

# Low-cost dual, quad FET op amps implement complex functions

Multiple general-purpose FET op amps in one package offer more than basic gain and control capabilities. By fully exploiting their high-performance potential, you can derive a variety of low-cost special-purpose circuits.

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FET op amps in dual and quad packages furnish the same performance as their single-op-amp relatives, but they cost less per amplifier, occupy less board area and require fewer bypass capacitors and power-supply buses. To show you how to implement these advantages effectively, this article examines temperature-control, sine-wave-oscillator and A/D-converter circuit designs

that each utilize one dual or quad FET op-amp package.

## Controller maintains stable temperature

Fig 1, for example, shows a complete high-efficiency pulse-width-modulating oven-temperature controller. A single LF347 package contains the four op amps shown (A<sub>1</sub> through A<sub>4</sub>).

A<sub>1</sub> functions as an oscillator whose output (Fig 2, trace A) periodically resets integrator A<sub>2</sub>'s output

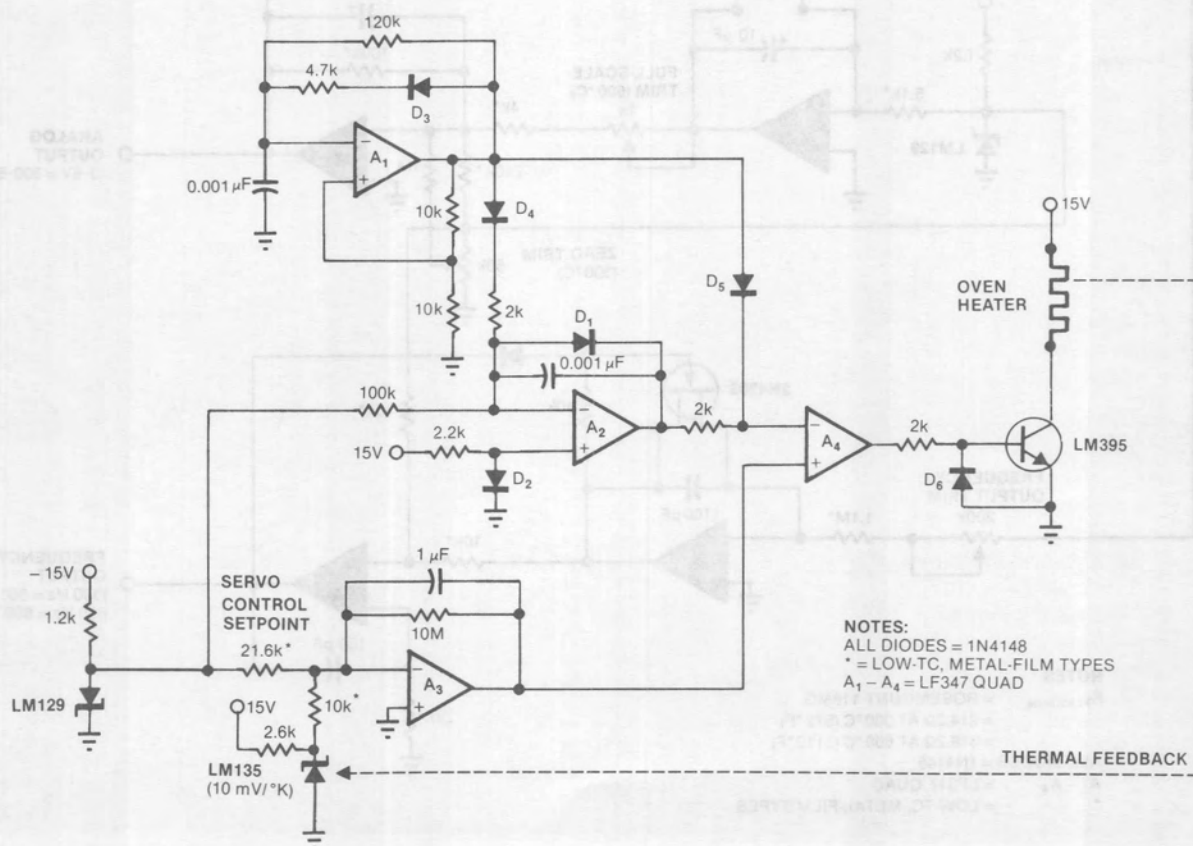


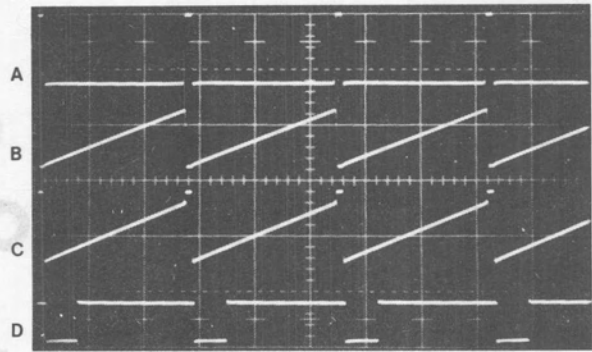
Fig 1—Connecting appropriate components to an LF347 quad FET-op-amp IC produces a high-efficiency precision oven-temperature controller. This design can hold a temperature within 0.05°C despite wide ambient-temperature fluctuations.

## FET op amps serve efficiently in temperature-measurement circuits

(trace B) to 0V. Each time  $A_1$ 's output goes high, a large positive current flows into  $A_2$ 's summing junction. This current overcomes the negative current flowing through the 100-k $\Omega$  resistor into the LM329 reference. As a result,  $A_2$ 's output heads negative, ultimately limited by  $D_1$ 's feedback bound.

Diode  $D_2$  provides bias at  $A_2$ 's positive input to compensate for  $D_1$ . Accordingly,  $A_2$ 's output settles close to 0V. When  $A_1$ 's positive output pulse ends, the positive current into  $A_2$ 's summing junction ceases. Then  $A_2$ 's output ramps linearly until the next reset pulse.

$A_3$  operates as a current-summing servo amplifier that compares the currents derived from the LM135 temperature sensor and the LM329 reference. In this configuration,  $A_3$  achieves a gain of 1000, and the 1- $\mu$ F feedback capacitor permits a 0.1-Hz servo response.  $A_3$ 's output represents the amplified difference between the LM135's temperature and the desired control setpoint. You can vary the setpoint by changing the



TRACE	VERTICAL	HORIZONTAL
A	20V/DIV	
B	10V/DIV	50 $\mu$ SEC/DIV
C	10V/DIV	
D	20V/DIV	

Fig 2—Oven-controller waveforms from Fig 1's circuit show  $A_1$ 's oscillator output (trace A) and  $A_2$ 's integrator output (B) as the latter resets periodically to 0V. Trace C displays  $A_3$ 's ramp output, and D indicates the LM395's power input to the oven heater.

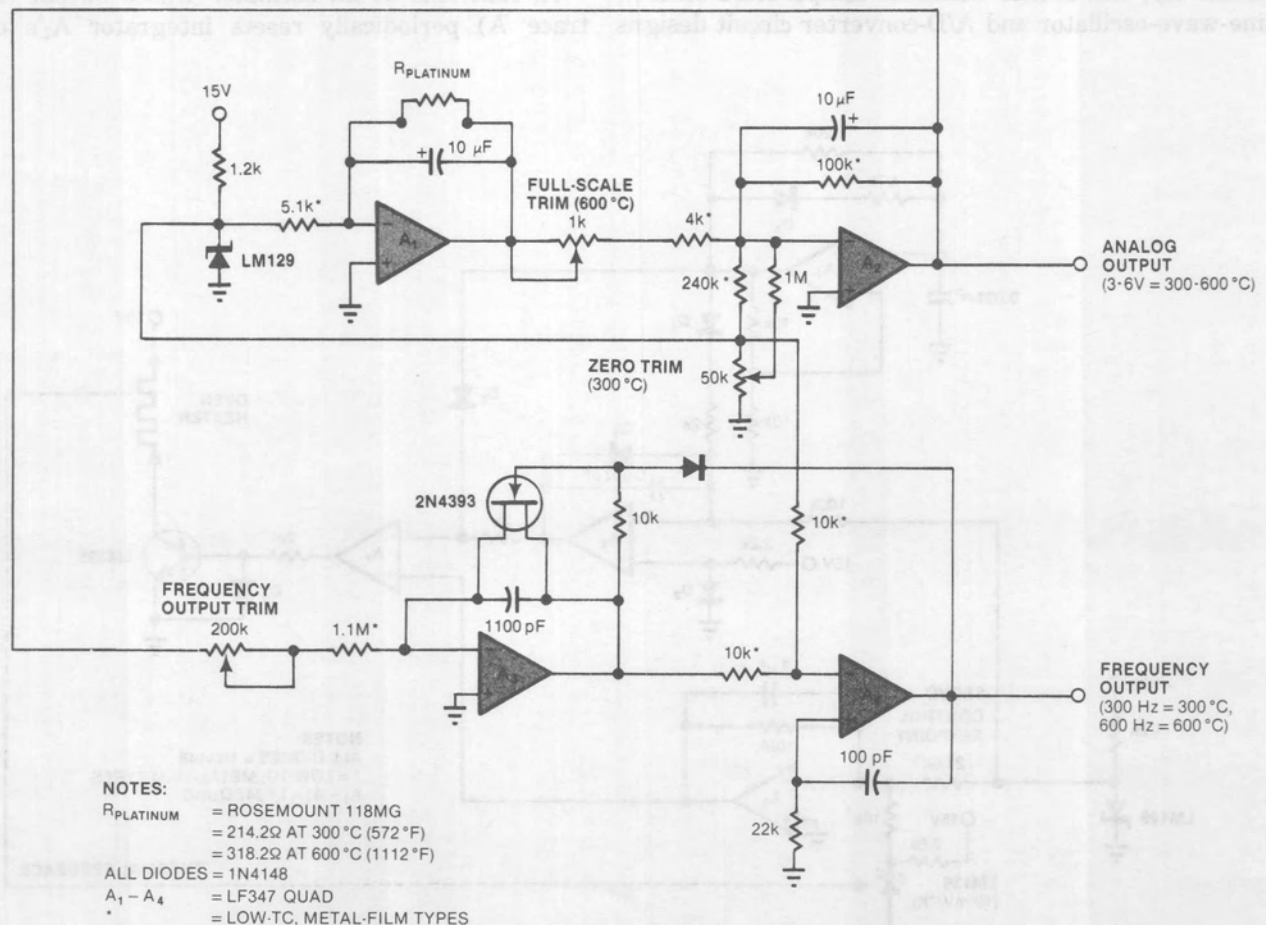
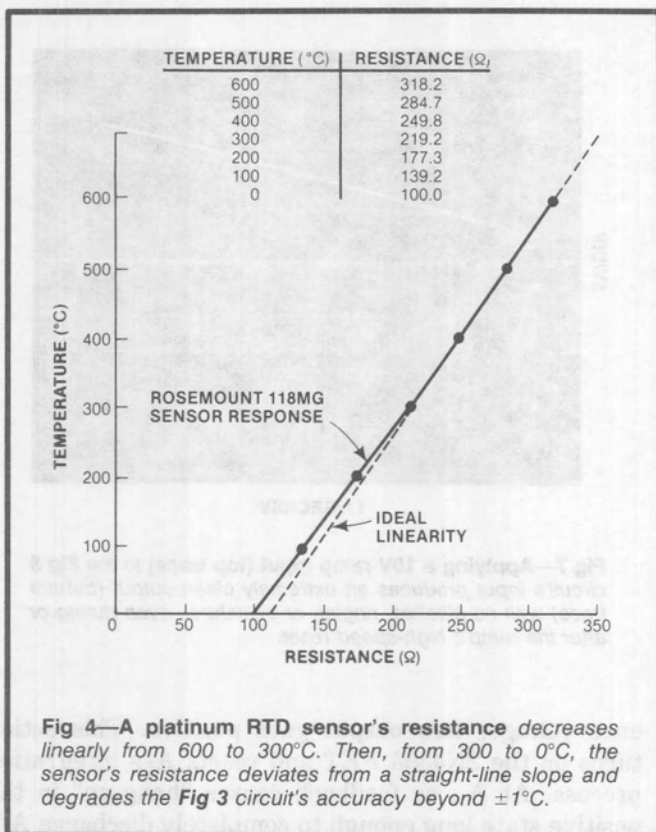


Fig 3—Generate simultaneous analog-level and frequency outputs using one LF347 package by signal-conditioning a platinum RTD sensor. You can calibrate this high-temperature (300 to 600 $^{\circ}$ C) measuring circuit to  $\pm 1^{\circ}$ C by using three trimming pots.



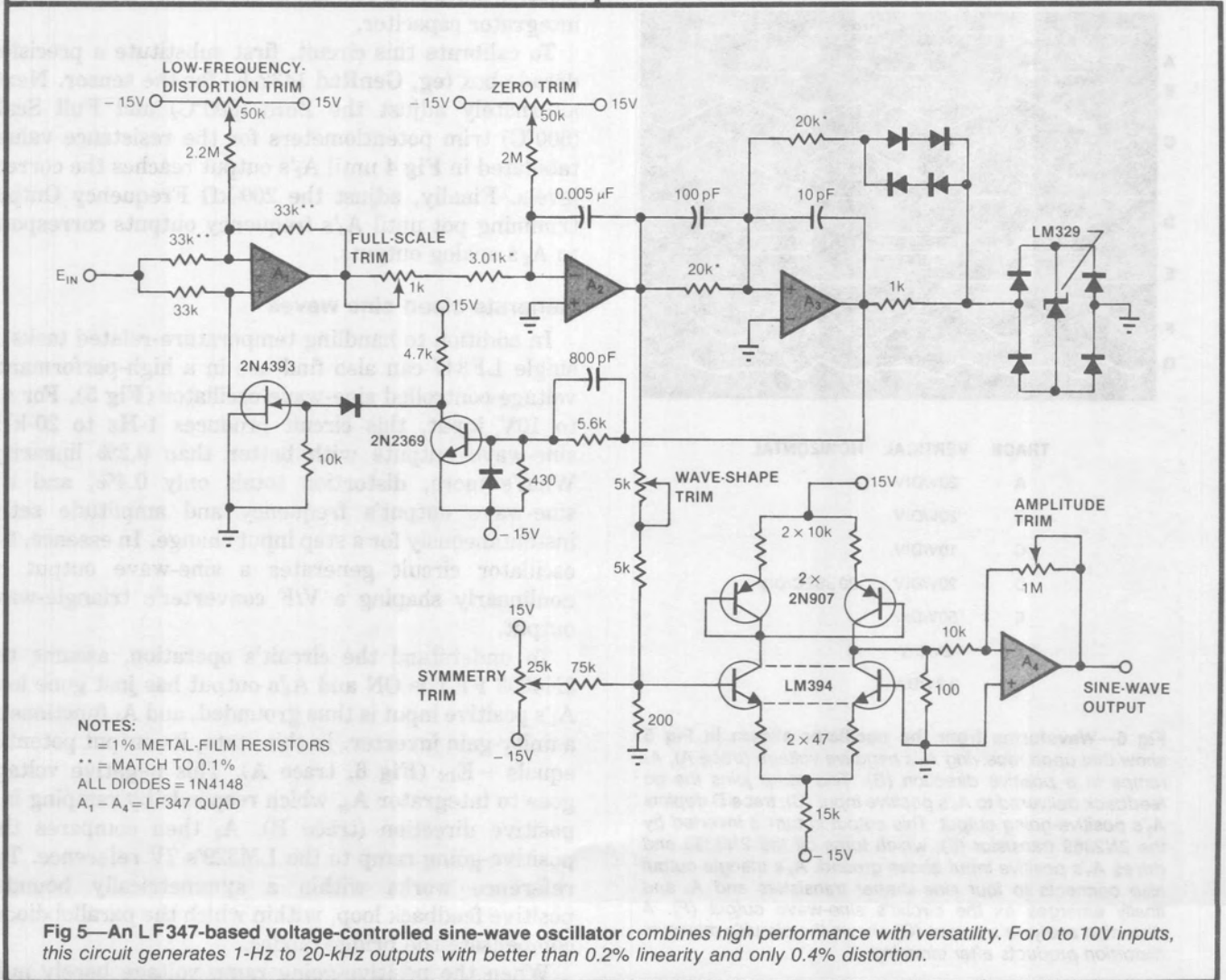
21.6-kΩ resistor's value. In Fig 1's version, the 21.6-kΩ resistor provides a setpoint of 49°C (322°K).

Configured as a comparator, A<sub>1</sub> measures A<sub>3</sub>'s output against A<sub>2</sub>'s ramp output. Specifically, A<sub>1</sub>'s output is high only when A<sub>3</sub>'s output exceeds the ramp voltage. The ramp-reset pulse from A<sub>1</sub> is diode summed with the ramp output (trace C) at A<sub>4</sub> to prevent A<sub>4</sub>'s output from going high during the reset-pulse period.

Additionally, A<sub>1</sub>'s output biases the LM395 power transistor, which switches power (trace D) to the heater. If you tightly couple the LM135 sensor to the heater and adequately insulate the oven, this controller circuit can easily hold a setpoint within 0.05°C over wide ambient-temperature excursions.

### Sensor circuit generates dual outputs

Another temperature-related circuit employing one LF347 package appears in Fig 3. In this design, the LF347 op amps signal-condition a platinum RTD sensor and provide simultaneous analog-level and frequency outputs. These outputs stay accurate to ±1°C over 300 to 600°C (572 to 1112°F). Although the conditioning circuit can maintain linearity over an even wider range, the sensor's nonlinear response from 0 to 300°C limits overall accuracy (Fig 4).

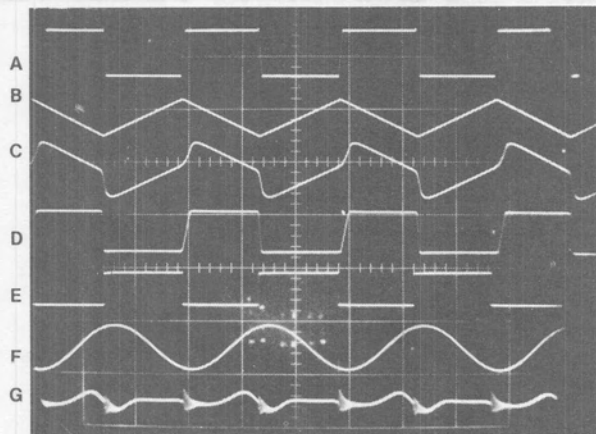


## Low-distortion oscillator generates clean sine waves

$A_1$  functions as a negative-gain inverter and drives a constant current through the platinum sensor. Both the LM329 and the 5.1-k $\Omega$  resistor supply the current reference. Because  $A_1$  provides negative gain, the sensor's developed voltage remains extremely low and eliminates self-heating-induced errors.

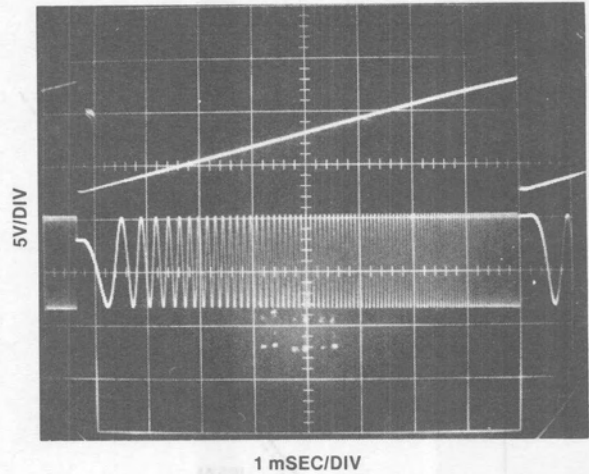
$A_1$ 's output potential—which varies with the sensor's temperature—goes to  $A_2$ . In turn,  $A_2$  furnishes scaled gain and offsetting to produce an analog output that ranges from 3 to 6V for a corresponding 300 to 600°C temperature swing at the sensor.

Performing as a voltage-to-frequency (V/F) converter,  $A_3$  and  $A_4$  generate a 300- to 600-Hz output from  $A_2$ 's 3 to 6V analog output.  $A_3$  integrates in a negative-going direction with a linear slope that depends on  $A_2$ 's output voltage. Then  $A_4$  compares  $A_3$ 's negative ramp with the LM329's positive reference voltage by current-summing in the 10-k $\Omega$  resistors. When the ramp's negative potential barely exceeds the LM329's refer-



TRACE	VERTICAL	HORIZONTAL
A	20V/DIV	
B	20V/DIV	
C	10V/DIV	
D	20V/DIV	20 $\mu$ SEC/DIV
E	50V/DIV	
F	2V/DIV	
G	0.2V/DIV	

**Fig 6**—Waveforms from the oscillator shown in Fig 5 show that upon receiving  $A_1$ 's negative voltage (trace A),  $A_2$  ramps in a positive direction (B). This ramp joins the ac feedback delivered to  $A_3$ 's positive input (C); trace D depicts  $A_3$ 's positive-going output. This output in turn is inverted by the 2N2369 transistor (E), which turns off the 2N4393 and drives  $A_1$ 's positive input above ground.  $A_2$ 's triangle output also connects to four sine-shaper transistors and  $A_4$  and finally emerges as the circuit's sine-wave output (F). A distortion analyzer's output (G) shows the circuit's minimum distortion products after trimming.



**Fig 7**—Applying a 10V ramp input (top trace) to the Fig 5 circuit's input produces an extremely clean output (bottom trace) with no glitches, ringing or overshoot, even during or after the ramp's high-speed reset.

ence voltage,  $A_4$ 's output goes positive. This action turns on the 2N4393 FET and resets  $A_3$ 's integration process. At  $A_4$ , ac feedback causes "hang-up" in the positive state long enough to completely discharge  $A_3$ 's integrator capacitor.

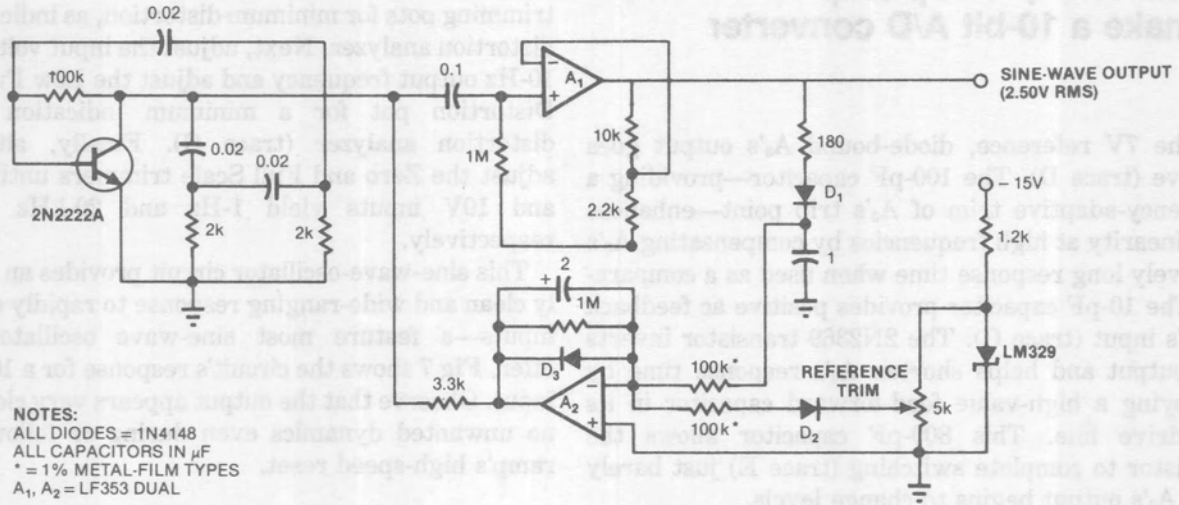
To calibrate this circuit, first substitute a precision decade box (eg, GenRad 1432-K) for the sensor. Next, alternately adjust the Zero (300°C) and Full Scale (600°C) trim potentiometers for the resistance values tabulated in Fig 4 until  $A_2$ 's output reaches the correct levels. Finally, adjust the 200-k $\Omega$  Frequency Output trimming pot until  $A_4$ 's frequency outputs correspond to  $A_2$ 's analog outputs.

### Generate clean sine waves

In addition to handling temperature-related tasks, a single LF347 can also find use in a high-performance voltage-controlled sine-wave oscillator (Fig 5). For a 0 to 10V input, this circuit produces 1-Hz to 20-kHz sine-wave outputs with better than 0.2% linearity. What's more, distortion totals only 0.4%, and the sine-wave output's frequency and amplitude settle instantaneously for a step input change. In essence, the oscillator circuit generates a sine-wave output by nonlinearly shaping a V/F converter's triangle-wave output.

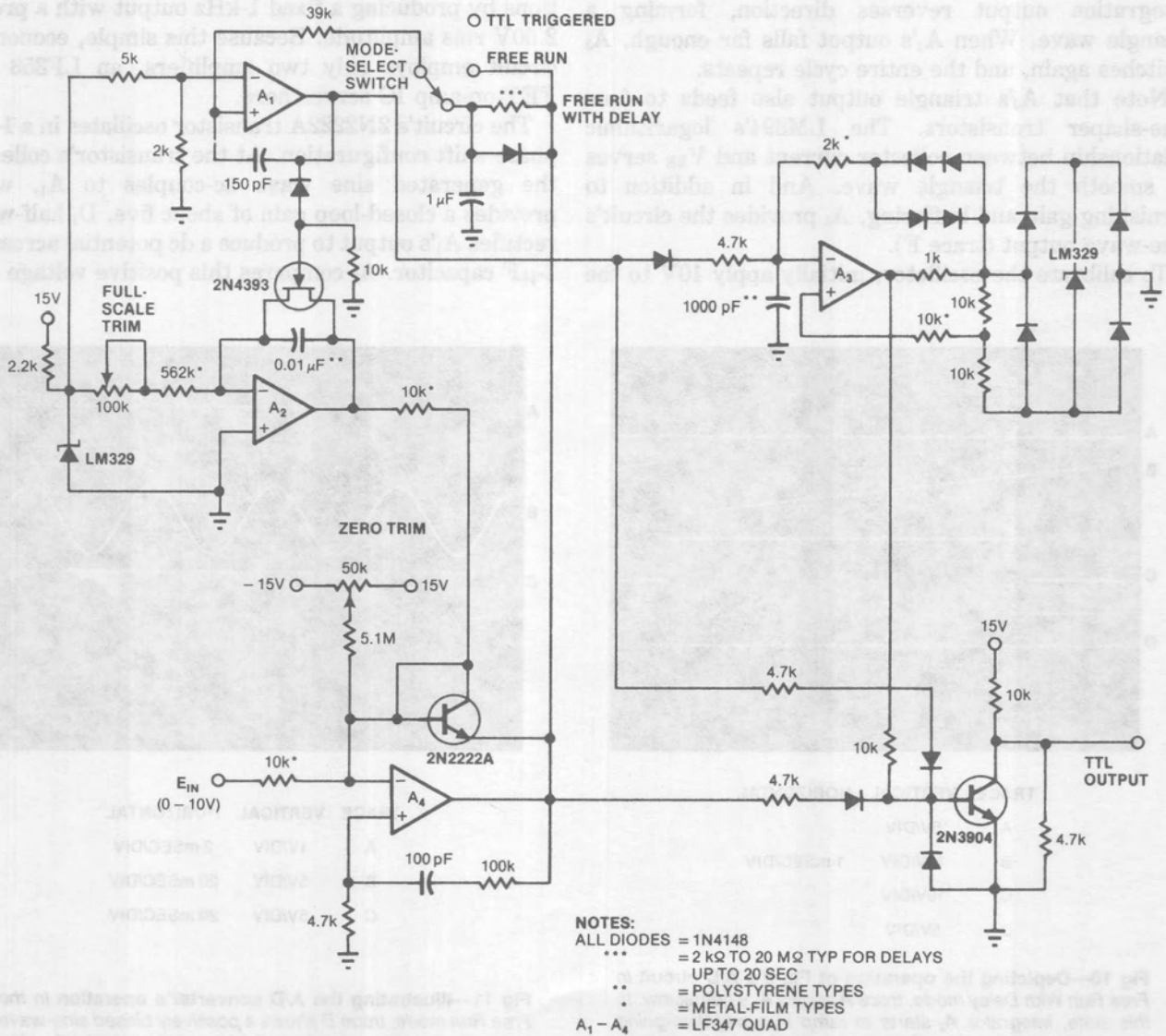
To understand the circuit's operation, assume the 2N4393 FET is ON and  $A_1$ 's output has just gone low.  $A_1$ 's positive input is thus grounded, and  $A_1$  functions as a unity-gain inverter. In this state, its output potential equals  $-E_{IN}$  (Fig 6, trace A). This negative voltage goes to integrator  $A_2$ , which responds by ramping in a positive direction (trace B).  $A_3$  then compares this positive-going ramp to the LM329's 7V reference. The reference works within a symmetrically bounded positive feedback loop, within which the parallel diodes compensate the bridge diodes.

When the positive-going ramp voltage barely nulls



NOTES:  
 ALL DIODES = 1N4148  
 ALL CAPACITORS IN  $\mu\text{F}$   
 \* = 1% METAL-FILM TYPES  
 A<sub>1</sub>, A<sub>2</sub> = LF353 DUAL

**Fig 8—Reduce parts count and save money** by basing this precision sine-wave voltage reference on an LF353 dual FET-op-amp IC. This circuit generates a 1-kHz sine wave at 2.50V rms. The 2N2222A transistor functions as a phase-shift oscillator. The A<sub>1</sub>, A<sub>2</sub> combination amplifies and amplitude-stabilizes the circuit's sine-wave output.



NOTES:  
 ALL DIODES = 1N4148  
 ... = 2 k $\Omega$  TO 20 M $\Omega$  TYP FOR DELAYS UP TO 20 SEC  
 .. = POLYSTYRENE TYPES  
 . = METAL-FILM TYPES  
 A<sub>1</sub> - A<sub>4</sub> = LF347 QUAD

**Fig 9—Three Mode Select switch positions** offer a choice of internal or external trigger conditions for this integrating A/D converter. Over 15 to 35°C, this trimmable converter provides a 10-bit serial output, converts in 10 msec and accepts 0 to 10V inputs.

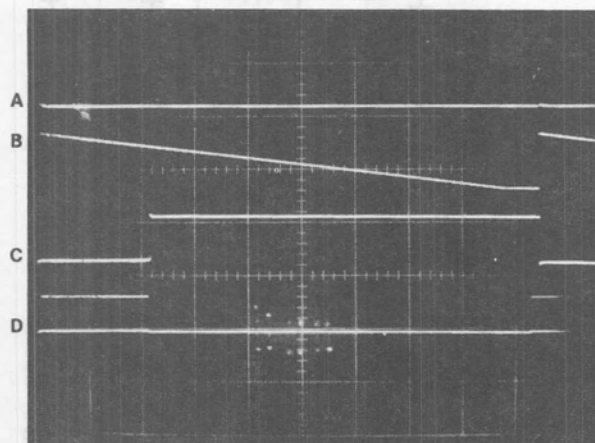
## Utilize one quad op-amp IC to make a 10-bit A/D converter

out the 7V reference, diode-bound  $A_3$ 's output goes positive (trace D). The 100-pF capacitor—providing a frequency-adaptive trim of  $A_3$ 's trip point—enhances V/F linearity at high frequencies by compensating  $A_3$ 's relatively long response time when used as a comparator. The 10-pF capacitor provides positive ac feedback to  $A_3$ 's input (trace C). The 2N2369 transistor inverts  $A_3$ 's output and helps shorten  $A_3$ 's response time by employing a high-value feed-forward capacitor in its base-drive line. This 800-pF capacitor allows the transistor to complete switching (trace E) just barely after  $A_3$ 's output begins to change levels.

The 2N2369's negative output turns off the 2N4393. As a result,  $A_1$ 's positive input rises above ground and causes  $A_1$  to act as a unity-gain follower.  $A_1$ 's output then slews immediately to the value of  $E_{IN}$ , and  $A_2$ 's integration output reverses direction, forming a triangle wave. When  $A_2$ 's output falls far enough,  $A_3$  switches again, and the entire cycle repeats.

Note that  $A_2$ 's triangle output also feeds to four sine-shaper transistors. The LM394's logarithmic relationship between collector current and  $V_{BE}$  serves to smooth the triangle wave. And in addition to furnishing gain and buffering,  $A_4$  provides the circuit's sine-wave output (trace F).

To calibrate the oscillator, initially apply 10V to the



TRACE	VERTICAL	HORIZONTAL
A	5V/DIV	
B	10V/DIV	1 mSEC/DIV
C	10V/DIV	
D	5V/DIV	

**Fig 10**—Depicting the operation of Fig 9's A/D circuit in Free Run With Delay mode, trace A shows  $A_1$ 's output low. In this state, integrator  $A_2$  starts to ramp in a negative-going direction (trace B). When  $A_2$ 's ramp potential barely exceeds the input voltage's negative value,  $A_3$ 's output goes high (C). This transition turns on the 2N3904 transistor, which shuts off the TTL output pulse train (D).

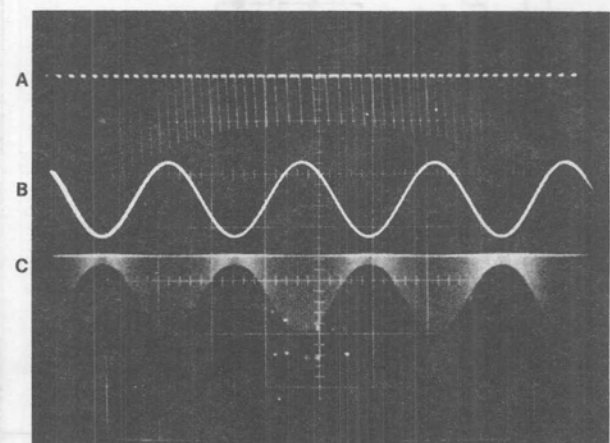
input and adjust the Wave Shape and Symmetry trimming pots for minimum distortion, as indicated on a distortion analyzer. Next, adjust the input voltage for a 10-Hz output frequency and adjust the Low Frequency Distortion pot for a minimum indication on the distortion analyzer (trace G). Finally, alternately adjust the Zero and Full Scale trimmers until 500- $\mu$ V and 10V inputs yield 1-Hz and 20-kHz outputs, respectively.

This sine-wave-oscillator circuit provides an unusually clean and wide-ranging response to rapidly changing inputs—a feature most sine-wave oscillators don't offer. Fig 7 shows the circuit's response for a 10V-ramp input. Observe that the output appears very clean, with no unwanted dynamics even during or following the ramp's high-speed reset.

### Set up a sine-wave voltage reference

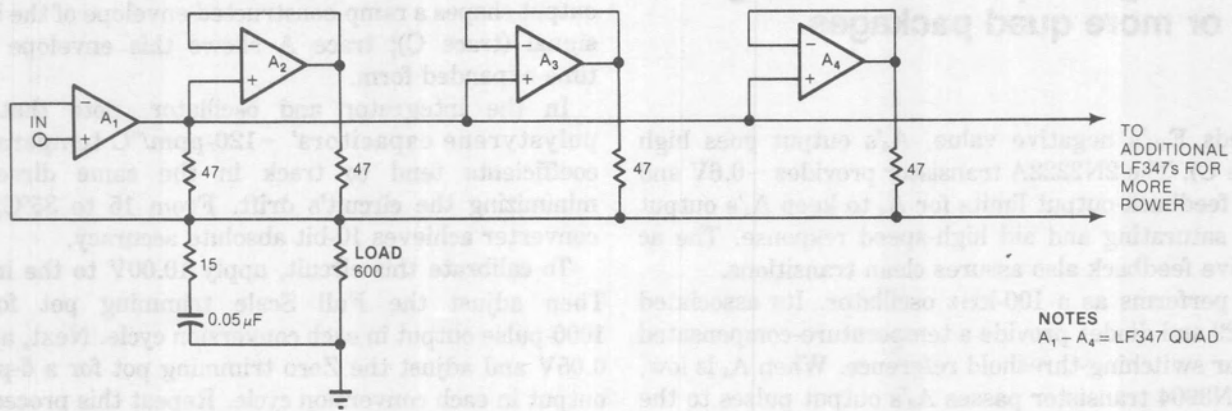
Common applications for sine-wave outputs include use as ac-calibration or amplitude-stabilized sources. Another sine-wave circuit (Fig 8) suits these applications by producing a fixed 1-kHz output with a precise 2.50V rms amplitude. Because this simple, economical circuit employs only two amplifiers, an LF353 dual FET-op-amp IC serves here.

The circuit's 2N2222A transistor oscillates in a 1-kHz phase-shift configuration. At the transistor's collector, the generated sine wave ac-couples to  $A_1$ , which provides a closed-loop gain of about five.  $D_1$  half-wave-rectifies  $A_1$ 's output to produce a dc potential across the 1- $\mu$ F capacitor.  $A_2$  compares this positive voltage with

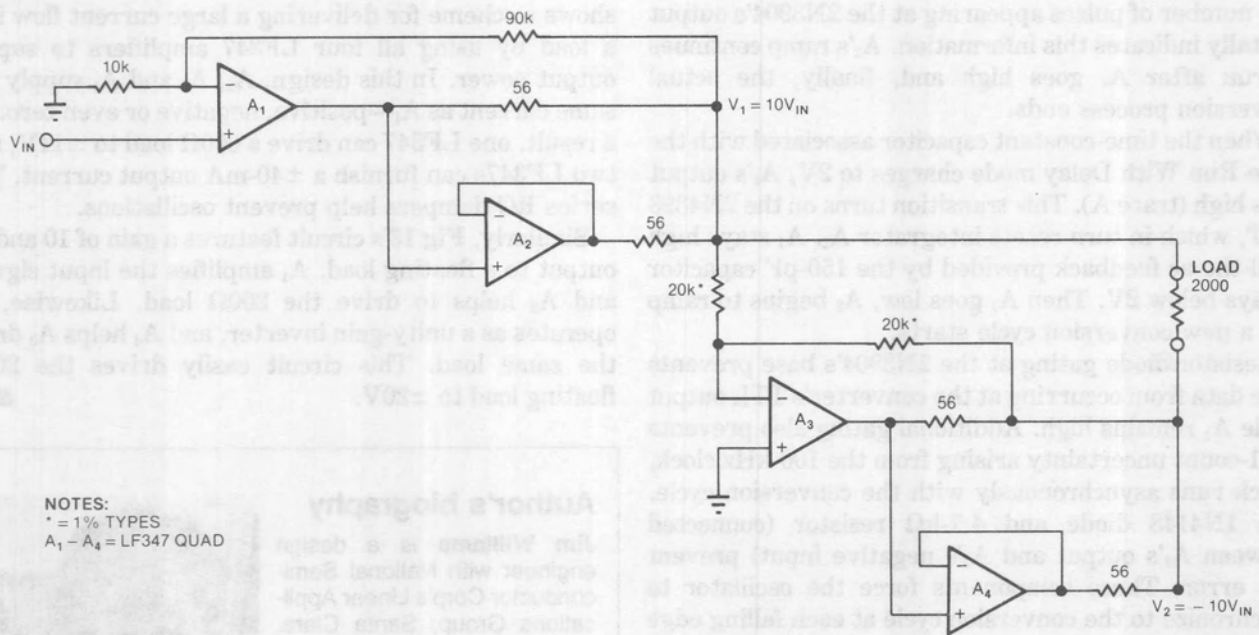


TRACE	VERTICAL	HORIZONTAL
A	1V/DIV	2 mSEC/DIV
B	5V/DIV	20 mSEC/DIV
C	5V/DIV	20 mSEC/DIV

**Fig 11**—Illustrating the A/D converter's operation in the Free Run mode, trace B shows a positively biased sine-wave input. Because reset and self trigger occur instantly after conversion,  $A_2$ 's output produces a ramp-constructed envelope of the input (trace C). Trace A shows a time-expanded form of the envelope waveform.



**Fig 12—Utilizing current-amplifying capabilities, one LF347 can drive a 600Ω load to ±11V. For additional power, two LF347s can supply an output current of ±40 mA.**



NOTES:  
 \* = 1% TYPES  
 A<sub>1</sub> - A<sub>4</sub> = LF347 QUAD

**Fig 13—Configured as a high-output-current amplifier with a gain of 10, this LF347 circuit can drive a 2000 Ω floating load to ±20V.**

a voltage derived from the LM329 reference. Diode D<sub>2</sub>, located in the Reference pot's wiper arm, compensates for D<sub>1</sub>. In A<sub>2</sub>'s feedback loop, D<sub>3</sub> prevents negative voltages from conducting to the transistor and the electrolytic 2-μF feedback capacitor upon start-up.

At a gain of 10, A<sub>2</sub> amplifies the difference between the reference and output signals. Additionally, A<sub>2</sub>'s output provides collector bias for the 2N2222A, completing an amplitude-stabilizing feedback loop around the oscillator. The electrolytic capacitor furnishes stable loop compensation.

To set the circuit's output amplitude, adjust the 5-kΩ pot until a precision voltmeter reads 2.50V rms at the sine-wave output terminal. For a ±5V variation in either power supply, the sine-wave output shifts less than 1 mV. Other key specs include 250-μV/°C typ drift

and less than 1% distortion.

### Versatile A/D converter employs quad op-amp IC

In addition to temperature- and oscillator-type circuits, the LF347 quad IC further demonstrates its versatility by implementing an integrating A/D converter (Fig 9). Either internally or externally triggered, this circuit delivers a 10-bit serial output word in 10 msec (full-scale conversion time).

To understand this circuit's operation, assume that the Mode Select switch is set to the Free Run With Delay position and the 2N4393 FET has just turned off. The A<sub>2</sub> integrator—biased from the LM329 reference—then begins to ramp in a negative-going direction (Fig 10, trace B). A<sub>4</sub> compares this ramp with the positive E<sub>IN</sub> input voltage. When A<sub>2</sub>'s ramp potential barely

## Obtain high output current using one or more quad packages

exceeds  $E_{IN}$ 's negative value,  $A_4$ 's output goes high (trace C). The 2N2222A transistor provides  $-0.6V$  and  $+7V$  feedback-output limits for  $A_4$  to keep  $A_4$ 's output from saturating and aid high-speed response. The ac positive feedback also assures clean transitions.

$A_3$  performs as a 100-kHz oscillator. Its associated LM329 and diodes provide a temperature-compensated bipolar switching-threshold reference. When  $A_4$  is low, the 2N3904 transistor passes  $A_3$ 's output pulses to the TTL output terminal. When  $A_4$  goes high, the 2N3904 is biased ON, and the transistor shuts off the output pulses (trace D).

Because  $A_2$  generates a linear output ramp, the time  $A_4$  spends low is directly proportional to  $E_{IN}$ 's value. The number of pulses appearing at the 2N3904's output digitally indicates this information.  $A_2$ 's ramp continues to run after  $A_4$  goes high and, finally, the actual conversion process ends.

When the time-constant capacitor associated with the Free Run With Delay mode charges to 2V,  $A_1$ 's output goes high (trace A). This transition turns on the 2N4393 FET, which in turn resets integrator  $A_2$ .  $A_1$  stays high until the ac feedback provided by the 150-pF capacitor decays below 2V. Then  $A_1$  goes low,  $A_2$  begins to ramp and a new conversion cycle starts.

Resistor/diode gating at the 2N3904's base prevents false data from occurring at the converter's TTL output while  $A_1$  remains high. Additional gating also prevents a  $\pm 1$ -count uncertainty arising from the 100-kHz clock, which runs asynchronously with the conversion cycle. The 1N4148 diode and 4.7-k $\Omega$  resistor (connected between  $A_1$ 's output and  $A_3$ 's negative input) prevent this error. These components force the oscillator to synchronize to the conversion cycle at each falling edge of  $A_1$ 's output.

You can adjust the time between conversions in Free Run With Delay mode by changing the RC components connected to this selection-switch position. Moreover, you can trigger the converter externally using a 2V source.

In Free Run mode, the converter self-triggers immediately after  $A_4$  goes high. The conversion time thus varies with the input voltage. Here, a positively biased sine wave (Fig 11, trace B) feeds to the converter's input. Because the converter resets and

self triggers immediately after converting,  $A_2$ 's ramp output shapes a ramp-constructed envelope of the input signal (trace C); trace A shows this envelope in a time-expanded form.

In the integrator and oscillator, note that the polystyrene capacitors'  $-120$ -ppm/ $^{\circ}C$  temperature coefficients tend to track in the same direction, minimizing the circuit's drift. From 15 to 35 $^{\circ}C$ , the converter achieves 10-bit absolute accuracy.

To calibrate this circuit, apply 10.00V to the input. Then adjust the Full Scale trimming pot for a 1000-pulse output in each conversion cycle. Next, apply 0.05V and adjust the Zero trimming pot for a 5-pulse output in each conversion cycle. Repeat this procedure until the adjustments converge.

### Amplifiers supply high output current

Yet another role the LF347 quad can play is as an element in high-output-current amplifiers. Fig 12 shows a scheme for delivering a large current flow into a load by using all four LF347 amplifiers to supply output power. In this design,  $A_2$ ,  $A_3$  and  $A_4$  supply the same current as  $A_1$ —positive, negative or even zero. As a result, one LF347 can drive a 600 $\Omega$  load to  $\pm 11V$ , and two LF347s can furnish a  $\pm 40$ -mA output current. The series RC dampers help prevent oscillations.

Similarly, Fig 13's circuit features a gain of 10 and an output to a floating load.  $A_1$  amplifies the input signal, and  $A_2$  helps to drive the 200 $\Omega$  load. Likewise,  $A_3$  operates as a unity-gain inverter, and  $A_4$  helps  $A_3$  drive the same load. This circuit easily drives the 200 $\Omega$  floating load to  $\pm 20V$ .

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### Author's biography

Jim Williams is a design engineer with National Semiconductor Corp's Linear Applications Group, Santa Clara, CA, specializing in analog-circuit and instrumentation development. Previously, he worked as an analog systems and circuit consultant at Arthur D Little Inc and directed the Instrumentation Development Lab at the Massachusetts Institute of Technology. Jim studied psychology at Wayne State University. In his spare time, he enjoys tennis, skiing, art and collecting antique scientific instruments.

