ANALOG DEVICES

AN-285
APPLICATION NOTE

ONE TECHNOLOGY WAY • P.O. BOX 9106 • NORWOOD, MASSACHUSETTS 02062-9106 • 617/329-4700

A Function Generator and Linearization Circuit Using the AD7569

by James M. Bryant, MIERE

INTRODUCTION

A function generator is an electronic circuit which has an input/output relationship defined as a function of the form:

$$V_O = f(V_I) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

(It is perfectly possible to have function generators with current inputs and outputs, or even transconductance or transimpedance function generators – with voltage in and current out or current in and voltage out, respectively – but the commonest case is the simple one of voltage in and voltage out.)

Function circuits are used in analog computations of all sorts to generate functions and are also used to linearize the responses of nonlinear transducers and circuits – this last application wil be described in detail towards the end of this application note.

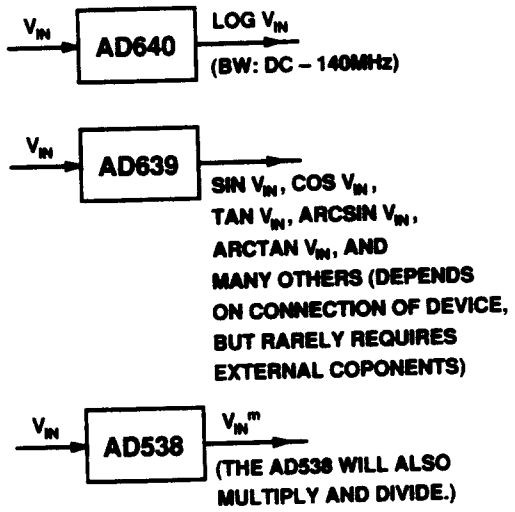


Figure 1. Some Monolithic Function Generators

Such circuits (some of which are shown in Figure 1) include logarithmic circuits such as the AD640, whose output is the logarithm of its input over a 45 dB dynamic range (and with a bandwidth of dc to over 140 MHz), trigonometric ones such as the AD639, which can be configured to have transfer functions corresponding to most trigonometric functions (including sine, cosine, tangent, contangent, versine, haversine, arcsine, arccosine and many more), and root and power circuits, which can be made with such devices as the AD538, and whose output is a power of the input of the form

$$V_O = V_{IN}{}^m. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where m may have any integer or noninteger value between 0.2 and 5. (The AD538 is much more versatile than this, being a log-amp based multiplier/divider/power circuit with an output of the form

$$Y\left(\frac{Z}{X}\right)^m$$

but in the present application note we are interested in function generators and not in more general computation.)

Equation (2) is not dimensionally correct since the output is a voltage, rather than (voltage)^m, and should strictly be expressed as

$$V_O = 1\,V\left(\frac{V_{IN}}{1\,V}\right)^m. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where the function is more complex, or perhaps discontinuous, there is unlikely to be a ready-made integrated circuit that will perform the necessary operation. In such a case a function generator may be made from an analog-digital converter (ADC), a digital-analog converter (DAC) and a read-only memory (ROM). It is a function generator of this type that this application note describes.

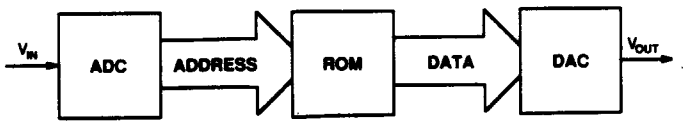


Figure 2. Basic "Convert/Lookup/Convert" Function Generator

The basic design of such a function generator is obvious: the input voltage is applied to the ADC and the resulting digital code is used as the address of a memory location in a ROM (Figure 2). The data word at that location is then applied to a DAC to produce an output voltage. With suitable ROM programming *any* function may be produced by such a circuit – the accuracy will depend on the resolution of the ADC and DAC.

THE AD7569 USED AS A FUNCTION GENERATOR

The AD7569 (which is illustrated in Figure 3) consists of an 8-bit ADC and an 8-bit DAC, with a integral voltage reference. It is available in a 24-pin "skinny-DIP" dual-in-line (DIP) package, a 28-pin leadless chip carrier (LCC) and a 28-pin plastic leaded chip carrier (PLCC).

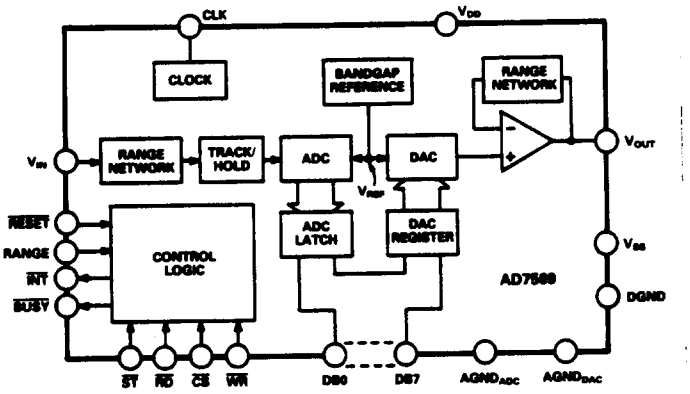


Figure 3. AD7569 Functional Block Diagram

The ADC contains an integral sample-and-hold (SHA) circuit and performs a conversion in 2 μs, and the DAC settles in 1 μs. Input and output ranges of 0–1.25 V, 0–2.5 V, ±1.25 V and ±2.5 V may be programmed by a range pin and the use, or not, of a negative supply. The ADC and DAC ranges are identical – it is not possible to program them separately. The table in Table I shows how these ranges (and the data formats associated with them) are programmed.

Range	V_{SS}	Input/Output Voltage Range	DB0–DB7 Data Format
0	0 V	0 to +1.25 V	Binary
1	0 V	0 to +2.5 V	Binary
0	−5 V	±1.25 V	2s Complement
1	−5 V	±2.5 V	2s Complement

Table I. AD7569 Ranges and Data Formats

The data output from the ADC and the data input to the DAC use a common data port. While it would be perfectly possible to multiplex this data onto the separate address and data buses of a normal ROM, it is obviously simpler, if possible, to use a ROM with a multiplexed address/data bus. The SC22102 EEPROM from Sierra Semiconductor is an 18-pin 256 × 8 device which is ideal for the application.

The input voltage is applied to the V_{IN} pin of the AD7569. The input impedance is quite low and the bias current quite large (and both vary with range – for details see the AD7569 data sheet), so it is well to use a buffer amplifier. It will also be necessary to use a buffer amplifier if the input range is not one of the ranges available from the AD7569.

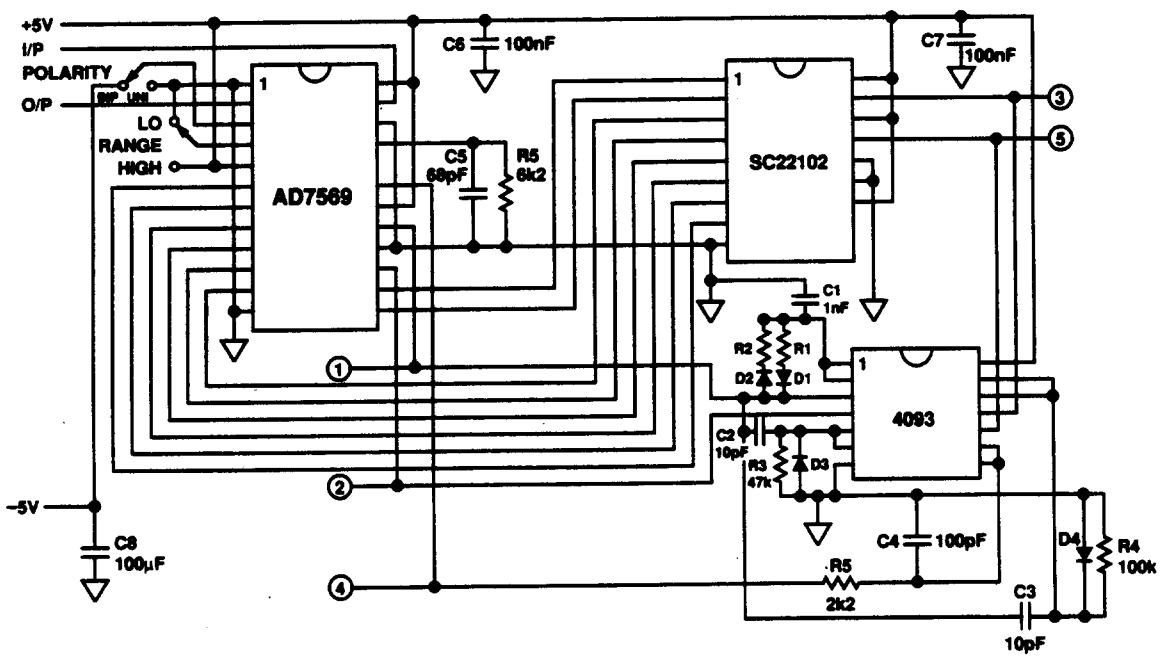


Figure 4. Circuit Diagram of Basic Function Generator

The ADC of the AD7569 performs an A-D conversion and the resulting 8-bit word is latched into the SC22102 EEPROM as an address. The data byte at that address is then read back from the SC22102 into the AD7569 DAC where its analog value is output onto the V_{OUT} pin. Again, the range available from the AD7569 is limited to the range used for the input, so if a different output range is required, an output buffer with appropriate gain and level shifting must be used.

The basic system uses only the AD7569, the SC22102, and a 4093 CMOS quad schmitt NAND gate which performs all the logic and timing functions (unused 4093 inputs are tied to +5 V).

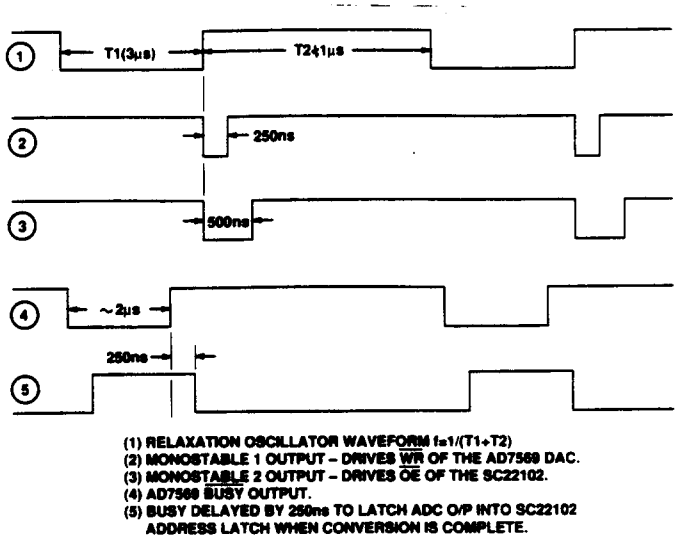
Gate 1 of the 4093 acts as a relaxation oscillator. Its output consists of 3 μs negative pulses separated by positive periods which must be at least 1 μs in duration. R1 sets the duration of the negative part of the cycle (T1), and R2 sets the duration of the positive part (T2). The overall sampling frequency is 1/(T1+T2). The minimum sampling frequency depends on the bandwidth of the input signal and should be 256 times the maximum component of the input signal – in practice, since the maximum sampling frequency is 250 kHz, this limits the maximum component of the input spectrum to about 1 kHz.

A-D conversion is triggered by the falling edge of the gate 1 output. Shortly afterwards (about 100 ns) the AD7569 $\overline{BUSY}$ line goes low. $\overline{BUSY}$ is applied to gate 4 of the 4093 after a delay of about 250 ns set by C4 and R5 (the ease with which delays and sharp edges may be produced is the reason for the use of the 4093 schmitt device rather than a simple quad NAND gate). The output of gate 4 is applied to the ALE input of the SC22102 – thus, 250 ns after $\overline{BUSY}$ goes high the result of the A-D conversion is latched into the address latch of the SC22102 (250 ns is much longer than is necessary but allows an ample margin for the rather inexact thresholds of the 4093).

When the output of gate 1 goes high again, two monostables are triggered. One, formed by C2, R3, D1 and gate 2, has a period of about 250 ns and is applied to the $\overline{WR}$ input of the AD7569; the other, formed by C3, R4, D2 and gate 3, has a longer period and is applied to the $\overline{OE}$ of the SC22102. This reads the contents of the memory at the latched address into the DAC. In most cases the output of gate 2 could be used top drive both $\overline{WR}$ and $\overline{OE}$, but a potential race condition is involved and since the fourth gate of the 4093 would otherwise be unused, it is safer to hold the memory output enabled until the DAC is safely latched.

The basic function generator circuit is shown in Figure 5 – it uses the three integrated circuits (AD7569, SC22102 & 4093), four diodes, five resistors, five capacitors (plus three supply decoupling capacitors), and two switches. In most practical applications the switches will not be necessary and the gain range required will be hardwired. If the circuit will be used only in the unipolar mode, the negative supply and its decoupling capacitor, C8, are also unnecessary.

The waveforms at the main points of the system, indicated by circled numbers in the circuit diagram Figure 4, are shown in Figure 5.



(1) RELAXATION OSCILLATOR WAVEFORM f=1/(T1+T2)
(2) MONOSTABLE 1 OUTPUT – DRIVES $\overline{WR}$ OF THE AD7569 DAC.
(3) MONOSTABLE 2 OUTPUT – DRIVES $\overline{OE}$ OF THE SC22102.
(4) AD7569 $\overline{BUSY}$ OUTPUT.
(5) BUSY DELAYED BY 250ns TO LATCH ADC O/P INTO SC22102 ADDRESS LATCH WHEN CONVERSION IS COMPLETE.

Figure 5. Control Waveforms of the Basic Function Generator

The circuit is so simple that no set-up adjustments are necessary unless the sampling frequency must be set particularly accurately – in this case R1 is set so that T1 is at least 500 ns longer than the BUSY signal of the AD7569 and T2 is then set to give the correct sampling frequency (T2 must be at least 1 μs). The timing of the remaining 4093 circuits is imprecise, but the component values chosen will work over the full range of 4093 thresholds.

PROGRAMMING THE SC22102

The data in the SC22102 EEPROM define the function of the function generator. The word at each of the 256 addresses defines the DAC output when the ADC output (and, of course, input) corresponds to that address.

The function is defined, therefore, by a lookup table programmed into the SC22102. Both the creation of the table, which depends on the function required, and the programming itself, which is done according to quite simple instructions given on the SC22102 data sheet, are beyond the scope of this application note. It is worthwhile mentioning, however, that the author has built a programmer for the SC22102 which plugs into the Centronics printer port of a personal computer and uses very simple software. Since the design and software depends on the computer used (a 12 year old Commodore PET with a heavily modified operating system – the unmodified PET does not have a Centronics printer port!), it is scarcely worthwhile to publish it – but the total design and construction time was less than two hours and a similar exercise could easily be done on most other PCs.

APPLICATIONS

In its simplest application a signal from a low impedance source is applied to the input of the basic circuit and an output is taken from its output. This is appropriate when the input and output ranges are identical and equal to one of the AD7569 ranges, and the signal source is low impedance. The resolution of both input and output being 8 bits, the accuracy will be 0.4% FS.

If the input and output range differ, or do not conform to one of the AD7569 ranges, or both, buffer amplifiers will be necessary. A single buffer can alter both span and offset of a signal.

If a signal has a span from 0 to V volts, or from −V to +V, then no offset is necessary and a simple amplifier, with suitable gain, between the signal source and the input of the ADC, or between the DAC and the output, is all that is required. If the gain required is greater than 1, a simple noninverting amplifier, using an op amp and two resistors, is all that is required. Such an amplifier is illustrated in Figure 6 (a).

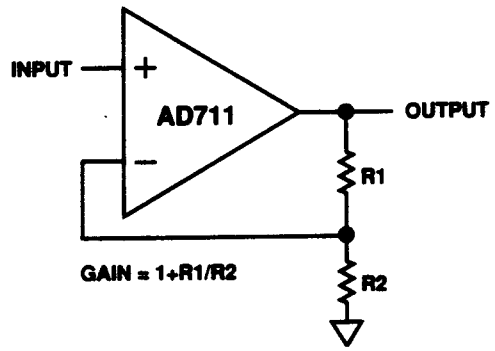


Figure 6a. Simple Noninverting Buffer

It is not possible to design such an amplifier with a gain of less than 1. In cases where the necessary gain is less than unity the input should be attenuated with two resistors, and a unity gain amplifier used to buffer the attenuated signal. Figure 6 (b).

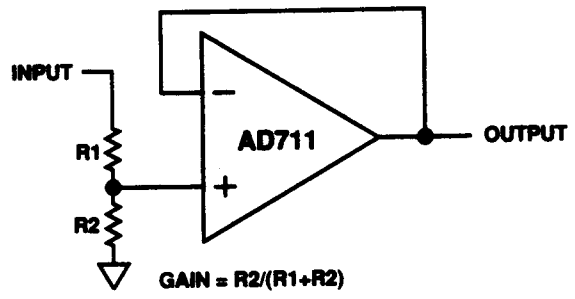


Figure 6b. Buffer for Gain ≤1. (R2 Omitted and R1 = 0 when G = 1)

If the signal span is from V_1 to V_2 ($V_1<V_2$), then both the amplitude and the offset of the signal must be altered. In this case let us assume that the AD7569 is set to its −2.5 V to +2.5 V range. The design and construction of the amplifier is simplest if we use an inverting buffer so that an input of V_1 gives $+2.5\,V_{OUT}$ and V_2 in gives $-2.5\,V_{OUT}$. The offset required on this amplifier is $\frac{(V_1+V_2)}{2}$ and the gain is $-\frac{5}{(V_2-V_1)}$.

A suitable amplifier is shown in Figure 7. Its gain is $\frac{-R1}{R2}$, and its offset is $\frac{-V_R \cdot R1}{R3}$. These two formulae allow us to choose values for R1, R2 and R3 and the correct polarity of V_R, the reference voltage (an external voltage reference is required for this circuit because, although the AD7569 contains a band gap voltage reference, it does not have its output available externally). The advantage of this circuit is that any value of gain may be set, greater or less than, or equal to, unity.

The disadvantages are that (a) the input impedance is only R2, which can only be a few tens of kilohms, and (b) the signal is inverted – so the lookup table in the ROM must also be inverted (i.e., V_1 will correspond to FS positive at the ADC and V_2 to FS negative). Neither is very important and (b) is trivial – provided the programmer remembers the inversion when calculating the EEPROM program!

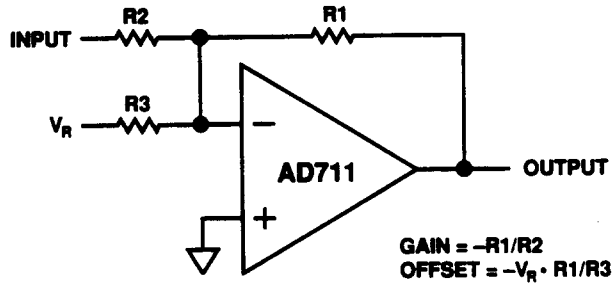


Figure 7. Inverting Amplifier. Gain May Be Set to Any Value <1< Offset is Independent of Gain

The same circuit can be used for the output. If the output range is V_1 and V_2 ($V_1<V_2$), then the gain required is $-\frac{(V_2-V_1)}{5}$, the offset is again $\frac{(V_1+V_2)}{2}$, and the resistors may be calculated as before. Again, when programming, remember that with this inverting amplifier +2.5 V from the DAC will give V_1 and −2.5 V will give V_2.

LINEARIZATION

Suppose that the output of a temperature transducer is a voltage V_T defined by the law

$$V_T = V_1 \cdot T + V_2 \cdot T^2 + V_3 \cdot T^3$$

where T is temperature in degrees Celcius and V_1, V_2 and V_3 are constant voltages. If we are using this transducer to measure temperature and display it on a meter, we will find that the meter must have a nonlinear scale.

Many transducers and electronic circuits behave in this way. In some cases the nonlinearity is accepted by the user, but there is a steady demand for circuits which will linearize such responses – that is, in the case above, a circuit which accepts as an input V_T and has an output V_{T_1} such that

$$V_{T1} = V_K \cdot T$$

where the output voltage is proportional to the temperature.

If a circuit or transducer is very nonlinear, the basic function generator described above will be required to linearize it, and the accuracy will be that of the basic function generator (in the present case 8 bits or about 0.4%). Many circuits or transducers, however, are only slightly nonlinear, perhaps deviating from a straight line response by only a few percent. In this case it is evident that a correction to 0.4% is not great gain.

By suitable design, however, a function generator with 0.4% accuracy may be used to linearize such a slightly nonlinear circuit to much higher accuracy. The principle is shown in Figure 8.

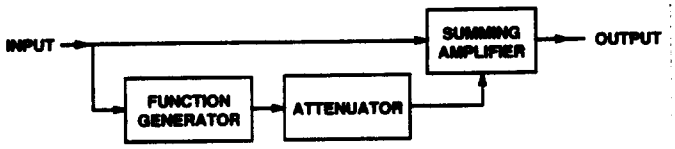


Figure 8. The Basic Principle of Linearization

If the maximum nonlinearity of the signal is ±1%, then a corection is applied to the signal from the DAC of the function generator. If the maximum possible correction is arranged to be ±1% (=2%), then the resolution to which the correction can be applied is 0.4% of 2% (0.008% or almost 14 bits).

Thus an 8-bit function generator, as described in this application note, can linearize a slightly nonlinear transducer to 14-bits or even more, with suitable summing circuitry. Of course if 14-bit performance is required, the accuracy and linearity of the remainder of the system must also be 14-bit and great care must be exercised in its design and the choice of components.

A practical circuit is shown in Figure 9. The use of two cascaded inverting amplifiers results from the difficulty of summing a signal into a unity gain buffer (of course many amplifier arrangements do allow this but the one in Figure 9 is one of the simplest). The design of input and output amplifiers for high accuracy linearization of this type is similar in principle to that described earlier, but considerably more care is necessary if amplifier offset and gain errors, and even thermal effects in resistors, are not to spoil the performance.

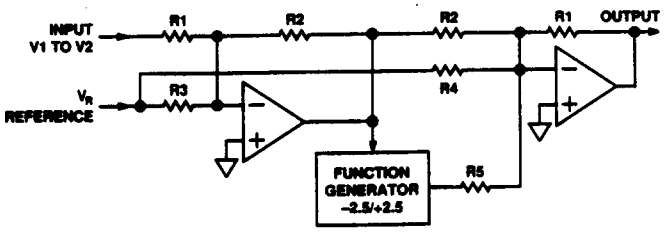


Figure 9. High Accuracy Linearizing Circuit

The resistor values are calculated as follows, assuming that the input and output range is V_1 to V_2 and that we are using end-point linearization (i.e., V_1 and V_2 are unchanged by the linearization procedure but intermediate values are corrected). We shall use the basic function generator in its −2.5 V to +2.5 V range.

We first of all choose a value for R1. This should not be so large that Johnson noise or offsets due to amplifier bias currents are objectionable, nor so low that it unnecessarily loads the signal source. A value in the range of 3–10 kΩ is likely to be suitable.

If $(V_1 + V_2)$ is zero then the voltage reference, R3 and R4 are unnecessary. Otherwise we must next choose a voltage reference, V_R, which must have the OPPOSITE polarity to $(V_1 + V_2)$. Any standard voltage reference circuit, such as the AD586 or AD587, is suitable, but the AD588 is particularly suitable when high stability is required – and it has the additional convenience of both positive and negative outputs.

Once R1 has been selected, R2 may be calculated.

$$R2 = R1 \cdot \frac{5\ V}{(V_2 - V_1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

If necessary we then use V_R (inluding its sign – i.e., if V_R is −5 V then −5 V must be used in the equation, not +5 V), R1 and R2 to calculate R3 and R4.

$$R3 = R2 \cdot \frac{-2 \cdot V_R}{(V_1 + V_2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$R4 = R1 \cdot \frac{-2 \cdot V_R}{(V_1 - V_2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Finally, to get the best possible resolution from the linearization circuit full-scale output from the function generator must correspond to the maximum error. Therefore if the maximum nonlinearity to be corrected is ±A% then

$$R5 = \frac{50 \cdot R1}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

When programming the function generator for linearization, one must set each data word so that when the input calls that address the output, added to the signal with the gain of R1/R5, brings the output of the circuit to its desired value. Where the nonlinearity obeys a predictable law the program in the function generator may be obtained by calculation but where it does not simple empiricism rules: the response of the circuit or transducer is measured at 256 points across its curve and the necessary correction at each point programmed into the EEPROM.

CONCLUSION

The function generator described in this application note is simple (using only three chips), easily constructed, and requires little or no setting up. It can perform as a function generator with accuracies of 0.4% FS and, with the addition of one or two functions to much higher accuracies. There are in development combined ADC/DAC circuits with higher resolutions (e.g., the AD7869 14-bit circuit) which will make higher resolution versions of the system as easy to implement – but for many everyday tasks 8-bit performance is more than adequate, and remarkably easy to achieve.

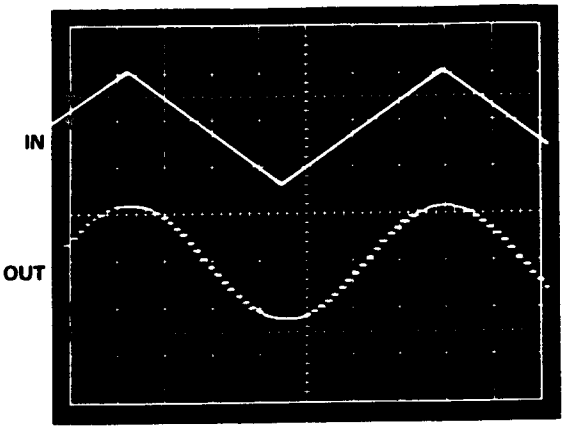


Figure 10a. Sin X

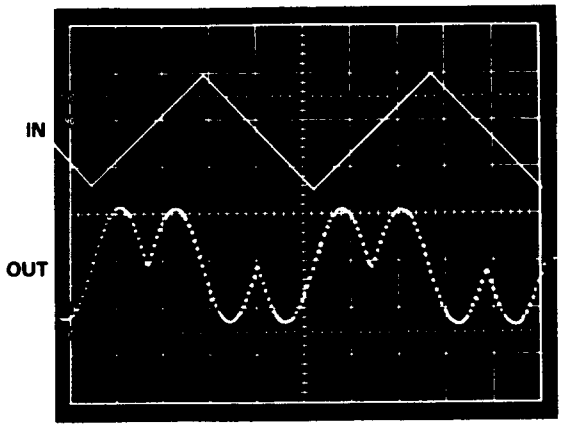


Figure 10b. Sin 2 X

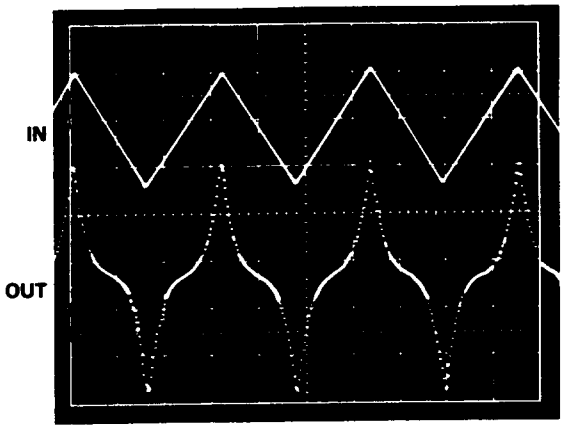


Figure 10c. X^3

Figure 10. Typical Function Generation

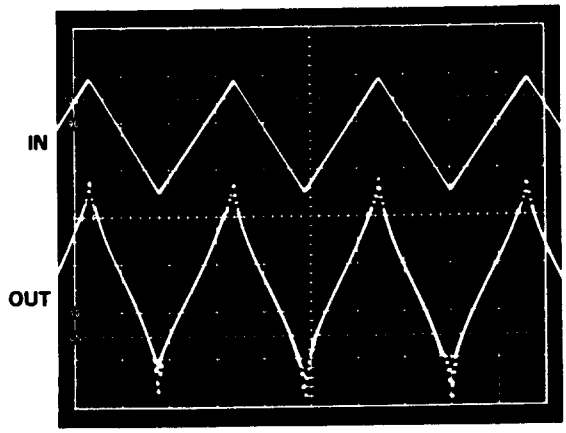


Figure 11a. Arc Sin X with Triwave Input

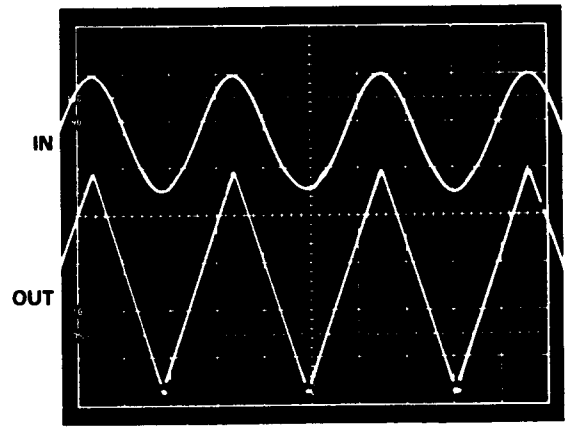


Figure 11b. Arc Sin X with Sine Wave Input Gives Linear Triwave Output

Figure 11. Linearization with a Function Generator