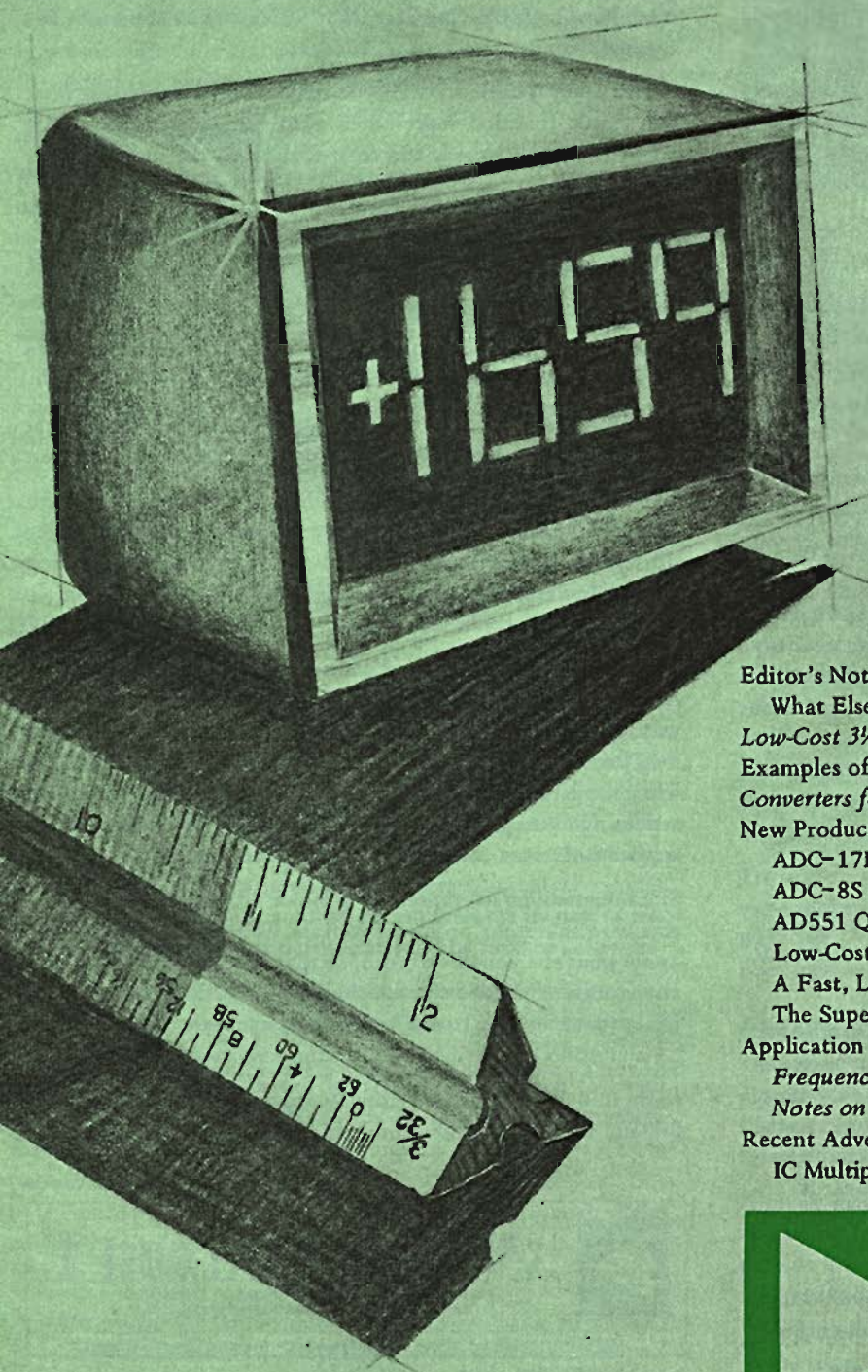# ANALOG DIALOGUE

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

**LOW-COST
DIGITAL PANEL METER
HAS 3½ DIGITS — See Page 3**

## Contents: Volume 5, Number 5

# ANALOG DEVICES

*Circuit Specialists*

# Editor's Notes

This issue of *Dialogue* marks the entrance of Analog Devices into a new product area: the digital panel meter.

It is new to us only in that it has a display, which for the first time in our history gives us the exhilarating feeling that goes with having a *visible* product that we can proudly show our families and non-technical friends.

Though users of our nearly one million op amps and converters have an excellent appreciation of their key role in technology, our products have always been somewhat of a mystery to the world at large. They are little black packages, that have "something to do with computers," and they are invariably kept out of sight, deep within the guts of equipment.

## Not So New

Though it is not immediately apparent, DPM's have much in common with our earlier products.

In the first place, much of the circuit design and engineering and applications savvy is identical with what it takes to design and use op amps and converters.

Secondly, digital panel meters are poised, just as op amps were ten years ago, on the verge of becoming low-cost electronic components of instruments, equipment, and systems — our *metier*.

Finally, not even the display is entirely new to us. Since we're circuit- and test-equipment designers, like the users of many of our products, we've been designing and reading instruments for many years. With this background, we can know what users like and want: a simple, readable, reliable display, at the lowest cost, without any frills, that can be used as a component, and is backed by a company with a worldwide reputation, a manufacturer who thinks like a user.

## The User Benefits

The entry into the marketplace doesn't mean just that a new, smaller, better DPM, at lower cost has arrived on the scene, with more to come (though that is certainly true).

The more important meaning to designers of instruments, equipment, and systems, is that the *same team* that has been designing, manufacturing, and helping you choose and use those other elements whose performance *and cost* are crucial to the precision and reliability of your system — op amps, converters, multipliers, power supplies, and high-performance linear IC's — can now provide you with another key electronic element of your system.

Unlike a narrow specialist, evolving from conventional design of electromechanical meter movements into a not-entirely-familiar field of electronics, we are already there. Our specialty has *always* been to serve integrated needs of precision electronic instrumentation designers in meeting sophisticated goals economically. The DPM is one more tool in our kit. ▶▶▶

## NOT REALLY HIRSUTE

$$Z = f(X,Y) = X + \cfrac{Y^2}{2X + \cfrac{Y^2}{2X + \cfrac{Y^2}{2X + \ldots}}}$$

If one is not very smart about it, the behavior of feedback circuits can be expressed by infinite series, instead of neat closed-form implicit expressions.

Consider the above example. It is a needlessly complicated expression for one of the quite useful functions that will be available with a new multi-purpose versatile nonlinear analog module, a LAMDE Operator, that we expect to announce in a forthcoming issue of *Analog Dialogue*.

If you enjoy puzzle-solving, you may wish to figure out what the simple function represented above actually is and how it might be implemented, and to speculate on the nature of our new product.

The answer, plus any exceptionally interesting responses from readers, will appear in a future issue. ▶▶▶

## READER FEEDBACK

To maintain the "Dialogue," we incessantly issue invitations to our readers to correspond with us, and many do.

With this issue, many of our readers will receive a somewhat more formal opportunity to correspond: a Questionnaire about your reading of industry magazines.

Recognizing that *Dialogue* is not your sole means of receiving timely technical information, and that infrequent publication limits what we can communicate, in both quantity and timeliness, we seek to reach you in other ways, via the industry press.

The most obvious of these "other ways" is advertising (a few recent examples will be found on page 16.) But it is not the only way: We also furnish all the magazines on our list routinely with new product and new literature releases. We also work closely with magazine editors on product background stories, tutorial articles, industry surveys, and we try to provide a flow of application notes, some of which get published.

Since our mailing list represents a major portion of those engineers who share our product interests, we think it important to know what else you like to read, so that we can concentrate our cooperative efforts on those technical publications that are most likely to reach you . . . and find you in a proper frame of mind.

So won't you help us by taking a few minutes to fill out the form, fold it, staple it, and drop it into the mail? We'll be grateful, and we think it will ultimately benefit *you*. ▶▶▶

*Dan Sheingold*

# Low-Cost 3½-Digit Panel Meter for OEM Applications

by Lawrence T. Sullivan and Thomas J. Mealey

The AD2001* is a complete 3½-digit panel meter designed for original equipment requiring high performance at low cost. Its accuracy is within 0.05% of reading, ±1 digit, with a temperature coefficient of ±50ppm/°C. In addition to BCD digital output, the meter's logic is designed to permit it to interface with an external data-handling system.

Through an unusual circuit approach in the analog section, the meter's excellent accuracy and versatility are obtained with far fewer components than are found in conventional DPM's. This austere circuit design results in small size (1¾" H x 3" W x 1½" D), high reliability, and remarkably low cost ($89 in 100's). It also allows a unique benefit: the ability to operate from a single source of power, 5VDC.

## WHY THE AD2001?

When digital panel meters were introduced in 1968, it was predicted that they would gain wide acceptance among equipment designers. Their advantages of high resolution and accuracy, non-ambiguity of reading, and ability to interact with data-processing equipment would allow DPM's to make the analog panel meter obsolete.

Unfortunately, the predictions have not yet been fulfilled. When equipment designers considered digital panel meters, they immediately ran into a very practical obstacle: *cost.* Except for very expensive instruments, the designer could not justify using a $250 DPM in place of a high-accuracy analog meter at $60–$75. They also met with another practical difficulty: *size.* Designers were used to working with meters that occupied no more than two inches (5cm) of back-panel space. Typical DPM's required from 4 to 7 inches!

A survey among equipment and instrument designers has revealed latent plans to use DPM's in new designs, provided that two conditions could be met: The first is good performance at a price below $90. The second is compact size. If a 3½-digit DPM were available, with errors less than 0.1% of reading (±1 digit), BCD outputs as a standard feature, and high reliability, at a price approaching the $75 level, typical of high-accuracy analog meters, it would be widely adopted. If a meter with these characteristics could be comparable in *size* to the analog meter, its appeal to designers would be further enhanced.

The AD2001 was expressly designed to meet the DPM specifications desired by instrument and equipment designers. It more than meets the accuracy requirement. BCD digital outputs are an inherent feature. As will be seen, it is designed for high reliability and long life. Not only is the AD2001 a nearly direct replacement for the most common size of panel meters (whose errors specifications are usually of the 1–2% class), but it is considerably smaller than the 5½" to 7½" typical of the most accurate and expensive analog meters. And its price in 100's is only $89!

A meter with such performance, economy, and size advantages provides a viable digital alternative to analog meters for new equipment designs. The AD2001 is expected to find widespread application in analytical and scientific instruments, medical



electronic equipment, industrial test instruments, and process control instruments and systems.

When one first sees and handles this new DPM, he is immediately aware of the fact that it is a *modular component* for use in metering applications. The light weight, small size, crisp lines, rugged metal case, and lack of frills are clear evidence that it is, physically, *not an instrument but a component,* that can be used with or as part of instrument packages.

## DESIGN OBJECTIVES

The AD2001 was designed as an OEM panel meter by first finding out what the OEM wanted and then devoting substantial engineering resources toward the fulfillment of this need. The important requirements (which include those already mentioned) are: 3½-digit performance, < $100 price, high reliability, attractive display, ease of interfacing, small front-panel dimensions — roughly equivalent to those of a 2½" analog panel meter, shallow depth (< 2 inches), mechanical ruggedness, light weight, low power consumption, and easily-concealed manufacturer identity.

To achieve these goals, new circuit and assembly concepts were applied (patents pending), and modern circuit components were used. As a result, the basic requirements have not only been met, but exceeded.

## ELECTRICAL DESIGN

The basic circuit idea is akin to the dual-slope integrator design. This concept is almost universally employed in state-of-the-art panel meters because of its inherent simplicity and freedom from component tolerance errors.

A block diagram of a dual-slope integrating converter is shown in Figure 1. A review of the way it achieves conversions will provide a frame of reference for understanding the differences inherent in the AD2001 design.

At the beginning of a measurement, the input switch is set to $V_{IN}$, the capacitor has zero charge, and the counter is set to zero. $V_{IN}$ is integrated, and the integrator output appears at the input of the zero comparator with an average slope of $\overline{V_{IN}}/RC$. When the counter accumulates its maximum count
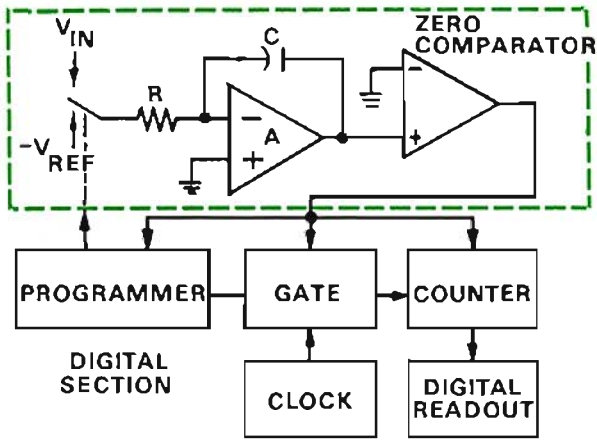
Figure 1. Block Diagram of Dual-Slope A/D Converter

(typically 1000, for a 3-digit meter), it tumbles over to zero, and the logic switches the integrator input to the $V_{REF}$ position. $V_{REF}$, being opposite to $V_{JN}$ in polarity, causes the integrator's capacitor to start discharging; at the same time, the counter starts counting. The input to the zero comparator is changing at a rate $V_{REF}/RC$, as indicated by the second slope in Figure 2. When the integrating capacitor's charge reaches zero, the zero detector triggers the logic to stop the counter. The counts accumulated up to that time (N) are proportional to the input voltage and are displayed on the digital readout.

Since the time integral of the signal during the 1000 counts is equal and opposite to the time integral of the opposite-polarity reference,

$$1000\ V_{IN}/RC = N\ V_{REF}/RC$$

whence, N = 1000 $V_{IN}/V_{REF}$. The output of the counter is inherently encoded in BCD (binary-coded decimal), and the BCD is then decoded to produce the appropriate number in the display.

Advantages of this approach that have tended to make it the most common one in use today include:

1. The parametric accuracy of the integrating capacitance is of no importance. Since both the signal and the reference are integrated with the same capacitor, its nominal capacitance value does not affect the result. However, it should be a high-
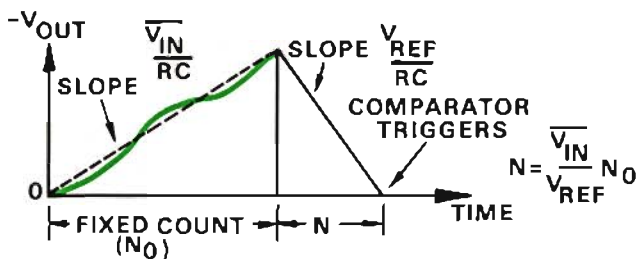


Figure 2. Integrator Output

quality capacitor, because dielectric hysteresis can affect accuracy.

2. The clock frequency, unless it changes during conversion, does not affect measurement accuracy, because the N counts and the full count have the same time scale.

Although the dual-slope approach eliminates a number of potential causes of error, it does not eliminate drift errors in the analog section. The input signal-conditioning circuits, the auto-polarity circuit, the integrating op amp, and the comparator all contribute to offset and drift. Circuits traditionally used to compensate for or eliminate these errors tend to increase both cost and bulk to the point of unsuitability for use in a successful OEM meter.

## THE ANALOK™ CONCEPT

A new circuit concept has been invented and dubbed Analok™ because it *locks out* sources of drift and *locks in* the inherent accuracy of a dual-slope converter.

Analok can be outlined with the aid of Figure 3, which shows the blocks of a dual-slope converter. The blocks within the colored triangle (amplifier symbol) represent the circuits compensated by the Analok potentiometric feedback.

The input signal passes through an RC filter, to improve normal-mode rejection, and on to a set of analog switches. The switches selectively switch the reference and the input signals, as in a standard converter, but they also switch in correction signals derived from the analog stabilization network. These correction signals compensate for the dc error of the integrator and comparator amplifiers.
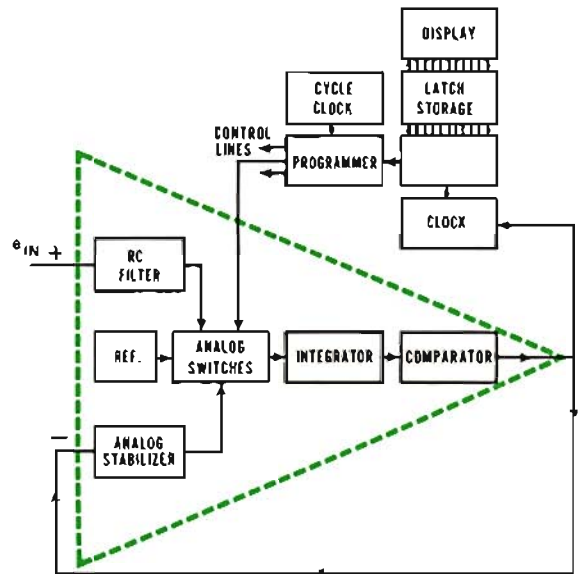


Figure 3. Dual-Slope Converter with *Analok*

The method of switching and the type of feedback used present a very high input resistance to the input signal, eliminating the need for an input amplifier. The effective offset voltage is typically $5\mu V$, and bias current is of the order of 200pA.

The reduction of circuit complexity using Analok is impressive: in fact, the active elements in the analog section consist of 3 integrated circuits. The analog switch block is a standard CMOS quad switch; the integrator is basically an AD308 integrated-circuit op amp, and the comparator is an AD301A I.C. op amp, both standard ADI products.*

## SINGLE DC POWER SUPPLY

For reduced size and to allow easy interfacing, the AD2001 uses a single non-critical +5VDC supply, rather than 115VAC or dual power sources. Keeping in mind that the AD2001 is for OEM new-equipment designs, +5VDC is as readily available as 115VAC in these applications, and it is much more convenient for the user to route in his equipment, because there are no shielding problems, electric or magnetic. Besides the reduction of power-frequency noise, the meter itself gains a saving in space and weight, since the bulky power transformer is eliminated.

To operate an analog section capable of handling bipolar inputs from +5VDC, without using a DC/DC converter, required additional new circuit ideas, which are incorporated into the Analok circuit: The input reference level is operated away from ground, with the integrator and comparator circuits operating at + and − levels with respect to the reference. The level shift is accomplished with the analog switches and analog stabilizing networks.

## NUMITRON DISPLAY

The requirements of +5VDC operation necessitated a display that could also operate from +5VDC. From the many types available, including GaAs, the RCA Numitron was chosen because of its high brightness (4000 ft-lamberts, ten times brighter than LED's), long life (100,000 hours), large character size, and general aesthetic appeal. This 7-segment display is both in-line and coplanar, and can be used with any color light filter.

A display that can be operated at +5VDC eliminates many of the interfacing problems that can occur in OEM equipment. DPM's employing Nixie-type displays have created radio-frequency interference that is difficult and costly to shield against. Manufacturers of medical equipment may delight in the AD2001's low-voltage operation because of the safety advantages.

## MECHANICAL DESIGN (Figure 4)

To house the AD2001 circuitry, an aesthetically-attractive and mechanically rugged case was designed (patent pending). Unlike housings of other DPM's, the AD2001 case is aluminum, not plastic. It is aluminum because aluminum is far superior as a DPM enclosure. Although DPM's dissipate only a few watts, a substantial temperature rise can result if safeguards are not taken. Plastic is a wonderful thermal (as well as electrical) insulator, and cases made from plastic must be vented to allow convection cooling. These same holes allow unwanted items, such as condensation, oil drops, etc., to enter — items the OEM does not want to worry about.

Aluminum, on the other hand, besides having excellent thermal conductivity, also allows radiational cooling, which can result in cooler, and thus more reliable, circuit operation. The aluminum case also acts as a shield against sources of noise in the nearby equipment, which simplifies the interface problem even further.

An attractive cast aluminum alloy bezel is used to mount the DPM in the equipment panel. Studs are cast in the bezel, and the panel is sandwiched between the bezel and the case. The user need only tighten two nuts to secure the DPM to his panel.

## REVIEW OF DESIGN FEATURES

**Bright, Sharp Display.** The display is bright, sharp, and highly readable over a wide range of ambient lighting, with choice of colors provided by filtering. Standard features are automatic polarity, programmable decimal points, automatic zero, 199.9mV full scale, and automatic out-of-scale indication. The normal display rate is 5 flickerless readings per second.

**High Reliability.** The novel circuit design of the AD2001 results in substantially fewer components than conventional panel meter designs. It also allows the elimination of multi-level power supplies. Both of these design simplifications result in inherently higher reliability. Use of the RCA Numitron display tubes, with their 100,000-hour lifetime, further augments reliability. In addition to these inherent features, all meters are subjected to 7 days burn-in prior to shipment.
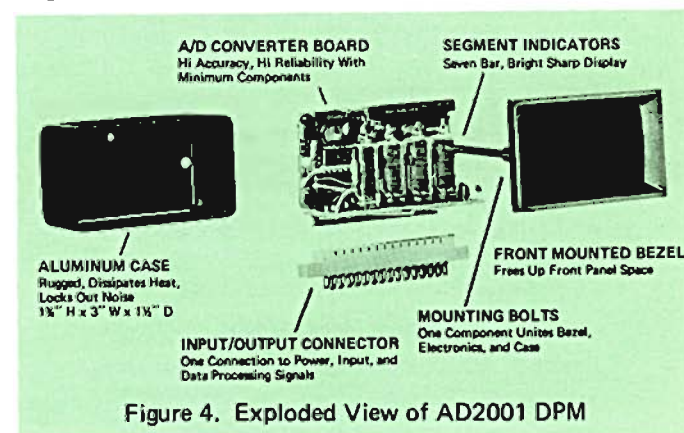


Figure 4. Exploded View of AD2001 DPM

**Small and Rugged.** The AD2001 is the smallest commercially-available digital panel meter. Its compact case size, 1¾″ H x 3″ W x 1½″ D, allows it to be easily substituted for conventional lower-accuracy analog panel meters. The AD2001 is housed in an aluminum case, which provides light weight, structural strength, optimum heat dissipation, and shielding against external noise.

**Easy to Use in New Designs.** The AD2001 was designed with the equipment of the '70's in mind. Its logic levels are compatible with DTL and TTL integrated circuits. Operation is from the same +5VDC that supplies the integrated circuits, eliminating the shielding and decoupling normally needed for 115V meters. Separate DC inputs to the converter and the display may be utilized by the OEM designer to minimize effects of display transients in signal circuits in the most critical applications. The front bezel design allows easy installation and removal. Its light weight allows the AD2001 to be used with hinged-panel displays.

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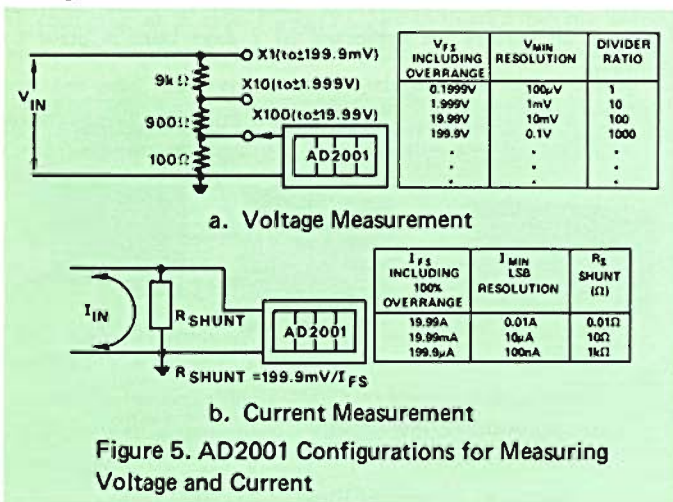*For information on the AD308 and AD301A op amps use the reply card. Circle E2

Because of its automatic polarity indication, its excellent resolution, TTL-compatible BCD outputs, and numerous control signals, the AD2001 is suited to a wide variety of applications. These fall into several general classes:

- Accurate voltage and current measurement, replacing high-precision analog panel meters
- Instrumentation applications, with numerical readout in engineering units
- General-purpose instrumentation, with auto-ranged gain and decimal point settings
- Systems applications, as A/D converter, with readout facility

## REPLACING ANALOG PANEL METERS

The AD2001 can be favorably compared in size, cost, and accuracy with analog panel meters having centred zero and 0.05% linearity and resolution over a ±200mV range (±100mV plus additional 99.9mV "overrange"). In addition, it has high input resistance, which allows the use of external voltage dividers and current shunts that do not need correction for the meter's resistance. Although not fully floating, it may be used with a separate 5V supply or an external isolation amplifier to perform measurements in which ground level is an important consideration.

a. Voltage Measurement

b. Current Measurement

Figure 5. AD2001 Configurations for Measuring Voltage and Current

As a voltmeter, its ±200mV full-scale sensitivity is roughly comparable to that of a ±200μA analog panel meter, but its resolution is at least an order-of-magnitude better. For measuring voltages that exceed its input range, it may be used with a resistive attenuator, as shown in Figure 5a. For current measurement, a 100mV shunt, or one having resistance of $100mV/I_{FS}$, will provide 100% overrange capability. The basic full-scale current sensitivity of the meter-cum-shunt, used in this way, is 0.1 ohm-ampere; the basic resolution is 0.1 ohm-mA.

## INSTRUMENTS WITH READOUT IN ENGINEERING UNITS

The numbers in the AD2001's display represent levels of dc voltage applied to the meter terminals. However, the quantity that is of interest may be degrees Celsius, pounds of lettuce, millibars of pressure, litres per minute of water, etc. Since numbers are inherently dimensionless, if the input voltage is scaled so that the number of millivolts is numerically equal to the number representing the physical quantity (multiplied by an appropriate power of ten), over the range of variation, the meter may be read and understood by a user who has little inclination, or training, or even ability, either to read an analog dial or to make a scale conversion.

Furthermore, the data available at the meter's digital outputs can be applied to data processing equipment, which may generate and display related parameters, such as cost, trend, etc., tabulate, store, and print out the information, determine whether "flag" conditions exist, and perhaps even sound an alarm.

Figure 6 shows the AD2001 as used in a weighing application, in which the output of a load-cell or strain-gage preamplifier is scaled by the appropriate amount, via a resistive attenuator, to provide direct readout of weight in kilograms.

Figure 6. DPM in Electronic Weighing, with Direct Readout in Engineering Units
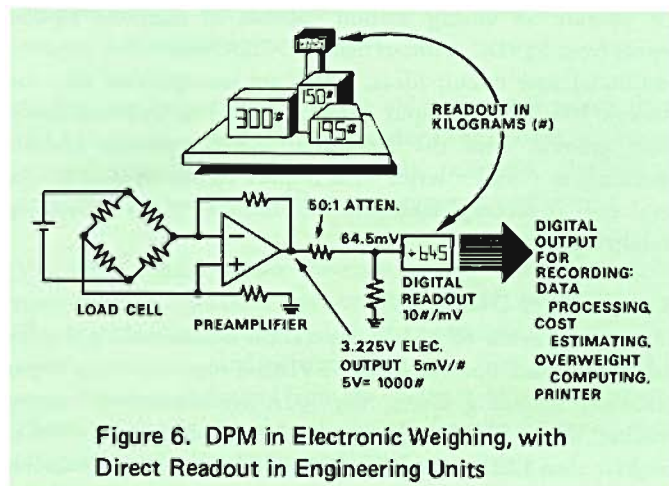
## AUTORANGING

The effective dynamic range of the AD2001 can be greatly increased by the use of an attenuator that is range-switched in response to the input level, increasing attenuation when the input is in "overrange," and decreasing attenuation when the input is insufficient to activate the most significant digit. An example of this mode of operation is shown in Figure 7. Relays are used to switch the input level, and the relay drivers are also used to position the decimal point.

Figure 7. Using a DPM in Measurement with Auto-Ranging and Automatic Decimal-Point Shifting
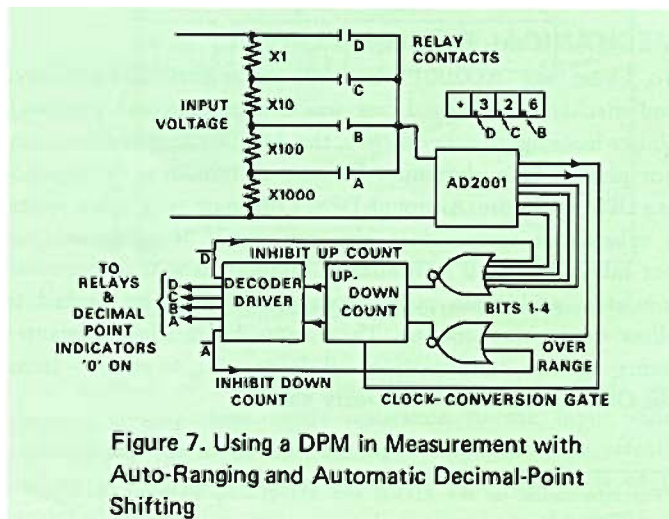
An up-down counter, clocked by the conversion gate, counts up 1 level (i.e., towards less attenuation) when none of the first four bits — which form the first digit — is present. It counts down (i.e., towards greater attenuation) when an overrange indication is present. The counter is inhibited from seeking either more or less attenuation than is available. Again, the meter can provide both visual readout and digital output signals for further processing.

## A/D CONVERTER, WITH READOUT AS A BONUS

Because of its low cost and small size, the AD2001 may be applied simply as an A/D converter with 3½ digit sign-magnitude binary-coded decimal (BCD) output. While furnishing its digital output to a data-handling system, it may be located near the analog input source, providing a human operator with means of visual check on the source and the conversion.

In the example of Figure 8, a 2001 is shown reading out a number of multiplexed variables, which could be switched randomly, sequentially, or even manually. ▶▶▶
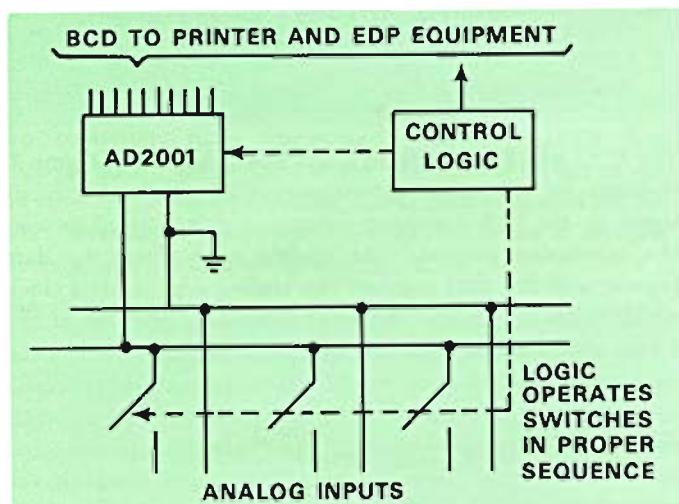


Figure 8. DPM as a Multiplexed A/D Converter with Incidental Readout

## THE AUTHORS
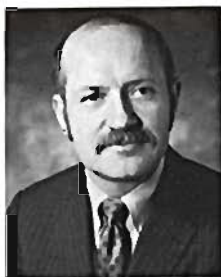
*Larry Sullivan* is Vice President — Marketing at Analog Devices. A native of Vermont, with advanced degrees in both E.E. and Business Administration, he has had more than 15 years' experience in the engineering, planning, and marketing of advanced technological products. He brings to Analog a powerful combination of talents, that are devoted to finding and nurturing the new products that will most benefit our customers.

*Tom Mealey,* Marketing Manager for Digital Panel Meters, is an E.E. with an advanced degree from CCNY. His 15 years of diversified experience in product design and development, project management, and numerous other areas of achievement form a strong asset for Analog's marketing effort.

## AD2001  BRIEF SPECIFICATIONS
(@ 25°C and 5V supply unless otherwise noted)

### DISPLAY
- 4 RCA Numitrons (7-segment incandescent readout tubes) for 3 data digits, overrange, polarity, and decimal-point indication
- Overvoltage: 3 data digits read "0", and overrange "1" flashes when reading exceeds 200% of full scale
- Decimal points: Selectable at input connector

### ANALOG INPUT
- Full-scale range: 0 to ±199.9 millivolts, automatic zeroing and polarity indication
- Bias current: < 1 nA
- Resistance: 1000MΩ
- Overvoltage protection: 100x full scale sustained without damage

### DIGITAL OUTPUTS AND CONTROL LOGIC SIGNALS (TTL)
- 3 BCD Digits (8-4-2-1), Positive Logic 99.9mV code: 1 0 0 1  1 0 0 1  1 0 0 1
- Overrange output: Logic "1" indicates overrange
- "Out-of-scale" output: Logic "1" indicates out-of-scale condition
- Polarity output: Logic "0" indicates positive polarity (sign-magnitude BCD)
- Conversion gate ("status") output: Logic "1" when conversion is complete, "0" during conversion. During sustained out-of-scale condition, output changes state with each conversion trigger pulse (internal or external)
- Decimal point inputs (3): One for each BCD digit, "0" (or ground) is *on*, sinks 24mA
- External *Hold* input: For "0" or ground, holds and displays the last conversion. To resume conversion, apply +5V or allow to float
- External *Trigger* input: With external *Hold* grounded, apply 1-10ms pulse. Leading edge ("1" – "0") resets; returning edge starts conversion.

### ACCURACY
- Maximum error: 0.05% of reading ±1 digit
- Resolution: 0.1mV
- Temperature coefficient: ±50ppm/°C (0° – 60°C)
- Long term drift: < 1 digit/60 days
- Normal-mode rejection: 40dB @ 60Hz

### CONVERSION RATE
- Internal cycle clock rate: 5Hz
- External trigger: to 20Hz
- Response time (to within 0.05%): 250ms
- *Hold* reading on external command

### POWER REQUIRED
- +5VDC ±5%, 1A (5 watts, max), total, via 2 inputs:

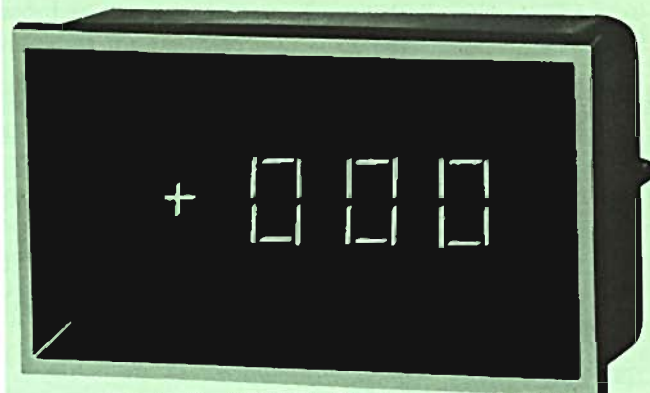   Logic: 200mA (regulated)
   Display: 800mA (unregulated)



Figure 9. AD2001 Display: Actual Size

# Converters for the Ruggednova Computer

## How the μDAC's are Used in Converters Designed for Severe Environments
### by H. Thiel

Rolm Corporation's *Ruggednova** is a mini-computer whose architecture, software, and input-output formats are identical to those of the Data General *NOVA*. The difference is that the Ruggednova, built to meet severe-environment military specifications, removes the environmental constraints that are generic in successful commercial machines. It is built to qualify in ground, airborne, shipboard, and missile applications.

As a natural adjunct to this computer, 8-, 10-, and 12-bit A/D and D/A converters are offered as standard input/output options. In order to achieve the desired operating characteristics over the temperature range, as well as physical compatibility, they utilize Analog's hermetically-sealed μDAC quad switches and resistor networks, and are built to essentially the same *electrical* design as the ADC-Q and DAC-Q.[†]

The paragraphs that follow describe the steps that were taken to adapt the ADC-Q and DAC-Q designs to the electrical and physical environments of the Ruggednova.

### WHY μDAC?

12-bit converters are available from a large number of manufacturers. Relatively few, however, will meet the environmental specifications of the Ruggednova (see Table 1). Add to this the requirement for packaging in a field-repairable module that plugs into one of the computer I/O slots, and the match between μDAC and Ruggednova becomes obvious.

First, the electrical specifications of the ADC-Q and DAC-Q converters meet Rolm's requirements. Second, the low-profile components used will fit on a standard I/O module without clearance problems. Finally, the ability to procure individual components and a proven electrical design enabled Rolm's engineers to do what they do best — interface devices to the computer in its environment — without duplicating the efforts of the device designers (i.e., re-inventing the wheel).

### A/D CONVERTER CIRCUIT

The A/D Converter was used for the initial test and integration with the Ruggednova, since it contains a 12-bit DAC as well as the control circuitry common to all of the ADC's. During the integration of this circuit, virtually all of the problems apt to occur with any DAC or ADC configuration had to be solved.

### THE AUTHOR

Harold "Bud" Thiel received the BS and MS degrees from the University of California. Prior to joining Rolm in January, 1970, he spent 12 years at Sylvania's Electronic Defense Laboratory and at ESL, Inc., doing development work. At Rolm, he is involved in I/O device development, as well as memory and power-supply design.

Figure 1. RUGGEDNOVA Computer with the Severe Environment Control Panel. The Computer is Packaged in a Standard ATR Box and Weighs about 40 Pounds.

The ADC, which is illustrated in the block diagram of Figure 2, operates by successive approximation of the analog input signal by the D/A converter output. A pulse is used to start the conversion process. The leading edge clears the data register and the shift register. The trailing edge starts a clock which shifts a "1" into the most significant position of the 12-bit shift register. This sets the most significant bit in the data register, which turns on the μDAC switch that generates an analog output from the D/A converter equal to one-half the full-scale analog reference ($E_{FS}$). This voltage is compared to the analog input, and the next clock pulse turns *off* the most significant bit in the data register if the DAC output is *greater* than the analog input, or leaves it *on* if the DAC output is *less* than the analog input.
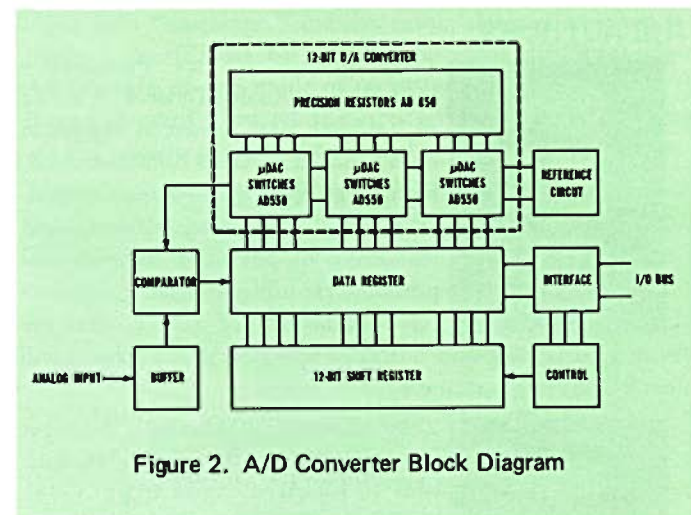


Figure 2. A/D Converter Block Diagram

The second clock pulse also shifts the "1" from the most significant position in the shift register to the next position, which causes the D/A converter to add a voltage equal to one-fourth $E_{FS}$ at the comparison point. The new DAC output (equal to 3/4 $E_{FS}$ or 1/4 $E_{FS}$, depending on the results of the previous test) is compared to the analog input, and the result is used to set or reset bit 2 of the data register at the start of the third clock period. This process is repeated until all 12 bits have been exercised, after which the clock is turned off. The DAC output should now be within $E_{FS}/4096$ of the analog input, and the data register holds the digital representation of this magnitude.

Not surprisingly, the principal sources of error are the analog circuits: the reference circuit, buffer, comparator, AD850 resistor network, and the µDAC switches. In addition to minimizing the normal sources of environmentally-generated error, it turns out that minimizing the effects of computer-generated noise on these analog circuits, in spite of their close proximity to sources of noise, is the key to successful integration. A look at the Ruggednova configuration will permit one to observe the potential problem areas.

## RUGGEDNOVA CONFIGURATION

The computer main frame is a standard ATR box 7-5/8" x 10-1/8" x 12-1/2", which contains the power supply and slots for 14 circuit modules, five of which are used for the CPU. The modular memory and control console are in separate housings, which attach to the main frame.

Table 1. Ruggednova Environmental Specifications

| | |
|---|---|
| TEMPERATURE: | −55°C to +95°C Case Temperature. Conductive cooling, with no forced air or liquid coolant required |
| SHOCK: | 15g's, 11 milliseconds, 3 axes |
| VIBRATION: | MIL-E-5400 Curve IV, to 10g's. |
| RELIABILITY: | MTBF in excess of 11,000 hours calculated according to MIL Handbook 217A |
| HUMIDITY: | 95% relative humidity |
| RFI: | MIL Standard 461A |
| ALTITUDE: | 80,000 feet |

Explosive atmosphere, sand and dust, salt spray, and fungus resistance in accordance with MIL-E-5400K.

One of the keys to successful operation of electronic equipment in a severe environment is to build the 7" x 10" circuit modules for ruggedness and maximum heat transfer, as illustrated in Figure 3. Dual in-line IC's rest on the 0.03" copper frame, which is laminated to, and insulated from, the printed wire board. The frame conducts heat to the chassis and also stiffens the board. Further stiffening is provided by a "cookie sheet" that covers each board. Stamped from 0.062" aluminum, the covers are fastened to the printed-circuit boards at four points near the board centers and are pressed against the cooling-frame edges in the sidewall slots.

High-noise-immunity digital circuits are not adversely affected by this cooling-frame, cookie-sheet combination. To the sensitive analog circuits, however, this structure provides capacitive coupling to every noise source in the system, including the power-supply chopper, memory current generators, CPU clock, and a plethora of high-speed switching circuits.



Figure 3. All Printed-Circuit Cards for the Ruggednova Use the Same Construction Techniques. This Picture Shows a Standard Printed-Circuit Card, the Heat Frame and "Cookie Sheet."

## BREADBOARDING THE ADC

So the problem was to arrive at a layout for the ADC module that would minimize the susceptibility of the critical circuits to conducted and radiated interference, while meeting the severe environmental specifications. It seemed a logical approach to adapt the proven package to the needs of the analog circuitry, making modifications, where necessary, in critical locations.

Methods had to be devised for efficiently breadboarding, testing, evaluating, and making trial modifications of various circuit layouts. Certain techniques were obviously necessary from the very outset: segregation of the digital and analog circuits, use of a single tie point between digital and analog grounds, local sensing of analog-circuit supply voltages, and careful attention to signal and ground-current paths.

The standard Ruggednova heat frame provides for 6 rows of dual in-line circuits, with up to 7 packages per row. The ADC, including the computer interface, contains 26 integrated circuits and 2 voltage regulators. These circuits were bread-boarded in the first 4 rows of a standard package. The heat-frame arms for the next two rows were removed, leaving an "island" of roughly 1/3 of the module surface area for the analog circuits. This area was cut out so that different arrangements of the analog circuits could be breadboarded separately, inserted, and tested in the physical and electrical environment of the ultimate system.

## THE COMPUTER ITSELF AIDS CIRCUIT EVALUATION

The next step was to arrange for convenient test, evaluation, and comparison of various configurations as the package evolved. The computer, which was the principal source of the interfering signals, also became of great help in solving the

problems associated with these signals. A program was written that would cause the ADC, under computer control, rapidly to make a large number* of measurements. These were transmitted to a specified buffer area of the memory; the computer would then compute the mean value and the distribution about the mean, and halt. By connecting an input voltage source with good short-term stability (such as a battery) and exercising the ADC with this program, a measure of the computer-induced scatter of ADC outputs could be obtained in seconds.

A number of experiments were conducted, beginning with a baseline system, using a simple double-sided printed-circuit board. A methodical process of postulation, verification, and mitigation of conducted and radiated interference entry points led to the final configuration (Figure 4). It was necessary to shield the resistor module electrostatically, and to use a multi-layer board to provide a ground plane in the area of the analog circuits. In addition to improving the electrical behavior, the ground plane conducts heat to the edges of the module, making up for the conductive surface lost by removing the heat-frame arms.
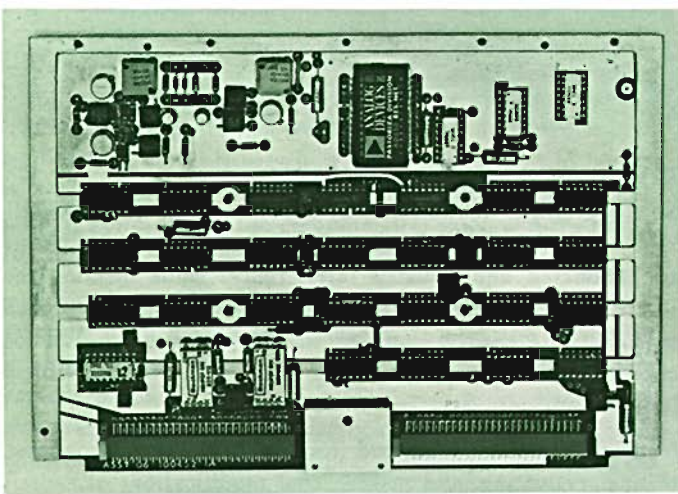


Figure 4. Closeup View of the 1601/56 Analog-to-Digital Converter. This Card Plugs Into One of the Five Available Input/Output Slots of the Computer

The final ADC module meets the requisite electrical and environmental specifications and is fairly easy to produce and test. The computer itself is used as the test vehicle.

## PRODUCTION TESTING
Each ADC produced goes through complete electrical tests over the full temperature range in a test computer. If it is delivered with a computer system, it undergoes the same tests as part of final system testing.

A new unit coming off the assembly line is put through the following sequence of tests:
- Initial turn-on, debugging, setting of range, zero, and offset (for bipolar units)
- Checking of range, zero, and differential linearity over the full temperature range

Differential linearity tests are made using the computer and

---

a voltage source that sweeps slowly through the full input range of the ADC. The computer, which triggers the ADC at close to the maximum conversion rate, computes the differences between consecutive measurements. If this difference is within the specification, no action is taken; if it is out of spec, the two numbers are stored in a table for examination by the operator. If a unit is defective, these numbers generally point to the circuit area where the error originates. Thus, this test system and program are useful for trouble-shooting, as well as for logging long-term error rates.
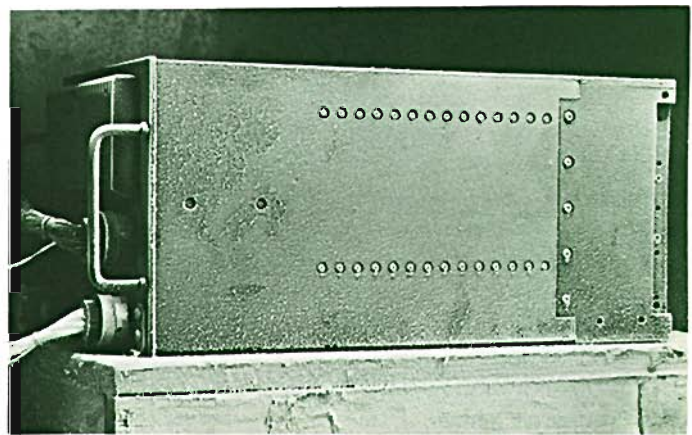


Figure 5. Before Ruggednovas Are Shipped, They Are Tested Over the Complete Specified Temperature Range of −55°C to +90°C. This Picture Shows the Frost that Accumulates During Final Testing In the Environmental Chamber.

Currently, converters are tested one-at-a-time. However, expansion of the present system and program to test up to four units together will be quite simple when the need arises. Each ADC may be addressed as a separate I/O device. Hence, all inputs may be driven in parallel and the outputs sampled in time sequence as directed by the program. ▶▶▶

## Multiplier Nonlinearity

ESTIMATING SMALL-SIGNAL ERRORS
After all the adjustments have been made, multipliers have an irreducible error called "nonlinearity," a function, $f$, of both $x$ and $y$. In general, it is small near zero and increases rapidly near full scale. By taking advantage of nonlinearity specifications on the data sheet, you can (1) often use a less-costly multiplier to obtain adequate small-signal accuracy, and (2) determine which input to use for best accuracy, if one of the input signals has a small range of variation.

The way to do this is to use the nearly-always-conservative approximation: $f(x, y) \cong |x| \epsilon_x + |y| \epsilon_y$, where $\epsilon_x$ and $\epsilon_y$ are the fractional nonlinearities specified for the $x$ and $y$ inputs.

EXAMPLE: For Model 426, $\epsilon_x$ = 0.6%, $\epsilon_y$ = 0.3%. What maximum error can I expect for $x$ = 5V, $y$ = 1V? Can I get less by interchanging inputs?
1. Nominal output is $x\,y/10$ = (5)(1)/10 = 500mV
2. Expected error is (5) (0.006) + (1) (0.003) = 33mV, 6.6% of output (0.33% F.S.)
3. Interchanging inputs, (1) (0.006) + (5) (0.003) = 21mV, 4.2% of output (0.21% F.S.)

Compare this with the overly-conservative error predicted by the overall 1%-of-full-scale specification: 100mV, or 20% of output!!

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*In this case, 1024 measurements in about 30 milliseconds

# 3 New A/D Converters

## ADC-I FAMILY FEATURES HIGH RESOLUTION
## ADC-14 I:  14-Bit Binary + Sign
## ADC-17 I:  4½ Digit BCD + Sign

## ADC-8S IS LOWEST IN COST $49.00 in 100's

Models ADC-14I and ADC-17I* are high-resolution A/D converters encapsulated in compact 3" x 4" x 0.4" modules. Model ADC-14I, which has 14-bit-plus-sign binary output, will resolve 1 part in $\pm 2^{14}$ ($\pm 16,384$); while ADC-17I, with "4½-digit" BCD output, will resolve 1 part in $\pm 12,000$.

They are specifically designed to obtain accurate conversion of the *average value* of an input signal, typically a dc voltage in the presence of large amounts of high-frequency *normal-mode* noise. The averaging period is set at 16 2/3ms, for optimum rejection of 60Hz line frequency; it is adjustable to 20ms to reject 50Hz.

The principle used for conversion is *dual-ramp*, an indirect technique, in which the analog signal is first converted into a time interval, represented by a train of pulses, the number of which is proportional to the signal magnitude. Then the pulses are counted and the count is made available in digital form. (See Figure 2, page 4).

There are two major advantages to this approach:

- Since integration is used, the converter averages out fast fluctuations, such as might be caused by noise, attenuates high frequencies, and — because of the fixed averaging period — will null out those frequencies that have whole numbers of cycles during the integration.
- Differential linearity is excellent, because the analog function is free from discontinuities, there are no missed codes, and the full resolution is always available.

Besides the built-in references, these converters will also accept external reference signals for *ratiometric* conversion: the digital number is proportional to the ratio of the analog signal to the reference.
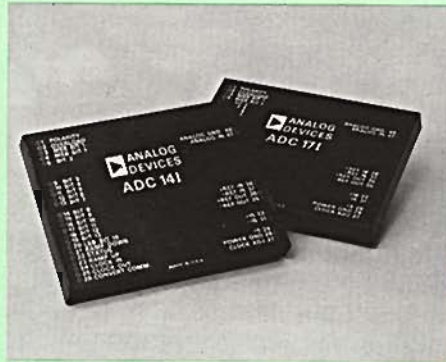
Polarity is automatically determined, and out-of-scale indication is provided. Logic is TTL/DTL compatible; the clock frequency is externally controllable; and the maximum sample rate for 60Hz-line-frequency rejection is 25/second. Separate analog-input and power grounds are provided.

The built-in 6.2V ±5% reference is stable to within 5ppm/°C, gain is stable to within 5ppm/°C, and zero is stable to within 1 ppm/°C (0° – 40°C) and 3ppm/°C (40° – 70°C). When adjusted, the maximum scale factor error at 25°C holds within 0.01% over intervals up to 6 months.

Because of its excellent stability and resolution, the ADC-I should find applications wherever precise measurements must be made. These include

- Weighing systems
- Analytical ratiometric measurements
- Scientific data transmission, reduction, and display
- Process-control instrumentation

An optional plug-in mounting board is available, wired with all adjustments. ADC-I is available from stock. Price is $259. (1–9) ▷▷▷
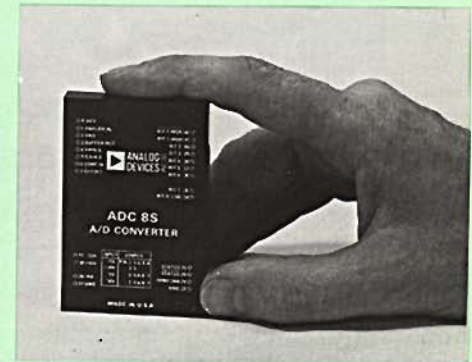
Model ADC-8S* was specifically created to benefit designers of data acquisition systems by making it feasible to think in terms of converting near the signal source to avoid multiplexers and analog wiring. Although multiplexers are decreasing in cost, the avoidance of noise pickup and crosstalk, and system design to minimize analog uncertainty, have their own cost, *even at the 8-bit level*. (Compare TTL noise immunities of 0.4V with the LSB of a 5-volt analog range: 5/256 = 20mV).

With the ADC-8S, the designer can "go digital all the way," economically, aided by:

- Programmable input range; choice among +5V, +10V, ±5V, ±10V with 2's complement or offset-binary bipolar coding
- No adjustments; monotonic behavior, with no missed codes, from 0° – 70°C
- High input impedance (> 100MΩ) unity-gain buffer follower with accessible output allows moderate-impedance inputs, active- or passive RC filtering, attenuation from high levels, current drive (2mA F.S.)
- 1 kHz conversion rate
- Small size: 2" x 3" x 0.4"
- Binary (8 bits) or 2-digit BCD
- Parallel binary output. With external shift register, user can get serial output for single-line transmission.
- Stock availability, $79. (1–9) ▷▷▷

# New μDAC's

## AD551 QUAD SWITCHES FOR CONVERSIONS

- **Have Better Than 12-Bit Linearity**
- **Settle To ½LSB Of 12 Bits In 200ns**
- **Are Fully TTL-Compatible**
- **Are Interchangeable With AD550**
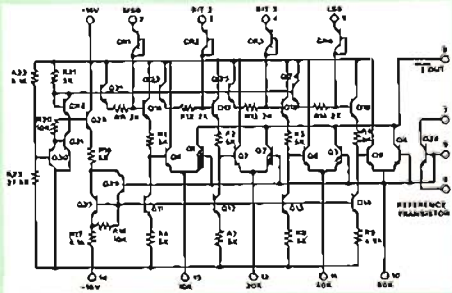


The AD551 Series* of quad current switches for A/D and D/A conversion are a second-generation design based on the highly-successful AD550[†] design introduced by Analog Devices in early 1970.

Since their introduction, the AD550's have been used as the key components of a number of low-cost, high-performance A/D and D/A converters, many of which were introduced in these pages. They have also been bought in ever-increasing numbers by engineers for use as key elements in either original designs for converters, or by making use of our published designs. An example of such an application is given on pages 8–11 of this issue.

The major virtues of the AD550 lay in the matching and close thermal tracking of its switches, which have made it possible routinely to obtain 12-bit performance, as well as permitting 16-bit D/A and A/D converters[‡] to be introduced.

The major drawback of the AD550's is that their speed (500ns switching, 1.8μs settling to ½LSB of 12 bits), didn't measure up to the performance inherent in the current-switching approach. Com-

petitive versions with somewhat greater speed have appeared on the market, but they have been hampered by marginal digital noise immunity, due to lack of full TTL compatibility. (see *Dialogue*, Vol. 5, No. 3, page 11).

The AD551 is fully TTL-compatible (0.8V threshold for "0" and 2.0V for "1"), it switches within 60ns (delay + rise time to 90%), settles to within 0.01% in 200ns, and has reasonably symmetrical "on" and "off" characteristics, tending to minimize major-carry "glitches." Settling time is shorter for less-stringent accuracy: 120ns for 10 bits, 80ns for 8 bits.

As with the AD550, full-scale output is nominally 1.875mA (1mA MSB), multiple emitters are used to improve temperature tracking, and the nominal external resistor network for 10V reference is

10-20-40-80kΩ. (AD850's,[†] etc.)

The AD551's reference, like that of AD550, may be varied over a wide range (better than 10:1) without seriously affecting linearity. Hence the AD550 may be used in building multiplying D/A converters; and the improved speed makes it especially applicable to DAC's for vector generation, ($r\cos\theta$ and $r\sin\theta$), where $r$ is a unipolar analog input, and the cosine and sine functions are 2's complement or offset-binary bipolar digital inputs.

The AD551's are plugin interchangeable with AD550 (high speed may require some external circuit changes). They are available from stock in matched sets of 3 for 10 and 12-bit resolution (3BCD), or 2 for 8 bits (2 BCD), in 14-lead ceramic DIL packages, for both commercial and military temperature ranges. Prices about the same as for AD550 ceramic DIL's. ▷▷▷

## LOW-COST QUAD SWITCHES

## AD550N's Are Reliable Silicone DIL's, Cost Only $15. In 1000's For 12-Bit Sets

As noted above, the AD551 is an order-of-magnitude state-of-the-art improvement over the AD550's design. Now, the AD550N* provides comparable improvements in *price* and *packaging*, for all but the most taxing of military applications. Housed in a new, reliable, silicone 14-pin DIL package, the AD550N has electrical performance identical to that of the commercial AD550's (0° to 70°C). The AD550N's are available in matched sets of

2 for 8-bit applications at *$6 per set* in 1000's, or 3 for 12-bit applications at $15 per set in 1000's, 75¢ and $1.25 per bit, respectively. ▷▷▷
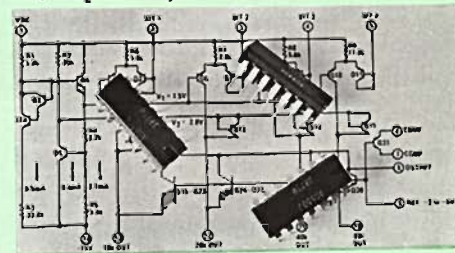
# Op Amps: Chopper and IC

## THE 234: A LOW-NOISE, LOW-DRIFT, FAST CHOPPER OP AMP Competitively-Priced For OEM's

Model 234* is a low-drift (to $0.1\mu V/^\circ C$) chopper-stabilized operational amplifier that has low peak-to-peak and rms noise, virtually no "chopper spikes," and unusually wide bandwidth (500kHz full power). These features make it uniquely suitable for low-drift amplification of wideband signals, integration of low-duty-cycle pulse trains, and as a high-precision general purpose op amp for analog and hybrid computing.

Besides these applications, its low noise (the lowest among low-cost modular chopper-stabilized op amps) makes it the preamplifier of choice, even for low-frequency-only applications, such as DVM's, A/D converters, and control systems.

Here is a noise and bandwidth comparison of Model 234 with two earlier types. Its superiority in performance to the 233, and in both performance and price to the older 232 are evident. (All models listed here are 1 $\mu V/^\circ C$ versions, denoted by the J suffix. $0.3\mu V/^\circ C$ (K) and $0.1\mu V/^\circ C$ (L) versions are also available.)

| | 234J<br>High<br>Performance | 233J<br>Economy<br>(3rd Gen.) | 232J<br>Economy<br>(2nd Gen.) | Units |
|---|---|---|---|---|
| **INPUT NOISE** | | | | |
| Voltage, 0.01 – 1 Hz | 1 | 1 | 1.5 | µV p-p |
| Voltage, 0.1 – 10Hz | 1.5 | 3 | 10 | µV p-p |
| Voltage, 5Hz – 10kHz | 2 | 3 | 5 | µV rms |
| Current, 0.01 – 1 Hz | 3 | 3 | 10 | pA p-p |
| Current, 0.1 – 10Hz | 6 | 6 | 35 | pA p-p |
| **BANDWIDTH** | | | | |
| Unity-Gain | 2.5 | 0.5 | 0.5 | MHz |
| Full-Power | 500 | 4 | 3 | kHz |
| Slew Rate | 30 | 0.25 | 0.2 | V/µs |
| PRICE (1–9) | $54 | $45 | $62 | |

Not only is the noise measurably lower in Model 234, but it is also more consistent from unit-to-unit, and it even "looks better" on an oscilloscope (see illustration). The reason for this (and the bandwidth improvement) is that the designers have taken a step "backward" and used discrete input circuitry for the main and stabilizing amplifiers, rather than the cost-cutting IC's, to obtain premium performance at a less-than-premium price.

*For further information, use card. **Circle E11**

Other specifications of Model 234 are fairly conventional: gain:$10^7$V/V, output range: ±10V at ±5mA, power supply: ±15V (12–18V operating) at ±5mA quiescent current. Settling time to 0.01% (20kΩ load, 10V step) is 4µs. Maximum voltage and current drifts ($0^\circ - 70^\circ C$) are: for Model 234L, $0.1\mu V/^\circ C$ and 2pA/$^\circ C$, for Model 234K, $0.3\mu V/^\circ C$ and 2pA/$^\circ C$, for Model 234J, $1.0\mu V/^\circ C$ and 4pA/$^\circ C$.

Supply sensitivity is $0.2\mu V$ and 0.5pA per %$\Delta V_S$, long-term drift is ±2µV/month, warmup drift (turn on) ±3µV from 10s to 10 minutes.

Delivery is from stock, and price, as noted, is $54 for 234J (1–9). ▶▶▶
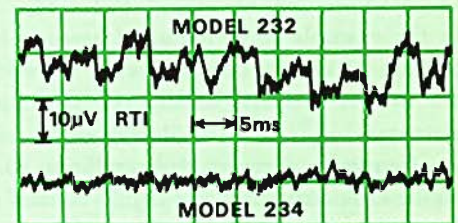


0 to 1 kHz Noise, Referred to the Input; 234 vs 232. $R_{in}$ = 50kΩ, Gain = 500, 10µV/div, 5ms/div, 1 kHz Low-Pass Filter

## AD512, A "741" WITH ±12mA OUTPUT Safe, Reliable; Improved Specs, Yet Low Price ($4. In 100's)

AD512K and AD512S* are monolithic operational amplifiers specifically designed for high output-current capability. High-efficiency output transistors, thermally-balanced chip design, and precise short-circuit current control insure against gain degradation at high current levels and temperature extremes.

In addition, the devices offer excellent input characteristics and common-mode and power-supply rejection ratios, and are internally compensated. Both are available in the hermetically-sealed TO–99 package: the AD512K, with a guaranteed minimum gain of 20,000 swinging ±12 volts into a 1 kΩ load from $0^\circ C$ to $70^\circ C$; and the AD512S, with a guaranteed minimum gain of 15,000, swinging ±10V into a 1 kΩ load, from $-55^\circ C$ to $+125^\circ C$.

The circuit design is based on that of the internally-compensated AD741, and no compensation is needed for dynamic stability. With a full load of 1 kΩ in parallel with load capacitance up to 100pF, the overshoot is only 5%.

DC gain at $25^\circ C$ for both versions is 50,000 minimum, 200,000 typical, with 1 kΩ load. Maximum offset voltage untrimmed is 3mV, with 20µV/$^\circ C$ and 25µV/$^\circ C$ maximum average T.C.'s for the respective versions, over their rated operating temperature ranges.

Maximum bias currents at room temperature are 200nA, maximum offset current is 50nA, and offset current T.C.'s are 0.1nA/$^\circ C$. CMRR is 80dB minimum.

Units are in stock; price of AD512K by the 1's is $6.00. ▶▶▶

*For further information on these new I.C. op amps, use reply card. **Circle E12**

# Application Briefs
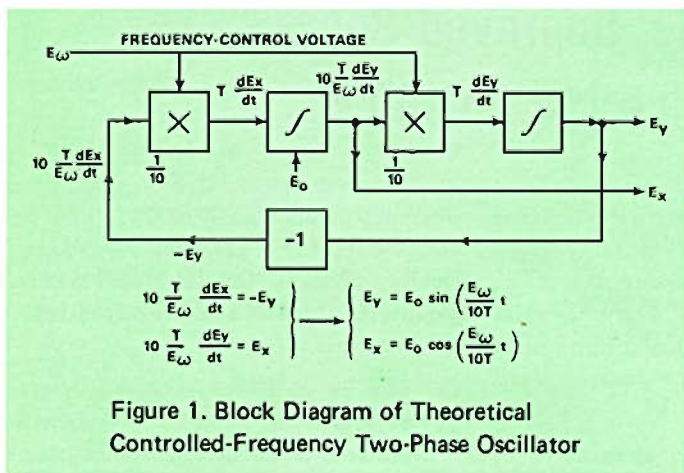
## Frequency Modulator

### A FREQUENCY-MODULATED SINE-WAVE OSCILLATOR WITH TWO-PHASE OUTPUT USING IC MULTIPLIERS & OP AMPS

Low-cost high-performance complete-on-a-single-chip IC multipliers, such as the AD530,* make it feasible to build oscillators having two-phase sine wave output (i.e., $\sin\omega t$ and $\cos\omega t$), with frequency controllable by a voltage. The frequency may be varied over a wide range, depending on the dynamic range of the multiplier, for frequency-sweep applications, or it may be centred about a fixed frequency for highly-linear frequency modulation. If the slightly-regenerative damping and amplitude-control circuitry used for oscillators is replaced by slightly-degenerative damping, and an additive input signal is applied, the circuit becomes a variable-frequency tuned filter.

In the example to be discussed here, an IC multiplier is used because of its low cost. However, there is no inherent bar to the use of modular multipliers, such as Model 422, for increased bandwidth (to 5MHz), or Model 427, for increased low-frequency accuracy and resolution (0.1%), or even multiplying D/A converters, for digital control of frequency.[†]

### HOW IT WORKS

These applications are all based on the analog scheme for solving a second-order differential equation, as shown in Figure 1. Damping is omitted for simplicity, but it is provided in the form of an additive feedback loop around either integrator, as will be seen in the practical example.



$$10\frac{T}{E_\omega}\frac{dE_x}{dt} = -E_y \quad\longrightarrow\quad E_y = E_o\sin\left(\frac{E_\omega}{10T}t\right)$$
$$10\frac{T}{E_\omega}\frac{dE_y}{dt} = E_x \quad\quad\quad E_x = E_o\cos\left(\frac{E_\omega}{10T}t\right)$$

Figure 1. Block Diagram of Theoretical Controlled-Frequency Two-Phase Oscillator

If we assume that a voltage $E_x$ occurs at the output of the first integrator and $E_y$ occurs at the output of the second integrator, then the inputs are, respectively, $TdE_x/dt$ and $TdE_y/dt$, where T is a dimensional constant. The integrators are preceded by multipliers, one of the inputs to which is the control voltage, $E_\omega$. The other inputs to the multipliers must therefore be: $(10T/E_\omega)dEx/dt$ and $(10T/E_\omega)dE_y/dt$, where 10 is the dimensional constant of the multipliers ($e = e_1e_2/10$). The loop

*For information on the monolithic AD530 Multiplier-Divider-Squarer-Square Rooter, use reply card. Circle E13
†For information on other multipliers and multiplying D/A converters, use reply card. Circle E14

is closed through a sign-inversion, and it therefore embodies the pair of differential equations shown in Figure 1, the solution to which is indicated for an initial condition $E_o$ on the first integrator. It will be seen that the natural frequency is directly proportional to $E_\omega$, for fixed values of same. Of course, if $E_\omega$ varies, the differential equations have time-varying coefficients, and the equation describing the solution is considerably more difficult to express (but the circuit will faithfully provide the correct response, however complicated the mathematical function it represents).

In practical designs, the important factors are: frequency scaling, amplitude establishment and maintenance, and damping. The frequency scale is determined, as shown in the equations by T, which is the integrators' characteristic time (=RC, for operational-amplifier integrators). For one-shot, or keyed oscillators, the amplitude is established by initial conditions, to which the integrators are reset after each run. For free-running oscillators, the amplitude builds up, with the aid of negative damping, until a limiting value is reached, at which point positive damping is applied to the peaks, and the amplitude stabilizes, with net zero damping. The essential elements are an amplitude reference and a nonlinear element to switch the damping (a zener diode can serve both purposes).

### A PRACTICAL OSCILLATOR (WIDE RANGE)

The oscillator shown in Figure 2 delivers a 2-phase sine-wave output tuneable over a 10:1 frequency range by means of a dc control voltage. The output amplitude is stabilized by zener reference diodes at 7V rms, and maintained constant within 1 dB over the range of frequencies.



Figure 2. Practical Controlled-Frequency Two-Phase Oscillator
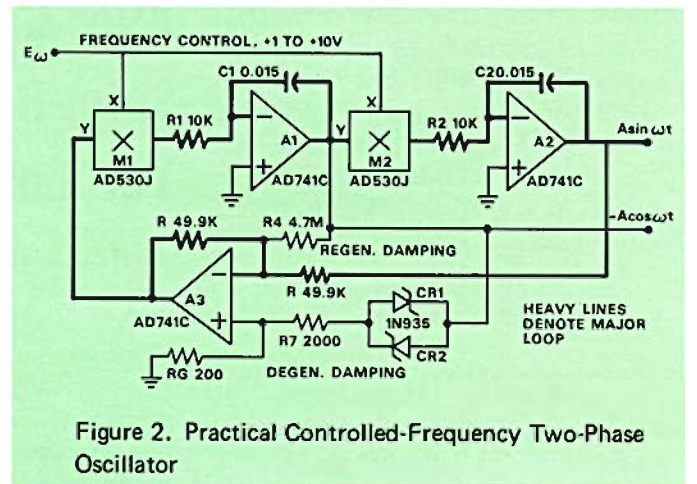
The oscillator system consists of two integrators, A1 and A2, and a unity-gain inverter, A3, which form a negative feedback loop. The effective time constants of the integrators are varied by a pair of multipliers, M1 and M2, which serve to (in effect) increase the conductance of R1 and R2 as the control voltage is increased, thus decreasing the time constant and increasing the natural frequency. Viewed in terms of gain and phase, at frequency $f_n = 1/(2\pi T)$, with $E_\omega = 10V$, both integrators have 90° phase lag and unity gain, the multipliers also have unity gain, and there are three sign inversions, all of which looks like a loop gain of $1/\underline{0°}$, at $f_n$ (and only at $f_n$).

To assure sufficient regeneration to start and maintain oscillations, a small amount of positive feedback is fed from the output of A1 through R4 to the input of A3. This causes

oscillations to build up until the zener diodes CR1 and/or CR2 begin to conduct at the tips of the waveform and produce increased negative feedback via the positive input of A3. The positive feedback must be kept small enough to provide buildup at a reasonable rate without requiring a large amount of negative feedback to keep the amplitude under control, since the zener diodes introduce some distortion. (Fortunately, this small distortion is integrated once in A1 and again in A2, so that the output of A2 is quite clean, and that of A1 is "oscilloscope-clean.")

With the values shown, the oscillator can be tuned from 100Hz to 1 kHz. Distortion at the cosine output was measured at 0.74% at 100Hz and 0.46% at 1 kHz. At the sine output, distortion was 0.64% at 100Hz and 0.18% at 1 kHz. Distortion at the lower end of the tuning range is somewhat affected by nonlinear "Y" feedthrough in the multipliers, and this feedthrough, plus temperature drift in the low-cost IC multiplier, places a limit on the useful tuning range.

It should be noted that, for negative values of $E_\omega$, though the main loop still has the proper polarity to enable it to work undamped, the damping polarities are, unfortunately, reversed.

## FREQUENCY-MODULATED OSCILLATOR

It's easy to modify this design to operate with frequency modulation about a fixed frequency. For example, to operate at 1 kHz, with ±10% frequency variation linearly controlled by $E_\omega$ (now ±10V), change R1 and R2 to 100kΩ, and add 10kΩ resistors between the output of A3 and the input of A1, and between the output of A1 and the input of A2. ▶▶▶

Figure 2. Line Driver Application
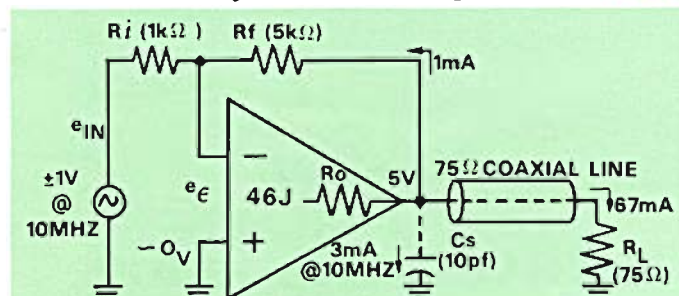
DESIGN REQUIREMENTS:
Output Current ($I_L + I_f + I_C$) ≅ 70mA      Gain-Bandwidth = 50MHz
Slew Rate ($2\pi f_{co} E_o$) = 314V/μs      $f_{co}$ = 10MHz
Voltage Gain = 5V/V @ 10MHz (–3dB)
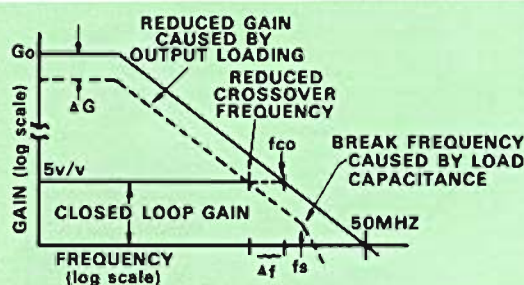
Gain Reduction ($\Delta G$) = $G_o \left( \dfrac{R_o}{R_L + R_o} \right)$      $f_s = 1/(2\pi C_s R_p)$

Bandwidth Reduction ($\Delta f$) = $f_{co} \left( \dfrac{R_o}{R_L + R_o} \right)$      ($R_p = R_o \| R_f \| R_L$)

Figure 3. Effect of Output Impedance on Performance

# Application Briefs

## Notes on a Fast Op Amp

Model 46,* introduced in the last issue of *Dialogue*, is a wideband differential operational amplifier optimized for applications requiring exceptionally fast settling times (to 0.1% in 100ns, to 0.01% in 300ns), fast slew rates (1000V/μs), and high output currents (±100mA at ±10V). To obtain, measure, and make use of such performance is no trivial matter. The data sheet* outlines many of the salient considerations. Also, the literature is replete with articles on the meaning and measurement of settling time (e.g., Demrow in *Analog Dialogue*, Vol. 4, No. 1, Pease in the notes for the *EEE* L.I.C. Seminars, 1971).

In these columns, we offer a digest of two of the topics covered in the Model 46 technical data, with the hope that they will be found useful and inspire further study and application of fast op amps.

### SETTLING TIME vs SIGNAL SWING

The curves in Figure 1, which represent the typical performance of Model 46, may be used to evaluate tradeoffs between settling time, error band, and step size. They can furnish approximate answers to such questions as: What is the largest output voltage step that can settle to within ±10mV in 70ns?

### LINE-DRIVER APPLICATION

The combination of high power output and wide bandwidth make the Model 46 unusually suitable for transmitting high-frequency signals over data lines, usually at MHz rates. In these applications, the amplifier must provide substantial power gain at wide bandwidths, which places significant demands on amplifier slew rate and output current capability. A typical application is illustrated in Figure 2, which indicates the key amplifier requirements for driving a terminated 75-ohm coaxial line at 10MHz. The design hinges on the effect of the amplifier's output impedance on overall performance (Figure 3). ▶▶▶
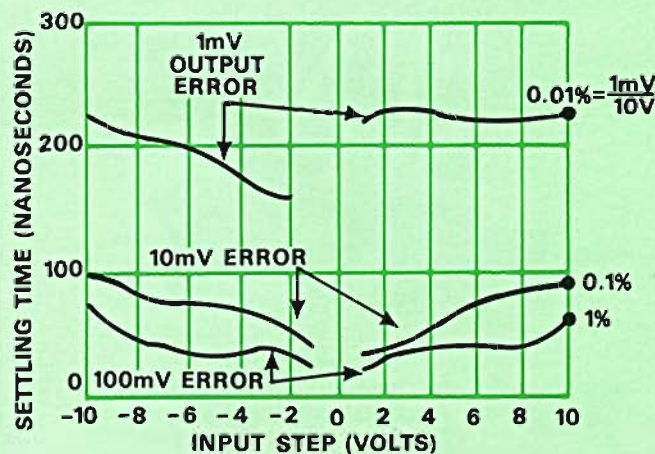
Figure 1. Model 46 Settling Time vs Input Step and Error Band (Unity-Gain Inverter)