, it computes the rms by the implicit equation

$$V_{RMS} = \sqrt{V_{IN}^2} = \frac{V_{IN}^2}{V_{RMS}} \cong \left(\frac{V_{IN}^2}{V_{RMS}} \right) \quad (1)$$

using the logarithmic form of computation¹

$$V_{RMS} = \text{average of } \exp(2 \log V_{IN} - \log V_{RMS}) \quad (2)$$

With the filter supplied, -3dB response is 30Hz to 300kHz, with <1% error at frequencies from 45Hz to 50kHz (except on the 1000V range). Terminals are provided for external capacitance to extend the low-frequency range. Midband accuracy on any range can be calibrated to within $\pm 0.1\%$ of reading $\pm 0.1\%$ F.S. ± 1 digit. Crest factors are 7 max at 100% F.S. and 10 max at 25% F.S.

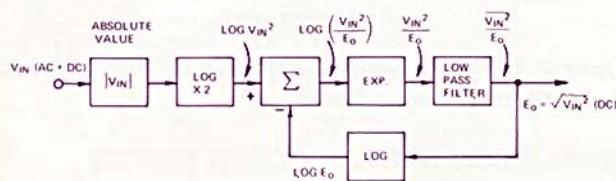


Figure 2. AD2011 log-antilog RMS to DC converter (using implicit computing)

¹ Details of circuitry to perform such computations may be found in the *Nonlinear Circuits Handbook*.

The analog-to-digital conversion section uses an economical, compact, easy-to-isolate single-slope conversion technique, using standard TTL integrated circuits. Standard parallel BCD data outputs are available, and conversions can be externally triggered or held, upon command. Decimal points are programmable, and the overload function (indicated by displayed dashes) is also programmable at any value (other than the normal 999 counts) by the use of external logic. The AD2011 has an up-to-40% overrange capability; when it is used for accurate computation beyond the normal range, overload indication can be shown externally.

The analog front end is isolated from the power supply and the digital circuitry. Besides providing good common-mode rejection, the isolated input permits off-ground measurements at CMV's up to 300VRMS, even in system applications with the digital outputs and control signals in use. Common-mode rejection on the 1V range is 100dB @ 60Hz. High common-mode rejection is especially useful when the AD2011 is used in measuring rms currents, since current measurements are often performed using shunts that are away from ground.

NEW APPLICATIONS

With the coming of the AD2011, the cost of making true-rms measurements has decreased significantly. Now, many ac measurements can be made more-accurately by replacing iron-vane analog meters or average-reading digital meters by the AD2011. An obvious application is in the design of in-house test equipment for faster, easier, and more-valid production testing of ac devices. Substantial quantity discounts make the AD2011 attractive for many instrument and systems applications including

- Measuring SCR-chopped waveforms from motor, lighting, and furnace controllers
- Noise and vibration measurements
- Accurate measurements of transformer parameters
- Fluid-flow measurements
- Production testing of modems and other communications apparatus

HIGH PERFORMANCE AT LOW COST (\$295)

The AD2011 offers instrument-grade performance at a DPM price. Even though it performs as well as many true-rms multimeters, it actually costs less than the true-rms option for many multimeters. Part of the reason is obvious: no switches, knobs, banana plugs, or any other hardware associated with the usual packaging of a bench-top multimeter. Its purpose is different: it is meant to be built into instruments and systems, and this is easily done because of its small size and easy panel-mounting without extra hardware.

Another reason is that the A/D converter and the display were designed to fit the overall accuracy of the meter. Surely, the ability to display readings with 0.02% error on a 20,000-count display permits wide dynamic range without switching (but one must remember to ignore all but the first three digits). Instead, the AD2011 provides 4 frequency-compensated input ranges, so that all the digits are significant.



AN IMPROVED 12-BIT MULTIPLYING D/A CONVERTER

The DAC1125 Has Less Than 1/2 LSB 4-Quadrant Feedthrough at 40kHz

Pin-Compatible With the Slower, More-Costly DAC-12M

by Herb Riddle

The DAC1125* is a 12-bit multiplying digital-to-analog converter with high analog linearity, low feedthrough, wide bandwidth, and monotonic performance. It accepts analog inputs of either polarity and multiplies them by a digitally-set gain that has 12 bits of unipolar resolution (complementary-binary digital input), or 11 bits-plus-sign of bipolar resolution (offset-binary or 2's-complement coding†).

It obeys the relationship

$$E_O = K V_{IN} \quad (1)$$

where V_{IN} is the positive or negative analog input and K is the "conversion-relationship" — the digitally-set positive or negative gain.

A multiplying DAC can be thought of as a digitally-controlled voltage-divider, where the input is applied to a series of equal resistances, and the output "tap" position is determined by the digital input code. Figure 1 is a functional model of this interpretation, showing 2- and 4-quadrant operation of a 3-bit multiplying DAC. In two-quadrant multiplication, only the amplitude is controlled; in four-quadrant multiplication, the range of amplitude control includes choice of polarity. (However, some 2-quadrant DAC's (e.g., AD562) accept only one polarity of analog input (half-sine in Fig. 1B) and have bipolar digitally-set gain.)

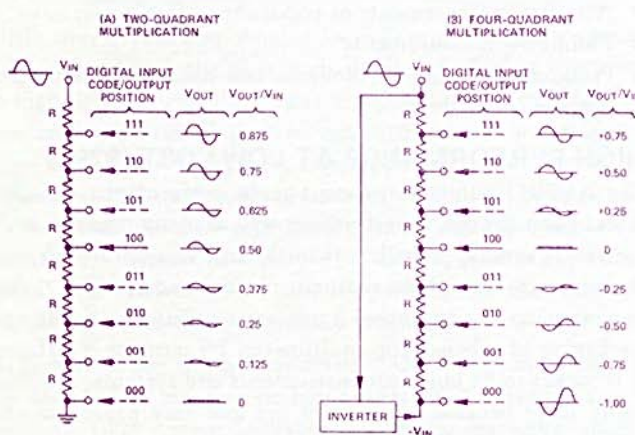


Figure 1. Functional models for a 2 quadrant and 4 quadrant multiplying DAC. A 3-bit device ($2^3 = 8$ steps) is shown for simplicity

ABOUT FEEDTHROUGH

Modeling a multiplying DAC is easy; but building one that works isn't! Performance of a real DAC is determined, not only by its dc accuracy and stability, but also by how well the

*For technical data on the DAC1125, use the reply card.
†Extensive information on coding, and other aspects of A/D and D/A conversion may be found in the 402-page *Analog-Digital Conversion Handbook* (Analog Devices, 1972, \$3.95)

accuracy is maintained as the amplitude and frequency of the analog signal are increased.

One of the many uses for multiplying DAC's is in CRT deflection systems, where character generation and beam positioning are under the control of a multiplying DAC and a digital processor. Often, a pair of DAC's is employed for X-Y vector generation. It is of vital importance in high-speed systems that the code for zero output produce *exactly that*, even with 20V p-p input.

In Figure 1B, the code 100 (called for obvious reason the *four-quadrant zero code*) provides a theoretically-zero output, regardless of V_{IN} . Just how good this null is determines, to a great extent, the useful operating range of a multiplying DAC. As the input frequency goes up, it becomes increasingly difficult to keep from the output small amounts of input signal, as switch leakage, board leakage, and phase shifts begin to degrade the dynamic accuracy. This *zero-code* feedthrough, then, is the critical parameter to consider when judging a DAC's performance.

The meaning of the DAC1125's 1/2LSB @ 40kHz feedthrough spec can be best appreciated if one realizes that at digital zero (4-quadrant) two 10V p-p signals are being subtracted (one lagged by an op amp), with the need for a differential phase error of $<0.03^\circ$! In addition, effective stray feedthrough capacitance must be (and is) reduced to less than $0.1pF$!

Figure 2 shows the zero-code feedthrough of a typical DAC1125 as a function of operating mode and input frequency.

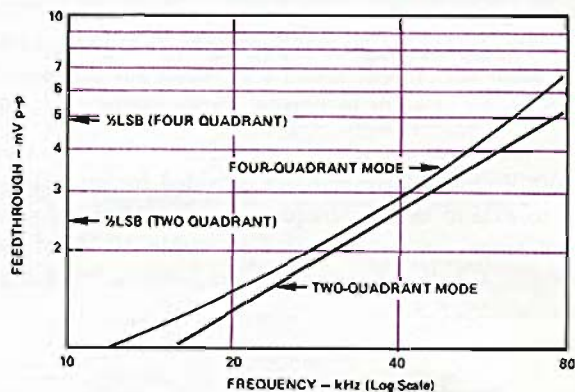


Figure 2. Typical zero-code feedthrough vs. input frequency (for a 20V p-p sinewave input)

COMPARISON WITH AN OLDER DESIGN

Innovative application of the latest developments in analog CMOS technology is the key factor that enables the DAC1125 to reach a level of performance undreamt of only a few years ago. Here is how it compares with the DAC-12M, a device somewhat representative of the older four-quadrant designs in existence throughout the industry:

Resolution	12 bits	12 bits
Modes of operation	2 & 4-quadrant	2 & 4-quadrant
Feedthrough (4-quad. zero for 20V p-p input)	1/2LSB, typ., 0-400Hz	1/2LSB max., 0-40kHz
Settling time (to 0.01%)	15μs	3μs
Slewing rate	10V/μs	30V/μs
Differential nonlinearity T.C.	NS	3ppm/°C
Monotonicity temperature range, min	NS	0° to +70°C (2-quadrant) 0° to +50°C (4-quadrant)
Package	2" x 2" x 0.4"	2" x 2" x 0.4"
	51 x 51 x 10.2mm	51 x 51 x 10.2mm
Price (small quantity)	\$310	\$295

HOW IT WORKS (Figure 3)

The analog input voltage, which can vary in the range ±10V, is applied to a resistance network. The resistors develop a series of 12 binary-weighted currents, which are proportional to the input signal magnitude. These 12 currents are directed to either of 2 op-amp summing junctions by 12 digitally-controlled single-pole, double-throw IC CMOS switches. As Figure 3 shows, the DAC125 consists, in effect, of two complementary DAC's in a single package. The switches have been specially designed so that their ON resistances (inverse with junction area) are also given a binary weighting. Temperature variations of junction resistance therefore can only produce minute gain changes, rather than bit-weighting (differential nonlinearity) errors, because the increase of switch resistance for higher-order bits is compensated for by the corresponding decrease of current. See the description of the AD7520 in *Dialogue 8-1*.

When a logic '1' is applied to a switch input, the corresponding current is directed to the summing junction of A1; a '0' input directs the current to A2. For the code 1111 1111 1111, then, all the bit currents are directed to A1, and A2's output is 0V. For an input of 0000 0000 0000, the situation is reversed, and A1's output is 0V. The normal output terminal is at A2.

In the *two-quadrant* mode of operation, the complementary input and *4-quadrant* offset pins are grounded. The output voltage is then related to the analog input signal by

$$E_O = K V_{IN} \quad (-0.99976 \leq K \leq 0) \quad (2)$$

where K is determined by the digital input code. Since the input code is *complementary binary*, all 1's gives zero output. Since K is negative, the analog output is always opposite in polarity to the input; its attenuation depends on the bit combination. At the same time, the output of A1, the complementary output, is equal to K' V_{IN}, where

$$K' = -0.99976 - K \quad (3)$$

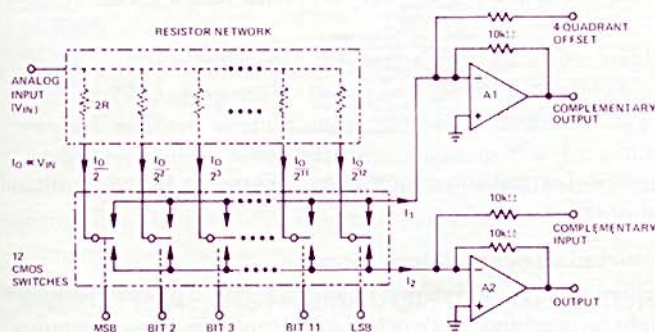


Figure 3. Simplified DAC125 circuit

Thus, the sum of the outputs of A1 and A2 will always be equal to $-0.99976V_{IN}$, regardless of the input code.

For *four-quadrant* operation, the basic connection is of the complementary output (A1) to the complementary (summing) input of A2. The output of A2, then, is equal to the difference between $K V_{IN}$ and the output of A1, or

$$E_O = (2K + 0.99976) V_{IN} = K'' V_{IN} \quad (4)$$

This provides a symmetrical positive-true range; for example, if $K = 0$ (all 1's), the gain is $+0.99976$, and if $K = -0.99976$ (all 0's), the gain is -0.99976 . Unfortunately, a code for exactly-zero is lacking; i.e., when $K = -0.5$ (0111 1111 1111), the gain is -0.00024 , and when $K = -0.49976$ (1000 0000 0000), the gain is $+0.00024$.

In order to provide a code for zero, a small fraction of V_{IN} ($1/2$ LSB, or $0.00024 V_{IN}$) is added in proper phase to the input of A2 to make the gain (K'') zero for code 1000 0000 0000. The conversion relationships for both 2- and 4-quadrant multiplication are tabulated below, for several salient digital codes.

DIGITAL INPUT	K (TWO-QUADRANT) (Complementary Binary, LSB = 0.00024)	K'' (FOUR-QUADRANT) (Offset Binary, LSB = 0.00049)
1111 1111 1111	0.00000 (0)	+0.99951 (+1 - LSB)
1111 1111 1110	-0.00024 (-LSB)	+0.99902 (+1 -2LSB)
:	:	:
1100 0000 0000	-0.24976 (-1/4 + LSB)	+0.50000 (+1/2)
1011 1111 1111	-0.25000 (-1/4)	+0.49951 (+1/2 - LSB)
:	:	:
1000 0000 0001	-0.49951 (-1/2 + 2LSB)	+0.00049 (+ LSB)
1000 0000 0000	-0.49976 (-1/2 + LSB)	0.00000 (0)
0111 1111 1111	-0.50000 (-1/2)	-0.00049 (- LSB)
:	:	:
0100 0000 0000	-0.74976 (-3/4 + LSB)	-0.50000 (-1/2)
0011 1111 1111	-0.75000 (-3/4)	-0.49951 (-1/2 - LSB)
:	:	:
0000 0000 0000	-0.99976 (-1 + LSB)	-1.00000 (-1)

If 2's-complement coding is desired (instead of offset-binary), it is necessary only to invert the MSB (1 ↔ 0). For convenience, the DAC125 contains a logic inverter, available for this purpose.

APPLICATIONS

A multiplying DAC has so many potential uses that it can almost be considered as one of the "universal" components. Naturally, digitally-controlled precise gain control can be used for the manipulation of system parameters of all sorts by micro-, mini- or full-scale processors and computers. Such parameters might include voltages, currents, gains & attenuations, filter time-constants. One might also include modulation (and not only of amplitude) and the construction of high-accuracy analog multipliers (using A/D conversion ahead of the digital input).

Other applications include radar displays and CRT graphics, control of synchro-resolver systems, numerical control of machines, and computer-based automatic test and process-control systems. Or programmable waveform-generation and phase-shifting, or inverse-scale-factor generation.

Conclusion: the fast, high-accuracy multiplying DAC is an important key to circuits and systems in which analog and digital techniques work together fruitfully and harmoniously.



ISOLATION AMPLIFIERS FOR EFFECTIVE DATA ACQUISITION

They Help Designers Solve Problems in Instrumentation, Industrial Monitoring, Process Control, and Patient Monitoring

by Fred Pouliot

The isolation amplifier is a data- or instrumentation amplifier in which the output circuit is completely isolated from the input circuit. Some Analog Devices types also include power-supply isolation, for a complete 3-port isolation capability.

What is "complete isolation"? In the case of our transformer-coupled modulator/demodulator types, the resistive component of common-mode impedance is of the order of $10^{11} \Omega$, and ac leakage — at 115V, 60Hz — is as low as $1 \mu A$ (a boon for clinical applications). In addition to having a completely-guarded front end, their common-mode rejection (CMR) is of the order of 140dB at high common-mode voltage (CMV up to 5kV), and input noise is low (less than $10 \mu V$ p-p in a 100Hz bandwidth).

These characteristics allow small (millivolt) signals to be processed accurately, despite hundreds of volts of CMV, and safely, despite CMV or fault voltages in the thousands of volts. Since no input return path is required from the signal source to power ground, ground wires (and ground-loop headaches) may be avoided.

When low-level signals are close to lines operating at high energy levels, there is a possibility that induced voltages will mask the low-level signals and saturate the amplifier. An amplifier with high CMV and CMR capability (plus isolation) can be a big help (if not absolutely essential) in such applications.

PREFERRED DATA AMPLIFIER

If the voltage to be measured and processed has a high common-mode component or a large impedance imbalance between the two leads from the source, designers often consider 3 popular circuit approaches: *Op-amp subtractor circuits*, in a variety of configurations and capabilities; *committed data- or instrumentation amplifiers**, such as the 610 (see page 14) or the AD521; or *isolation amplifiers*.†

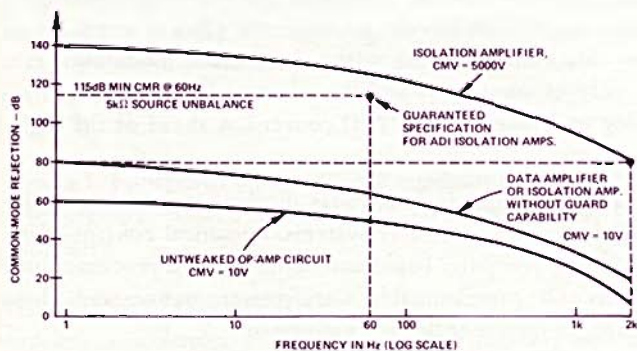


Figure 1. Common-mode rejection vs. frequency for several kinds of differencing amplifier

*For information on ADI instrumentation amplifiers, request P1.
†For information on isolation amplifiers, request P2. Request data on specific types mentioned here (if desired) by model number.

Operational-amplifier configurations generally require "tweaking" of precision resistor ratios§ and capacitance neutralization; even then, CMR better than 80dB is hard to achieve consistently, unless one is truly committed to "make rather than buy". With unbalanced source, 60dB is more typical (Figure 1).

Committed data amplifiers (or unguarded isolation amplifiers) offer more-predictable behavior, over a wider range of price-performance capabilities. Performance is generally excellent at dc and low frequencies, with small source unbalance and CMV of about 10V. At higher frequencies, capacitive source- and line-unbalances reduce CMR, often by up to 40dB at 60Hz. CMR, excellent at high gain, may be 40dB worse at unity gain.

Isolation amplifiers (from Analog Devices) are graced by a completely-guarded front end, that can be driven at the common-mode voltage (up to 5000V). The inputs are surrounded by an equipotential surface (at the CMV), greatly reducing effective capacity. CMR, for source unbalance of $5k \Omega$, @ 60Hz, is 115dB min.

TYPICAL ISOLATION-AMPLIFIER APPLICATIONS

Ground-Loop Eliminator

Figure 2 shows how an isolation amplifier eliminates grounding problems in two ways. First, since a bias-current return to the supply is not necessary, the input circuit can be independent of system ground with its logic spikes, voltage drops, etc. Second (especially with 3-port isolation) the amplifier's power ground is independent of the output low; returning the amplifier's power ground to system ground does not cause grounding errors in the output signal line.

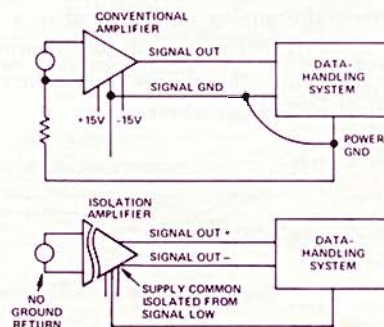


Figure 2. Comparison of grounding techniques for conventional and isolation amplifiers

Multichannel Series-Voltage Monitor

Figure 3 shows a system of cells in series. Each cell — which might be providing electrochemical deposition using a common current — is monitored independently by an isolation amplifier, irrespective of what may be happening elsewhere. If a cell should go open-circuit, its associated amplifier is protected

§ For data on precision thin-film resistor networks, request P3.

against the entire open-circuit voltage. The amplifier power-supply is protected against faults in the circuit being measured.

Isolation and Fault Protection with a 3-Port Isolator

In Figure 4, a signal that provides essential information about a process variable for use in control must also be independently monitored. The isolator's high input impedance protects the transducer against faults in either amplifier or the power supply. If the signal-processing system should fail, the amplifiers' power supply (hence any other amplifiers using the supply) is protected against any fault voltages that may occur, even if 115VAC should be imposed at A1's output terminal. Finally, any faults developed in the monitor do not affect performance of the control loop. The process can continue to operate uninterrupted while the monitor is being restored.

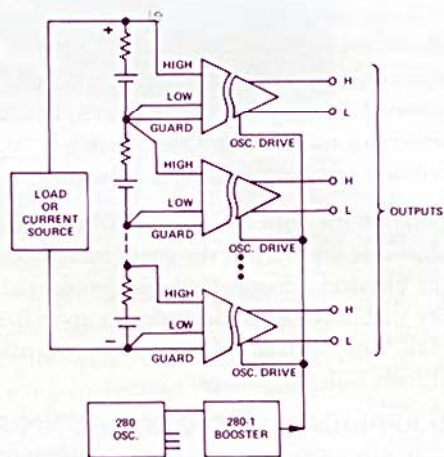


Figure 3. Multichannel amplification at high voltage using isolators with common oscillator drive to eliminate beat effects.

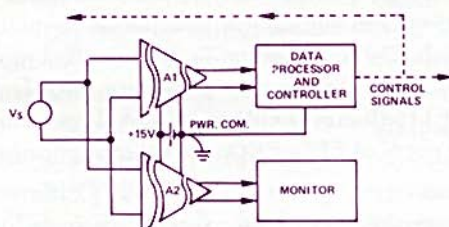


Figure 4. Use of 3-port isolator in monitoring and control for isolation and protection of source, power supplies, and connected equipment

NEW DEVELOPMENTS IN ISOLATION AMPLIFIERS

We've come a long way since the first isolation amplifier (Model 272) appeared in *Dialogue* 5-2 (1971). Following the original medical orientation, a number of industrial applications have arisen, with different requirements. In addition, uses of many isolators in close proximity require intermodulation-free systems with common carriers. Here are the newcomers:

INDUSTRIAL-INSTRUMENTATION ISOLATOR

Model 275 sets a new standard for modular isolator performance. It combines the excellent performance specifications of instrumentation amplifiers ($5\mu\text{V}/^\circ\text{C}$ drift and 0.05% non-linearity) with the inherent performance of an isolator: 140dB common-mode rejection at 2000V CMV. Dynamic range of

both input and output signals is a full 10V, and gain can be adjusted from 1 to 100 by a single external resistor.

Besides sustaining a maximum common-mode voltage application of 2500V peak sinusoidal 60Hz for 1 minute, the fully-guarded input of the Model 275 has a higher CMR than is achievable with any known commercially-available isolation amplifier. Figure 5 shows its CMR as a function of frequency for CMV up to 2000V (dc or peak ac). Note that at 60Hz, with 1k Ω source unbalance, CMR is still greater than 120dB.

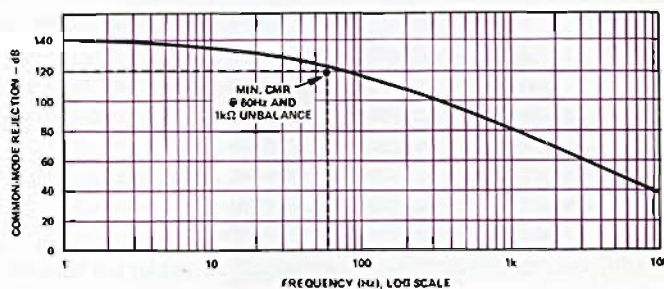


Figure 5. Common-mode rejection of Model 275 as a function of frequency

Increasing source-resistance unbalance naturally degrades CMR. One should always try to keep the unbalance as low as possible – but this is sometimes impractical. Figure 6 demonstrates that, in such cases, the Model 275 will still provide respectably-high common-mode rejection.

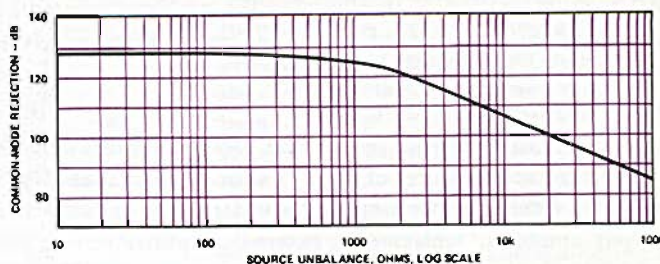


Figure 6. Common-mode rejection of Model 275 @ 60Hz as a function of resistive source unbalance

Nonlinearity of Model 275L is guaranteed to be less than 0.1% for $\pm 10\text{V}$ outputs, 0.05% for $\pm 5\text{V}$ outputs, and less as the output range is limited further. Model 275 is available in 3 versions, selected for linearity and temperature coefficient. The table summarizes the performance grades; Figure 7 is a plot of nonlinearity as a function of output-voltage range.

SALIENT SPECS OF MODEL 275 OPTIONS

	275J	275K	275L
Gain (adjustable by external resistor)	1-100	1-100	1-100
Nonlinearity, $\pm 5\text{V}$ output range	$\pm 0.15\%$ max	$\pm 0.1\%$ max	$\pm 0.05\%$ max
Nonlinearity, $\pm 10\text{V}$ output range	$\pm 0.2\%$ max	$\pm 0.15\%$ max	$\pm 0.1\%$ max
Input/Output range ($R_L = 50\text{k}\Omega$)	$\pm 10\text{V}$	$\pm 10\text{V}$	$\pm 10\text{V}$
Total offset voltage, referred to input ($G = 100$)	$\pm 25\mu\text{V}/^\circ\text{C}$ max	$\pm 15\mu\text{V}/^\circ\text{C}$ max	$\pm 5\mu\text{V}/^\circ\text{C}$ max
CMV, input to output, absolute max.	2500V peak	2500V peak	2500V peak
CMV, output to power common	200V	200V	200V

Environmental Effects

Designed to withstand rugged environments involving high humidity, shock, vibration, temperature-cycling, moisture, and other conditions to be found in MIL-STD-202E, the 275 will also withstand line voltage (115VAC) directly across the inputs.

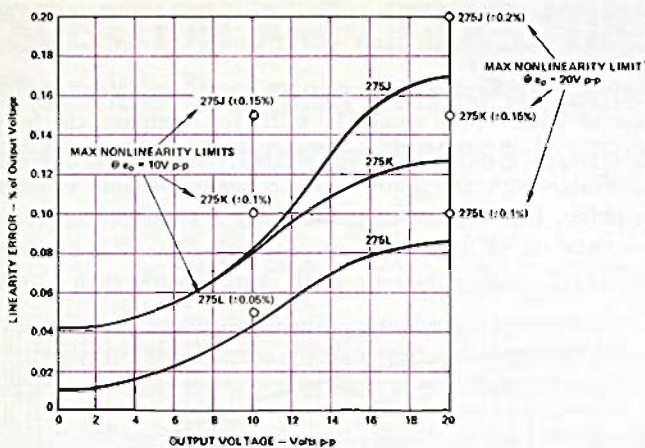


Figure 7. Linearity error as a function of output voltage, $R_L = 50k\Omega$. Typical performance and limits.

In addition, integrity of performance when subjected to EMI and RFI was given careful design consideration, so that the Model 275 can provide high performance – even when subjected to industrial noise created by relay closures, motor brushes, and other machinery.

A host of new applications for modular isolation amplifiers is now evident. They can be considered for general-purpose high-voltage amplification (with exceptionally good CMR and CMV specifications), for instrument amplification with high CMR at line frequency (with or without high source unbalance), for test instrumentation – to eliminate the problems created by ground loops and ground noise, and to alleviate problems caused by the introduction of high CMV's.

Model 285 for Increased Flexibility

Model 285, to be introduced in June, 1975, combines most of the performance features of the 275 with an additional output stage for filtering, offsetting, and a wider range of gains. The output amplifier, replacing an external amplifier serving the same function, provides its increased convenience at the sacrifice of 3-port freedom: the output and power grounds can be separated by only a few volts instead of Model 275's 200V.

MULTICHANNEL APPLICATIONS

Those familiar with our earlier isolation-amplifier designs know that the dc supply energizes an oscillator, which couples power (via a proprietary transformer-coupling arrangement) into both the input modulator and the output demodulator sections; the only coupling between the input and the output is via an isolation transformer for carrier-frequency information. Since perfect carrier attenuation around a small, compact module is difficult to achieve (if one wants all its other blessings), users have had to minimize beat-frequency generation with shielding and power-supply decoupling in systems using a number of the modules. A better solution, now available, is to use a single oscillator for a number of channels of isolation amplifiers in close proximity and sharing a common power supply.

Synchronized Single Channels

An example that illustrates the technique is the system of isolation amplifiers shown in Figure 3. The amplifiers comprising the system might well be Model 279 single-channel isolation amplifiers, designed to be driven by a common external oscillator, Model 280, which is capable of providing exci-

tion for as many as 16 Model 279's. For larger numbers of channels, a power booster, the 280-1, can increase the system capability to as many as 200 channels from a single oscillator.

The use of a single oscillator eliminates the effects of beat frequencies. The common oscillator is itself protected from faults occurring in any of the amplifiers (or their output circuits) by protective resistor strings in each amplifier.

Performance is otherwise typical of what one might expect from an isolation amplifier: CMV of 5000V, and CMR of 120dB. Other salient features include $10\mu V$ noise for a 100Hz bandwidth and ground-fault current less than $10\mu A$.

2- and 3-Channel Isolators

Most applications do not require the many channels and extreme flexibility provided by combinations of the 279, 280, and 280-1. A common multi-channel requirement is for just 2 or 3 channels. Models 282 and 283 provide this capability, with low input noise ($4\mu V$ p-p in 100Hz), adjustable gain (1 to 100), and isolated floating $\pm 6V$ and $\pm 3V$ outputs for powering isolated circuitry or transducers. Construction is "open-board" for user flexibility and lowest cost per-channel.

Channel separation for both designs is 60dB at 100Hz. CMR of 130dB is achievable when using the guard assembly AC1043 or an equivalent physical scheme. Each independent channel provides linearity within 0.2% for input signals up to 0.5V and can withstand full line voltage of 220V rms across its input terminals without isolator damage.

MEDICAL APPLICATIONS: 276, L.A. APPROVAL

The present discussion is especially pertinent to the use of isolators in industrial applications; but one should bear in mind that the earliest purpose of Analog Devices' isolator designs was to help ensure patient safety in the wake of the increased use of electronics in clinical instrumentation for patient monitoring. Models 272 & 273 were, in fact, the first modular isolation amplifiers in the industry to feature $10\mu A$ fault current and CMR of 115dB min at 60Hz with a $5k\Omega$ source unbalance, to meet the needs of EEG, EKG, and other applications.

The newest entry to the market, Model 276, offers two additional features that have been expressly desired: lower noise ($8\mu V$ p-p in a 100Hz bandwidth) and lower cost (less than \$50 in 100's).

In addition, both the 273 and the 276 now bear the seal of approval of the Los Angeles City Testing Laboratory, which sets standards for all medical equipment sold in California, regardless of where it is manufactured. Use of these devices in equipment front-ends should simplify the lives of medical-OEM equipment designers, since the isolator is usually the key element affecting equipment safety. The use of an approved isolator should make system approval easier to obtain.



CONVERSION AND DISPLAY

12-Bit ADC1133 Compact and Low-Cost



Model ADC1133*, a high-performance 12-bit analog-to-digital converter, is the first device of its type to be packaged in a small 2" x 2" x 0.4" (51 x 51 x 10mm) module. A 25 μ s conversion time, no-missing-codes from 0 to +70°C, $\pm\frac{1}{2}$ LSB linearity error, and a 7.5ppm/°C gain-temperature-coefficient are ample proof that performance has not been sacrificed to achieve small size.

The ADC1133 combines an AD5621 integrated-circuit D/A converter with a precision reference source, a high-speed comparator, and successive-approximations logic, to form a completely self-contained conversion package. It is half the size and 50% less costly than earlier models with comparable performance, such as our ADC-12QM.

Characterized by flexibility, the ADC1133 accepts $\pm 5V$, $\pm 10V$, and 0 to +10V analog inputs; its digital outputs are TTL-compatible binary (unipolar) and offset-binary or 2's-complement (bipolar), positive-true. In addition to its parallel outputs, the ADC1133 makes available serial data in NRZ (non-return-to-zero) form. A clock output is provided to synchronize the serial data.

The ADC1133 is expected to become available during the summer of 1975. Price is expected to be \$159 (1-9), less in quantity.



3½-Digit AD2009: Beckman Displays, Low Cost AC Line Power, Standard Cutout and Pinout

Many of the products in our digital panel meter line have been industry "firsts", for example, the first meter to use a +5V supply, the first true-rms panel meter, the first really low-cost panel meter.

However, one cannot become a solid force in any business if one is deterred by the "NIH (not-invented here) factor." When something appears to fill the needs of users and in some way sets a standard that makes sense, we would consider it folly to disregard the wisdom of the marketplace.

Besides the standard feature, we would naturally seek to provide the user with additional benefits such as low cost, improved reliability, or better performance that would make our product a "best buy."

The AD2009* is a 3½-digit, ac-line-powered DPM which measures bipolar input voltages over full-scale ranges of either $\pm 1.999V$ or $\pm 199.9mV$, with an error less than $\pm 0.1\%$ of reading ± 1 digit. The AD2009 displays its readings on the large 0.55" (14mm), bright, Beckman gas-discharge displays, and provides for external control of the decimal points and display blanking.

In response to industry's urgent need for DPM standardization, the AD2009 not only uses the industry-standard panel cutout (for ac-powered meters), 3.924" x 1.682" (99.7 x 42.7mm), but also uses the same pinout on the external connector as do several other popular DPM's. This provides for 2nd sources (when needed) and allows the user to utilize new advanced-technology products without massive redesign.

Going beyond these standard specifications and physical features, the AD2009 incorporates several features (missing in many other low-cost DPM designs) that facilitate application and enhance reliability.

First, it is designed around standard TTL integrated circuits and offers as standard features parallel BCD data outputs and

*Use the reply card for an AD2009 data sheet.



full conversion control (external trigger and hold), all TTL/DTL-compatible.

To maintain the Beckman display's brightness, despite low line voltages, and to enhance its reliability, it uses continuously-illuminated "keep-alives."

To ensure that the AD2009 will withstand the shock and vibration encountered in many DPM applications, the AC power transformer is securely mounted to the circuit board by crimping and soldering of the tabs on the transformer mounting frame.

The AD2009 uses a dual-slope conversion technique with an absolute-value voltage-to-current converter. The entire conversion cycle takes less than 10ms, allowing a complete conversion to take place during the negative half-cycle of the ac line, and the resulting reading is displayed during the positive half-cycle. This scheme ensures a flicker-free display. Under internal control, the AD2009 converts at a nominal rate of 6/s. With the use of the Hold and Trigger controls, up to 100 conversions per second can be externally triggered, making the AD2009 ideal for use as a dual-slope converter with a display.

Typical applications include general-purpose readout, where the advantages of a self-contained ac power supply are desired, along with a high-visibility display. The BCD data outputs and external-control features make it useful in data-logging and digital feedback-control systems, by permitting easy interfacing to a variety of data peripherals, such as digital comparators and line printers.

Price (1-9) is \$140, much less in quantity.



*Use the reply card for ADC1133 information.
†Use the reply card for AD562 information.

New Products

INSTRUMENTATION AMPLIFIER IS A "BEST BUY"

Model 610 Has Max Noise and Drift to $2\mu\text{V}$ and $1/2\mu\text{V}/^\circ\text{C}$ RTI, 0.02% Max Nonlinearity & 86dB Min CMR ($G \geq 100$), Price from \$39



Model 610* is a general-purpose instrumentation amplifier that combines high performance with low cost. While more expensive than integrated circuits (such as the AD521†), it provides performance approaching that of the premium model 606§ at less-than-premium prices.

The Model 610 guarantees high performance by assuring $\pm 0.02\%$ maximum nonlinearity ($G \geq 100$), combined with $\pm 1/2\mu\text{V}/^\circ\text{C}$ maximum input drift (610L, $G = 1000$), $2\mu\text{V}$ p-p maximum input noise (0.01-10Hz, $G = 1000$, 610K & L), and 86dB minimum CMR ($\text{CMV} = \pm 10\text{V}$, dc-100Hz, $1\text{k}\Omega$ source unbalance, $G \geq 100$).

Requiring only one external resistor to program its differential gain, the model 610 has little variation in bandwidth for gains from 1 to 1000. At $G = 100$, small-signal bandwidth for $\pm 1\%$ amplitude error is 10kHz, slewing rate is $0.4\text{V}/\mu\text{s}$, full-power bandwidth is 6kHz, and settling time to within 0.1% for $\pm 10\text{V}$ step is $50\mu\text{s}$.

The above performance characteristics, plus gain temperature-coefficient of $\pm 15\text{ppm}/^\circ\text{C}$, enable the model 610 to maintain total amplifier errors below 0.2% over a $+20^\circ\text{C}$ temperature variation for low-level input signals.

Consuming only 90mW, and capable of operating over a $\pm 12\text{V}$ to $\pm 18\text{V}$ power-supply range, the 610 may be applied in portable or remote measuring instruments and recorders.

"Sense" and "Reference" terminals are provided for offsetting the output, providing remote sensing for distant loads,

*Use the reply card for a 610 data sheet.

†For an AD521 data sheet, use the reply card.

§For information on the 606 and other ADI instrumentation amplifiers, request P1.

using output power boosters without loss of accuracy, and programming currents through grounded or floating loads.

The 610 is specifically designed for use as a high-impedance differential preamplifier to recover with accuracy low-level (millivolt) signals carried on noisy lines or at high common-mode voltage levels. It can rescue millivolts of signal from volts of CMV, from essentially balanced sources, such as bridges, or from such grossly unbalanced sources as "single-ended" transducers or analog-computing circuitry with low-quality grounds (e.g., ground loops, or induced ground noise).

Typical surroundings and applications might include laboratory, aerospace, and harsh industrial environments, when processing transducer and control signals, such as might be produced by thermocouples, strain-gage bridges, and null-detector circuits.

The model 610 is packaged in a compact $2'' \times 2'' \times 0.4''$ ($61 \times 51 \times 10.4\text{mm}$) module and is specified for operation from 0 to $+70^\circ\text{C}$. Three versions, graded for drift and noise, are available: 610J — $\pm 3\mu\text{V}/^\circ\text{C}$ and $2.5\mu\text{V}$ p-p, 610K — $\pm 1\mu\text{V}/^\circ\text{C}$ and $2\mu\text{V}$ p-p, and 610L — $\pm 1/2\mu\text{V}/^\circ\text{C}$ and $2\mu\text{V}$ p-p. All versions are identical in other respects and are available from stock. Prices (1-9) for 610J/K/L are \$39/\$49/\$59.

Figure 1 is a plot of typical common-mode rejection as a function of gain-

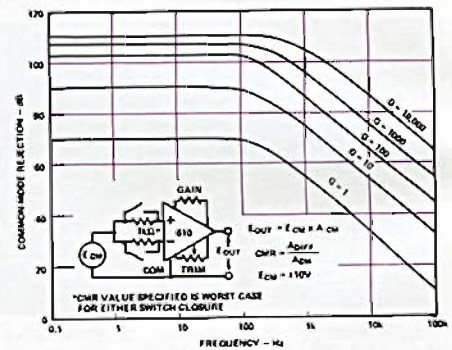
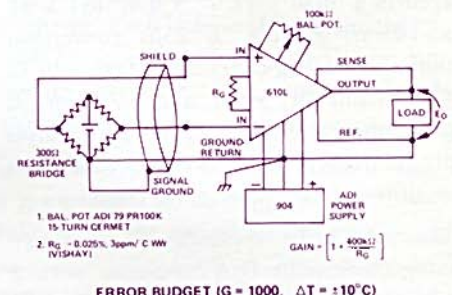


Figure 1. Common Mode Rejection vs. Frequency and Gain



ERROR BUDGET ($G = 1000$, $\Delta T = \pm 10^\circ\text{C}$)

Error	% of F.S. (10V)	Specified @ 10V F.S.
Gain Nonlinearity	0.02%	0.0015% $\times 10^\circ\text{C}$
Gain Drift	0.015%	
Offset Drift	0.05%	$0.5\text{mV}/^\circ\text{C}$ (RTI) $\times \Delta T \times 1/10\text{V}$
Amplifier Offset	0.006%	$200\text{pA}/^\circ\text{C} \times G \times \Delta T \times 1/10\text{V}$
Current Offset	0.0004%	$0.2\% \times 0.2\text{V}/\% \times G \times 1/10\text{V}$
Power Supply Change	0.01%	Specified (10Hz B.W.)
Noise	0.100% max	
Total Output Error	(0.04% typical)	

Figure 2. Typical Connections and Errors in Resistance-Bridge Application

setting and frequency. Figure 2 shows the typical connections and error budget of a bridge-transducer application.



2.5V MONOLITHIC REFERENCE AD580M & U Have Improved Specs (10 ppm/ $^\circ\text{C}$)

The highly-popular AD580 2.5V, 0-10mA reference* has met with excellent response and is becoming widely used as a 3-terminal source of constant voltage and a 2-terminal current limiter. Now, in response to near-universal demand for versions with closer initial tolerance and less drift, the AD580M (0 to $+70^\circ\text{C}$) and

*See pp.20-21. For a revised AD580 data sheet, including the new types, use the reply card.

AD580U (-55°C to $+125^\circ\text{C}$) have become available.

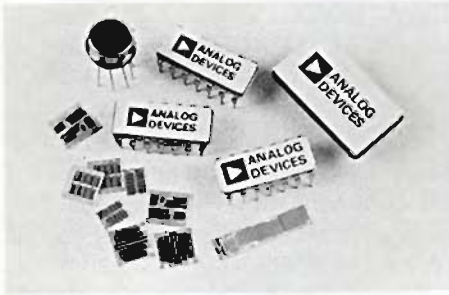
Both have initial tolerance of 1% (25mV) at $+25^\circ\text{C}$ and tempo of less than $10\text{ppm}/^\circ\text{C}$ over the temperature range. Applications of the new units include DAC's and ADC's, precision supplies, and analog constants for instruments and systems.



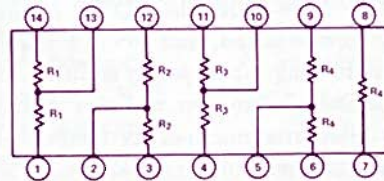
THIN FILMS AND HYBRIDS

Thin-Film R-Network "Starter Kit" Includes 5 Devices--Chip or Package--0.1% or 0.01%

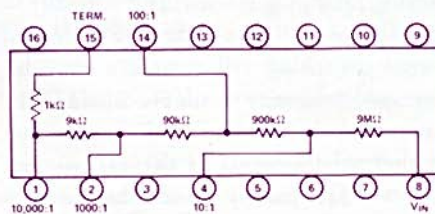
Precision Reference 10V ± 1mV, 5ppm/°C



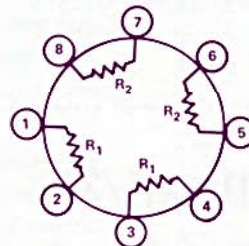
AD1890 Kit Contents:



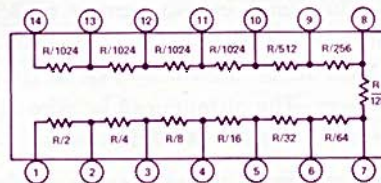
AD1800-1/10k: 3 Matched Pairs and a Triad



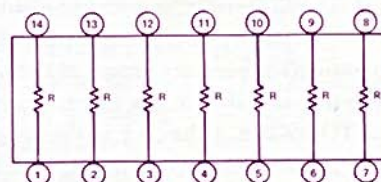
AD1803-2: Decade Divider Maximum Ratio 10,000:1



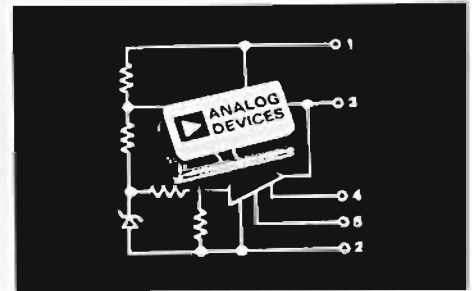
AD1805/10k: 4 Equal Independent Resistors in a TO-99 Can



AD1807/10k: 10-Bit Binary-Weighted Resistor String



AD1830/10k: 7 Independent 10kΩ Resistors



The AD2700* is a stable, accurate reference supply designed for use in 12-bit A/D and D/A converters and other precision analog-reference applications in circuits, instruments, apparatus, and systems.

It consists of a temperature-compensated reference diode and a low-drift op amp on a thin-film "precircuit" substrate, assembled in a hermetic 14-pin dual in-line package, laser-trimmed to within the specified tolerance.

Besides the AD2700L's factory trim to within 0.01%, a pair of terminals allows external tweaking of the output in applications needing greater accuracy, or to compensate for the inevitable long-term component drifts, specified at 50ppm/yr. Tempco is ±5ppm/°C for the "L". It thus offers, in a single package, a convenient source of accurate 10V that would ordinarily call for user skill, component selection, tweaking, time, and a non-trivial parts list.

It is also offered in "J" and "K" versions (2mV tolerance and 10 and 25ppm max tempco) at lower cost, where convenience is more important than extreme accuracy. "S, T, U" wide-temperature-range versions are also available, with or without processing to MIL-STD-883A, Method 5004.2, Class B. A related product, the AD2710, consists of just the network and op amp in a TO99 can, for use with an external matched Zener diode (provided). Costs range sharply downward from the premium "U" versions (AD2700/U, \$15 in 100's, AD2710/L, \$7 in 100's).

In number 8-2 of this Journal, we introduced a variety of standard thin-film resistor networks* for high-accuracy designs with op amps and switches. The networks, available in a variety of tolerances, forms, packages, and environmental-qualification levels, had such characteristics as:

- Ratio tolerances to 0.01%
- Temperature-tracking to 0.5ppm/°C
- Excess noise to -50dB
- Low drifts to 50ppm/year @ 25°C
- Negligible voltage coefficients
- MIL-STD-883 certifiability
- Available in DIP's, FLATPAK's, chips

The response to these networks was heartening, but many engineers who were used to matching discrete resistors tended to remain on the sidelines, partly because of skepticism that these networks were all we said they were (and could replace discretely), and partly due to the mind-boggling plethora of choices available.

As a stimulus to investigation, we've decided to offer 5 of these networks as a "starter kit", that can be purchased at nominal cost. Nevertheless, recognizing that different users have differing needs, we've still given you a number of options: chips vs. packages, 0.1% vs. 0.01% ratio-tolerance, and screening to MIL-STD-883. However, all of these networks are the premium -55°C to +125°C "S" or "U" versions. They can be ordered through your local sales office or directly from Analog Devices.

Model	C(Chip)	D(Pkg.)	D/883
AD1890S (0.1%)	\$24.95	\$29.95	\$39.95
AD1890U (0.01%)	\$29.95	\$34.95	\$49.95



*For information on standard resistor networks and on starter kits, request P3.

*For data on the 2700 family, use reply card.

I.C.'s: COMPARATORS AND D/A CONVERTERS

AD559 — 8-Bit Monolithic DAC A Preferable Alternative to 1408-1508

The AD559* is an 8-bit monolithic low-cost digital-to-analog converter characterized by monotonic performance over the entire temperature range. It consists of high-precision bipolar switches, a control amplifier, and high-stability Si-Cr thin-film resistors, all on a single monolithic chip, mounted in a hermetically-sealed 16-lead dual in-line package. The maximum error at 25°C is limited to ½LSB (K version), and the gain temperature-coefficient is limited to 20ppm/°C max.

The AD559 is recommended for all low-cost, 8-bit DAC requirements and as a replacement for the Motorola 1408/1508 8-bit DAC in most applications. The AD559K is specified for operation over the 0°C to +70°C temperature range and the AD559S for operation over the full extended temperature range, -55°C to +125°C.

Besides the low cost inherent in monolithic design with decent yield, the AD559 has a number of characteristics that make it not only superior to the 1408-1508 for

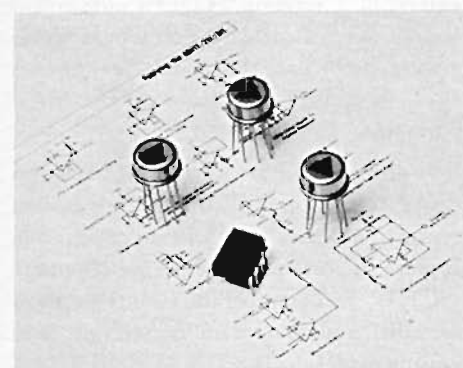
most applications, but an excellent choice for new designs as well. For example, unlike the 1408-1508, the AD559 is internally compensated, and doesn't require the stabilizing capacitor. In addition, the high-stability thin-film resistors provide low differential nonlinearity tempco; the low digital input currents make the AD559 compatible with CMOS, as well as DTL/TTL logic; its excellent linearity permits 2-quadrant (digital) multiplication when a varying reference is used; and — finally — the differential non-saturating precision current-switching cell structure provides increased immunity to supply-voltage variations and also reduces nonlinearities due to thermal transients as the various bits are switched; nearly all critical components operate at constant power dissipation.

And price is also competitive: In 100's, AD559KD is \$5.95, AD559SD is \$8.55.



*Use the reply card for an AD559 data sheet.

Precision Comparators AD111/211/311



These popular precision comparators are now available from Analog Devices*. They are designed for low-level signal detection and high-level output-drive capability. Typical applications include A/D conversion (e.g., with the AD7570, see p.4), multivibrators, sorting and grading, and other functions involving signal comparison and detection, and selective operation of switches.

They will operate with a variety of power-supplies, from single-ended +5V to ±18V, and will tolerate wide swings of both common-mode and differential signal voltage. The 50mA output current or 35V output voltage allows TTL, RTL, DTL, and MOS to be driven, as well as lamps and relays. The outputs can be wire-or'd for window and threshold detectors.

A *strobe* input allows flexible logical operations and prevents chatter in the presence of noise. The bias currents below 100nA and gains of 200,000, of the AD111 series, permit reasonable resolution and versatility. Differing principally in operating temperature range, the three versions are available in the hermetically-sealed TO-99 can. (The 311 is also available in plastic mini-DIP form.) Prices (100's) are \$15, \$7.50, \$2.00.



*Use the reply card for 111/211/311 data.

AD563 12-Bit DAC Includes Reference, \$27

The AD563* has all the excellent characteristics of the AD562†, introduced in these pages (No. 8-2). We simply added an AD580 voltage-reference chip to the AD562 to make a true, 12-bit current-output DAC with a fixed reference. It has the same hermetically-sealed 24-pin DIP package, the same high-accuracy performance, and all with only 3 chips.

The AD563 is specified in six different versions of accuracy, gain temperature-coefficient, and temperature range for widest possible utility. The low-cost J version, for example, offers ±½LSB (max) initial error and a 30ppm/°C gain tempco. Cost is only \$27 in 100's.

The 'MIL' temperature range T version provides ¼LSB (max) initial error and a gain tempco less than 10ppm/°C. As is the case with the AD562, all versions are monotonic over the full temperature range.

The AD563 is recommended for all high-accuracy 12-bit D/A converter applications where true 12-bit performance is required, where low cost and small size are considerations, and where some flexibility in choice of output amplifier (or comparator) to meet various speed or configuration requirements (such as A-D conversion) are necessary. Because of its monotonicity, the AD563 is ideal for use in constructing A/D conversion systems and as a building-block for even higher-resolution D/A converters.

Both binary and BCD (binary-coded decimal) versions are available. The laser-trimmed thin-film resistor network includes gain-range and bipolar offset resistors, so that various output voltage ranges can be programmed simply by changing connections to the device terminal leads. The digital inputs are flexible. Both TTL and CMOS inputs can be accommodated for positive supply voltages from +5V to +15V. In addition, the internal AD580 reference chip is designed to work well from any voltage in that range.



*Use the reply card for AD563 data.
†Use the reply card for AD562 data.

AUTOMATIC GAIN ADJUSTMENT USING D/A CONVERTERS

Circuit Permits Direct Readout of Concentration in Atomic-Absorption Spectrophotometer Measurements

by R. Sachenbacher

In the Instrumentation Laboratory, Inc., Series 351 Atomic-Absorption Spectrophotometers*, the user can preset an arbitrary number, in appropriate physical units, corresponding to the concentration of an element in a reference solution. With the reference (or an equivalent input) applied, the instrument will then automatically calibrate its own gain, after which concentrations of the unknown element in other solutions being tested will be readable directly. The process involves setting an 8-step "coarse" gain range, and a 14-bit (1/16,384 resolution) "fine" gain adjustment. Three AD7520 monolithic multiplying D/A converters† are at the heart of this autocalibration process.

ATOMIC-ABSORPTION SPECTROPHOTOMETRY (AAS)

Atomic-absorption spectrophotometry is an analytical method for determining the concentration of metals in solution. Though used originally for detecting trace concentrations, it has developed into a tool for precision measurement of concentrations in solutions, including very high concentrations of the major components of a material. While superficially similar to flame photometry, AAS is considerably more versatile; normal flame-photometric methods permit the determination of about 10 elements, but AAS can be used successfully in the determination of some 65 different elements.

Droplets of a solution containing the element of interest are sprayed into a flame, which dries and volatilizes them, after which the compounds are broken down into clouds of neutral

of light by the solution. Obtaining an actual measure of the concentration involves calibration against a standard solution. An automatic means is described here.

THE BASIC SCHEME (Figure 1)

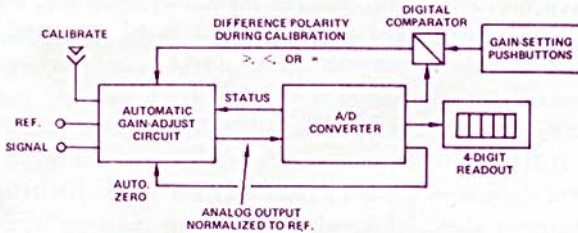
The system consists of a 4-digit BCD A/D converter, which reads out the input voltage, multiplied by the gain of the automatic gain-adjust circuit; a set of 4-digit BCD pushbuttons; a digital comparator, which compares the converter's output with the pushbuttons' state; and a logic-operated step-by-step gain adjustment in the *calibrate* mode. It adjusts the gain, in the *reference* condition, until the A/D converter output (hence its analog input) agrees with the pushbutton setting, which could be the numerical fractional concentration corresponding to the reference input. Once calibrated, the output reading will read out directly the actual concentration of an unknown signal input.

HOW IT WORKS (Figure 2)

With a numerical switch setting and a reference voltage applied (by the "scale expand" switch), the *calibrate* switch sets the AD7520 DAC (1) in the feedback path of A1 for full feedback (minimum gain), and the two AD7520's in the forward path of A2 (2 & 3) for minimum attenuation (maximum gain, about 1.5).

The ADC performs a conversion. Its BCD output is compared with the pushbutton setting (B). If $A > B$, the coarse gain is sufficient, and the system goes on to adjust the fine gain. If $A < B$, the coarse gain is insufficient; the logic decrements the input to DAC (1) by 1 bit (increasing A1's gain), a conversion is performed, the coarse test is repeated, etc., and the gain of A1 continues to be increased until $A > B$, following which the coarse gain is latched, and the fine-gain successive-approximation register is enabled.

(continued on page 22)



PROCEDURE

- A. DESIRED FULL SCALE OUTPUT IS SET BY PUSHBUTTONS
- B. ZERO IS ADJUSTED AUTOMATICALLY WITH NO INPUT
- C. THE REFERENCE IS APPLIED; PUSHING THE CALIBRATE BUTTON CAUSES THE GAIN TO BE STEPPED UNTIL THE A/D CONVERTER READS THE VALUE SET IN THE PUSHBUTTONS. CALIBRATION OCCURS IN TWO STAGES - COARSE, THEN FINE.
- D. APPLIED INPUT SIGNALS WILL BE PROPERLY SCALED TO READ OUT ACCURATELY IN THEIR TRUE PROPORTION TO THE REFERENCE SETTING.

Figure 1. Block diagram of automatic gain-adjusting system.

atoms. A light from a hollow-cathode lamp (the cathode constructed from the element of interest) shines through the flame, and the neutral atoms absorb this light, to a degree depending on the concentration of the material in the solution. Therefore, the concentration can be measured by measuring the absorption

*Manufactured by Instrumentation Laboratory, Inc., Jonspin Rd., Wilmington, MA 01887

†Use the reply card to request AD7520 data.

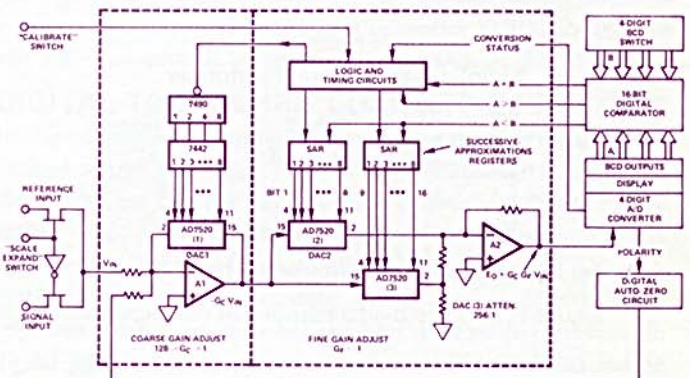


Figure 2. Functional schematic diagram of the auto-calibration circuit employing AD7520's to set gains

TWO-SPEED SYNCHRO CONVERSION SYSTEMS

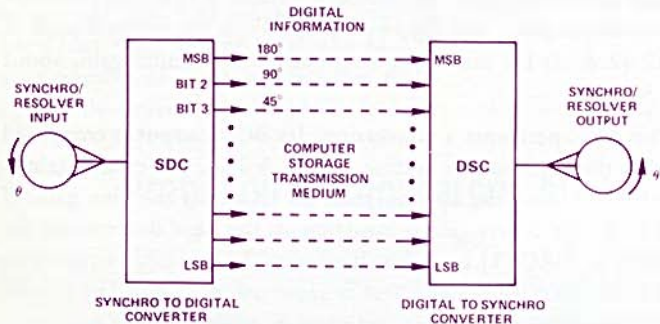
Use Moderate-Resolution Converters for High Angular Resolution, Limited Only by Gear Quality

by D. McDonnell

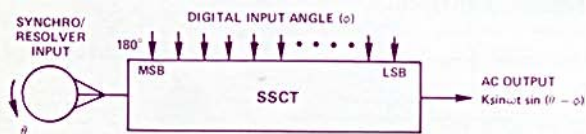
Synchro-Control Generator — A rotary component for transforming the shaft angle to a corresponding set of electrical signals for ultimate retransformation to the shaft position in a remote location.¹

The transmission of angular shaft position by the use of ac synchro transmitters and receivers is a well-established field of engineering. Recent developments have widened the application of these electromechanical devices enormously.

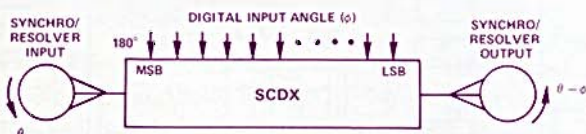
The original synchro transmission systems were purely electro-mechanical; electronics was used only in phase-sensitive rectification and power amplification. When the digital computer arrived, angular data in digital form had to be translated into synchro-type signals (and *vice versa*). This interface requirement was satisfied by the development of the synchro-to-digital converter (SDC) and the digital-to-synchro converter (DSC). These were soon followed by solid-state versions of the electro-mechanical control transformer (solid-state control transformer, SSCT), and control differential transformer (solid-state control differential transformer, SCDX).^{*} Functional block diagrams of these units are shown in Figure 1.



a) Synchro/digital and digital/synchro converters



b) Solid-state control transformer



c) Solid-state control differential transformer

Figure 1. Synchro-digital conversion components

Accuracy of transmission of angular data with simple systems is limited by the precision with which the output amplitudes of the synchro can be made to vary sinusoidally with the angle of rotation. With a good synchro, this limits the practical angular resolution to about 2 arc-minutes (93ppm of one revolution). Since it is possible to couple shafts with less than 2' gearing error, so-called *two-speed* (or *coarse-fine*) systems of angular-positional transmission are used. Even if greater errors are tolerable, it may simply be better economy to use two inaccurate synchros with accurate gears instead of a single high-accuracy synchro system.[†]

In a two-speed system, the shafts representing the angular position at both the transmitting and receiving ends are geared to additional shafts with step-up gearing. Synchro transmitters are coupled to both pairs of shafts at the transmitting end; receivers are coupled to both pairs of shafts at the receiving end. Typical gearing ratios might be 9:1 to 36:1, or (in the digital era) the binary ratios 8:1 to 32:1. This means that for each degree of arc traversed by the slow (coarse) shaft, the fast (fine) shaft turns through 9°, 36°, 8°, 32°, or whatever (60:1, or 60° in the clock-face analogy).

With two-speed systems, it is possible to transmit angular data representing the angle of the slow shaft (the hour-hand) with an accuracy limited only by the backlash plus nonuniformity of gearing referred to the slow shaft, without the use of very precise synchro receivers and transmitters. To transmit the angular position accurately, the coarse synchro should be capable of determining the angle to within one revolution of the fine synchro, and the precision of the fine-synchro data should be much better than the gearing backlash-angle, referred to the fine shaft.

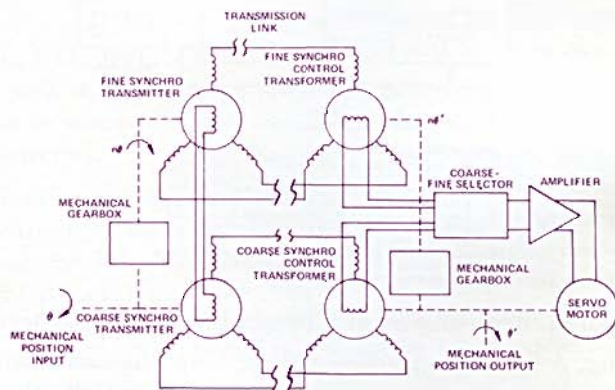


Figure 2. Electromechanical two speed synchro system

[†]Perhaps the most-familiar example of a visual-readout coarse-fine system is the familiar clock face. A three-speed system, its second-hand offers a 3600:1 improvement in resolution over the hour hand; the resolution of the entire system, even in the cheapest such watches, is of the order of 23ppm of 12 hours.

¹ *Modern Dictionary of Electronics*, R. F. Graf, Howard W. Sams, Inc., 1972

^{*}For information and prices on ADI synchro conversion products, request P4.

Figure 2 portrays an electromechanical two-speed system. The dotted lines represent mechanical coupling. The block marked "coarse-fine selector" in the remote-receiver portion determines whether *coarse* or *fine* signals are fed to the amplifier. Once the *coarse* error signal has determined the output angle to within one cycle of the fine synchro, the coarse-fine selector can switch to the *fine* converter to correct the remaining error.

Electromechanical two-speed systems have been in use for many years. Their special considerations are well-documented: e.g., the best point to switch over from *coarse* to *fine*, dealing with the change in loop gain, the possibility of stable false nulls with even gear-ratios, combatting them with "stick-off", etc.

TWO-SPEED DIGITAL TECHNIQUES

Besides the need to interface the *simple* synchro-format signals to digital computers, a need also arises to interface *two-speed* synchro signals to and from computers. This brief note considers mainly the acquisition problem: to develop a digital word representing the coarse shaft angle accurately from the coarse and fine synchro-format signals.*

Given the S/D transmitter system of Figure 3, with two sets of signals from the two synchros on the coarse and fine shafts, the problem is to produce an *unambiguous* digital word representing the angle of the coarse shaft with error less than the gearing imperfections and backlash referred to the coarse shaft angle.

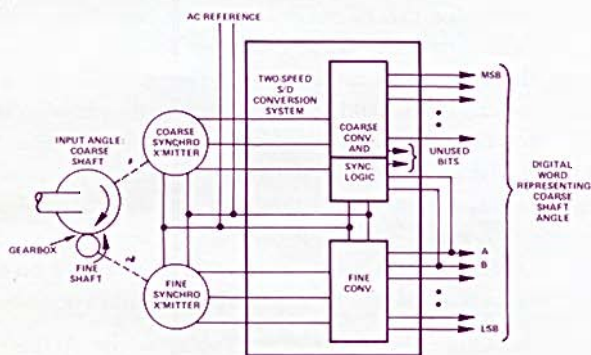


Figure 3. Two-speed synchro-to-digital conversion

For simplicity, let us assume a coarse shaft angle of 15° and a binary ratio (say 32:1). Using the angle-to-bit conversion scheme of Table 1, 10 bit S/D converters on the coarse and fine shafts would provide digital words corresponding to 15° and $32 \times 15^\circ = 120^\circ$ (modulo 360°), or 0000101010 and 0101010101. Since the fine shaft's reading represents 1/32 of its actual position (in terms of the coarse shaft rotation), it must be divided by 32. This is easily done in binary

Table 1. Angular bit weights

BIT NUMBER	WEIGHT (DEGREES)
1 (MSB)	180.0000
2	90.0000
3	45.0000
4	22.5000
5	11.2500
6	5.6250
7	2.8125
8	1.4063
9	0.7031
10 (LSB for SDC 10)	0.3516
11	0.1758
12	0.0879
13	0.0439
14 (LSB for SDC 14)	0.0220

*For a more-detailed application note on 2-speed conversion and appropriate converter- and processor data sheets, request PS.

fashion simply by shifting it 5 places to the right, viz., 000000101010101. We may now compare the two readings by listing them columnwise:

	CD
Coarse shaft reading	00001 01 010
Fine shaft reading/32	00000 01 01010101
	AB

In this case, there does not appear to be a conflict between the two shaft readings, and the output digital word will be 000010101010101 $\rightarrow 14.9963^\circ$. However, in a practical system, the overlapping digits will not change together at major transition points and the two digital readings will conflict. An unambiguous digital output is obtained by adding extra logic circuits, referred to as *synchronizing logic*.

The key to synchronizing is the fact that, considering errors in the coarse-shaft digitizing (bit 10), backlash on the coarse shaft (e.g., bit 11), and the fine synchro (bit 15), the fine synchro is certainly the most accurate. Therefore, the entire fine-shaft reading, starting with digit A, determines the last 10 digits and can answer the question as to whether or not the first 5 bits of the coarse shaft reading are correct (perhaps there is an erroneous carry or borrow at a major transition).

The synchronizing logic performs the operation indicated in the truth table, adding either +1, -1, or 0 to digit D, depending

A	B	Addition To D
0	0	+1
1	1	-1
0	1	0
1	0	0

on the state of A and B, and allowing borrows or carries to ripple back as far as they will go. The output word is then the resulting first 5 coarse digits, plus the fine digits.

For example, if the coarse word is 10000|00|000 and the fine word begins: |11| . . . , 1 must be subtracted from digit D, the resulting modified coarse bits are 01111|11|, and the correct word is 0111111 . . . (Note that in the first example given, the first five bits are unchanged by the application of this procedure.)

NON-BINARY RATIOS, HARDWARE

For non-binary ratios, the principle is similar, except that the digital multiplication and division by, say, 36, is not a mere matter of shifting the digits left or right. Since the logic circuitry is more extensive, it is usually embodied in a purely-digital *2-speed processor* (TSL1612), employed with two standard S/D converters (e.g., SDC1602, SDC1603). In the simpler case of binary ratios, however, the synchronizing logic is contained in a special *coarse* S/D converter (TSDC1610), and the fine converter is an ordinary type, such as the SDC1602.

DIGITAL-TO-SYNCHRO COARSE/FINE SYSTEMS

In digital-to-synchro systems, the input data, representing the desired coarse shaft angle, is used to generate digital inputs for the coarse and fine digital-to-synchro converters. Again, binary scaling (e.g., 32:1) requires merely shifting the fine data, while arbitrary scaling calls for shift-and-add multiplication. Control-system design requirements determine the nature of coarse-fine selection, which can now benefit by the flexibility inherent in digital processing. The conversion systems for D/A coarse-fine are straightforward; there is no complexity comparable to the synchronizing logic of two-speed S/D's.



APPLICATIONS OF THE AD580:

The Monolithic Voltage Regulator as a Flexible 3-Terminal Circuit Building Block

by Walter G. Jung

Three-terminal reference regulators — viz., the AD580^{1,2} — are emerging as low-cost circuit elements with surprisingly diverse uses. Though the original application for such devices was in providing small amounts of local regulated power, new uses are continually emerging, ranging from precision reference supplies (V & I), to stable level shifters, current sources and sinks, and high-performance ramp generators, plus a multitude of miscellaneous applications where “something more versatile or efficient than a Zener” (at only slightly greater cost) is desired, in a circuit or a system design (for example, in D/A and A/D converters).

The AD580 is designed to provide a constant 2.5V in low-power applications (to 10mA). Its output stability allows it to be used as a reference element with initial tolerance as low as $\pm 1\%$ and maximum output temperature coefficients as low as 10ppm/ $^{\circ}\text{C}$ over the 0 $^{\circ}$ to 70 $^{\circ}\text{C}$ or -55 $^{\circ}$ to +125 $^{\circ}\text{C}$ ranges (“M” and “U”). Its wide input-voltage range, 4.5V to 30V, allows it to operate, even from 5V “logic” power supplies, with an essentially-constant $\sim 1\text{mA}$ operating current drain (1.5mA max), irrespective of upstream supply voltage or load current.

One of the keys to effective application of the AD580 is an understanding of its workings. Figure 1 shows a functional equivalent circuit and the pinout of its TO52 case outline. Conceptually, it may be viewed as a 1.2V temperature-compensated Zener diode, with constant current through it, buffered by a voltage-follower-with-gain having 10mA output capability. When operating within its voltage and current constraints, it provides 2.5V between the output and common terminals; a constant current (about 1mA) flows through the common terminal.

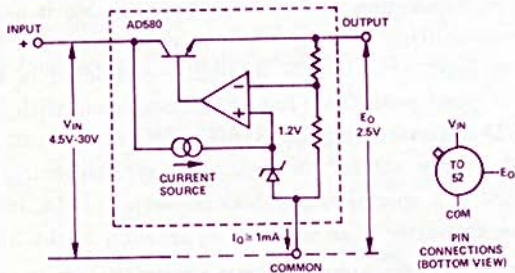


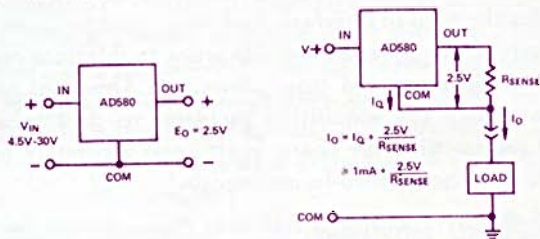
Figure 1. Functional schematic diagram and pinout of the AD580 regulator (see references 1, 2, for complete schematic)

APPLICATIONS

Figure 2 shows the two simplest forms of connection for constant voltage and for essentially-constant current output. The

*Use the reply card to request AD580 data. See also page 14.
¹ *Analog Dialogue* 9-1, 1975, “More About the AD580 Monolithic IC Voltage Regulator . . . or, Low-Cost Constants for Analog Circuits & Systems”, by A. P. Brokaw
² *IEEE Journal of Solid-State Circuits*, SC-9, No. 6, December, 1974, “A Simple, Three-Terminal IC Bandgap Reference”, by A. Paul Brokaw

constant voltage is, of course, fixed. When an external load is connected, the current that flows through the common leg of the circuit is $(I_Q + E_O/R)$; hence current may be programmed by the choice — or adjustment — of R (I_Q is about 11mA when $R = 250\Omega$).³



a) 2.5V reference circuit b) Basic current source

Figure 2. Basic voltage- and current-reference applications of the AD580

The output voltage can be made adjustable over a very wide range, and the current capability may be boosted, simply by buffering the AD580 by an op amp having suitable gain and output characteristics, and connected for the appropriate polarity. However, if we let our mind roam a bit and consider the AD580 just as a 3-terminal circuit element with predictable properties, a number of other uses and ways of applying it may come to mind. In fact, it turns out to be unexpectedly flexible. A representative sampling of its uses is shown on the adjacent page, accompanied by explanatory comments.

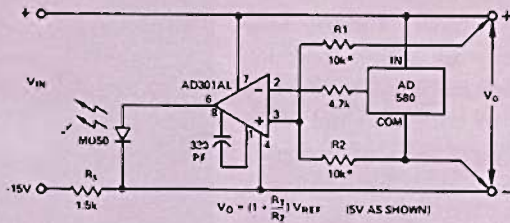
First, a few words about avoiding problems: the AD580 is short-circuit-protected and current-limited to 20mA at its output terminals, and it will withstand high input voltage (Absolute Max 40V) at its input terminal. Circuit applications likely to reverse the input polarity or force reverse currents into the output terminal should be avoided (the output may be protected against accidental destruction by series resistance (where loading is not critical) or by shunt diodes (a 3V Zener or 5 series forward-biased diodes with ratings appropriate to the power to be dissipated) connected across the load terminals.)

Some of the circuits to be discussed involve the use of the AD580 in feedback circuits with amplifiers. Since the AD580 is itself a feedback circuit, experienced feedback-circuit designers will recognize the possibility (but not always the exact manner or cure) of “latchup” or non-starting modes in some configurations, with some types of amplifier, and the potential need for debugging.

These circuits are representative examples that, to the best of our knowledge, work (well), but they are also presented as an invitation to and a starting point for your own design ingenuity to find ways to fill your own circuit needs using these intriguing devices.

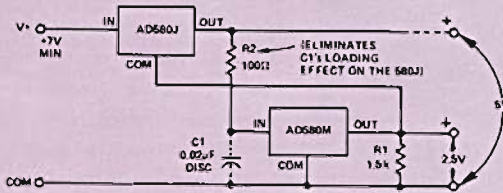
³ See *Electronic Design* 2, Jan 18, 1975, p.72.

PRECISION REFERENCE SOURCE



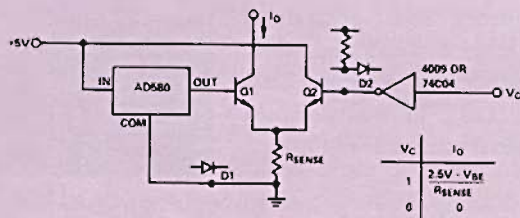
THE LOW-DRIFT AD741L ADJUSTS ITS OUTPUT VOLTAGE TO MAINTAIN ITS INPUTS TOGETHER AT 2.5V, AS DETERMINED BY THE AD580M. THE RESISTANCE RATIO ENFORCES A GAIN OF 4 (IN THIS CASE) FOR A STABLE 10V OUTPUT. THE AD580J IS USED IN PLACE OF A SERIES PASS TRANSISTOR (WHICH WOULD BE SOMEWHAT MORE ECONOMICAL) TO ABSORB INPUT VARIATIONS AND ELIMINATE DISSIPATION CHANGES IN THE AMPLIFIER. OPERATING THE AMPLIFIER FROM THE REGULATED VOLTAGE ELIMINATES COMMON-MODE ERRORS. OVERALL TEMPCD IS BETTER THAN 20ppm/°C.

SIMPLE "SUPERREGULATED" REFERENCE



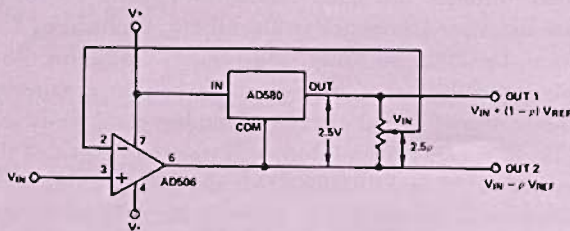
IN THIS CIRCUIT, THE AD580J PRE-REGULATES THE INPUT TO THE AD580M, RENDERING THE 2.5V OUTPUT FROM THE AD580M VIRTUALLY INDEPENDENT OF INPUT VOLTAGE VARIATIONS. THE AD580J, WHICH IS REFERENCED TO THE OUTPUT, DEVELOPS A TOTAL VOLTAGE OF 5V, SUFFICIENT TO OPERATE THE AD580M. C1 IS ADDED FOR STABILITY, AND R1 IS USED TO GUARANTEE A 1.5mA SINK CURRENT FOR THE INPUT 580's I_Q .

LOGIC-PROGRAMMABLE CURRENT SINK



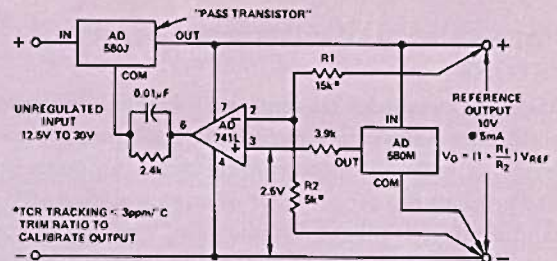
IN THIS CIRCUIT, Q1 OPERATES AS A CURRENT SINK, WITH THE 2.5V REFERENCE VOLTAGE APPLIED TO ITS BASE. Q2 IS AN EMITTER-COUPLED SWITCH THAT STEERS THE CURRENT IN R_{SENSE} EITHER TO OR AWAY FROM Q1. THE SWITCHING THRESHOLD AT Q2 IS 2.5V, IDEALLY CENTERED FOR A 5V SUPPLY CMOS DRIVE (AS SHOWN) OR TTL COMPATIBLE, WITH A PULLUP RESISTOR. THE V_{BE} OF Q1 CAN BE COMPENSATED FOR BY DIODE D1 INSERTED AS SHOWN (AND D2 FOR LEVEL COMPENSATION), AT THE COST OF HIGHER (ABOUT 5.25V) SUPPLY VOLTAGE.

ANALOG LEVEL SHIFTER (BIASED HIGH-IMPEDANCE FOLLOWER)



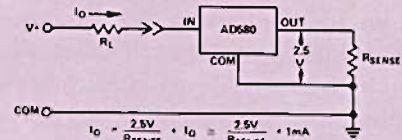
IN ANALOG MEASUREMENT CIRCUITRY, IT IS OFTEN DESIRABLE TO COMBINE A HIGH-IMPEDANCE MEASUREMENT WITH A PRECISELY-ADJUSTABLE AND STABLE OFFSET. IN THIS CIRCUIT, IT IS DONE WITH A SINGLE OP AMP AND AN AD580. THE OP AMP MAINTAINS THE ARM OF THE POT AT THE INPUT VOLTAGE, DRIVING THE EXTREMITIES TO $V_{IN} - \rho V_{REF}$ AND $V_{IN} + (1 - \rho) V_{REF}$. SINCE THE POT IS NOT LOADED, THE VOLTAGE ADJUSTMENT IS LINEAR WITH THE DIAL SETTING. IF THE TWO OUTPUTS ARE SUMMED, THE RESULT IS A BIAS ADJUSTMENT THAT IS CENTERED SYMMETRICALLY ABOUT ZERO.

PRECISION NEGATIVE REFERENCE



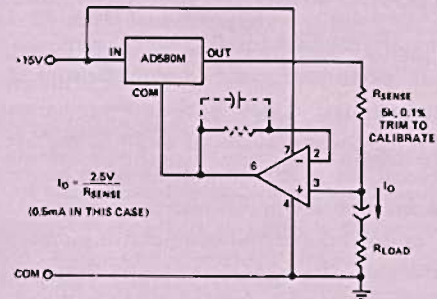
GENERALLY USEFUL AS A POSITIVE REFERENCE SOURCE, THE AD580 CAN ALSO BE USED AS SHOWN IN A BOOTSTRAPPED SHUNT-REGULATOR LOOP FOR NEGATIVE REGULATION. THIS CONFIGURATION ELIMINATES AMPLIFIER PSRR ERROR, AS WELL AS REDUCING OVERALL SENSITIVITY TO INPUT CHANGES. OUTPUT VOLTAGE, DETERMINED BY R_1/R_2 , RANGES FROM THE AD580'S 4.5V INPUT LIMIT TO THE MAXIMUM RATING OF THE AMPLIFIER. WITH 1ppm/°C RESISTOR TRACKING, THE OVERALL CIRCUIT TEMPCD CAN BE LESS THAN 15ppm/°C. USING THE AD580M, THE CIRCUIT CAN ALSO FLOAT AS A 2-TERMINAL "ZENER".

BASIC CURRENT SINK



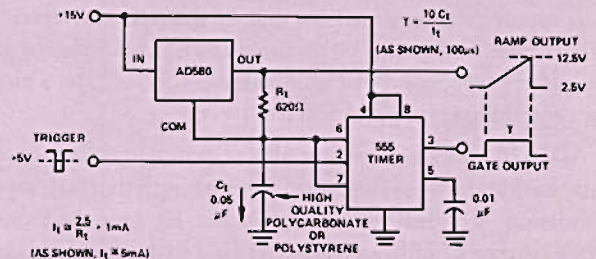
QUITE SIMILAR TO THE BASIC SOURCE IN FIGURE 2b, THIS CIRCUIT WILL SINK A CONSTANT CURRENT EQUAL TO $I_0 + E_{REF}/R_{SENSE}$. THE COMPLIANCE VOLTAGE WILL RANGE FROM THE MAXIMUM RATING OF THE AD580 TO THE MINIMUM OF 4.5V. I_0 MAY BE ANY CURRENT BETWEEN 1 AND 11mA, WITH I_0 ESTABLISHING THE LIMIT OF PREDICTABILITY.

PRECISION CURRENT SOURCE



THE OP-AMP FOLLOWER MAINTAINS THE DROP ACROSS R_{SENSE} AT E_{REF} ; THUS THE OUTPUT CURRENT IS SIMPLY $2.5V/R_{SENSE}$. A HIGH-QUALITY OP AMP, SUCH AS THE AD504, WILL MINIMIZE AMPLIFIER DRIFT, COMMON-MODE, AND BIAS-CURRENT ERRORS, LEAVING THE LINE REJECTION AND DRIFT OF THE AD580 AS THE PREDOMINANT ERRORS. SINCE OP-AMP BIAS CURRENT IS THE ONLY LIMIT TO PRECISION AT THE LOW END, THE FET-INPUT AD506 WILL PROVIDE PRECISION CURRENTS WELL INTO THE NANOAMP REGION.

MONOSTABLE TIMER WITH GATE & LINEAR RAMP OUTPUTS



IN RESPONSE TO A TRIGGER PULSE, THE CONSTANT CURRENT I_1 CHARGES CAPACITOR C_1 LINEARLY, AND THE OUTPUT RAMP UP TO 10V, FLIPPING THE 555, DISCHARGING C_1 . TO END THE TIMING CYCLE, THE USUAL GATE OUTPUT APPEARS AT THE 555'S PIN 3, AND A BUFFERED RAMP APPEARS AT THE AD580 OUTPUT, SHIFTED BY +2.5V. THE TIMING PERIOD MAY BE TRIMMED VIA R_1 OR THE 555'S CONTROL (PIN 5), WHICH ALSO TRIMS RAMP HEIGHT.

Potpourri

THE AD562 IC DAC WITH ARBITRARY RESISTORS

The AD562*, as faithful readers (and users) would know, is a high-performance D/A converter. A current-input, current-output device, it includes — for convenience — an input resistor scaled to produce the proper value of current with a 10V reference, and a set of feedback “application” resistors in the output circuit to provide a set of appropriately-scaled output voltages from the external op amp, depending on the mode of operation chosen. Because the input resistor and the application resistors track one another, and the current gain of the DAC itself is quite independent of temperature, the gain tempco overall is quite low.

The need often arises for a *different* input-output relationship, for example, different output ranges, a different value of voltage reference, an added offset, or perhaps, even, a *current* input, as in a multiplying DAC application. The important factor to recognize is that while the *tracking* of the input and the output resistors is excellent, their *absolute values* have somewhat greater drift with temperature. For best results, then, in such cases, the built-in application resistors should be ignored, and externally-connected precision resistors or matched thin-film sets should be used as the input and the output-summing-points, as required by the application. ►►►

*Use the reply card to request AD562 data.

AGC IN ATOMIC ABSORPTION (continued from p.17)

When it turns off the first bit of DAC (2), the gain is halved, a conversion is performed, and a comparison is made by the digital comparator. If $A < B$, the correction was too great, and the bit is turned on again. If $A > B$, the bit is left off. Then the second bit is turned off, another conversion, comparison, and decision are made, and the process is repeated 15 more times, or until the digital comparator indicates $A = B$. At this point, the gain of the AGC is exactly that needed to scale the reference input to the desired reading. When the “scale-expand” switch is switched to “signal”, the signal input will suffer the same gain, hence will provide a properly-scaled output reading.

Note that DAC's 2 & 3 form a 16-bit DAC; if their relative scaling is correct, and if each DAC is individually monotonic for at least 7 bits, any necessary value of gain for $A = B$ will be attained. The actual overall scaling is unimportant, since the gain accuracy is determined by that of the A/D converter; the AD7520's will be adjusted to produce any needed value of gain. (Any offsets will have been eliminated by an autozero circuit before the calibration process starts.)

The AD7520's which act essentially as switched resistive attenuators having high analog linearity and symmetrical bipolar transmission, are ideal in this application, because the input to the DAC can be of either polarity or zero without affecting the programmed gain.

This technique should have interesting implications for automatic calibration and measurement in other fields besides atomic absorption spectrophotometry. ►►►

Fred Pouliot (p.10) is Marketing Manager, Analog Modules, at ADI. He has a BSEE from Northeastern University and has done graduate work, while teaching undergraduate courses. He is a member of both TBII and HKN. After several years of designing analog circuitry, he became a marketing specialist, then Marketing Manager in the Modular Instrumentation Division.



Dennis McDonnell (p.18) is a consultant to Analog U.K. Previously, he was with Vickers Research, Ltd., after heading the Vickers electronic GW group. He has published papers on Z-transform theory and generalized Wiener-Hopf filtering equations. The founder of Fenlow Electronics, Ltd., he has designed instruments such as DVM's.

Rudolf Sachenbacher (p.17), a native of Lenggres (Bavaria), was educated at RCA Institute in New York. Then, at RCA Aerospace, he designed test fixtures for missile-system testing, including an Apollo transponder. He has been an Engineer at Instrumentation Laboratory, Inc., for the last 7 years with project design responsibilities for many of their products.



Walter G. Jung (p. 20) is a design engineer at AAI Corporation in Maryland. Specializing in analog circuitry, he is involved with op amps, A/D and D/A converters, and other circuitry used in signal-processing, test-measurement, and control. A prolific writer, he has recently authored 3 books on op amps (one of which is reviewed on page 23).

DIGITAL ELECTRONICS COURSE USES SERDEX

We have received an announcement of a short course in “Digital Electronics for Automation and Instrumentation”, presented through the cooperation of Virginia Polytechnic Institute and State University at Blacksburg, Virginia, by David G. Larsen, Dr. Peter R. Rony, and Jonathan A. Titus. The 5-day laboratory/lecture course provides hands-on experience with the wiring of digital circuits of modest complexity involving TTL IC's. Mr. Larsen informs us (for the benefit of those readers interested in SERDEX) that the last two days of the course are spent on the use of Asynchronous Serial for interfacing, perhaps the only course that teaches about SERDEX in any formal manner†. Those interested should get in touch with Mr. Larsen at (703)-951-6478 or Dr. Rony at (703)-951-6756. ►►►

†If other such courses exist, we would relish hearing about them. For further information about SERDEX, see t, page 6.

Book Review

IC Op-Amp Cookbook, by Walter G. Jung, 1974, Howard W. Sams & Co., Inc., Indianapolis, Indiana 46268, 591pp.

The title of this book promises that it is what many of us want, but it also sounds like one of the titles "cooked up" by the electronic bibliopegists for their case books of inane circuits or collections of outdated application notes. Well, the good news is that the book lives up to its name; and there isn't any bad news, unless it's the price (\$13 is a little stiff for a paperback, but this one is worth the cost if you plan to use it and not just display it).

The first 25% of the book's 500+ pages of text and illustrations is devoted to generalized IC op amps. It begins with (you guessed it!) "The Ideal Op Amp" and moves on quickly to "IC Op Amp Specifications". This section is a good review (or a good no-nonsense primer for neophytes) of basic op-amp principles mixed with an explanation of the bells-and-whistles . . . and problems . . . which come with real IC op amps.

The rest of the book is an indexed and cross-referenced collection of practical op-amp applications. The applications include a brief description of how the circuit works, the basic design equations, and an example of a working circuit complete with resistor and capacitor values, diode 1N numbers, and real IC op-amp type-numbers (unlike another well-known op-amp text which shall go unnamed in these columns).

Many of the circuits are extracted from manufacturers' application notes or from published articles, and the references to them provide good follow-on reading for engineers who require more depth. The book is topically quite broad, and the most serious omission is the total lack of mention of ADI's high-performance products in the specialized applications, although, of course we also make the general-purpose types to which the author refers. I can only hope he is saving the best for later and will honor us at some future time, since he could easily get another 500-page book out of the applications and special features of our IC products alone. (Seriously, I recommend that after reading his sections on Instrumentation Amplifiers and Multipliers, you take a look at ADI's applications for AD520's, AD521's, AD530, AD531, AD532*, etc., etc., to see that "life can be beautiful".)

The purist may find that the book lacks a little in rigor and technical depth. Nevertheless, there's something in it for just about every op-amp user, and almost every part of the book will have some sound practical value to somebody who wants a circuit that works.

A. Paul Brokaw

*(Ed. - You may use the reply card to request any of these.)

PRODUCT GUIDE - FREE

If you have not yet received the 272-page Analog Devices Product Guide, replete with catalog information and technical background on all of our product lines, we invite you to get a copy. Simply request it on the reply card.

Worth Reading

LAST ISSUE OF ANALOG DIALOGUE Volume 9 (1975) Number 1

If you haven't seen the last issue of *Dialogue*, you can get a copy by requesting it. Here's what you've missed:

Second-Generation Monolithic Differential Instrumentation Amplifier (AD521)

More About the AD580 Monolithic IC Voltage Regulator Is There an "883" for Modules? (High-Rel Converter Modules)

Line-Powered 4½-Digit Panel Meter (AD2008)

Compact 12-Bit DAC Includes Registers (DAC1132)

Monolithic 12-Bit 4-Quadrant Multiplying DAC (AD7521)

10-Bit Low-Power CMOS A/D Converter (ADC1123)

Fast A/D Converter at Low Cost (ADC1109)

High-Performance, High-Linearity, High-Speed ADC (ADC1102)

Analog Multiplier with 0.1% Performance (435)

Dedicated Analog Divider, Pretrimmed to 0.25% (436)

Low-Noise Wideband Premium-Grade Instrumentation Amplifier (606)

Thin-Film Attenuator Circuit, 0.001 to 1 in 9 Steps (AD1804)

Ni-Cr Thin-Film Coated Substrates

Application Briefs:

The ADC1105 in Industry - Analog-to-Pulse-Train Converter for Numeric Displays in Physical Units
Current Inverter with Wide Dynamic Range

Potpourri: Modular Power Supply Guide

Book Review: Low-Noise Electronic Design, by C. D. Motchenbacher and F. C. Fitchen



ERRATA - Analog Dialogue 9-1

If you missed the last issue, you've also missed a few errors. Corrections of those found so far are given below.

- P.2 Authors, reading Left to Right, in the group of 3 are: Mike Timko, Paul Brokaw, Bill Maxwell.
- P.3 In Figure 1, Q26 is an NPN transistor.
- P.9 Price of ADC1111 is \$895.
- P.10 Col. 1, Par. 2, full-scale range of the AD2008 is $\pm 1.9999V$.
- The illustration of page 19, itself a correction of Figure 29, page 11-53 in the *Analog-Digital Conversion Handbook*, has the wrong polarities indicated for comparators 1, 2, 4, & 5. A corrected version of the illustration is given below. Please copy it and substitute it directly for Fig. 29, p. 11-53 in your copy of the *Handbook* (without having to mutilate this copy of *Dialogue*)?

