ANALOG DEVICES

AN-343
APPLICATION NOTE

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Circuit Ideas for IC Converters

by Walter Jung,[1] Jeff Riskin, and Lew Counts

The alert circuit designer is constantly on the lookout for new devices and new ways to use existing devices to realize needed functions more efficiently, at lower cost, or in ways not previously practical. Some recently introduced analog-digital-conversion integrated circuits fit in this class. In these pages, we offer a few circuit ideas, either for direct application, or to stimulate the Reader's thinking about related possibilities.

Included in the discussion are such devices* as the AD537 V/f converter, the AD1408, AD561, and AD7520 d/a converters, and the AD581 reference, as well as some older devices, in a variety of circuits suited for instrumentation, data-acquisition, and process-control applications. All these ideas are workable; a few of them are ready to hook up and use as they stand. The others are useful to illustrate concepts and are ripe for adaptation and further modification for specific applications.

OHMS-TO-FREQUENCY CONVERTER

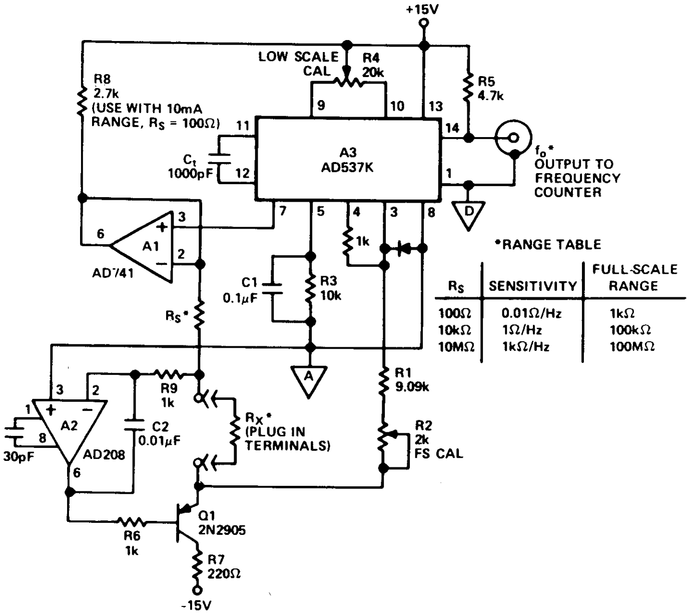
Ohms-to-volts conversion is a familiar property of many digital voltmeters. However, ohms-to-*frequency* conversion provides added flexibility, since it facilitates remote measurements, averaged measurements, and optional a/d or f/V conversion at the destination.

In the circuit of Figure 1, the 1V reference voltage available at the AD537 is unloaded by buffer amplifier A1, which drives a reference current into the resistor under test in the feedback circuit of amplifier A2. The output voltage, proportional to resistance, develops a current at the input of the V/f converter, which generates a square wave at a frequency proportional to current, and hence to R_X. Since the reference for the measurement is the same as the reference for the conversion, ratiometric operation minimizes the effects of variation of the AD537's reference with temperature.

A counter can be used to read resistance directly. Typical laboratory counters have more than adequate resolution; models with adjustable gate time permit the decimal place to be located as appropriate for the resistance range being measured. For example, a gate time of 1s will provide a readout in Hz, and the central measurement range will provide a direct readout, 1Ω/Hz, or 1kΩ/kHz, up to the 100kHz full-scale range.

In this application, we are taking advantage of the typically wide dynamic range of V/f conversion to provide a readout of the most-frequently used resistance values on a single range. After calibration at 100kHz full-scale, with a 100kΩ standard, (R2 is adjusted), and at 100Hz low-scale, with a 100Ω standard, (R4 is adjusted), the linearity error will typically be no more than ±0.06%.

R_S and R1-R2 should be stable precision types, and C_t an NPO ceramic, for best stability and repeatability. C1 and C2 serve as noise bypasses, but C2 should have low leakage (polystyrene), since it is effectively in parallel with R_X.



*RANGE TABLE

R_S	SENSITIVITY	FULL-SCALE RANGE
100Ω	0.01Ω/Hz	1kΩ
10kΩ	1Ω/Hz	100kΩ
10MΩ	1kΩ/Hz	100MΩ

Figure 1. Ohms-to-Frequency Converter

As the chart notes, two additional ranges are suggested. The 0.01Ω/Hz range has greater resolution and accuracy, for R_X < 1kΩ, with a 1kΩ (= 100kHz) full-scale limit. Resistances

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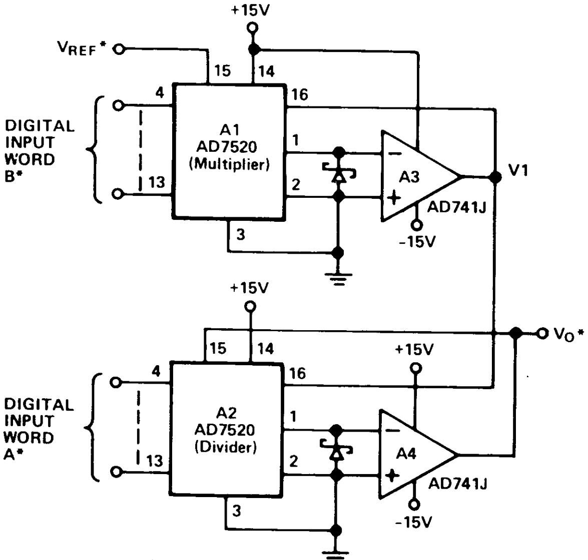
[1] This article is adapted from portions of Walter Jung's *IC Converter Cookbook*, published by Howard W. Sams & Co., Indianapolis, Indiana (1978).

less than 0.1 ohm can be resolved on this scale. A pullup resistor, R8, should be used on this range, to minimize loading on A1, since R_S (= 100Ω) will draw 10mA.

The highest scale range (1kΩ/Hz) allows resistances in the tens of megohms to be read. A low-bias-current amplifier, such as the AD208 (or the AD517, or a FET-input amplifier) should be used to minimize errors due to the flow of bias current in R_S.

ALGEBRAIC MANIPULATIONS – QUOTIENTS OF DIGITAL INPUTS

Since d/a converters multiply analog inputs by digital numbers, devices that permit a wide range of analog variation can perform a variety of algebraic manipulations involving multiplication or division of analog and digital quantities.[2,3] An example of the technique can be seen in Figure 2, a circuit that produces an analog quotient of two digital words, multiplied by a constant or variable reference.



$$^*V_O = \left(\frac{B}{A}\right)\left(V_{REF}\right)$$

$$\text{where } \frac{0}{1024} \leq B \leq \frac{1023}{1024}$$

$$\frac{1}{1024} \leq A \leq \frac{1023}{1024}$$

$$-10V \leq V_{REF} \leq +10V$$

$$-10V \leq V_O \leq +10V$$

Figure 2. Algebraic manipulations – Analog quotient of two digital words.

In this circuit, two CMOS d/a converters are used. Converter A1 is connected in the forward path of op amp A3, producing an output, $V_1 = -B\ V_{REF}$, where B is the fractional binary value corresponding to the input code. Converter A2 is connected in the *feedback* path of op amp A4, producing an output, $V_O = -V_1/A$, where A is the fractional binary value associated with A2's input code. The overall relationship, therefore, is

$$V_O = \frac{B}{A}\ V_{REF} \tag{1}$$

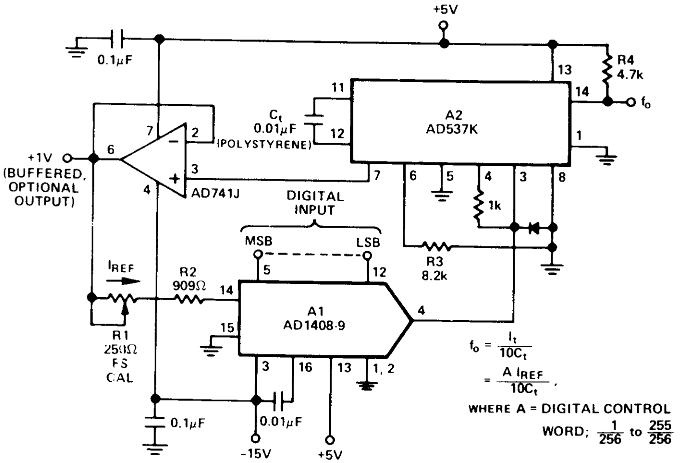
V_{REF} may be of any value in the range ±10V, B may be any number from 0 to 1023/1024, in steps of 1/1024, and A may be any such number from 1/1024 to 1023/1024. Naturally, the ratio is limited to values for which the output, V_O, is within bounds. V_{REF} may be positive or negative, ac or dc, and the output will be of the same polarity.

Like analog division circuits, this circuit has an output error-characteristic inversely proprotional to the denominator, A.

8-BIT-PROGRAMMABLE SQUARE-WAVE OSCILLATOR

Programmability is an important new degree of freedom in analog circuit and system design. Virtually any circuit parameter can be made digitally controllable with little difficulty, using a/d and d/a conversion devices. It is important to be aware that "digitally controllable" doesn't necessarily mean that programmed circuits *must* interface with computers, processors, or even digital systems. In many cases, the digital input can be provided by manually operated switches, which need not be fancy, since they need only to switch binary levels. This circuit and those that follow illustrate a variety of practical examples of programmable circuits.

Figure 3 shows an 8-bit (255-frequency) programmable oscillator with square-wave output. The circuit comprises a current-output d/a converter (AD1408 family) and a current-to-frequency converter (AD537 family). The digital input produces a linearly related current from the DAC; this current, driven directly to the input of the VFC, produces a square-wave that has a frequency proportional to the numerical value of the digital input word.



$$f_o = \frac{I_t}{10C_t} = \frac{A\ I_{REF}}{10C_t},$$

WHERE A = DIGITAL CONTROL WORD; $\frac{1}{256}$ to $\frac{255}{256}$

AS SHOWN,

DIGITAL INPUT	f_o
00000001	39Hz
10000000	5000Hz
11111111	9961Hz

Figure 3. 8-bit programmable oscillator, square-wave output.

The AD1408-9 (9-bit-linearity) DAC is scaled for 1mA full-scale current output, to match the 1mA full-scale input of the AD537K. The 1mA reference current for the DAC is derived from the 1V reference output of the AD537, buffered by the AD741 follower-connected op amp. Since the basic reference source is common to both devices, errors due to its drift tend to cancel out.

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[2] *Analog-Digital Conversion Handbook*, D.H. Sheingold, ed. [3rd edition (1986), published by Prentice Hall. Available from Analog Devices, Inc., Norwood MA, 02062 P.O. Box 796.]

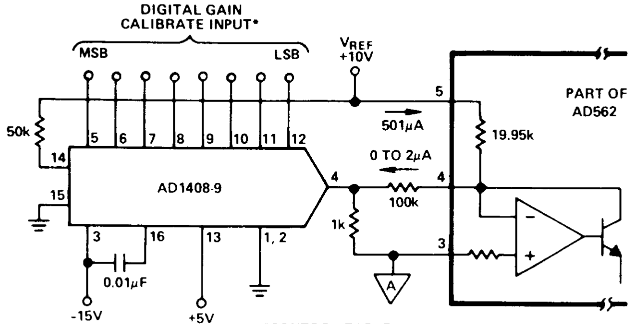
[3] "Application Ideas for Multiplying DACs," *Analog Dialogue* 12-1, 1978.

A polystyrene capacitor is used for C_t, and its tempco is compensated for by loading the AD537's V_T output with R3[4]. R3 can be adjusted to trim the overall system tempco. The circuit, as shown, has a nominal full-scale frequency of 10kHz (9961Hz for all-1's), with C_t = 0.01µF. Worst-case nonlinearity of the specified DAC-VFC combination is 0.16%. The output is a TTL-compatible square wave.

PROGRAMMABLE GAIN TRIMMING OR CALIBRATION

It is usual, in the design of devices such as converters or amplifiers, to concentrate design attention on linearity, since gain and offsets are considered to be reducible errors. Nevertheless, in high-precision applications, the gain must eventually be calibrated. D/A converters are improved substitutes for potentiometers, if the gain of the device-to-be-calibrated is set at a value near the nominal value, and the programmed converter provides the difference. Calibration can be performed automatically, under software control, with the required incremental value retained in a counter or latched; or it can be performed manually, using a thumbwheel switch.

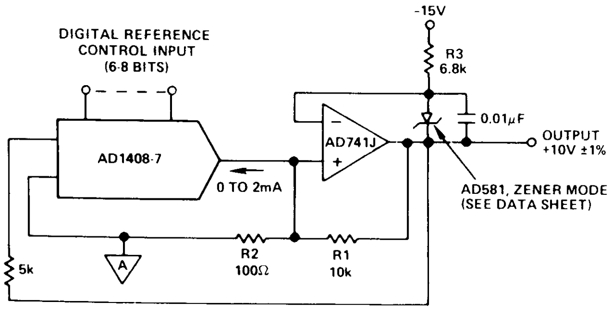
In the circuit of Figure 4a, an AD1408-9 (256 adjustment steps) provides the incremental adjustment range for the scale factor of an AD562 12-bit DAC. When pin 5 of the AD562 is connected to a 10V reference, the gain will be 0.2% high. In this circuit, a programmable 0 to -2µA current applied at the summing point will provide a ±0.2% range of gain change in 15.6ppm/LSB increments (1/16 of an LSB in the AD562).



*CONTROL TABLE

DIGITAL INPUT	GAIN
11111111	+0.2%
10000000	NOMINAL
00000000	-0.2%

(a) D/A gain calibration.



(b) Direct reference voltage calibration.

Figure 4. Gain calibration methods.

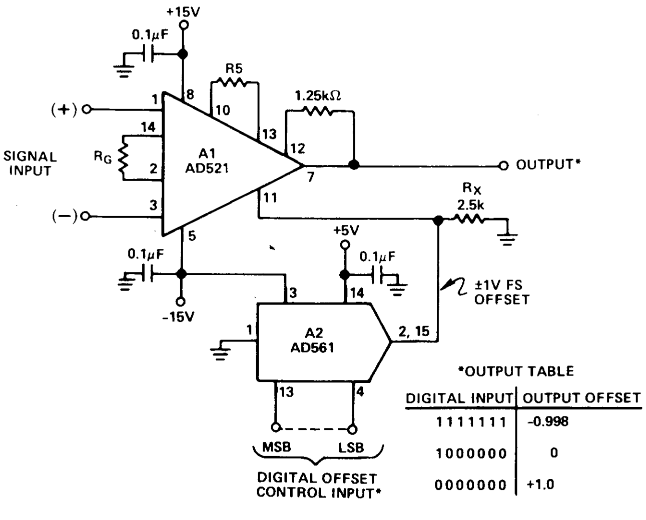
The performance of the components used to achieve this function is not highly critical, since their contribution to overall gain error is reduced by their small weighting. The use of this scheme with an AD562 DAC is a simple example, but it is applicable wherever automatic calibration to high absolute accuracy is required.[5] Coarser steps (fewer bits) could have been used (6 bits of a 1408-7) if appropriate.

In Figure 4b, a related scheme is used to calibrate the output of a buffered reference circuit. The basic reference is an AD581 10V bandgap reference, connected as a 2-terminal "Zener diode", in the feedback path of an op amp. The 1% positive feedback increases the output voltage to 10.1V, and the 2mA full-scale output from the AD1408-7 DAC, flowing in the 100Ω resistor, can reduce the output voltage to about 9.9V. Thus, the adjustable range is 10V ±0.1V, in increments of about 780µV/bit, for 8-bit control.

Amplifier gain can also be trimmed by using a DAC to set incremental gain values in the neighborhood of nominal gain. A typical scheme for programming inverting-amplifier gain would employ a CMOS DAC, with its input attenuated, in shunt with the input resistor of an inverting operational amplifier.

PROGRAMMABLE OFFSET

A programmed constant offset (or offset-zeroing voltage) can be introduced at the *reference* input of an instrumentation amplifier, to provide an output offset, independent of gain. Figure 5 shows how an AD521 instrumentation amplifier might operate in conjunction with an AD561 10-bit d/a converter. In this case, the nominal full-scale output range of the AD561 is ±1V, when loaded by 2.5kΩ. Larger offset ranges than ±1.67V would be available by using a follower-with-gain between the DAC output and the amplifier's *reference* input, or by providing a portion of the AD521 gain via *sense* feedback,[5] the offset would be amplified by the same amount. Smaller offset voltages are obtained by simply reducing R_X.



*OUTPUT TABLE

DIGITAL INPUT	OUTPUT OFFSET
1111111	-0.998
1000000	0
0000000	+1.0

Figure 5. Programmable offset instrumentation amplifier.

4-20mA CURRENT CONTROLLER

A common requirement in industry is for transmission of analog data in the form of a 4-20mA current, to minimize the effects of ground-potential differences, series resistance, and voltage-noise pickup. 4mA corresponds to zero, 20mA to full scale.

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[4] AD537 data sheet, page 4.

[5] For another example, see the AD572 12-bit ADC data sheet, Figure 11.

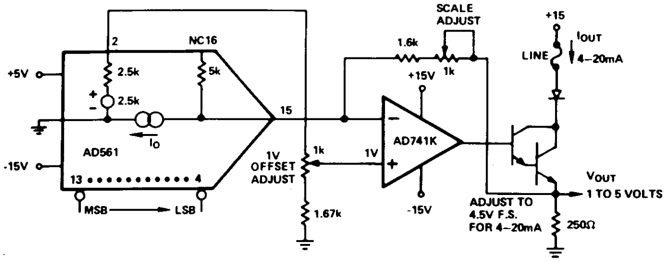

Figure 6. Process control current source.

Figure 6 shows a circuit to accomplish this with 10-bit resolution. An AD561 is used, in conjunction with an op amp and a Darlington transistor. With an all-0's digital input, the 1kΩ *offset* pot is adjusted for 4mA of output current. With all 1's, the *scale-adjust* pot is set for 20mA (or 19.98mA) of output current.

Although the load is shown here as being referred to a +15V supply, it may —in general— be returned to any positive voltage within the breakdown rating of the transistor used. The diode protects against reverse-polarity faults, the fuse against shorts.