Analog Functions With Digital Components

Chapter I-5

ANALOG FUNCTIONS WITH DIGITAL COMPONENTS

The "analog" world has numerous circuit tricks that occur time and again, employing op amps, multiplier/dividers, filters, phase shifters, function generators, etc. The term "analog" commonly has two meanings, *both of which* are intended here: "analog" in the sense of dealing with measurable quantities rather than abstract *digital* numbers, and "analog" in the sense of *continuous* (derivatives existing nearly everywhere), rather than *discontinuous* (quantized).

There have been a few excellent books on the applications of operational amplifiers, fewer on the applications of op amps and analog function modules, and virtually none on the use of digital components (converters, counters, shift registers, etc.) in the service of analog relationships.

There are many excellent auguries favoring an intimate, long, and happy marriage between the two families. Analog devices are cheap, plentiful, and capable of a great deal of functional versatility; digital devices are cheap, plentiful, and capable of a great deal of functional versatility. The reasons there has been little apparent intercourse between them are twofold: Interface devices, such as A/D and D/A converters have heretofore been too expensive to be wasted as components (remember the days of $227 op amps and $50 transistors?), and practitioners who volubly embrace the tricks of both trades are either extremely rare or remain well-hidden.

This chapter is in no sense intended as an encyclopedia (in either breadth or depth) of such connubial (i.e., "hybrid") circuits; that volume is yet to be written. Rather, the few representative items included here are intended to be suggestive of what is possible, and to stimulate the reader to bring his creative faculties to bear on new ways of looking at problems that he may have conceived of as being strictly "analog" or "digital." For those already laboring in the vineyard, there will be no revelations, but perhaps there is something a little new or different to make a scan worthwhile. The circuits are presented in the form of independent modular panels that stand alone ("bite-size morsels," to aid digestion). The selected examples are:

SOURCES

- Digitally-Controlled Voltage Source
- Manual Digital Inputs
  - Thumbwheel BCD switch
  - Toggle-switch register
- Digitally-Controlled Current Sources
  - "Current-output" DAC
    - Current gain: floating load
    - Current gain: buffered load
    - Current to grounded load

SCALE FACTORS AND MODULATIONS

- Digitally-Controlled Direct Gains
- Digitally-Controlled Inverse Gains
- High-Precision Analog Multiplication
- . . . or Division

FUNCTIONAL RELATIONSHIPS

- Analog Functions with Memory Devices
- Arbitrarily Programmable Functional Relationships
- Sinusoidal Input-Output Relationships

TRIGONOMETRIC APPLICATIONS

- Digital Phase Shifter
- Digital/Resolver Converter (Resolver Simulator)
- Resolver (Digital) Control Transformer

WAVEFORMS

- Sawtooth
- Triangular-Wave
- Sinusoidal

FUNCTIONS OF TIME

- Precision Analog Delay Line
- Tapped Delay Line
- Serial Delay Line
- Analog-to-Frequency Converter

DIGITAL SERVO DEVICES

- Tracking Sample-Hold (A/D Converter)
- Digital Pulse Stretcher
- Digital Peak-Follower (with Hysteresis)
- Automatic Zeroing Circuit

DIGITALLY-CONTROLLED VOLTAGE SOURCE

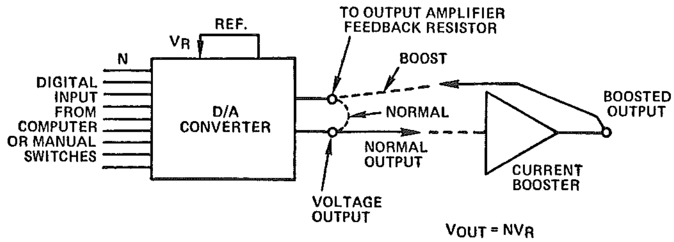
(or Precision Power Supply)

A well-calibrated D/A converter is probably the simplest available source of arbitrary precision voltages. Turn on the power, set the digital input, and expect (and receive) the voltage you asked for. With a 10-bit converter, resolution is 0.1%; with a 12-bit converter, 0.024%; and with a 16-bit converter, 0.0015% (15 ppm).

Let it be driven by a computer, and you have a ready supply of voltage for fast or slow automatic testing. Set it manually (with a "toggle-switch register," or with BCD thumbwheel switches), and it's a convenient "volt-box," or a handy reference source. Or set it permanently by hard-wiring its logic inputs. No resistors or pots necessary!

If its output op amp doesn't have adequate output current, follow it with an inside-the-loop current booster. Feedback to the built-in amplifier-feedback-resistor will make the output virtually independent of the booster's dc characteristics. It can be followed with an op amp having higher-voltage output and precisely-set fixed gain, if high voltage is needed. Doing this outside the DAC's loop protects the converter's circuitry (including the low-voltage digital components) from accidental exposure to fault voltages.

Because the setting is done digitally with (e.g.) TTL logic levels, the voltage can be set from a distant location, or in the presence of a fair amount of electrical noise, relying on the inherently-high noise immunity of digital signals (at the cost of additional wire for the parallel circuits). If noise pickup is not a major factor, it is interesting to note that in some cases the switches can be closed "passively," i.e., to the power-supply return for "0", left open for "1".* The double-buffered AD7522, with serial input, may permit remote voltage (or gain) settings, with minimal wiring, when appropriately pulsed.

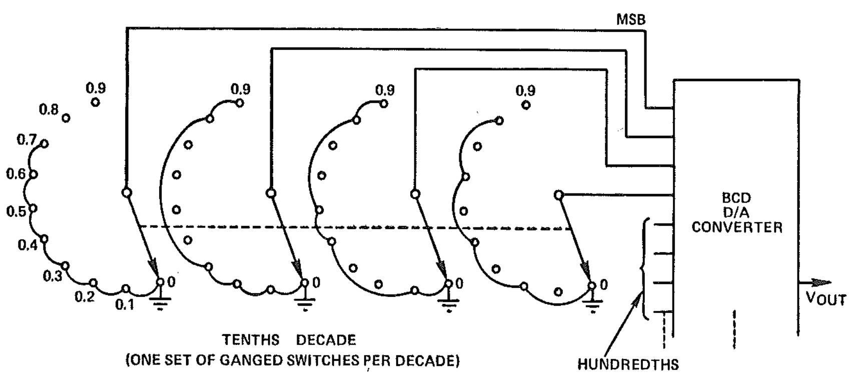


MANUAL DIGITAL INPUTS

All that is needed to obtain a given output voltage from a D/A converter is to close the appropriate switches. Human beings usually prefer base-10 numbers or BCD coding, despite the fact that it throws away inherent binary resolution at the rate of 2-bits-out-of-12 (12BCD = 1/1000, 10BIN = 1/1024).

Thumbwheel-switch Encoder

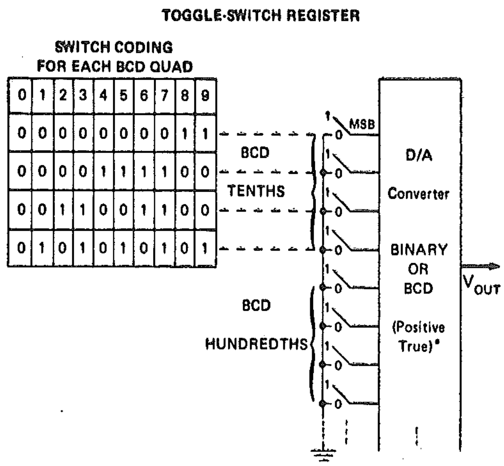
A thumbwheel-switch encoder is the simplest way for the operator, especially if he is mathematically unsophisticated, since the base-10 number can be set directly, and all the appropriate switches are automatically closed. A D/A converter with BCD coding should be used. The switch points that are "0" (positive true) are connected to ground; those that are "1" are either left open* or connected to $+V_S$ (but be sure to use a break-before-make switch). The wiring for one decade of thumbwheel switchery is shown ("1" open). If the converter has *complementary BCD* coding, the complementary switch connections should be used.



Toggle-Switch Register

The toggle-switch register is physically more elementary, and it may be used with either binary or BCD-coded DAC's. It does require some calculations, though, especially for binary settings. As an aid to calculation, two tables are given, one for BCD (the same code is used for each digit), and one for binary equivalents of representative decimal fractions of full scale. Interpolation is performed by adding or subtracting an appropriate set of terms (binary rules) to form the desired sum. Note that multiplication or division by 2 simply moves a number one place to the left or right: by 4, two places left or right, etc.

*TTL only.



*If converter operates with complementary logic, perform computations the same way, but use complementary switch settings.

For unipolar binary coding, the digits to the right of the "decimal" point form the code, MSB leftmost. For bipolar 2's complement, divide the magnitude by two for the positive number, then complement all digits and add 1LSB for the negative number. For offset binary, complement the 2's-complement MSB. (See Chapter 1, Part II, for a more-complete discussion of coding and conversion relationships in bipolar DAC's.)

BINARY EQUIVALENTS OF DECIMAL FRACTIONS

	← MSB				
0.8	0.1100	1100	1100	1101	0
0.5	0.1000	0000	0000	0000	0
0.4	0.0110	0110	0110	0110	1
0.25	0.0100	0000	0000	0000	0
0.2	0.0011	0011	0011	0011	0
0.125	0.0010	0000	0000	0000	0
0.1	0.0001	1001	1001	1001	1
0.08	0.0001	0100	0111	1010	1
0.0625	0.0001	0000	0000	0000	0
0.04	0.0000	1010	0011	1101	0
0.02	0.0000	0101	0001	1110	1
0.01	0.0000	0010	1000	1111	0
0.008	0.0000	0010	0000	1100	1
0.004	0.0000	0001	0000	0110	0
0.002	0.0000	0000	1000	0011	0
0.001	0.0000	0000	0100	0001	1
0.0008	0.0000	0000	0011	0100	1
0.0004	0.0000	0000	0001	1010	0
0.0002	0.0000	0000	0000	1101	0
0.0001	0.0000	0000	0000	0110	1

Converting Base-10 Number to Binary Switch Setting – 2 Examples (12-Bit Conversion)

1. +0.9FS (Note: 0.9 = 0.5 + 0.4)

0.5	0.1000	0000	0000	
+0.4	+0.0110	0110	0110	
0.9	0.1110	0110	0110	
Code:	1110	0110	0110,	Straight Binary

2. −0.6FS, 2's Complement (Note: 0.6 = 0.4 + 0.2)

0.4	0.0110	0110	0110	
0.2	+0.0011	0011	0011	
0.6	0.1001	1001	1001	
Code:	1001	1001	1001,	Straight Binary
X ½	0100	1100	1100	Scale Expansion
Compl.	1011	0011	0011	One's Complement
+1 LSB	1011	0011	0100,	Two's Complement

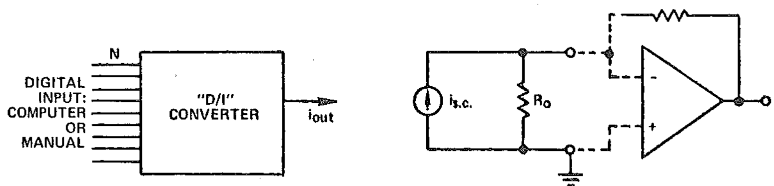
DIGITALLY-CONTROLLED CURRENT SOURCES

Many analog current sources have been developed with the variations that provide such diverse advantages as low cost, simplicity, ability to ground the load, etc. In conventional all-analog circuits, the original controlling input is derived typically from a precision potentiometer, zener diode, or other reference. However, availability of versatile D/A converters now permits convenient digital control of current values, making, for example, programmable current supplies an inexpensive reality. As with voltage sources, the adjustments may be performed by either a computer or a human operator. These are a representative few among the many ways of accomplishing current drive.

"Current-Output" DAC

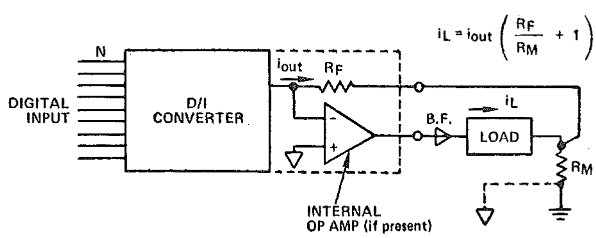
This would appear to be the simplest form of digital-to-current output source. However, it is unsatisfactory, because, except for devices such as the AD561, it generally has appreciable internal admittance "looking back," and this admittance (and the load) must be included in computations of the share of current reaching the load. For this reason, the principal application of the current-output DAC is to drive inverting-operational-amplifier input terminals, which are normally at zero potential and thus impose negligible loading error. The AD561, however, may be treated as a true current source (Chapter II-2).

The output resistance of these DAC's is often introduced by the resistive dividers used for attenuation of less-significant-bit currents (as is explained in Chapter 3, Part II). It is feasible, for applications in which a restricted number of discrete values of current (say 16) are required, to construct highly-precise fast current-output converters with high internal resistance, using quad current switches (*ibid.*) without attenuators.



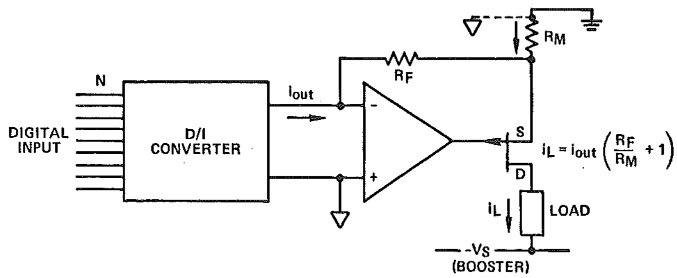
Current Gain – Floating Load

In this application, a load that has both terminals available is connected between the amplifier output terminal and the return lead of the feedback resistor. The attenuation introduced by R_M, if used, produces current gain. If the amplifier's output current is inadequate, a booster may be used, inside the loop (BF). For large currents, a separate booster supply should be used, with only the R_M pickoff point connected to the converter's analog ground.



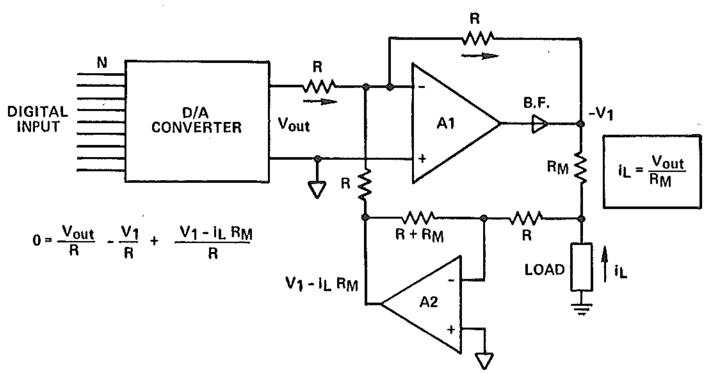
Current Gain – Buffered Load

For applications in which the amplifier's output range imposes serious restrictions on the kind of load that might be driven, a transistor with the load in its collector (or drain, in the case of FET's) allows a wide range of voltage swing across the load. Examples of loads that might be driven in this manner are CRT deflection coils, motor windings, chart-recorder pen drives, etc.



Current to Grounded Load

There are a number of ways of driving current to a grounded load, all of which employ both positive and negative feedback to measure and control the current. One example, using a voltage source and two operational amplifiers, is shown here. Amplifier A1 measures the difference voltage across R_M (direct from the top and inverted from the bottom via A2) and sets it equal to the DAC's V_{out}, thus forcing a current V_{out}/R_M through the load. In the general case, the resistor ratios can be adjusted for scaling, the drive could be from a current source, boosters could be used (at point "BF") etc. As with all operational-amplifier circuits having complicated (or even simple) dynamics, attention should be paid to dynamic stability: feedback capacitors may not be as helpful as capacitance shunting the load.



DIGITALLY-CONTROLLED SCALE FACTORS

A D/A converter that accepts variable references (i.e., a *multiplying* DAC) can be though of as a digitally-controlled potentiometer. As such, it can be used for setting gains, either by a computer or a human operator. Computer-setting might be used, for example, in adaptive control systems; manual setting might be employed where the device being controlled is remote (think of it as a potentiometer with a long shaft).

The multiplying D/A converter can also be thought of as a means of modulating a computer output by an analog signal. For example, if the computer is developing a square wave, the analog signal might be amplitude-modulating it.

The simplest device operates in one quadrant, with either a positive or a negative analog signal and straight binary or BCD coding.

For two-quadrant operations, there are two modes: bipolar analog and bipolar digital.. Bipolar analog operation simply requires a bipolar analog input and straight binary or BCD digital coding. It also requires a converter that can accept analog signals of either polarity. Such DAC's as the DAC1125 and AD7520, that use voltage switching and R-2R ladder networks, are capable of this form of operation; current-source DAC's are usually unipolar, though the devices employing monolithic Craven-cell switches, such as the AD561 and AD562 will accept a wide signal range without appreciable degradation of linearity.

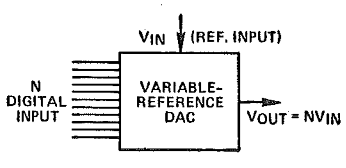
Bipolar digital operation can involve offset-binary (or 2's complement) coding, with an inverted version of the analog input applied to the offset reference terminal, or to one end of an R-2R ladder network; or sign-magnitude coding (unipolar DAC), with the sign bit switching the output polarity.

Four-quadrant operation involves a combination of circumstances: a DAC that can respond to both bipolar analog and bipolar digital inputs in the correct polarity, with appropriate speed and feedthrough performance. "Feedthrough" is the analog output signal that appears when the digital input is calling for zero gain.

Shown here are four ways (among many) that digital gain control can be used to perform useful functions.

Direct Scale Factor

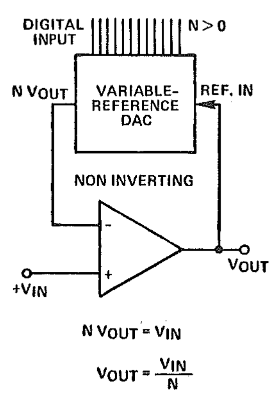
This circuit provides simple digital scale adjustment, proportional to the digital number. As noted, the digital number can be applied either by a computer signal, or manually.

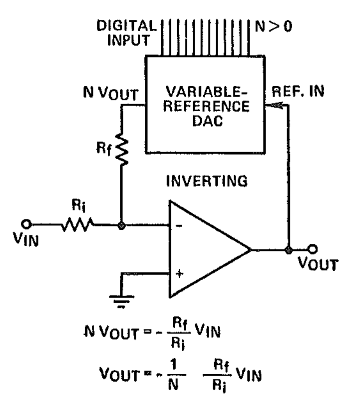


DIGITAL POLARITY	ANALOG POLARITY	
	UNIPOLAR	BIPOLAR
UNIPOLAR	ONE-QUADRANT	2-QUADRANT
BIPOLAR	2-QUADRANT	4-QUADRANT

Inverse Scale Factor

With the DAC in the feedback loop of an operational amplifier, the gain is inversely-proportional to the digital number. As a follower, all gains must be greater than unity, since even full feedback is 1LSB less than unity gain. As an inverter, the resistor ratio can be chosen for attenuation, so that normalized unity gain can occur at a mid-scale value (if $R_f/R_i = 0.1$, nominal minimum gain is 0.1 (N = F.S.), and unity gain is at N=0.1). But noise-and-error-gain will be $\cong 1/N$. The rules of feedback call for unipolar (positive) feedback gains only (signal may be bipolar).

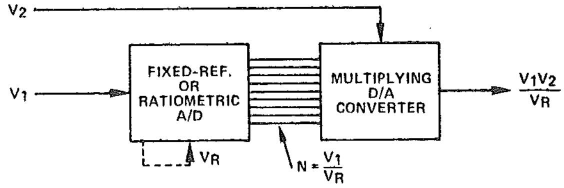




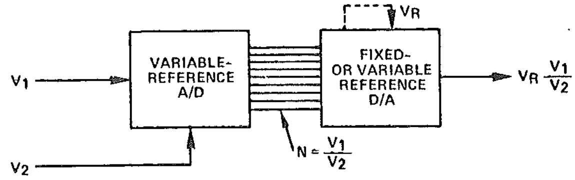
High-Precision Analog Multiplication

Since a 12-bit multiplying DAC develops accuracies to within considerably better than 0.1%, it is possible to make an analog multiplier having excellent accuracy by converting one of the inputs to digital form and using it to control the gain of a multiplying DAC. If the ADC is ratiometric, the output is a function of three variable. (V_R should always be larger than V_1, or else overrange indication will be necessary).

Since an A/D converter digitizes the ratio of the "input" to the "reference", a D/A converter will convert the ratio back to a voltage. Again, if the D/A is a multiplying type, the output is a function of three variables. For both of these applications, the A/D may be connected for free-running operation, and either the A/D or the D/A should have a register to buffer the D/A from the conversion process and store the previous value.



. . . *or Division*



FUNCTIONAL RELATIONSHIPS

The term "functional relationship" implies a black-box operation, linear or nonlinear, $y = f(x)$, f being any single-valued realizable function. It is distinguished from a "function generator," which implies a *time function* (i.e., in a function generator, $y = f(t)$). By applying a linearly-increasing function of time to a device having a given functional relationship, one can create a function generator.

In analog circuitry, functions are traditionally embodied in three ways:*

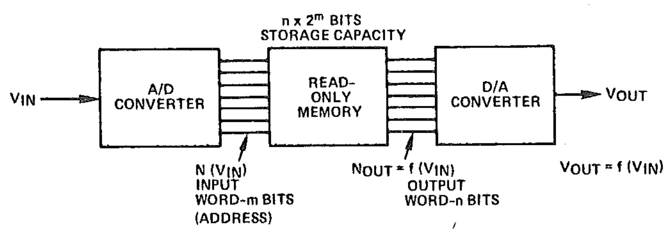
1. Using a natural function (e.g., the inherently logarithmic diode characteristic for log and antilog circuitry, the transconductance relationships of transistors for transconductance multipliers, the ability of a capacitor to store charge for integration).

2. Using diode-resistor networks to form piecewise-linear approximations to a nonlinear function.

3. Using combinations of natural functions to approximate arbitrary relationships, for example, power series using multipliers to generate the x^2, x^3, x^4, etc., terms.

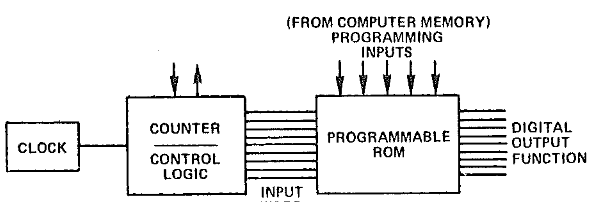
Now that converters and memories are available at low cost, a fourth approach becomes feasible:

4. Using memories (e.g., ROM's singly or in groups) to store a function digitally, and converting-in and -out with A/D's and D/A's, as shown in the illustration. Typical applications already in growing use are trigonometric transformations and thermocouple compensators.



Arbitrarily-Programmable Functional Relationships

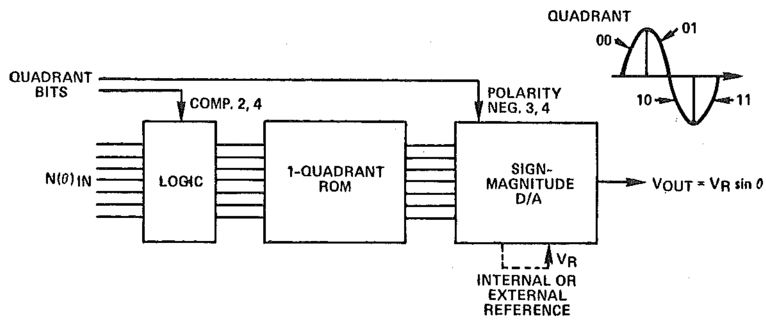
Besides standard functions that can be purchased in ROM's, it is also possible to buy programmable read-only memories, that can be programmed by the purchaser to simulate functional relationships.



**Nonlinear Circuits Handbook*, Analog Devices, Inc., 1974 & 1976, has many details of these methods. $5.95, P.O. Box 796, Norwood MA 02062.

Sinusoidal Input-Output Relationships

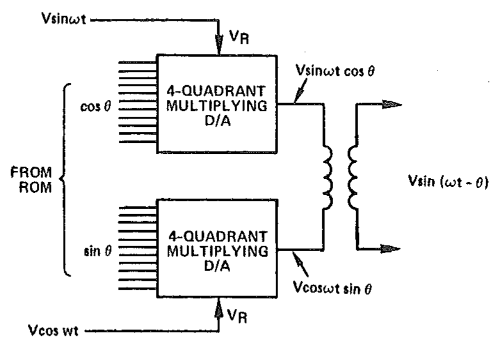
An example of the approach is the use of a read-only memory that has the values of $\sin\theta$ stored in it for $0° \leqslant \theta \leqslant 90°$. Two additional digits provide quadrant information, one to complement the input in the even-numbered quadrants, the other to provide the output sign-change for the 3rd and 4th quadrants. The input arrives from an angle-to-digital transducer, the corresponding sinusoidal number values are developed and applied to a D/A converter, and it makes the sine function available as a voltage. If the D/A converter is a multiplying type, computations of the form $R\sin\phi$ are readily performed.



TRIGONOMETRIC APPLICATIONS

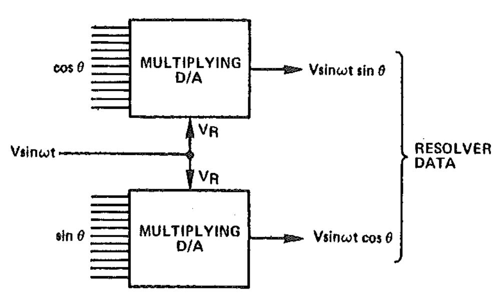
Digital Phase Shifter

The Figure shows two multiplying D/A converters used as digitally-controlled attenuators multiplying the reference signals V $\sin\omega t$ and V $\cos\omega t$ by the vector component of θ. The summed output from the two converters is then the vector V $\sin(\omega t + \theta)$, where the phase angle θ is set by the converter's digital inputs.



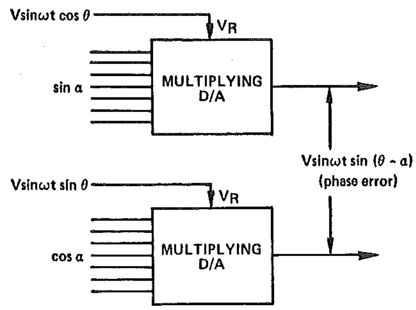
Digital/Resolver Converter (Resolver Simulator)

Similar to the above configuration, but having the common reference input to both multipliers, V $\sin\omega t$, this configuration obtains the two components, V $\sin\omega t \sin\theta$ and V $\sin\omega t \cos\theta$, which express resolver data for angle θ. The resolver data can be converted into synchro format with a Scott-T transformer, or an equivalent network in which operational amplifiers provide the appropriate voltage ratios. This resolver simulator can be enclosed within a feedback loop to operate as a resolver-to-digital converter.



Resolver (Digital) Control Transformer

Using the *actual* resolver line voltages V *sinωt sinθ* and V *sinωt cosθ* as the converter reference inputs, and multiplying by digital equivalents to *cos α* and *sin α*, an output proportional to the angular error, $\theta - \alpha$ (for small angular errors) is developed. Operated in this mode, the configuration simulates a resolver control transformer.

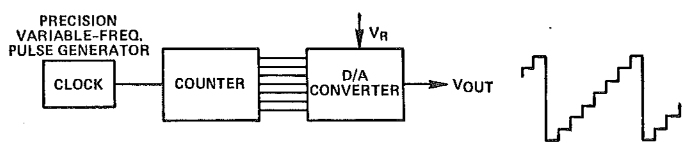


WAVEFORM GENERATION

Linear waveforms are generated digitally by clocks and counters, processed by ROM's or μP's to obtain arbitrary shapes, and converted to analog functions of time by DAC's[1]. As long as the original digital function can be created, then an analog output can be made to follow (within its speed limitations). The ease of manipulation and ability to lock timing operations to precise clocks give the digital approach considerable edge in versatility over many analog alternatives. Deglitching and filtering may be used as (and if) necessary to clean up the waveforms. Arbitrary counts and very-simple DAC's may be used to obtain pulse trains of few-step staircases of arbitrary duty cycle.

Sawtooth Generator

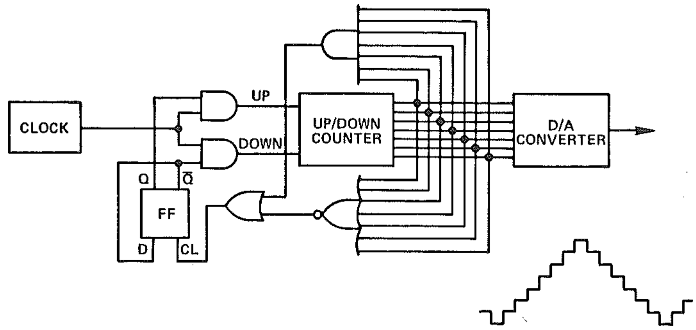
This sweep generator is composed of a digital clock, a counter, and a DAC. The clock pulses increment the counter, and the sequential counter steps increment the DAC output. After the counter is full, it returns to its empty state and starts counting again. Both amplitude and period of the sweep generator are easily and precisely adjustable. The resolution is determined by the number of counts and choice of D/A converter, ranging from the 16-bit DAC1136, with its 65,536 steps, down to 10- or fewer-bit converters with 1,024 steps, and below.

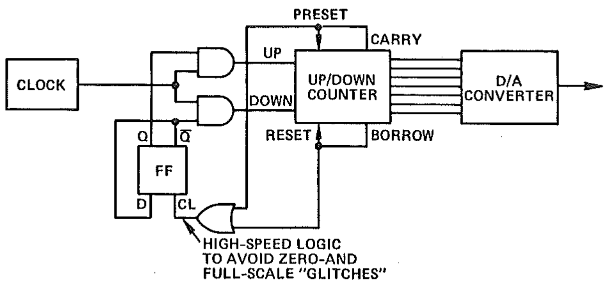


Triangular-Wave Generator

Instead of being allowed to overflow, the counter in this case is an up-down counter that is caused to change direction when it is full and again when it is empty. Two approaches to reversing direction are shown. In one, the reversal is generated during the full (and empty) states; in the other, it is generated by the carry (borrow) occurring at the leading edge of the next pulse. The result, at the DAC output, is essentially a triangular-wave of precise amplitude and frequency. With little additional logic, full-scale dwell (or dwell-and-reversal at any level) provides trapezoidal waveforms.

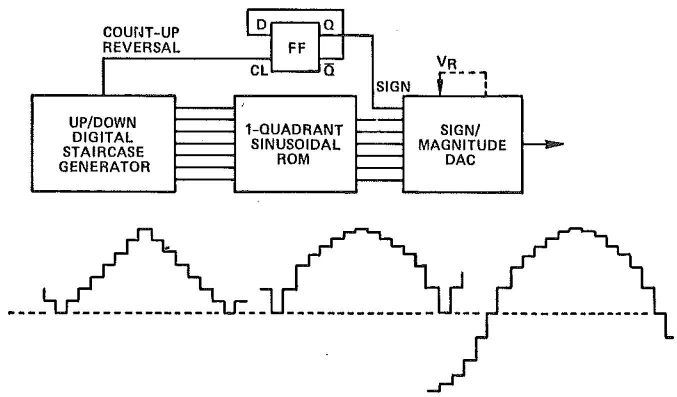
[1]See also Chapter I-6, section B.





Sine-Wave Generator

If the digital count is fed to a sinusoidal ROM, and its output, accompanied by polarity information, is applied to a sine-magnitude-coded DAC, the output of the DAC will be an n-bit quantized sine wave. Its frequency is determined by the clock, and its amplitude can be controlled externally or by the use of a multiplying DAC.



TIME FUNCTIONS

The ability of flip-flops to store information, undegraded by time, and the continually decreasing cost of storage capacity, are strong motivations to seek ways of eliminating capacitor circuits, with their leakage, dielectric hysteresis, and nonlinearity. "Distortionless" time delay, integration, and sample-hold are a few targets for such effort.

Precision Analog Delay Line

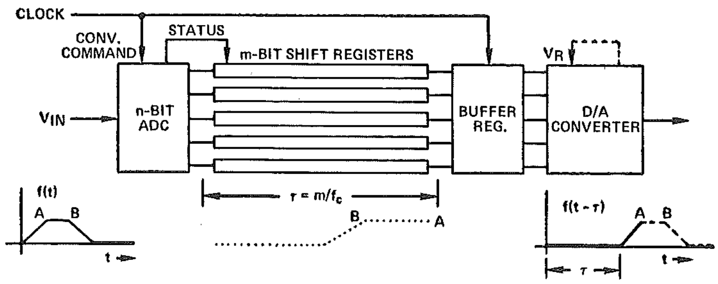
There are interesting applications for good analog delay lines: analog correlation, "distortionless" signal compression or expansion (i.e., "riding the gain" without missing a drumbeat), electronic echo-chamber effects, analog modeling of processes that incorporate pure time delay[2] for predictive control, design of filters with arbitrary transfer functions, are a few.

But there hadn't been a decent way of building a practical analog time-delay device that is variable over microseconds to minutes to months, until shift registers became available with many bits at low cost-per-bit. Microprocessors can also perform such functions.

[2] See also Chapter I-6, section B.

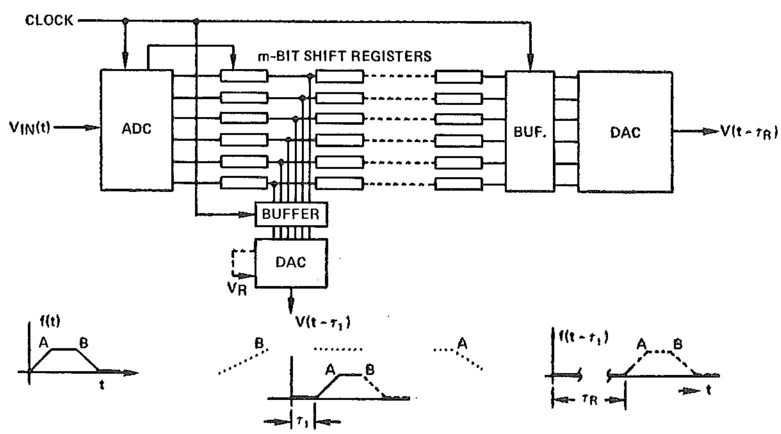
Active or passive filter-type delay lines were seldom "distortionless," analog "bucket brigades" had excessive leakage errors at low speeds, as well as a resolution-vs.-cost problem (this latter being solved by the new charge-coupled MOS high-speed bucket brigades), tape recording wasn't efficacious at high speeds, and the use of mainframe memory was too expensive (and bulky for portable instruments).

In the example shown, the delay is produced by shift registers (e.g., 256-bit) for *n* parallel digital channels, each channel representing 1 bit of converted analog signal. For 10-bit conversion, and 10 delay lines, signals that can be quantized into 1024 discrete levels can be delayed with a resolution of 1/256 of the delay time (e.g., 1μs of 256μs, 1/16s, 1.38° per cycle of a sinusoidal ac signal of period equal to the delay time, etc.).



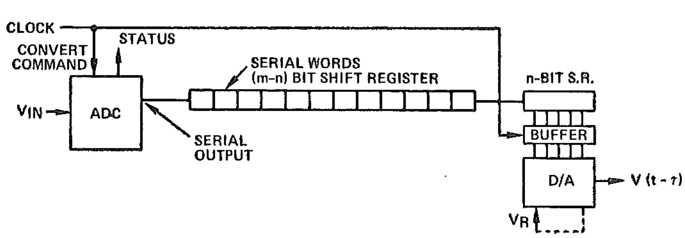
Tapped Delay Line

This device makes a number of points in the history of a waveform available simultaneously. It is simply the delay line with an increased number of discrete "chunks" of delay, and readout via DAC's at each point. Multiplying DAC's allow such interesting functions as $f(t) \cdot f(t-\tau)$ to be computed for a variety of values of τ.



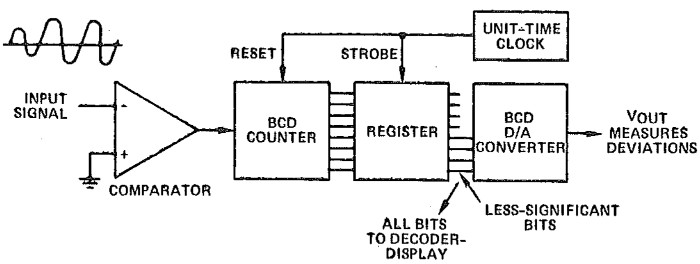
Serial Delay Line

For signals that do not require sampling at top speed, a considerable saving of the cost of delay lines (or increase in the time-resolution of the delay) can be achieved by feeding the converted signal into the line serially, and converting back to parallel information before the D/A conversion. Since the signal is being clocked through the line, a bit-at-a-time, few if any additional bits of shift register capacity are needed.



Precision Average-Frequency-to-Voltage Converter

In this application, the output of a frequency-or analog-event-meter (e.g., 16 bits) is applied to the usual BCD readout. In addition, the 8 (or more) least-significant bits are converted to voltage, providing a very sensitive analog measure of small frequency changes. It is feasible to also convert the top 8 bits, and use a low-cost analog divider, such as the AD534, to get a continuous analog readout of the fractional deviation.

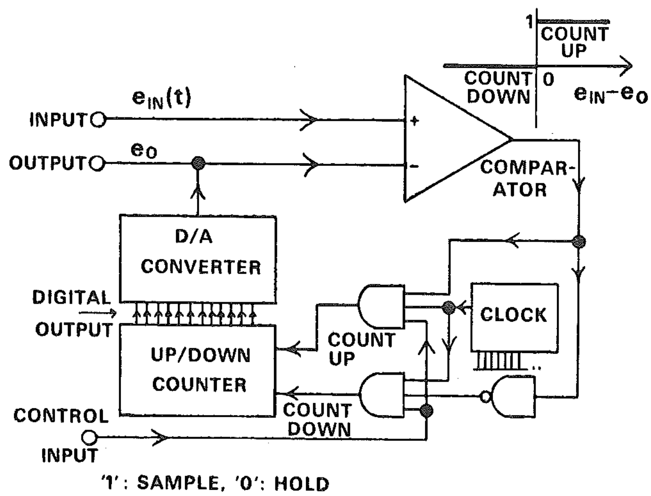


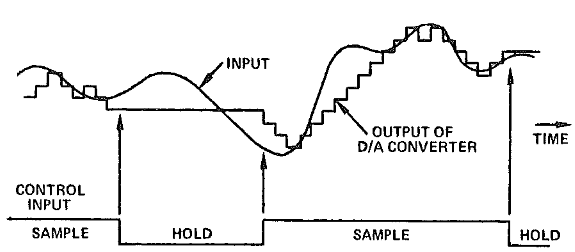
DIGITAL SERVO CIRCUIT

Most A/D converter designs involve feedback. Thus the very means of conversion implies that the combination of analog-digital interaction and the power of feedback can yield quite valuable results. A few examples are sample-hold, peak-detecting, and automatic zero-setting.

Tracking Sample-Hold (A/D Converter)

This circuit, also mentioned in the chapter on sample-holds, is especially useful as a track-and-infinite-hold device. It can acquire the analog signal within a minimum of 1 count and maximum of 2^n counts, and, upon command, *hold* it indefinitely without degradation, providing both digital and analog readout. Since it uses an up-down counter, it will track the analog signal at a constant rate (2^{-n} FS per count), and "hunt" between the two digital values that straddle the analog value, if it remains constant.

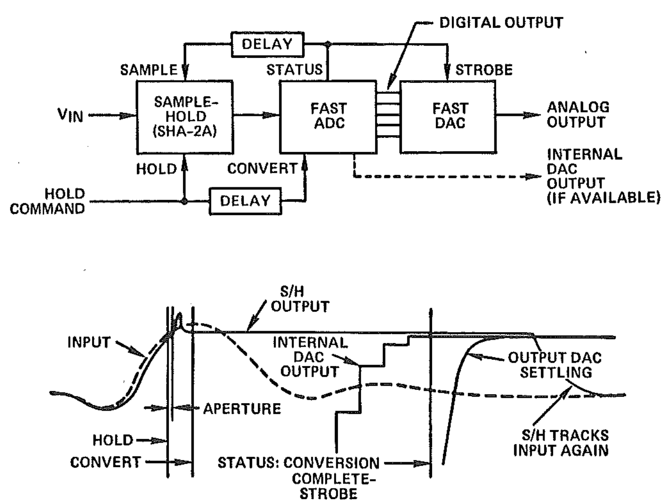




For slowly-varying analog signals, the tracking sample-hold is one of the lowest-cost ways to convert, since it eliminates the need for a sample-hold. However, its conversion time is variable, which introduces timing errors in sampled-data systems, since the most-recently acquired value may represent any value of signal during the interval between interrogations. Also, its response depends to a great extent on the amount and type of noise present.

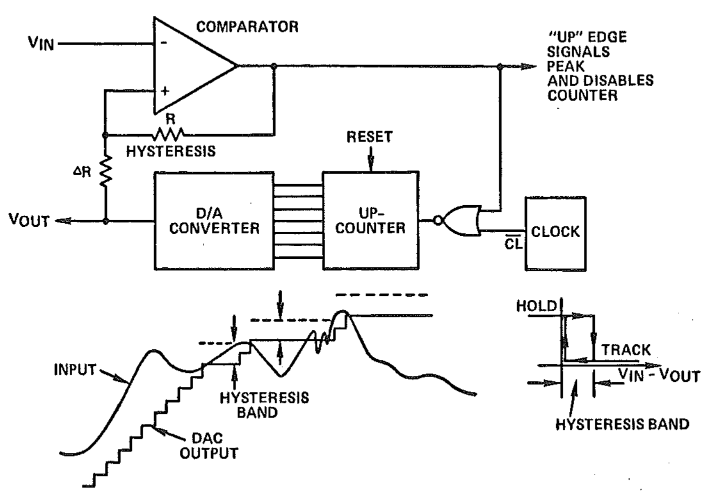
Digital Pulse Stretcher

For extremely-fast acquisition-very-long hold, this circuit, consisting of a fast sample-hold and a fast successive-approximations A/D converter will provide the best results. Both analog and digital outputs are available. If the internal D/A converter's output can be made available without slowing conversion, the output D/A shown in the Figure is unnecessary. The SHA-2A is kept in *sample* at all times except during conversion. When switched to *hold,* it should have a "head start" of about 100ns for its transients to die down before conversion starts. But aperture time is 10ns with 0.25ns jitter.



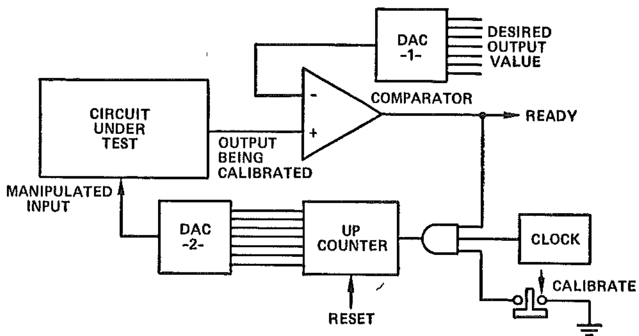
Digital Peak-Follower (with Hysteresis)

Similar to the tracking sample-hold, but using an up-counter (a valley-follower would use a down-counter), this circuit will *hold* the highest value of input that it has been able to track. However, to provide a small measure of immunity to noise, hysteresis makes the circuit insensitive to small changes; in order for the input to be followed, it must be higher than the stored value by a preset amount. A similar circuit can be used for valley following, and two such circuits with an output subtractor will provide peak-to-peak measurement.



Automatic Set-Point Circuit

If a circuit under test is to be calibrated from time to time (e.g., each time some element, perhaps a device under test, is changed), the resetting and the level to which a test value must be reset, may be adjusted digitally. In the example, an output of the circuit must be set to a value equal to a calibrating value set by DAC-1. The values are compared, and a clock increments a counter, which updates a DAC, setting the input that performs the calibrating adjustment. When the comparator changes sign, calibration is complete, and the sign change indicates a "Ready" condition. The calibration value is retained until a new calibration cycle is initiated by resetting the counter and gating the clock.



A FINAL NOTE:

SOFTWARE vs. HARDWARE

The examples given here all involve hard-wired analog-digital circuitry. For applications in which microprocessors are available, it should be evident that functions involving memory, control logic, and digital data can often be as well (if not quite as speedily) handled through the writing of appropriate microprocessor programs.

Rather than viewing the techniques as competitive, the designer should consider that the three-way tradeoff between analog, hard-wired, and software approaches provides at least one more degree of freedom for developing cost-effective instruments, apparatus, and systems. The flexible designer will not arbitrarily exclude a given approach; on the other hand, the committed designer should know that other alternatives to his own predilections do exist and may, on occasion, prove available to save the day.