Expand linear circuit functions with nonlinear design schemes

Circuits implementing logarithmic or exponential functions provide instrumentation and control designs with many features unobtainable using linear-only characteristics. Such circuits can gauge fuel level or a grape's ripeness.

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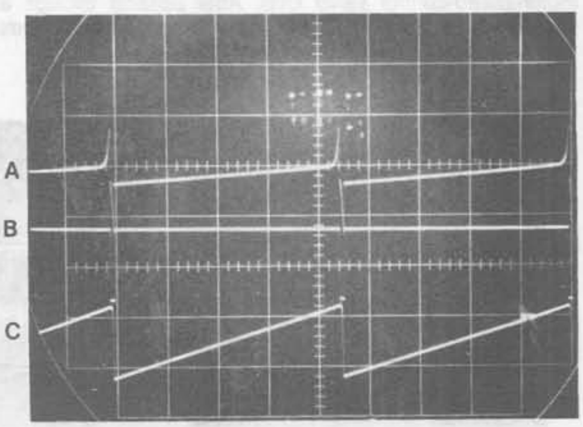
Just because a control or instrumentation design requires a logarithmic or exponential transfer function, don't assume that it must be complex, troublesome and expensive. It needn't be if you employ the correct basic circuit (see **box**, "Straightforward nonlinear circuits"). Indeed, the same concepts apply whether you must measure a tank's contents or control a motor's speed.

Govern a pump's rate

Although peristaltic pumps are generally driven by a continuously rotating motor, this technique isn't suitable when your application requires precise delivery at low rates as well as a high-throughput capability. (This situation often occurs in chemical or biological process-



TRACE	V/DIV
A	5
B	20
C	20

(b) HORIZONTAL SWEEP = 200 μSEC/DIV

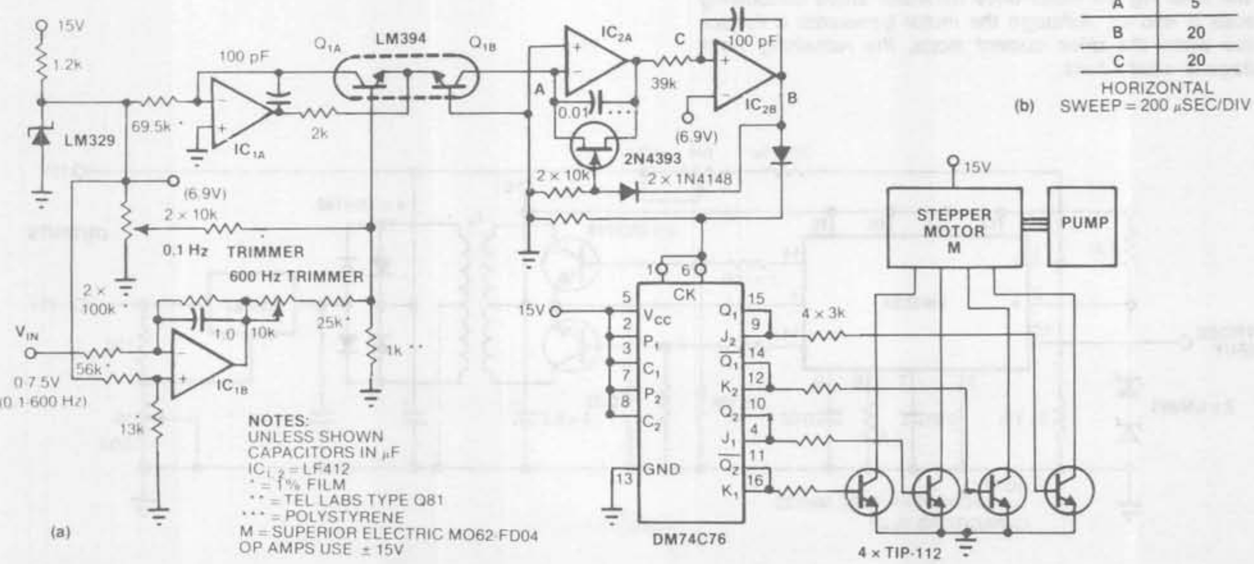


Fig 1—A stepper motor's speed varies exponentially *when driven by this voltage-to-4-phase converter. Using this approach, you can precisely govern a peristaltic pump's output flow for tight process control at low rates, yet speed it up for high throughputs. The waveforms correspond to points indicated on the schematic.*

Exponential expansion provides an 8-octave audio sweep signal

Straightforward nonlinear circuits

The theory and construction of logarithmic and exponential circuits isn't difficult, just different from what linear circuits require. By applying a few basic concepts, you can adapt the **figure**'s logarithmic **(a)** and exponential **(b)** schemes to a wide range of applications.

Capable of transforming a linear input voltage or current to a logarithmically equivalent output voltage, the design in **(a)** exhibits a 1% current-to-voltage conformity over a range of nearly six decades. This design, like most log circuits, is based on the inherently logarithmic relationship between a bipolar transistor's collector current (I_C) and base-emitter voltage (V_{BE}).

In the design, Q_{1A} functions as the "logging" device and is included within op amp A's feedback loop along with the 15.7-kΩ/1-kΩ divider. An input to A forces the amp's output to achieve the level required to maintain its summing-junction input at zero potential. But because Q_A's response is dictated by its I_C/V_{BE} ratio, A's output voltage is the log of its input.

Op amp B and Q_B provide compensation for Q_A's temperature-dependent V_{BE}. B servos Q_B's I_C to equal the 10-μA current established by the 6.9V LM329 voltage reference and its associated 700-kΩ resistor. This action fixes Q_B's collector current and therefore its V_{BE}. And under these conditions, Q_A's V_{BE} varies only as a function of the input, yielding

$$E_{OUT} = \left(\frac{15\cdot7k+1k}{1k}\right) \times (Q_BV_{BE}-Q_AV_{BE}).$$

With Q_A and Q_B operating at different I_Cs, the differential V_{BE}s are

$$\Delta V_{BE} = \left(\frac{KT}{q}\right)LOG_e\left(\frac{Q_AI_C}{Q_BI_C}\right),$$

where K=Boltzmann's constant, T=temperature in degrees Kelvin and q=electron charge.

To find the circuit's output, combine these equations to yield

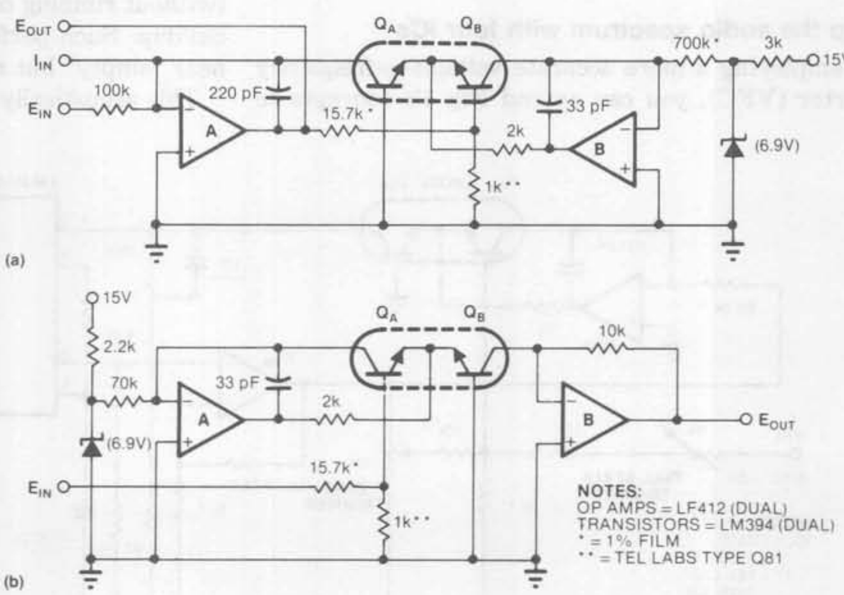
$$E_{OUT} = \left(\frac{-KT}{q}\right)\left(\frac{15\cdot7k+1k}{1k}\right) \times LOG_e\left(\frac{E_{IN}\ 700k}{6\cdot9V\ 100k}\right).$$

Here, 6.9V equals the LM329's output, 100k is the input resistor and $E_{IN}>0V$.

Although this relationship confirms the circuit's linear-to-log transfer function, it's not the whole solution; without some form of compensation, the circuit's scale factor varies with temperature. The simplest solution is to have the 1-kΩ resistor also vary with temperature; using the indicated resistor, the design is compensated to within 1% over −25 to +100°C.

If your application needs an exponential expansion instead of a logarithmic compression, just turn the circuit in **(a)** around. In the resulting exponentiator scheme **(b)**, Q_A gets driven via the 15.7-kΩ/1-kΩ divider. Here Q_B's I_C varies exponentially with its V_{BE}, and op amp B converts this current into an output voltage.

Although these circuits are easy to construct and use, you must take one precaution: Because of the devices' V_{BE} temperature dependency, you must keep the transistors and the 1-kΩ resistor at the same temperature. The transistors are a dual unit and thus track each other. The 1-kΩ resistor must be mounted as closely as possible to this unit, and the entire network must be isolated from air drafts and changing thermal currents on the pc board. The KT/q factor for which the resistor compensates varies by approximately 0.3%/°C; a few degrees difference between the components therefore introduces a significant error.



Logarithmic and exponentiating circuits *employ the inherent logarithmic relationship of a bipolar transistor's collector current to its base-emitter voltage. The logging circuit* **(a)** *displays an input-current-to-output-voltage transfer conformity within 1% over an input-current range of nearly six decades. Similar performance results when you reverse the circuit to form* **(b)**'s *exponentiator. A temperature-compensating resistor provides −25 to +100°C stability.*

control environments. Such applications require a high pumping rate for system flushing or process startup but a much lower, very accurate flow for maintaining the process.) Trying to meet these requirements with, say, a dc motor is difficult at best: If the motor can deliver high-speed performance, accurate control at, say, 0.1% of its maximum speed proves difficult.

Fig 1's design, however, satisfies a pump's conflicting high/low-speed drive requirements by employing an exponentially controlled stepper motor as the prime mover. In this scheme, the exponentiator—comprising IC_{1A} and Q_{1A}—gets driven by IC_{1B}. But here, unlike the version discussed in the **box,** Q_{1B}'s collector *draws* current from integrator IC_{2A}. This stage ramps up (trace **A**) until reset by level-triggered IC_{2B} (trace **B**). (Trace **C** shows how the 100-pF capacitor provides positive ac feedback to this stage's + input.) In this fashion, the oscillator's frequency follows the amount of current that Q_{1B} draws from IC_{2B}'s input. (Note that because IC_{2A}'s summing junction is always at virtual ground, this circuit is similar to the one in the **box**.)

IC_{2B}'s output clocks a dual JK flip flop that's wired to provide the 4-phase signal needed to drive the stepper motor. Using an exponentiator in this way, you achieve a very fine and predictable low-speed control (for example, 0.1 to 10 rpm), yet retain the motor's high-speed capabilities. To calibrate this circuit, ground the V_{IN} pin and adjust the 0.1-Hz trimmer until oscillation just ceases. Next, apply 7.5V to V_{IN} and adjust the 600-Hz trimmer for a 600-Hz frequency.

Sweep the audio spectrum with four ICs

By employing a more accurate voltage-to-frequency converter (VFC), you can extend **Fig 1**'s concepts to cover the complete audio spectrum **(Fig 2).** Intended for laboratory and audio-studio applications, this design provides an output frequency that varies exponentially with a linear input-voltage sweep. Because the scheme uses a VFC IC, its transfer specs remain within 0.15% from 10 Hz to 30 kHz. Thus, it's suitable for use in music synthesizers or for making swept distortion measurements. In the latter application, its output drives a sine-encoded ROM/DAC or analog shaper.

In the **Fig 2** circuit, IC_{1B} derives the voltage that drives IC_{1A}'s input and the zero trimmer from the VFC's internal reference. The exponentiator functions exactly like the design described in the **box** to convert a linear input voltage into a nonlinear collector current for driving the VFC. The VFC's direct 10-Hz to 30-kHz output also clocks a D flip flop and thus provides a 5-Hz to 15-kHz square wave. To align the circuit, ground the V_{IN} port and adjust the zero trimmer until a 2- to 3-Hz oscillation just starts. Then apply −8V and adjust the full-scale trimmer for a 30-kHz signal. For the component values shown, this process yields an exponentiator K factor of 1V/octave.

Try an electronic dipstick

Fig 3 demonstrates how an exponential measuring circuit satisfies the requirement for a noninvasive, high-reliability gasoline gauge. This scheme nonlinearly measures a fuel tank's contents to suit applications—such as remote irrigation-pump installations—that benefit from depleting the tanks as much as possible (without running out of fuel) to eliminate condensation buildup. Such performance requires a scale expansion near "empty" but not near "full."

This acoustically based design operates by bouncing

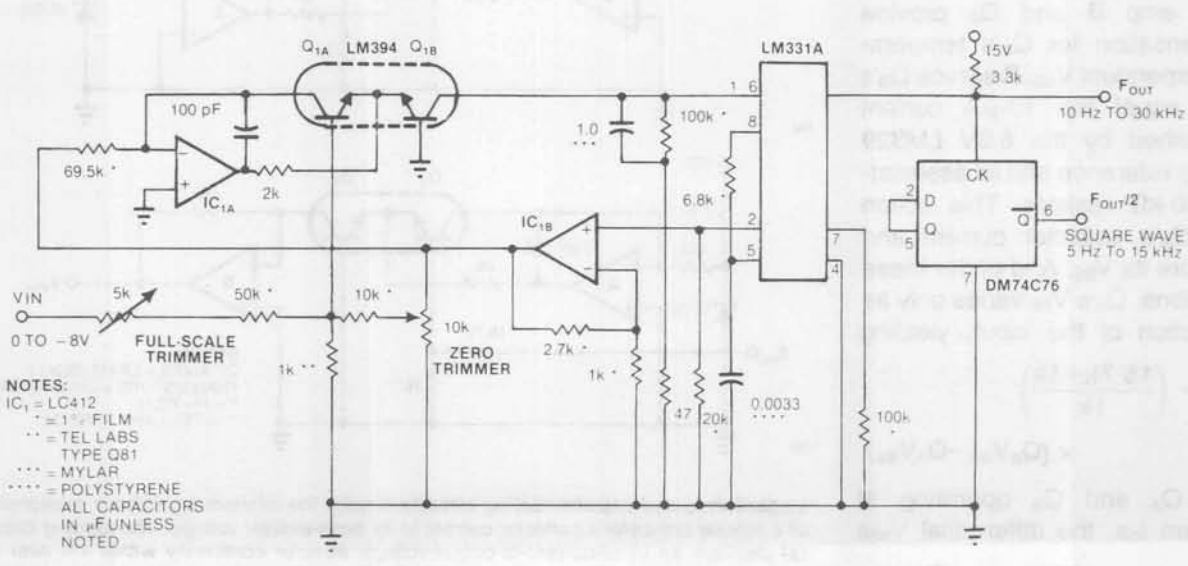
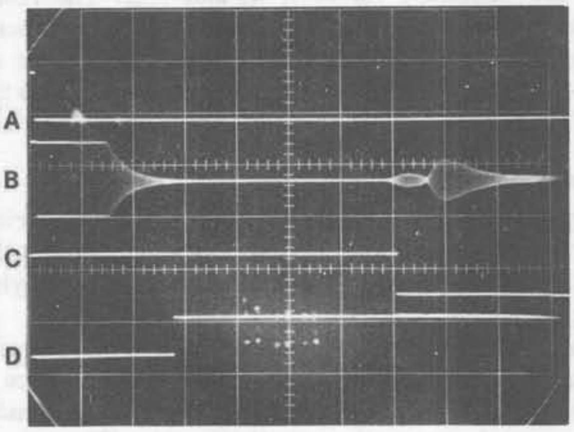


Fig 2—An exponentially swept audio spectrum *results when an input ramp voltage drives a voltage-to-frequency converter. Because the linear input is exponentiated, the circuit's output frequency varies 1V/octave.*

Ultrasonics and time expansion measure a fuel tank's contents

an ultrasonic signal off the fuel's surface and measuring the pulse's round-trip time—the longer the time, the lower the fuel level. Round-trip time gets converted to a voltage that in turn gets exponentiated to yield a high-resolution readout when the tank is nearly empty.

The 60-Hz-based clock pulse (trace **A**) drives a transistor pair and the sonic transducer ST with a 100V pulse. This same clock signal concurrently disables the receiver (to preclude false responses arising from noise) via a one-shot (traces **B** and **D**) and sets a flip flop (trace **C**). The one-shot then again goes HIGH (D), and the receiver (using the same sonic transducer) "hears" the echo and resets the flip flop (C). (This elapsed time (C) represents the tank's remaining fuel.) The flip flop's output gets clamped by the LM329, integrated by IC_{1D}



TRACE	V/DIV
A	10
B	20
C	20
D	20

(b) HORIZONTAL SWEEP = 1 mSEC/DIV

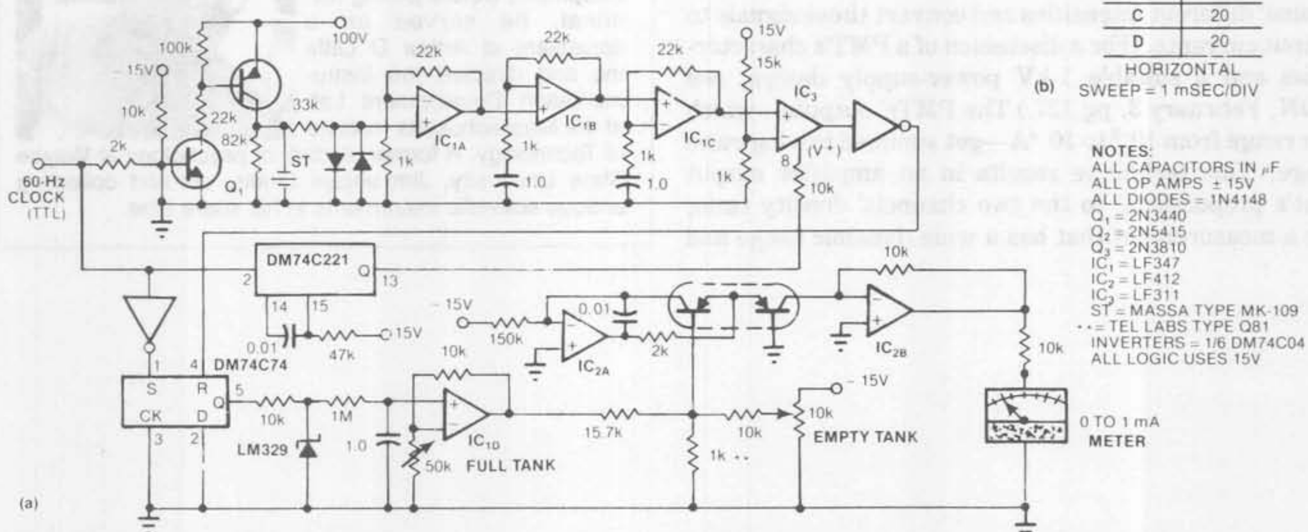


Fig 3—A sonic transducer (ST) *gauges a fuel tank's contents by transmitting a signal and measuring the echo's return time. When the 60-Hz clock fires the transducer (trace* ***A****), the receiver saturates (trace* ***B****) before it's disabled by the 221's LOW output, trace* ***D****. (Trace* ***C*** *shows the time-measuring flip flop being set HIGH by the same clock pulse.) A few milliseconds later, the 221 times out, going HIGH* ***(D)*** *and allowing the receiver to detect the echo* ***(B)*** *and reset the timing flip flop* ***(C)****.*

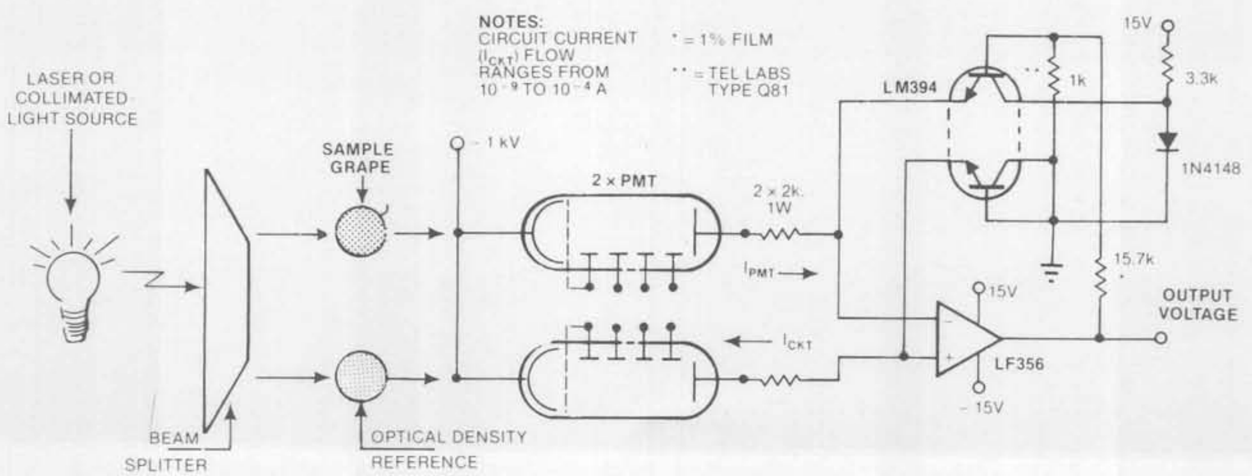


Fig 4—Photomultiplier tubes (PMTs) *determine a grape's ripeness by comparing its optical density with a reference. By using an active feedback, you can algebraically sum the PMTs' outputs in a log-ratio amplifier to yield accurate results over a 5-decade range.*

Photomultipliers determine grape ripeness, produce finer wines

and exponentiated via IC_{2A}, Q_3 and IC_{2B}. The result drives a 1-mA FS meter. The design's 1V/decade scale factor equates to a meter reading of 10% FS for an 80%-full tank; the meter's last 20% corresponds to the tank's last 2%.

Finer wines through science

Another example (**Fig 4**) demonstrates how logarithmic feedback networks can extend a photomultiplier tube's (PMT's) response range without employing complex current sources.

This design determines an object's optical density using photometric techniques. In it, a light source is optically split; one beam passes through a density reference, the other through the sample. (The sample in this case is a grape. The object of the test is to determine its ripeness.) The PMTs detect the light beams' different intensities and convert these signals to output currents. (For a discussion of a PMT's characteristics and a suitable 1-kV power-supply design, see EDN, February 3, pg 127.) The PMTs' outputs—which can range from 10^{-9} to 10^{-4}A—get summed in a log-ratio stage. This technique results in an amplifier output that's proportional to the two channels' density ratio; it's a measurement that has a wide dynamic range and isn't affected by variations in the light source's intensity. Theoretically, a less-than-perfect current-to-voltage conversion results because the log amp's inputs aren't at virtual ground. In fact, however, this error is insignificant because the PMTs' output impedance is very high. This simple circuit's most significant error results from the transistors' collectors operating at slightly different potentials. But for this application, you'll never taste the difference. **EDN**

Author's biography

Jim Williams, applications manager with National Semiconductor's Linear Applications Group (Santa Clara, CA), specializes in analog-circuit and instrumentation development. Before joining National, he served as a consultant at Arthur D Little Inc and directed the Instrumentation Development Lab at the Massachusetts Institute of Technology. A former student of psychology at Wayne State University, Jim enjoys tennis, art and collecting antique scientific instruments in his spare time.