ACCURATE, LOW-COST, EASY-TO-USE IC MULTIPLIER

The AD534 Has Differential Inputs, Many Potential Applications Laser-Trimmed on the Wafer to Accuracy Within 0.25% (AD534L)

by Barrie Gilbert

The Analog Devices AD534 is a monolithic laser-trimmed multiplier having accuracy specifications conventionally associated with discrete modules. The AD534L guarantees an *overall* error of less than 0.25% of full scale, while the AD534J is within 1.0%. These accuracies are for operation at ±15V and 25°C; while these are not as "tight" as the specs of some discrete circuits under the same operating conditions, many of the specifications regarding supply-sensitivity, temperature-sensitivity, and long-term stability are in fact better, making accurate operation feasible over worse environmental conditions than was previously possible. For example, the AD534J, as a multiplier, typically maintains less than 1.5% error *over the specified temperature range and ±1 V variation of the power supplies.*

In addition to this, the AD534 has lower noise and better linearity than any other monolithic multiplier presently available, and offers greater flexibility of use, which results from having *all* its inputs (X,Y, and Z) in differential form. Many complex algebraic functions can be synthesized with a single AD534, rather than in combination with other active elements, as was previously necessary, and, like earlier circuits, it may also be used as a Divider, Squarer, or Square-Rooter, (MDSSR), with added advantages, such as choice of input/output polarity in all modes.

Like all Analog Devices monolithic multipliers, the AD534 uses the highly-successful "linearized transconductance" or translinear principle[1], introduced by the author in 1968. The improved performance is due largely to the extreme care given to the design of the layout of the chip, which includes special thin-film resistor geometries designed to exhibit low post-trim drifts. A new active-feedback scheme is incorporated to achieve very low nonlinearities[2], particularly on the Y input, for which they are typically below 0.01%. Active laser-trimming on the wafer reduces initial parametric errors (*Analog Dialogue* 9-3) and eliminates the need for external trims.

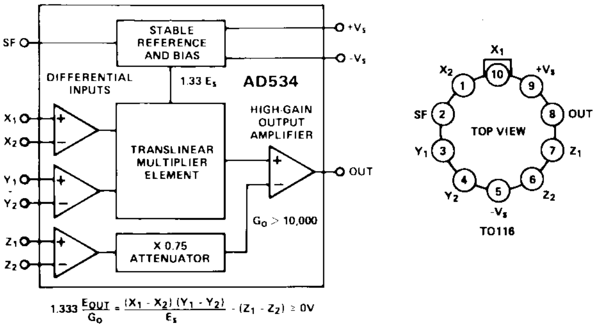


Figure 1. Functional block diagram and TO116 pin configuration of the AD534. The scale factor, E_S, is pre-trimmed to 10V.

The purpose of this article is to serve as a brief introduction to the device and to suggest a few of the applications that go well beyond the basic algebraic properties of conventional MDSSR's.

Figure 1 shows the overall scheme of the AD534, with its differential, high-impedance inputs. In most applications, the output voltage is fed back to one or more sets of inputs, and it is usually safe to describe its operation in terms of the balance: $(X_1 - X_2)(Y_1 - Y_2) = E_S(Z_1 - Z_2)$, where the variables all represent terminal voltages and E_S is a scale constant. Figure 2 shows the application as a simple multiplier, and Figure 3 shows the AD534 applied as a divider.

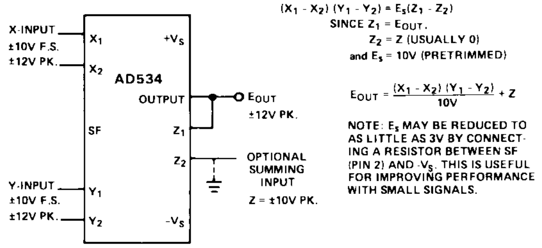


Figure 2. Basic multiplier connection. Overall gain can be achieved by attenuating the feedback from E_{OUT} to Z_1.

Though the most common and widely-used of applications, these are just a beginning. On the next few pages, we show a dozen applications that hint at the possibilities of the AD534, imaginatively applied. They are but a small sampling. The basic assumption—that the above equation is exact—should of course be modified by consultation of the specifications, weighing each parameter with respect to the specific application. However, as with operational amplifiers, the concept of an ideal device removes many barriers to creative design; the AD534 brings this concept a step nearer to actuality. Price of the "commercial" J/K/L versions are: \$16/\$24/\$36, and the "military" S/T: \$45/\$60.

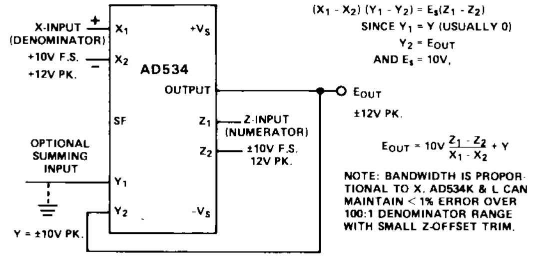


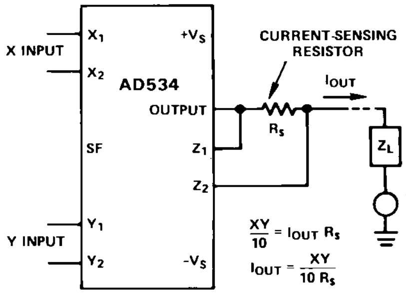
Figure 3. Basic divider connection.

---

[1] Gilbert, B., "A Precise Four-Quadrant Multiplier with Subnanosecond Response", IEEE Journal of Solid-State Circuits, pp. 365–373, December, 1968.

[2] Gilbert, B., "A High-Performance Monolithic Multiplier Using Active Feedback", IEEE Journal of Solid-State Circuits, pp. 364–373, December, 1974.

OUTPUT-TO-CURRENT CONVERSION



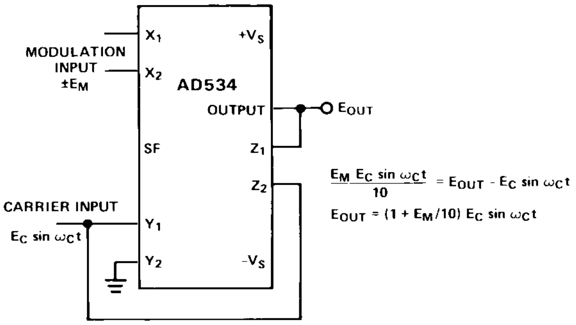
Occasionally, it is preferable to generate a current, rather than a voltage, output into the load. The availability of differential inputs allows this to be accomplished in any of the four basic modes. The illustration shows the appropriate connection for the multiplier mode.

If the output is to be integrated, Z_L can be a simple high-quality capacitor, unloaded by an op amp connected as a high-impedance follower. Note that, if desired, one side of a *reset* switch can be grounded.

The compliance constraint for this configuration, where V_L is an arbitrary common-mode potential, is

$$|V_L + I_{OUT}(Z_L + R_S)| \leqslant 12V$$

LINEAR (AM) AMPLITUDE MODULATOR



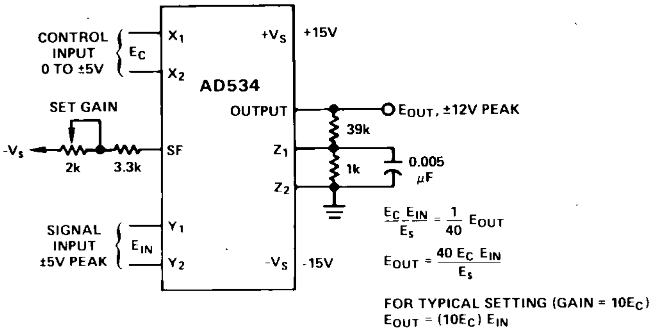
This is a very simple amplitude modulator. It makes use of the Z_2 terminal to add the carrier directly to the output, thus bypassing the multiplier for zero modulation-input. It has the advantage of allowing operation from a differential modulation input.

With Z_2 grounded, the circuit becomes a balanced modulator:

$$E_{OUT} = \frac{E_M E_C}{10} \sin \omega_C t$$

For overall signal amplification, attenuate the feedback to Z_1, or use resistance between SF and $-V_s$. To operate from a single supply, bias Y_2 to $V_s/2$ (bias Z_2 to $V_s/2$ for the balanced modulator on a single supply).

VOLTAGE-CONTROLLED AMPLIFIER

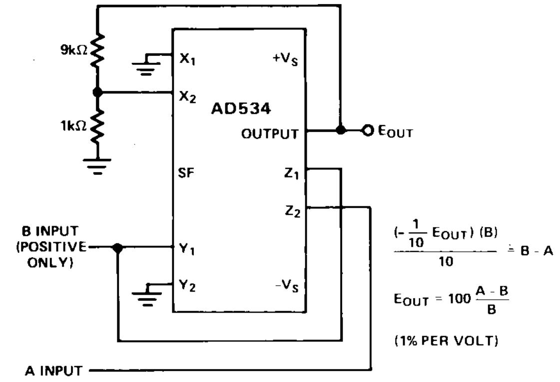


In this application, a constant or varying signal applied to the X input, E_C, controls the gain for a constant or variable signal applied to the Y input, E_{IN}. The inputs could be interchanged, but, as noted elsewhere, the Y input has the better linearity.

For this circuit, the "set gain" potentiometer is typically adjusted to provide a calibration for gain of X 10 per-volt-of-E_C.

Bandwidth is dc to 30kHz, independent of gain. The wideband noise (10Hz to 30kHz) is 3mV rms, typically, corresponding to full-scale signal-to-noise of 70dB. Noise, referred to the signal input (E_C = ±5V) is 60µV rms, typically.

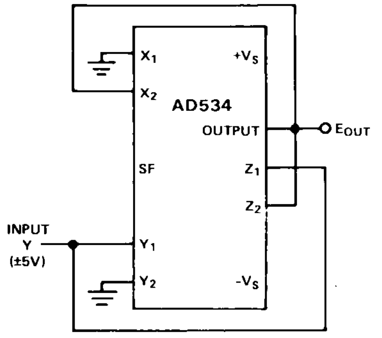
Δ% RATIO COMPUTER



The percentage-deviation function is of practical value for many applications in measurement, testing, and control. For example, the output of this circuit might be applied to a pair of biased comparators to stimulate particular actions or displays depending on whether the gain of a circuit under test were within limits, or deviating by a preset amount in either direction.

The indicated scale factor, 1%/V, is convenient and easily demonstrates the principle. However, other sensitivities, from 10%/V to 0.1%/V, as required by the application, can be obtained by altering the feedback attenuation ratio, from 1 to 1/100. Gain or attenuation is easily applied to the A signal externally for calibration to the normalized form.

BRIDGE-LINEARIZING FUNCTION



$$\frac{(-E_{OUT})(Y)}{10} = Y - E_{OUT}$$

$$E_{OUT}\left(1 - \frac{Y}{10}\right) = Y$$

$$E_{OUT} = 10\,\frac{y}{1 - y}$$

$$\text{WHERE } y = \frac{Y}{(10V)}$$

If one arm of a Wheatstone Bridge varies from its nominal value by a factor, (1 + 2x), the voltage or current output of the bridge will be (with appropriate polarities):

$$y \approx \frac{x}{1 + x}$$

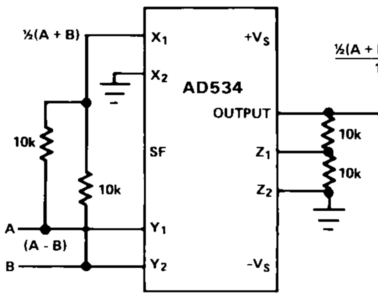
Linear response requires very small x and, usually, preamplification. The circuit shown here enables large-deviation bridges to be used without losing linearity.

This circuit computes the inverse of the bridge function, i.e.,

$$x \approx \frac{y}{1 - y}$$

Depending on which arm of the bridge varies, it may be necessary to reverse the polarity of the z connections.

DIFFERENCE OF SQUARES



$$\frac{\frac{1}{2}(A + B)(A - B)}{10} = \frac{1}{2} E_O$$

$$E_O = \frac{A^2 - B^2}{10}$$

$$|A - B| \leqslant 12.5V$$

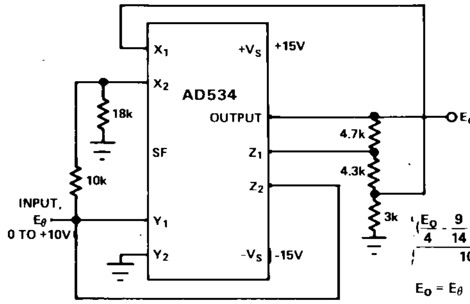
$$|A + B| \leqslant 25V$$

A single AD534 can be used to compute the difference of the squares of two input signals. The function may be useful in vector computations, and in weighting the difference of two magnitudes to emphasize the greater nonlinearly. The two matched sets of resistors could be those in the AD1805 precision-resistor quad. A slight variation of this circuit can also be used for absolute-value computation: let A be the input, let B be connected to E_O, through a diode which conducts when E_O is positive, and let both Z terminals be grounded. Since the balance equation becomes: $A^2 - B^2 = 0$, the output, B, must be equal to the absolute value of A.

Another variation of this scheme is used in the adjacent rms-computing circuit.

If |A - B| > 12.5V, Inputs Y1 and Y2 may be attenuated and the feedback attenuation increased in the same proportion (also suggested by G. Woollvin, Cossor Electronics, Ltd.).

APPROXIMATION FOR SIN θ



$$0^\circ \leqslant \theta \leqslant 90^\circ$$

$$\frac{\left(\frac{E_O}{4} - \frac{9}{14} E_\theta\right)(E_\theta)}{10} = \frac{7.3}{12} E_O - E_\theta$$

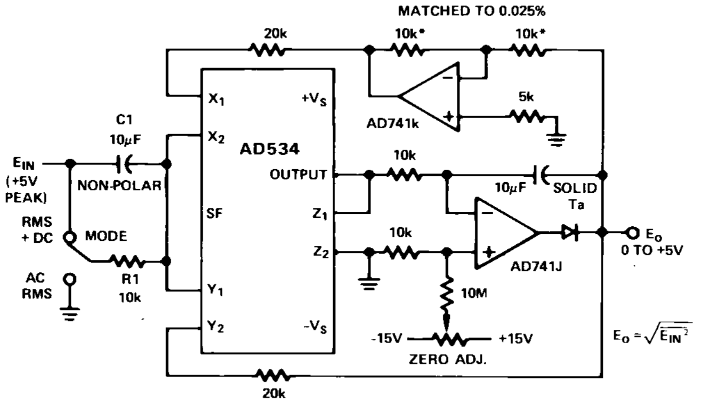
$$E_O = E_\theta \frac{(9/140)\,E_\theta - 1}{(1/40)\,E_\theta - (7.3/12)} \cong (10V)\sin\theta$$

$$\text{WHERE } \theta = \frac{\pi}{2}\,\frac{E_\theta}{(10V)}$$

The AD534 is remarkably easy to use in the implementation of the approximation formulas described in Chapter 2-1 of the *Nonlinear Circuits Handbook*. Many of these involve implicit loops to generate the function and previously required several additional op amps for the addition and subtraction of the various terms. This circuit is an example of what can be done with external resistors only. For θ between 0° and 90°, the approximation maintains a theoretical accuracy to within 0.5% of full-scale; 0.75% is practical with AD534L and 0.1% resistors.

Resistances are "preferred values" in the 5% resistor list, but since they determine vital constants, close-tolerance components must be used. In the practical evaluation, 0.1% resistances were used.

WIDEBAND, HIGH CREST RMS



The balance equation for this circuit is:

$$-(E_{IN} + E_O)(E_{IN} - E_O) = -10RC\,\frac{dE_O}{dt}$$

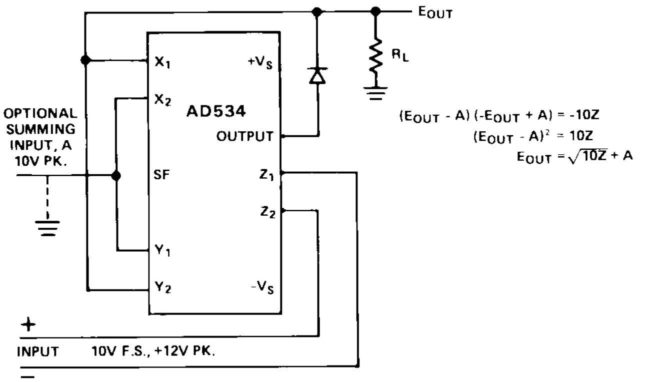
For steady-state values of E_O, the right-hand term is zero, the average value of E_{IN}^2 is equal to E_O^2, hence E_O measures the rms value of E_{IN}.

After calibration, error < 0.1% is maintained for frequencies up to 100kHz; it increases to 0.5% at 1MHz @ 4V rms. Crest factors up to 10 have little effect on accuracy.

To calibrate, with the mode switch at "RMS + DC", apply an input of (say) 1.00VDC. Adjust the zero until the output reads the same as the input. Check for inputs of ±5V.

See also *Electronics Letters*, (U.K.), Vol. 11, No. 8, p.181.

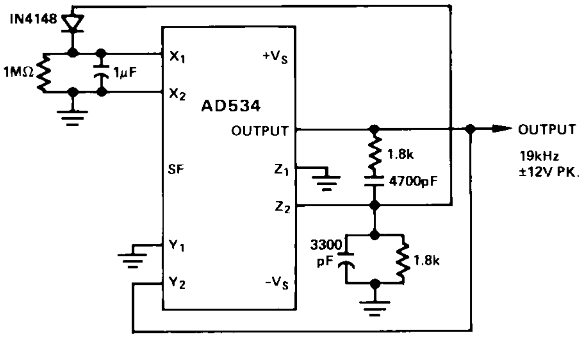
SQUARE ROOTER



This illustration shows the connection of the AD534 for square-rooting, with differential inputs. The diode prevents a latching condition – common to this configuration – which would occur if the input momentarily changed polarity. As shown, the output is always positive; it may be changed to a negative output by reversing the diode polarity and interchanging the X inputs. Since the signal input is differential, all combinations of input and output polarities can be realized.

If the output circuit does not provide a resistive load to ground, one should be connected to maintain diode conduction. For critical applications, the Z offset can be adjusted for greater accuracy below 1V.

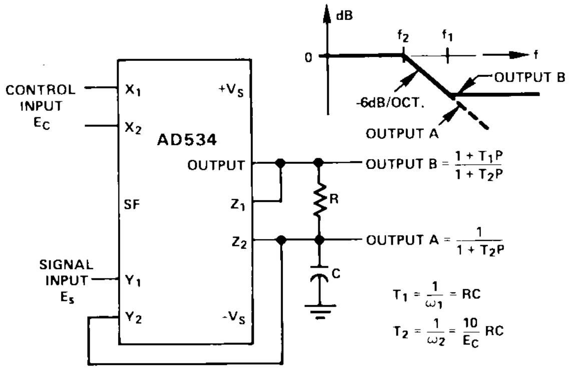
STABILIZED WIEN-BRIDGE OSCILLATOR



In this application, the AD534 is used as a variable-gain amplifier for the feedback signal from the output to the Y input, via the Wien bridge. The peak-rectifier & filter combination applies sufficient voltage to the X (denominator) input to maintain a stable oscillation-amplitude (with about 0.2% ripple). At startup, since X is small (divider mode), the gain is high, and the oscillation builds up rapidly.

This is but one of several possible schemes, involving no external active elements. Its forte is simplicity, rather than high performance; nevertheless, the amplitude is not greatly affected by supply and temperature variations, about 0.003dB per volt, and 0.005dB per °C.

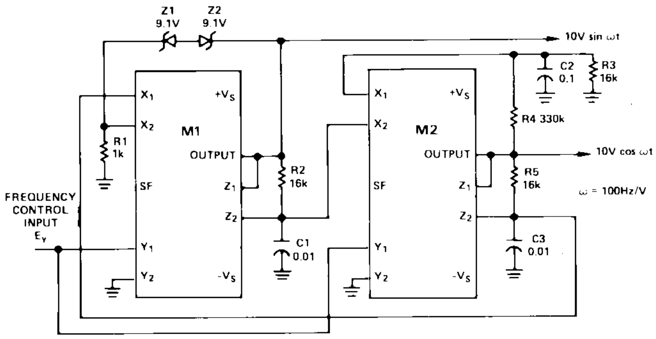
VOLTAGE-CONTROLLED LOW-PASS FILTER



The voltage at Output A, which should be unloaded by a follower, responds as though E_S were applied directly to the RC filter, but the filter's break frequency were proportional to E_C (i.e., $f_2 = E_C/(20\pi RC)$). The frequency response has a break at f_2 and a 6dB/octave rolloff. The voltage at Output B has the same response, up to f_1 ($f_1 = 1/(2\pi RC)$), then levels off at a constant attenuation of $f_2/f_1 = E_C/10$.

For example, if R = 8kΩ, C = 0.002μF, Output A has a pole at 100Hz to 10kHz, for E_C ranging from 100mV to 10V. Output B has an additional zero at 10kHz and can be loaded. The circuit can be converted to high-pass by interchanging C and R.

VOLTAGE-CONTROLLED 2-PHASE OSCILLATOR



This circuit, like the circuits shown on pp. 78–81 of the *Nonlinear Circuits Handbook*, employs two multipliers for integration-with-controllable-time-constants in a feedback loop. R2 and R5 will be recognized in the AD534 voltage-to-current configuration shown at the top of page 7; the currents are integrated in C1 and C3, and the voltages they develop are connected at high impedance in proper polarity to the X inputs of the "next" AD534. The frequency-control input, E_Y, varies the integrator gains, with a sensitivity of 100Hz/V, and frequency error typically less than 0.1% of full scale from 0.1V to 10V (10Hz to 1kHz).

C2 (proportional to C1 and C3), R3, R4 provide regenerative damping to start and maintain oscillation. Z1 and Z2 stabilize the amplitude at low distortion by degenerative damping above ±10V.

▶▶▶