A few proven techniques ease sine-wave-generator design

Perhaps the most fundamental of all signals, sine waves present generating-circuit design tasks that are anything but fundamental. Next time you design such a circuit—whether it's for 1 Hz or 1 MHz—try one of the techniques described here.

Jim Williams, National Semiconductor Corp

Because sine-wave oscillators come in as many forms as the units that use them, choosing the best circuit type and implementation for an application can prove difficult. This article, however, helps simplify those choices and furnishes guidelines for controlling critical design specs such as frequency, amplitude and distortion.

You can apply many analog and digital techniques to achieve your sine-wave-generator design goals; each realization offers unique strengths and weaknesses. You'll probably find that one of those listed in the **table** will meet your requirements. The specific circuit

SINE-WAVE-GENERATION TECHNIQUES

TYPE	TYPICAL FREQUENCY RANGE	TYPICAL DISTORTION (%)	TYPICAL AMPLITUDE STABILITY (%)	COMMENTS
PHASE SHIFT	10 Hz-1 MHz	1-3	3 (TIGHTER WITH SERVO CONTROL)	SIMPLE, INEXPENSIVE TECHNIQUE. EASILY AMPLITUDE SERVO CONTROLLED. RESISTIVELY TUNABLE OVER 2:1 RANGE WITH LITTLE TROUBLE. GOOD CHOICE FOR COST-SENSITIVE, MODERATE-PERFORMANCE APPLICATIONS. QUICK STARTING AND SETTLING.
WEIN BRIDGE	1 Hz-1 MHz	0.01	1	EXTREMELY LOW DISTORTION. EXCELLENT FOR HIGH-GRADE INSTRUMENTATION AND AUDIO APPLICATIONS. RELATIVELY DIFFICULT TO TUNE—REQUIRES DUAL VARIABLE RESISTOR WITH GOOD TRACKING. TAKES CONSIDERABLE TIME TO SETTLE AFTER A STEP CHANGE IN FREQUENCY OR AMPLITUDE.
LC NEGATIVE RESISTANCE	1 kHz-10 MHz	1-3	3	DIFFICULT TO TUNE OVER WIDE RANGES. HIGHER Q THAN RC TYPES. QUICK STARTING AND EASY TO OPERATE IN HIGH FREQUENCY RANGES.
TUNING FORK	60 Hz-3 kHz	0.25	0.1	FREQUENCY-STABLE OVER WIDE RANGES OF TEMPERATURE AND SUPPLY VOLTAGE. RELATIVELY UNAFFECTED BY SEVERE SHOCK OR VIBRATION. BASICALLY UNTUNABLE.
CRYSTAL	30 kHz-200 MHz	0.1	1	HIGHEST FREQUENCY STABILITY. ONLY SLIGHT (PPM) TUNING POSSIBLE. FRAGILE
TRIANGLE-DRIVEN BREAK-POINT SHAPER	<1 Hz-500 kHz	1-2	1	WIDE TUNING RANGE POSSIBLE WITH QUICK SETTLING TO NEW FREQUENCY OR AMPLITUDE.
TRIANGLE-DRIVEN LOGARITHMIC SHAPER	<1 Hz-500 kHz	0.3	0.25	WIDE TUNING RANGE WITH QUICK SETTLING TO NEW FREQUENCY OR AMPLITUDE. TRIANGLE AND SQUARE WAVE ALSO AVAILABLE. EXCELLENT CHOICE FOR GENERAL-PURPOSE REQUIREMENTS NEEDING FREQUENCY-SWEEP CAPABILITY WITH LOW-DISTORTION OUTPUT.
DAC-DRIVEN LOGARITHMIC SHAPER	<1 Hz-500 kHz	0.3	0.25	SIMILAR TO ABOVE BUT DAC-GENERATED TRIANGLE WAVE GENERALLY EASIER TO AMPLITUDE-STABILIZE OR VARY. ALSO, DAC CAN BE ADDRESSED BY COUNTERS SYNCHRONIZED TO A MASTER SYSTEM CLOCK.
ROM-DRIVEN DAC	1 Hz-20 MHz	0.1	0.01	POWERFUL DIGITAL TECHNIQUE THAT YIELDS FAST AMPLITUDE AND FREQUENCY SLEWING WITH LITTLE DYNAMIC ERROR CHIEF DETRIMENTS ARE REQUIREMENT FOR HIGH-SPEED CLOCK (EG, 8-BIT DAC REQUIRES A CLOCK THAT IS 256 × OUTPUT SINE-WAVE FREQUENCY) AND DAC GLITCHING & SETTLING, WHICH WILL INTRODUCE SIGNIFICANT DISTORTION AS OUTPUT FREQUENCY INCREASES.

1-IC Wein-bridge oscillators provide low-distortion signals

examples presented in this article, implementing the design techniques summarized in the **table,** demonstrate how easy it is to design a sine-wave source and achieve the kind of performance you need.

Phase-shift oscillators operate simply

Fig 1 depicts a 1-IC, 1-supply, amplitude-stabilized, phase-shift sine-wave oscillator. The LM389 audio-power-amplifier package contains the three discrete npn transistors shown (Q_1 through Q_3) in addition to the amplifier. Q_2 and the RC network constitute a phase-shift configuration that oscillates at about 12 kHz. The remaining circuitry provides amplitude stability.

The high-impedance output at Q_2's collector drives the LM389 amplifier's input via the 10-μF, 1-MΩ series network; the 1-MΩ resistor, in combination with the LM389 amplifier's internal 50-kΩ resistance, divides Q_2's output by 20—necessary because the amplifier has a fixed gain of 20. In this manner, the amplifier functions as a unity-gain current buffer capable of driving an 8Ω load.

The amplifier's positive output peaks are rectified and stored in the 5-μF capacitor, and the resulting potential then feeds to Q_3's base. As a result, Q_3's collector current varies with the difference between its base and emitter voltages. Because the LM313 1.2V reference fixes the emitter voltage, Q_3 performs a comparison function and utilizes its collector current to modulate Q_1's base voltage. Q_1 (an emitter follower) provides servo-controlled drive to the Q_2 oscillator.

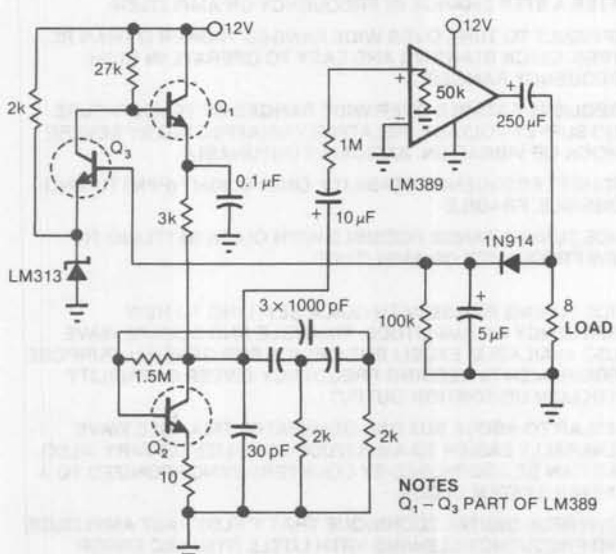


Fig 1—Phase-shift sine-wave oscillators *combine simplicity with versatility. This 12-kHz design can deliver 5V p-p to the 8Ω load with about 2% distortion.*

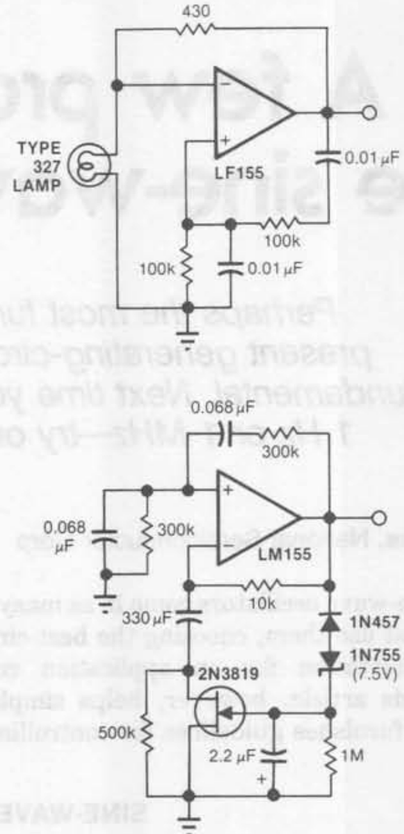


Fig 2—A basic Wein-bridge design (a) *employs a lamp's positive temperature coefficient to achieve amplitude stability. A more complex version* **(b)** *provides the same feature with the additional advantage of loop time-constant control.*

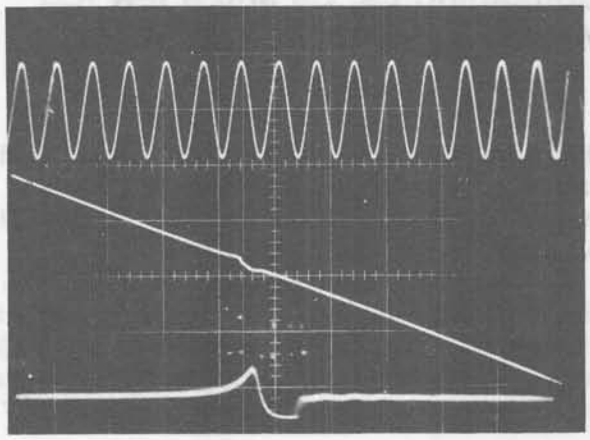
Note that you can realize an amplitude-control function with this circuit if you open Q_3's emitter and drive it with an external voltage. The LM389 output can deliver 5V p-p (1.75V rms) into an 8Ω load with about 2% distortion. A ±3V power-supply variation causes less than ±0.1-dB amplitude shift at the output.

A Wein bridge yields low distortion

In many applications, a phase-shift oscillator's distortion levels become unacceptable. A Wein bridge, however, can provide very low distortion levels. With this configuration, stable oscillation can occur only if loop gain remains at unity at the oscillation frequency. The circuit depicted in **Fig 2a** achieves this control by using a small lamp's positive temperature coefficient to regulate gain as the oscillator output attempts to vary—a classic technique for achieving low distortion that's been used by numerous circuit designers (including William Hewlett and David Packard, who built a few of this type of circuit in a Palo Alto garage about 40 yrs ago). The smooth limiting action of the bulb, in combination with the Wein network's near-ideal characteristics, yields very high performance.

The circuit shown in **Fig 2b** indicates how an electronic equivalent of a light bulb can also control loop gain. The zener diode determines output amplitude, and the 1-MΩ/2.2-μF combination sets the loop time constant. The 2N3819 FET, biased by the voltage across the 2.2-μF capacitor, controls ac loop gain by shunting the oscillator's feedback path. This circuit is more complex than the one diagrammed in **Fig 2a,** but it offers a way to control the loop time constant while maintaining almost the same distortion performance.

Fig 3 shows the performance of the **Fig 2a** circuit. The upper trace is the oscillator's output, and the middle trace shows that waveform's downward slope, greatly expanded. The slight aberration in the latter results from crossover distortion in the FET-input LF155, distortion almost totally responsible for the design's measured 0.01% distortion level. A distortion analyzer's output appears in the bottom trace.



TRACE	VERTICAL	HORIZONTAL
TOP	10V/DIV	10 mSEC/DIV
MIDDLE	1V/DIV	500 NSEC/DIV
BOTTOM	0.5V/DIV	500 NSEC/DIV

Fig 3—Low-distortion output (top trace) *is a Wein-bridge-oscillator feature. The very low crossover-distortion level (middle) results from the LF155's output stage. A distortion analyzer's output signal (bottom) indicates this design's 0.01% distortion level.*

You can achieve high voltages, too

Another dimension in sine-wave-oscillator design is stable amplitude control. In **Fig 4**'s oscillator version, not only does servo control stabilize the amplitude, but the servo loop includes voltage gain.

The circuit's ability to produce a 100V rms output stabilized to 0.025% demonstrates the technique's value. Although complex in appearance, the circuit requires only three IC packages. An LS-52 audio transformer provides voltage gain within a tightly controlled servo loop, and the LM3900 Norton amplifiers constitute a 1-kHz amplitude-controllable oscillator. The LH0002 buffer furnishes low-impedance drive to the transformer. By driving the transformer's secondary and taking the ouput from the primary, the circuit achieves a voltage gain of 100.

A current-sensitive negative-absolute-value amplifier—composed of two amplifiers in an LF347 quad—generates a negative, rectified feedback signal. The third LF347 amplifier (A_7) compares this signal with the LM329 dc reference and amplifies the

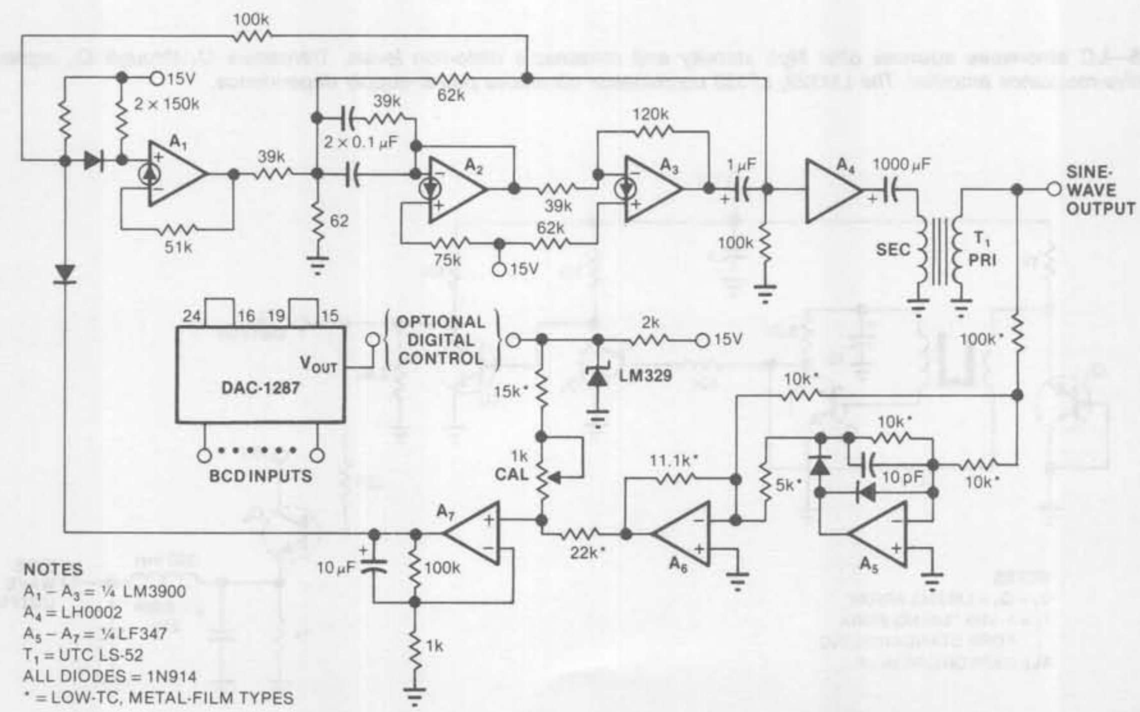


Fig 4—Generate high-voltage sine waves *using IC-based circuits by driving a transformer in a step-up mode. You can realize digital amplitude control by replacing the LM329 voltage reference with the DAC1287.*

Combining Ls, Cs and a few ICs yields high-stability sine waves

difference at a gain of 100. The 10-μF feedback capacitor sets the loop's frequency response. This stage's output controls the amplitude of the LM3900 oscillator, thereby closing the loop.

As shown, the circuit oscillates at 1 kHz with less than 0.1% distortion for a 100V rms (285V p-p) output. If you replace the summing resistors from the LM329 with a potentiometer, you can adjust the loop to remain stable for output settings ranging from 3 to 190V rms (542V p-p) with no frequency change. And if a DAC1287 D/A converter replaces the LM329 reference, a digital input code can control the ac output voltage with 3-digit calibrated accuracy.

Combine L, C and negative R for stability

All of the circuits presented so far rely on RC time constants to achieve resonance. But LC combinations can also serve and offer good frequency stability, high Q and fast starting.

A negative-resistance LC sine-wave oscillator appears in Fig 5, for example. The Q_1, Q_2 pair provides a 15-μA current source; Q_2's collector current in turn sets Q_3's peak collector current. The 300Ω pot and the Q_4, Q_5

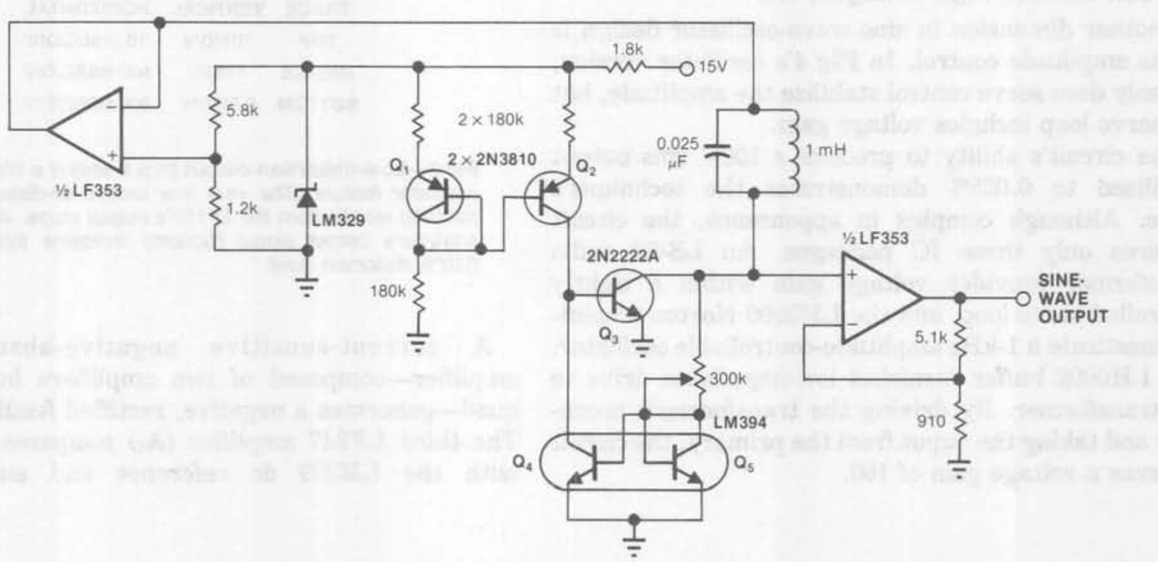


Fig 5—LC sine-wave sources *offer high stability and reasonable distortion levels. Transistors Q_1 through Q_5 implement a negative-resistance amplifier. The LM329, LF353 combination eliminates power-supply dependence.*

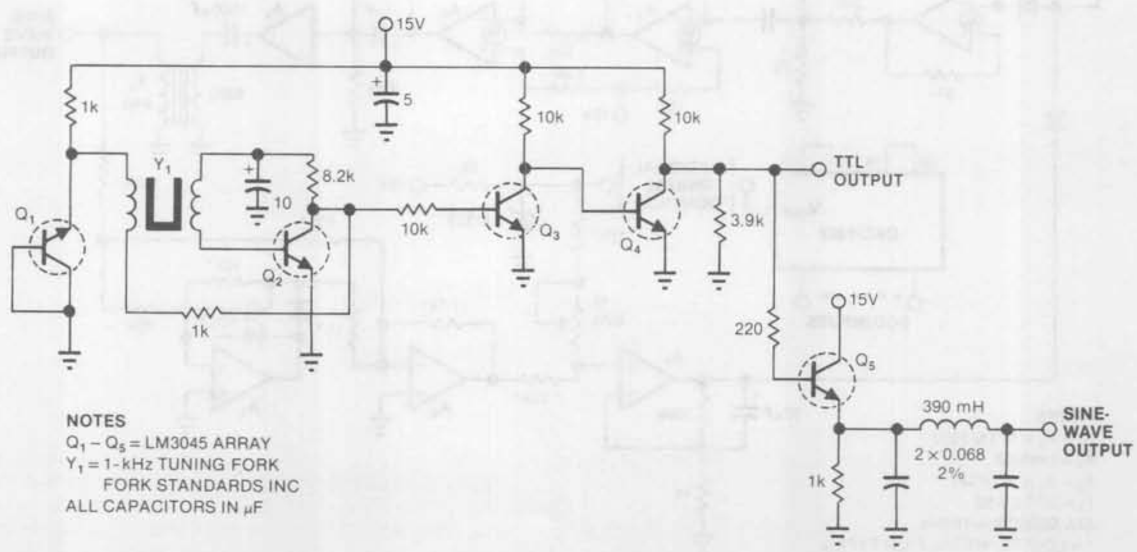


Fig 6—Tuning-fork-based oscillators *don't inherently produce sinusoidal outputs. But when you do use them for this purpose, you achieve maximum stability when the oscillator stage (Q_1, Q_2) limits. Q_3 and Q_4 provide a TTL-compatible signal, which Q_5 then converts to a sine wave.*

LM394 matched pair accomplish a voltage-to-current conversion that decreases Q_3's base current when this transistor's collector voltage rises—a process that furnishes the negative-resistance characteristic that permits oscillation.

The LC circuit in the Q_3, Q_5 collector line determines the oscillator circuit's operating frequency, and the LF353 FET amplifier provides gain and buffering. An LM329 zener diode and LF353 unity-gain follower eliminate power-supply dependence. This circuit starts quickly, and distortion remains within 1.5%.

Tuning forks offer another approach

Although oscillators for many applications can rely on combinations of passive components—whether RC or LC—to achieve resonance at the oscillation frequency, some circuits must utilize inherently resonant elements to achieve very high frequency stability. Such oscillators can generate stable low-frequency outputs under high-mechanical-shock conditions that would fracture quartz crystals.

In **Fig 6**'s circuit, for instance, a tuning fork works in a feedback loop with one of the transistors (Q_2) in an LM3045 array to achieve a stable 1-kHz output. Zener-connected Q_1 performs a combined reference and signal-limiting function. And because the oscillator is allowed to limit—a conventional technique in fork designs—it doesn't require amplitude stabilization. Q_3 and Q_4 speed up the oscillator's signal edges and furnish a TTL-compatible output level. Emitter follower Q_5 then drives an LC filter to produce a sine-wave output.

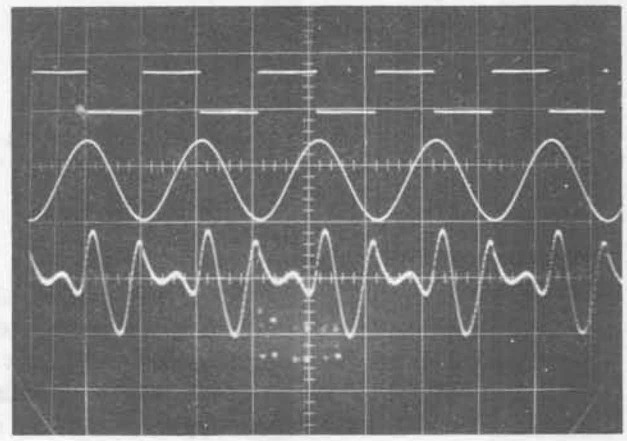
Fig 7 shows the circuit's TTL and sine-wave outputs. The 0.7% sine-wave distortion displayed in the bottom trace is a distortion analyzer's output signal.

Quartz crystals furnish high-frequency stability

If an application demands high-frequency stability—higher than a tuning-fork circuit can deliver—in the face of changing power-supply and temperature parameters, try a quartz-crystal oscillator. **Fig 8a** shows a simple example of a 100-kHz crystal oscillator—a Colpitts-class circuit that improves stability by using a JFET for low crystal loading. Voltage regulation eliminates the small effects (less than 5 ppm for a 20% shift) introduced by supply variations. And shunting the crystal with small-value capacitors allows very fine frequency trimming.

Crystals typically drift less than 1 ppm/°C, and temperature-controlled ovens can eliminate even this variation **(Fig 8b)**. The RC feedback values depend upon the thermal time constants of the oven used; the values shown are typical. Set oven temperature to coincide with the crystal's zero temperature coefficient or "turning-point" temperature, which the manufacturer specifies.

An alternative to temperature control **(Fig 8c)** places a varactor diode across the crystal. The varactor receives its bias via a temperature-dependent voltage from a circuit similar to the one shown in **Fig 8b** but without the output transistor. As ambient temperature



TRACE	VERTICAL	HORIZONTAL
TOP	5V/DIV	
MIDDLE	50V/DIV	500 μSEC/DIV
BOTTOM	0.2V/DIV	

Fig 7—Various output levels *are provided by the tuning-fork oscillator shown in* **Fig 6.** *This design easily produces a TTL-compatible signal (top trace) because the oscillator is allowed to limit. Low-pass filtering this square wave generates a sine wave (middle). The oscillator's 0.7% distortion level is indicated (bottom) by an analyzer's output.*

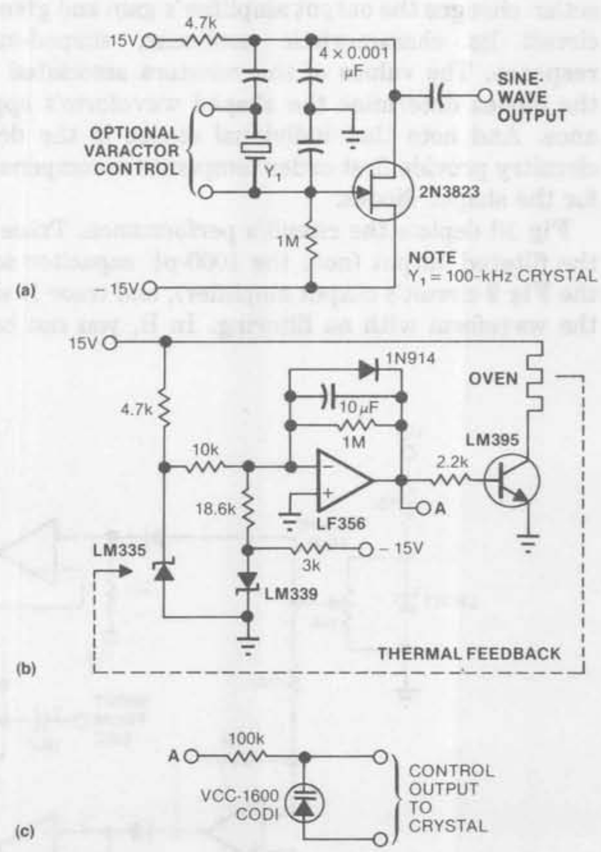


Fig 8—Stable quartz-crystal oscillators *can operate with a single active device* **(a).** *You can achieve maximum frequency stability by mounting the oscillator in an oven and using a temperature-controlling circuit* **(b).** *A varactor network* **(c)** *can also accomplish crystal fine tuning. Here, the varactor replaces the oven and retunes the crystal by changing its load capacitances.*

Quartz-crystal-based oscillators permit fine frequency trimming

varies, the circuit changes the voltage across the varactor, which in turn changes its capacitance. This capacitance shift trims the oscillator frequency.

Approximate sine waves

With the exception of the tuning-fork design, all of the preceding circuits operate as *inherent* sine-wave generators: Their normal operating mode supports and maintains a sinusoidal characteristic. Another oscillator class consists of circuits that *approximate* the sine function using a variety of techniques—usually a more complex approach but one that offers increased versatility in controlling amplitude and oscillation frequency. The adaptability of digital controls to these circuit types has markedly increased their popularity.

As an example, **Fig 9** diagrams a circuit that shapes a 20V p-p triangle-wave input into a sine-wave output. The two amplifiers in the center of the circuit establish stable bias potentials for the diode shaping network, which operates by turning individual diodes on or off depending upon the input triangle's amplitude. This action changes the output amplifier's gain and gives the circuit its characteristic nonlinear, shaped-output response. The values of the resistors associated with the diodes determine the shaped waveform's appearance. And note that individual diodes in the dc-bias circuitry provide first-order temperature compensation for the shaper diodes.

Fig 10 depicts the circuit's performance. Trace A is the filtered output (note the 1000-pF capacitor across the **Fig 9** circuit's output amplifier), and trace B shows the waveform with no filtering. In B, you can barely detect a breakpoint at the top and bottom of the waveform, but all the breakpoints become clearly identifiable in the distortion-analyzer output (trace C). Note that in **Fig 9**'s circuit, if the amplitude or symmetry of the input triangle wave shifts, the output waveform degrades badly. Typically, you can employ a D/A converter to provide input drive. Distortion in this circuit specs below 1.5% when filtered and about 2.7% without filtering.

Log shaping yields 10,000:1 frequency range

Applications that call for a wide frequency range can make good use of the shaper circuit shown in **Fig 11,** a complete sine-wave generator that you can tune from 1 Hz to 10 kHz using one variable resistor. Amplitude stability remains within 0.02%/°C, and distortion measures 0.35%. In addition, desired frequency shifts occur instantaneously because no control-loop time constants apply.

The circuit works by placing an integrator inside a comparator's positive feedback loop to produce triangle waves for shaping into sine waves. The LM311 drives a symmetrical temperature-compensated clamp arrangement, which then biases the LF356 integrator. The LF356 integrates this current into a linear ramp. At the 311's input, this ramp is summed with the clamp's output until the ramp voltage nulls out the bound voltage. At this time, the comparator changes state and the integrator output reverses.

The resultant repetitive triangle waveform then feeds to a sine-shaper section that utilizes the nonlinear, logarithmic relationship between V_{BE} and the collector current in the transistors to smooth the triangle wave. The LM394 dual transistor handles the actual shaping, while the 2N3810 provides current drive. The LF351 allows adjustable, low-impedance output-amplitude control.

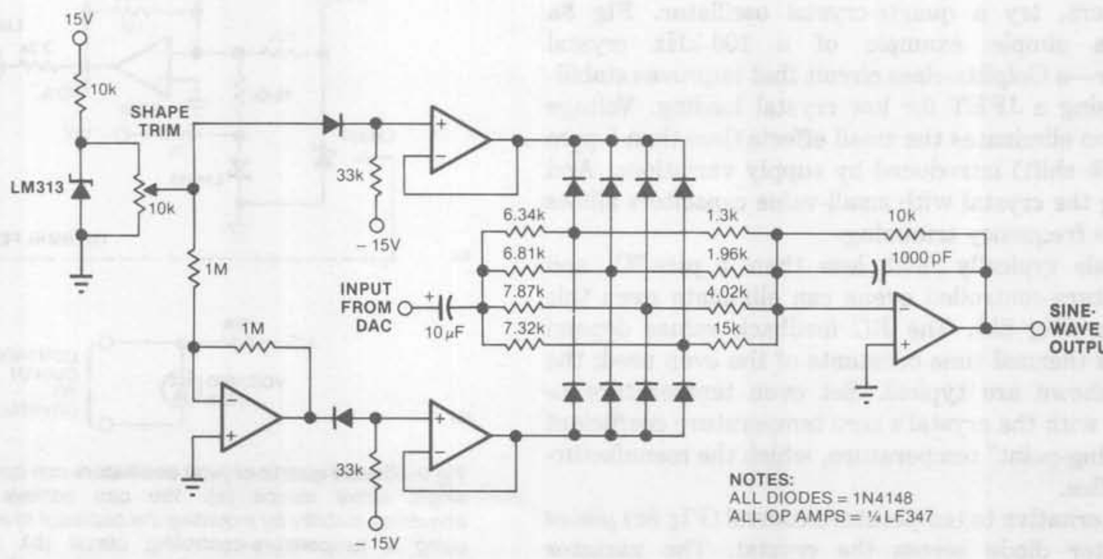
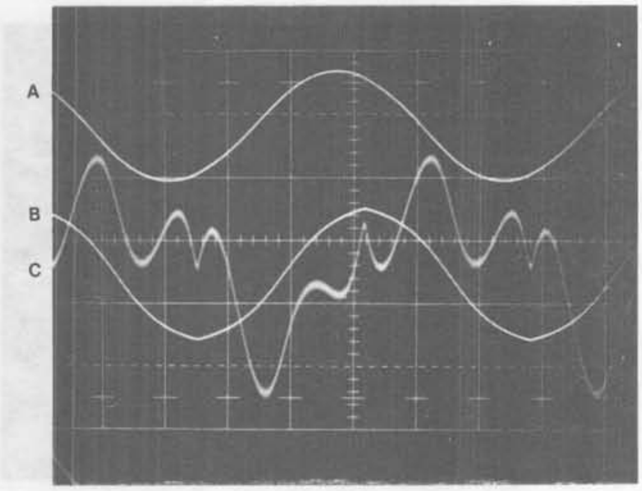
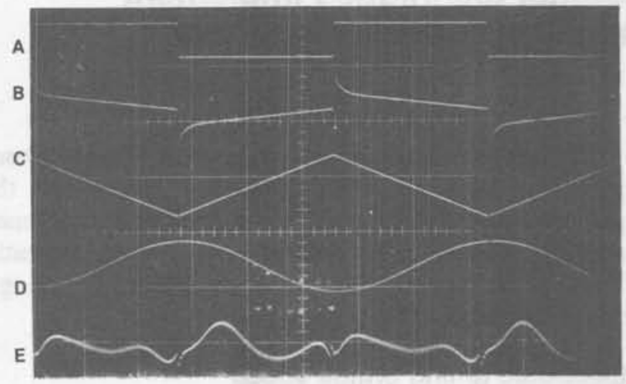


Fig 9—Breakpoint-shaping networks *employ diodes that conduct in direct proportion to an input triangle wave's amplitude. This action changes the output amplifier's gain to produce the sine function.*



TRACE	VERTICAL	HORIZONTAL
A	5V/DIV	
B	5V/DIV	20 μSEC/DIV
C	0.5V/DIV	

Fig 10—A clean sine wave results (trace A) *when* ***Fig 9****'s circuit's output includes a 1000-pF capacitor. When the capacitor isn't used, the diode network's breakpoint action becomes apparent (trace B). The distortion analyzer's output (trace C) clearly shows all the breakpoints.*



TRACE	VERTICAL	HORIZONTAL
A	20V/DIV	
B	20V/DIV	20 μSEC/DIV
C	10V/DIV	
D	10V/DIV	
E	0.5V/DIV	

Fig 12—Logarithmic shapers *can utilize a variety of circuit waveforms. The input to the LF356 integrator* ***(Fig 11)*** *appears here as trace A. The LM311's input (trace B) is the summed result of the integrator's triangle output (C) and the LM329's clamped waveform. After passing through the 2N3810/LM394 shaper stage, the resulting sine wave is amplified by the LF351 (D). A distortion analyzer's output (E) represents a 0.35% total harmonic distortion.*

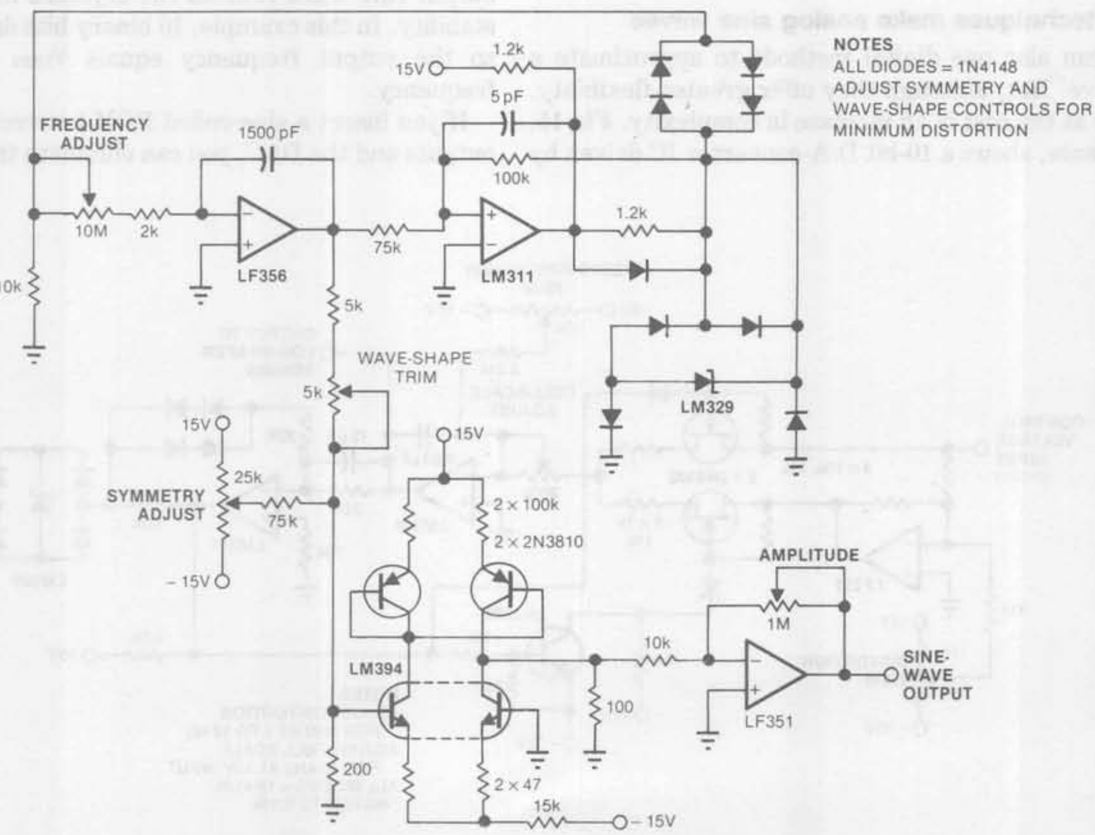


Fig 11—Logarithmic shaping schemes *produce a sine-wave oscillator that you can tune from 1 Hz to 10 kHz with a single control. Additionally, you can shift frequencies rapidly because the circuit contains no control-loop time constants.*

Digital techniques implement analog sine-wave sources

Typical circuit waveforms appear in **Fig 12.** Should you need an even wider frequency range than that provided by this circuit, bear in mind that more sophisticated versions **(references)** achieve operation from 1 Hz to 1 MHz while retaining the single-frequency-control feature.

Electronic tuning brings speed

A very-high-performance version of **Fig 11**'s log shaper design appears in **Fig 13.** Here, the LF356 integrator's input voltage is an externally supplied control voltage, rather than the zener-bridge output previously used. Inverted by the LF351, the control voltage is gated by the 2N4392 FET switches, which are in turn controlled by the LM311's output. Thus, oscillator frequency varies directly with the input control voltage. And because limiting rather than a servo-loop process determines the circuit's amplitude, an almost instantaneous frequency change occurs as the result of a step input.

A 10V input sweeps the oscillator from 1 Hz to 30 kHz with less than 0.4% distortion **(Fig 14).** Additionally, control-voltage input vs frequency-output linearity lies within 0.25%.

Digital techniques make analog sine waves

You can also use digital methods to approximate a sine wave. But, although they offer greater flexibility, it's only at the cost of an increase in complexity. **Fig 15,** for instance, shows a 10-bit D/A-converter IC driven by up/down counters to deliver an amplitude-stable triangle current into the LF357 FET amplifier. The LF357 then drives a shaper circuit of the type shown in **Fig 9.** The sine wave's amplitude remains stable, and its frequency depends solely on the clock speed used to drive the counters. If the clock is crystal controlled, the output sine wave reflects the crystal's high frequency stability. In this example, 10 binary bits drive the DAC, so the output frequency equals 1/1024 of the clock frequency.

If you insert a sine-coded ROM between the counter outputs and the DAC, you can eliminate the sine shaper

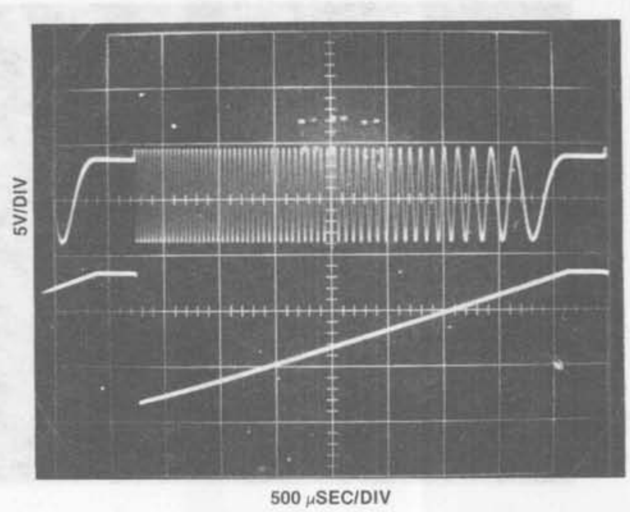


Fig 14—Rapid frequency sweeping *is an inherent feature of Fig 13's voltage-controlled sine-wave oscillator. You can sweep this VCO from 1 Hz to 30 kHz with a 10V input signal; the output settles quickly.*

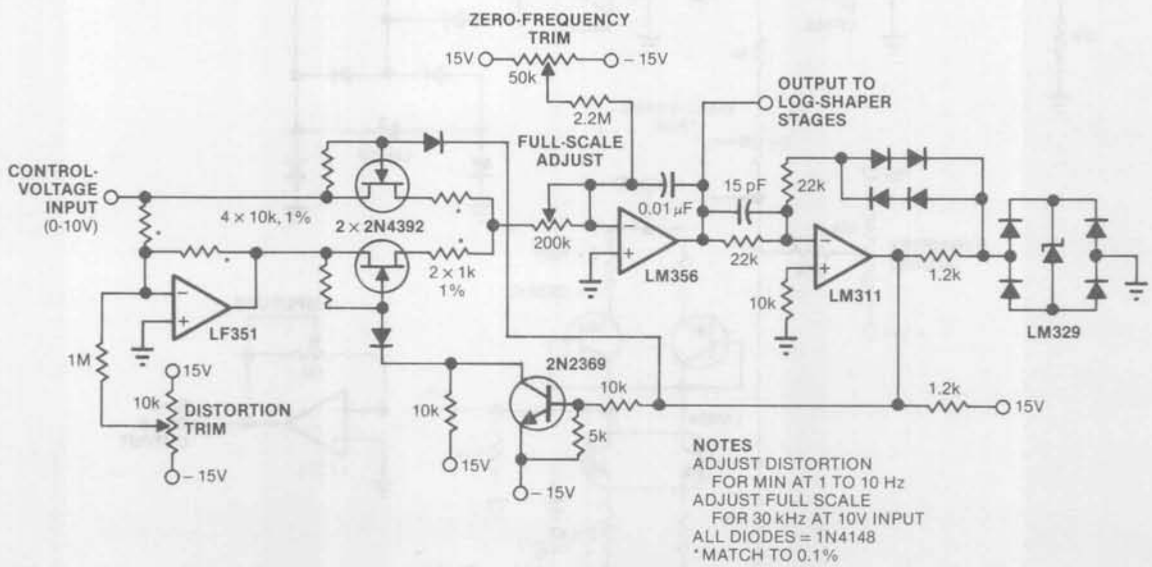


Fig 13—A voltage-tunable oscillator *results when Fig 11's design is modified to include signal-level-controlled feedback. Here, FETs switch the integrator's input so that the resulting summing-junction current is a function of the input control voltage. This scheme realizes a frequency range of 1 Hz to 30 kHz for a 0 to 10V input.*

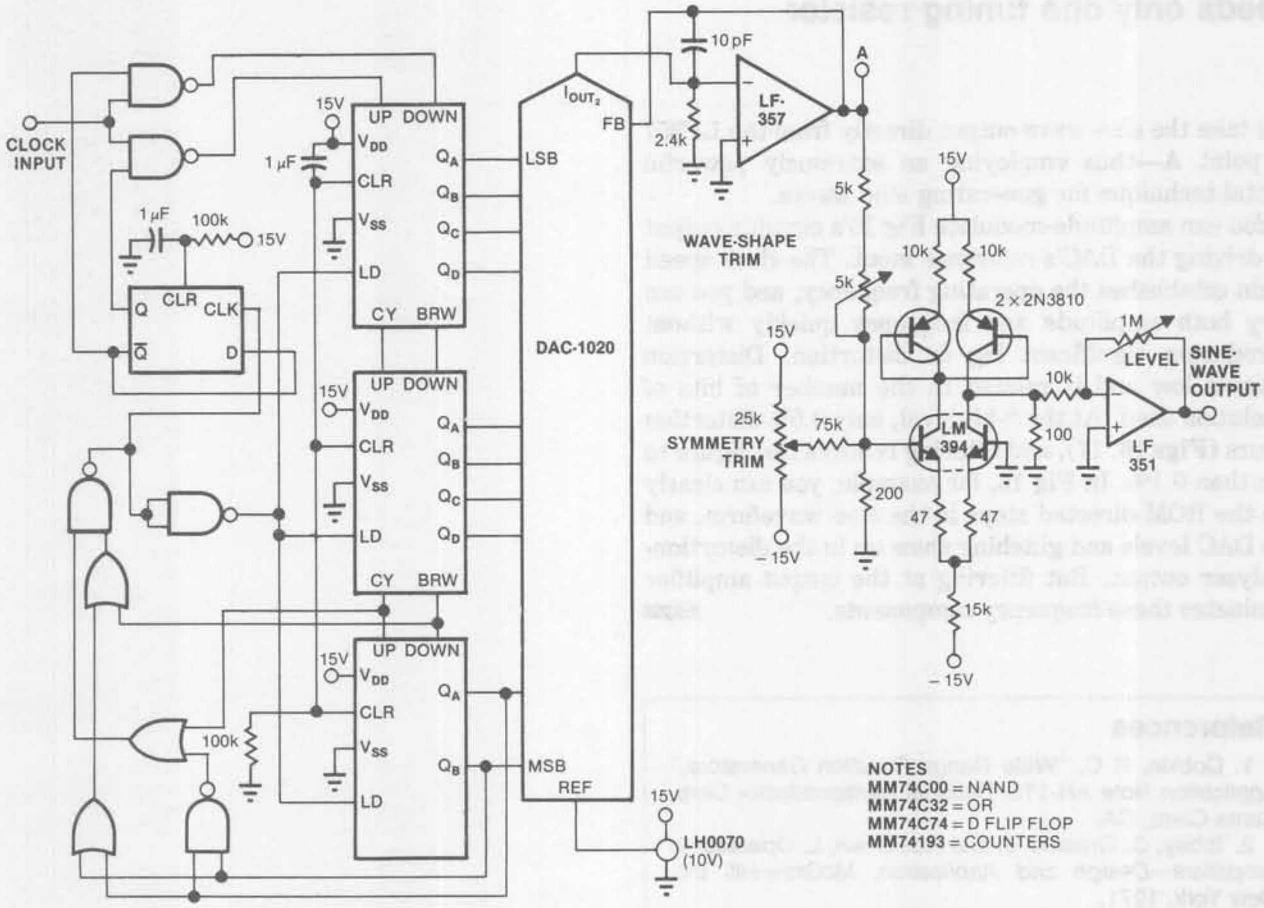
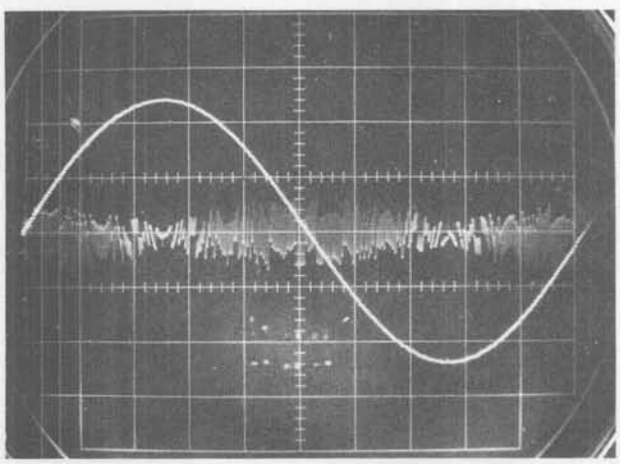


Fig 15—Digital techniques *produce triangular waveforms that methods employed in* **Fig 11** *can then easily convert to sine waves. This digital approach divides the input clock frequency by 1024 and uses the resultant 10 bits to drive a DAC. The DAC's triangular output—amplified by the LF357—drives the log shaper stage. You could also eliminate the log shaper and place a sine-coded ROM between the counters' outputs and the DAC, then recover the sine wave at point A.*



TRACE	VERTICAL	HORIZONTAL
SINE WAVE	1V/DIV	200 µSEC/DIV
ANALYZER	0.2V/DIV	

Fig 16—An 8-bit sine-coded-ROM version of Fig 15's circuit *produces a distortion level less than 0.5%. Filtering the sine output—shown here with a distortion analyzer's trace—can reduce the distortion to below 0.1%.*

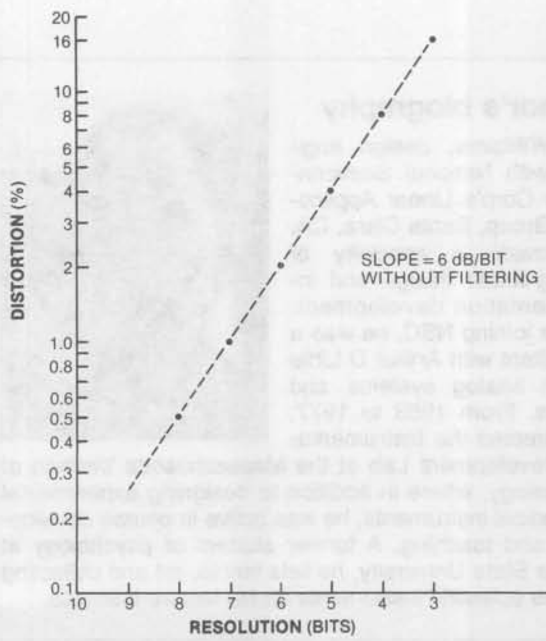


Fig 17—Distortion levels decrease *with increasing digital-word length. Although additional filtering can considerably improve the distortion levels (to 0.1% from 0.5% for the 8-bit case), you're better off using a long digital word.*

A log shaper circuit needs only one tuning resistor

and take the sine-wave output directly from the LF357 at point A—thus employing an extremely powerful digital technique for generating sine waves.

You can amplitude-modulate **Fig 15**'s circuit's output by driving the DAC's reference input. The clock speed again establishes the operating frequency, and you can vary both amplitude and frequency quickly without introducing significant lag or distortion. Distortion remains low and is related to the number of bits of resolution used. At the 8-bit level, only 0.5% distortion occurs (**Figs 16, 17**), and filtering reduces this figure to less than 0.1%. In **Fig 16**, for example, you can clearly see the ROM-directed steps in the sine waveform, and the DAC levels and glitching show up in the distortion-analyzer output. But filtering at the output amplifier eliminates these frequency components. **EDN**

References

1. Dobkin, R C, "Wide Range Function Generators," Application Note AN-115, National Semiconductor Corp, Santa Clara, CA.
2. Tobey, G; Graeme, J; and Huelsman, L, *Operational Amplifiers—Design and Application,* McGraw-Hill Inc, New York, 1971.
3. Williams, J, "A 0.1-Hz Sine Wave Oscillator Using Thermal Feedback," Massachusetts Institute of Technology, Cambridge, MA.
4. *Application Manual for Operational Amplifiers,* Teledyne Philbrick, Dedham, MA, 1969.

Author's biography

Jim Williams, design engineer with National Semiconductor Corp's Linear Applications Group, Santa Clara, CA, has made a specialty of analog-circuit design and instrumentation development. Before joining NSC, he was a consultant with Arthur D Little Inc in analog systems and circuits. From 1968 to 1977, Jim directed the Instrumentation Development Lab at the Massachusetts Institute of Technology, where in addition to designing experimental biomedical instruments, he was active in course development and teaching. A former student of psychology at Wayne State University, he lists tennis, art and collecting antique scientific instruments as his leisure interests.