# How to Use Transconductance Operational Amplifiers

*Often ignored by beginners, operational transconductance amplifiers are useful and easy to work with. This article will give you a good start toward designing and building your own projects using these versatile devices.*

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IT SEEMS HARD TO BELIEVE THAT THE first integrated-circuit operational amplifiers (op-amps) were introduced less than twenty years ago. The extremely low price of IC op-amps, and the almost unlimited number of applications for them, have served to make them one of the mainstays of modern electronic-circuit design. Indeed, it is difficult to flip through the pages of any electronics publication without seeing some reference to those useful IC's.

Actually, the term "op-amp" doesn't describe one integrated-circuit, but rather is a generic term for a whole family of linear circuits. There are compensated and uncompensated types, single-supply types, current-differencing types, BiFET types, and so on. But one breed of op-amp, known as the operational transconductance amplifier (OTA) hasn't received the amount of attention that it deserves. This article details both the theoretical and practical aspects of the OTA. By the time you are done reading it, you should feel confident enough to attempt your own design with this interesting type of IC.

One of the earliest OTA's was the 3080. There are now several others available and, while they offer several interesting additional features, they essentially obey the same rules and operate just like their predecessor. Hence, designing with the 3080 is emphasized in this article, but keep in mind that switching over to other OTA's is easy.

Before considering the internal makeup of the 3080, we should consider in general terms just what it is, and what it can do. In many respects, the 3080 is much like a common op-amp. It has differential inputs. The difference between the voltages at those two inputs is multiplied by a certain gain, and the result is available at an output pin. Also, the gain can be altered simply by changing the values of certain resistors. And, finally, the 3080 needs a bipolar power-supply.

What sets it apart from the common op-amp, however, is the inclusion of another pin that allows the user to change the gain (or more properly, the transconductance) of the amplifier. That control pin, pin 5, is a current-type input. The more current, $I_{ABC}$ that flows into the pin, the greater the IC's gain. In other words, that input current varies the transconductance of the device. In the January, 1983 issue of **Radio-Electronics**, in the series on analog-circuit design, the op-amp was modeled as a voltage source in series with an output resistance. (See Fig.3 of that article.) The transconductance amplifier, on the other hand, is modeled as a current source in parallel with an output resistance. So, yet another difference between an OTA and other op-amps is that an OTA features a current output. Speaking very generally, then, the 3080 is a current-controlled amplifier. If you consider the input for $I_{ABC}$ (the control current) to be a programming input, then the 3080 is a programmable OTA.

What can such a device be used for? There are countless applications, but some of the more interesting ones are voltage-controlled amplifiers, voltage-controlled oscillators, sample and hold circuits, analog switches, a trianglewave-to-sinewave converter, and so on. Several of those circuits will be discussed later in this article.

## Internal structure

Now that we know basically what a 3080 is and what it can do, we can start to consider its internal makeup. Unlike some other integrated circuits,

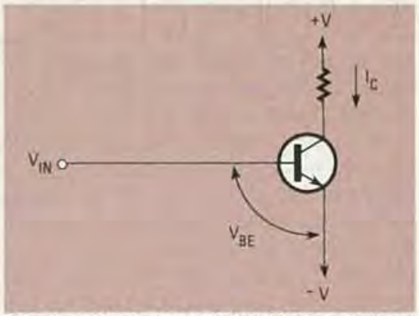

FIG. 1—THE OPERATION of the transistor differential-pair amplifier is based on the relationship of the input voltage to the collector current

where no specific knowledge of the internal circuitry is needed to use them, the unusual nature of the 3080 makes such knowledge very important.

The usual model used to demonstrate the internal structure of the 3080 is the differential-pair amplifier, although there are a few differences between them. Let's take a closer look at such an amplifier.

To understand the operation of the transistor differential-pair amplifier let's first look at the relationship of input voltage to collector current in a single transistor (see Fig. 1). That relationship is exponential and is given by the equation:

$$I_C = I'(e^{qV_{BE}/K_BT} - 1)$$

Several physical constants appear in that equation. The so-called emitter saturation-current, I prime, depends on the particular transistor used. Its value will generally be between 1 and 0.01 picoamperes. Other constants that appear include $K_B$, the Boltzmann constant, and q, the charge of a single electron. The equation can be considerably simplified by letting $V_T = K_BT/q$, where T is the temperature of the transistor in degrees Kelvin. The value of $V_T$ is then about 26 mV at room temperature. Finally, the $-1$ term can be ignored if the transistor is forward biased. The revised equation is then:

$$I_C = I'e^{V_{BE}/V_T}$$

That revised equation is considerably easier to work with.

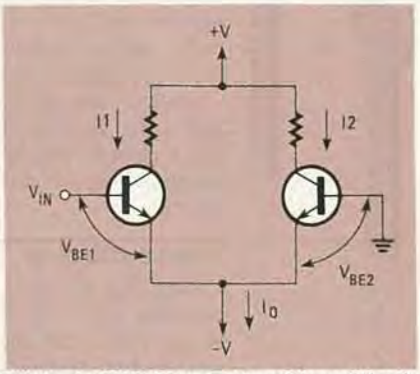

FIG 2—A SIMPLE transistor differential-pair amplifier. In analyzing it, it is convenient to assume that the beta of the transistors is very large.

Figure 2 shows a transistor differential-pair amplifier. The input of the amplifier is at the base of Q1, while the base of Q2 is grounded. A control current is drawn from the two tied emitters, and it is that control current that is used to alter the gain of the circuit. The output is taken from the two collectors.

In examining the operation of this amplifier, it is convenient to assume that the beta of the transistors is large. In that case, the emitter currents are approximately equal to the collector current. Hence, $I_O = I1 + I2$. Using the transistor equation we previously discussed, and Ohm's law, the equations for $I_1$ and $I_2$ can be derived. They are:

$$I1 = \frac{I_O}{(1 + e^{-V_{IN}/V_T})}$$

$$I2 = \frac{I_O}{(1 + e^{+V_{IN}/V_T})}$$

Note the symmetry of those equations; They must always sum to $I_O$. That relationship is shown clearly in Fig. 3. The asymptotes of that curve are quite important; neither I1 or I2 can be less than zero or greater than $I_O$. At $V_{IN} = 0$, the currents both equal $I_O/2$.

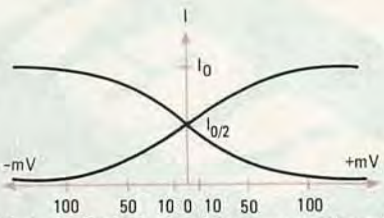

FIG. 3—THIS PLOT of emitter currents I1 and I2 shows that their sum is never greater than $I_O$. In fact, the sum of I1 and I2 is a constant and is equal to $I_O$.

The curves are, of course, exponential, but for input voltages of less than 10 mV or so, the relationship between I1 and I2, and $V_{IN}$, is more or less linear. Therefore, to keep distortion to an acceptable level in linear applications, $V_{IN}$ should be held to 10 mV or less. Also, once the input voltage exceedes 100 mV, raising $V_{IN}$ farther has no additional affect. One of the transistors will be cut-off, while the other will be saturated.

A simplified schematic of the 3080 is shown in Fig. 4. The transistor differential-pair is quite apparent, as is the absence of resistors. In their place, current mirrors are used. In a current mirror, the output current "mirrors" the input current, hence the name. Current mirrors CM1 and CM4 are current-sinking types, while CM2 and CM3 are current-sourcing types.

Current mirrors CM3 and CM4 mimic the collector currents of the two transistors of the differential pair. The sum of those currents is thus presented to the output. If the two currents are equal, indicating equal potentials at the inverting and noninverting inputs, the currents balance and there is no current at the output. If, however, CM3 sources more than CM4 can sink, the surplus is made available at the output. Similarly, if CM4 is sinking more than CM3 can provide, the difference must be provided through the output pin.

Figure 4 also shows a pinout of the 3080. The inverting and non-inverting inputs are at pins 2 and 3 respectively; those are voltage inputs. Pin 6 is the current output and may source or sink current depending on the conditions described above. Pin 5 is the input for the amplifier control-current, $I_{ABC}$. Finally, pin 7 is the positive supply pin and pin 4 is the negative supply pin.

## Some practical design-equations

Having described the internal structure

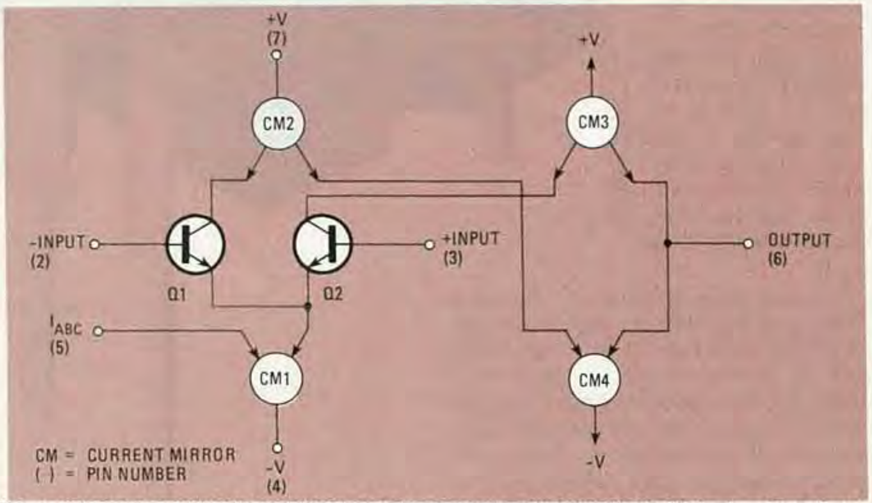

FIG. 4—SIMPLIFIED SCHEMATIC DIAGRAM of the 3080. The pin-out of the device is also shown here.

of the 3080 we can derive some practical design-equations. The most important is the so-called general transconductance equation that relates the output current to the input voltage and control current. It is: $I_{OUT} = 19.2 I_{ABC} V_{IN}$, where $I_{OUT}$ and $I_{ABC}$ are measured in milliamps and $V_{IN}$ is measured in volts.

Eventually, we will want to convert $I_{OUT}$ to a voltage, so that the unit will operate as a voltage amplifier, but for the moment, note that if $V_{IN}$ is some fixed input-signal, we can vary the output amplitude simply by modulating the control current $I_{ABC}$.

Before the foregoing equation can be put to good use, some practical limits must be specified. In general $I_{ABC}$ should always lie between 0.5 $\mu$A and 0.5 mA for best results. While it is possible to increase that upper limit somewhat, it is best not to do so since the 3080 can go into thermal runaway.

The inputs at pins 2 and 3 also have certain limitations that must be respected for good results. As we previously saw, the relationship between the input voltage and the output current is exponential and once the input reaches 100 mV any further increase will have no affect on the output current. Obviously, then, the input must be limited to less than 100 mV (or 200-mV peak-to-peak) for any sort of normal amplifier-response. But for true linear-response, the input voltage must be limited even more—a maximum value of 10 mV (20-mV peak-to-peak) is usually best. There is a trade-off here too, however, as the lower the input voltage, the lower the signal-to-noise ratio. Thus, keeping the inputs at the high end of the linear range—as close to 10 mV as possible—is desirable.

Let's now consider the supply voltage. The 3080 will work well with any power supply between ± 2 volts and ± 18 volts. Those high and low limits are extremes; best results are obtained with voltages that are somewhat between those. In many modern designs, a bipolar 15-volt supply is used, and that seems about right.

Before we move on, let's consider two other points. First of all, pin 5, the control-current input, is usually at a potential that is about one diode drop above the negative supply-voltage. Thus, if a bipolar 15-volt supply is used, the potential at pin 5 is − 14.4 volts. When calculating resistor values for that input, be sure to take the negative potential into account.

Secondly, even though the 3080 is an uncompensated-type op-amp, compensation is not usually needed since most applications use an open-loop design. Compensation is only needed when negative feedback is introduced. And simplifying things still farther, the two most common negative-feedback applications for the 3080, the voltage-controlled lowpass filter and the sample-and-hold, already use capacitors in their designs. Thus no additional compensation is needed.

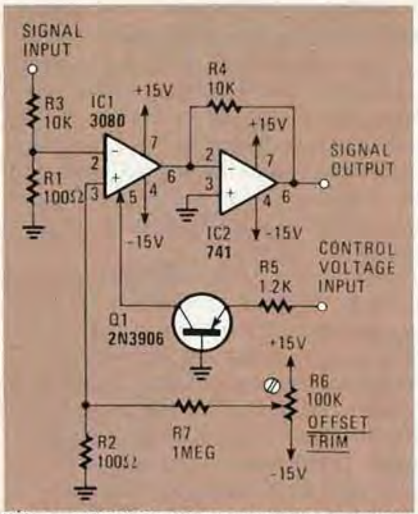

**FIG. 5—THIS VOLTAGE-CONTROLLED AMPLIFIER uses just two IC's and a transistor. Though simple, this circuit works surprisingly well.**

Of course, there is much more to working with the 3080, but that can be picked up with experience. For now, the rules we've presented are all that you need to begin designing. Let's see how to use them in practice.

## Some practical circuits

Figure 5 shows a common 3080 application, a voltage-controlled amplifier, (VCA). That circuit is common nowadays, and shows up in everything from noise-reduction units and computerized recording-studio mixing consoles to electronic music-synthesizers. (See the May, 1983 **Radio-Electronics** for a discussion of how VCA's are used in such synthesizers.) We'll examine that circuit first because it involves a very straightforward application of the design formulas and constraints we've discussed.

Suppose that our VCA is going to process a signal with a peak amplitude of ± 1 volt. As we've said, however, the 3080 works best when the input-level is limited to 10 mV. Hence, resistors R1 and R3 are used to drop the voltage to that level. Since R1 is 100 ohms, a similar resistor, R2 is placed at the other input of the 3080. In theory the 3080 should now be properly balanced, and there should be no DC feedthrough. In practice, however, offsets can still occur and when those are modulated by the amplifier severe "thumps" will result. Therefore, trimmer potentiometer R6 is added to the circuit so that any offsets can be nulled out. To adjust that trimmer, modulate the control voltage input rapidly while watching the output on an oscilloscope. Adjust R6 for minimum DC-feedthrough.

It was seen above that $I_{ABC}$, fed to pin 5, should be no greater than 0.5 mA under most circumstances. Resistor R5 and transistor Q1 provide a linear current that meets that requirement. At the maximum control-voltage of + 15 volts, Ohm's law shows that R5 will conduct a current of about 0.5 mA. (Remember, pin 5 is at − 14.4 volts).

A 741 op-amp, IC2 is configured as a current-to-voltage converter and will provide a low-impedance output as well. To calculate the value for R4, we apply the general transconductance equation. We know that $I_{ABC}$ is a maximum of 0.5 mA, and we know that the input voltage is 10 mV (thanks to the attenuator—R1 and R3). Substituting those numbers into the transconductance equation yields an output current of 96$\mu$A. Now using Ohm's law, a value for R4 can be calculated. For unity gain, divide 1 volt (the original peak input-voltage) by 96$\mu$A and the result is 10.4K. Pick 10K as the nearest standard value.

That VCA, while very simple, works quite well. Perhaps its main fault is the non-linear response of the control input when the control voltage is small. A better circuit can easily be realized with the addition of a few parts. Such a circuit is shown in Fig. 6.

That circuit is actually a linear voltage-to-current converter. It will produce a current that is linearly dependent on the input voltage. In addition, since the transistor is within the feedback loop, a very precise response is guaranteed whether the control voltage is small or large. The design equation is:

$$I_{ABC} = \frac{V_{IN}\,(R1/R2)}{R2||R}$$

where R2||R3 is the parallel combination of R2 and R3.

In designing this circuit, you determine the desired output-current and then select appropriate values for R1 and R2. Those three values are then used in the equation to determine the value of R3. The circuit, using the values shown, is set up to output a maximum current of 0.5 mA for a 15-volt input. That current is fed to pin 5 of the 3080. Diode D1 is included to protect the circuit from large negative input-

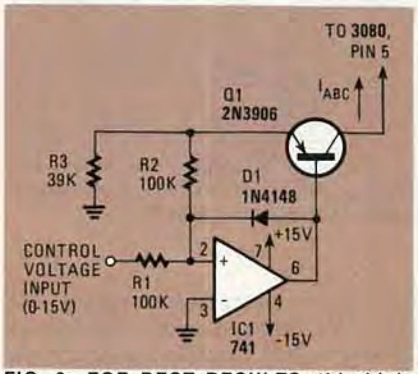

**FIG. 6—FOR BEST RESULTS, this high-precision current source can be used with the circuit shown in Fig. 5. Its output is fed to pin 5 of the 3080.**

voltages.

The VCA just described is actually a two-quadrant multiplier. It is a multiplier in the sense that the input signal is multiplied by a certain gain; that gain is determined by the control-voltage input. And it has two-quadrant operation because the signal is allowed to be bipolar; the control voltage, though, can only be positive. For that reason, the graph of the product of the two inputs, which is the output of the circuit, can lie only in one or the other of two quadrants of the four-quadrant Cartesian plane so familiar to most of us from elementary algebra. A four-quadrant multiplier, on the other hand, allows both the control voltage and the signal to be bipolar. Thus the output of that circuit can fall in any of the four quadrants.

### Four-quadrant multiplier

Perhaps one of the most interesting circuits to come along in quite a while is a four-quadrant multiplier that uses a single 3080 and a 741 op-amp. Figure 7 shows such a circuit; its simplicity is quite striking. Before describing the circuit in detail, a few things should said about four-quadrant multiplier applications. As mentioned above, either input of the amplifier will accept bipolar signals. The product of those two signals (divided by a suitable scaling factor) is available at the output. But, most important, the polarity of the output will be correct. For example, if two negative signals are multiplied, the output will be positive. That, of course, makes such a circuit quite interesting for, among other things, analog-computer applications. (Actually the circuit given here is inverting; that means that the output will be the opposite of the true product. That can easily be corrected, if needed, by adding an additional inverting-stage).

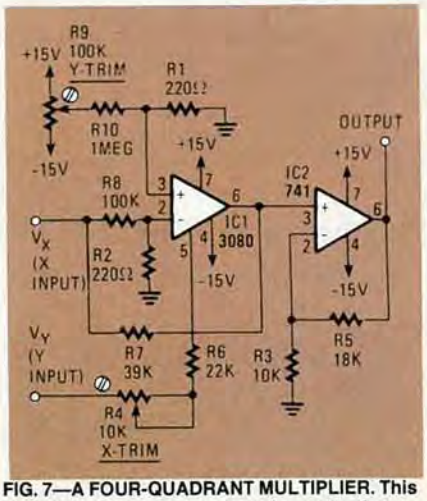

**FIG. 7—A FOUR-QUADRANT MULTIPLIER. This circuit could be used in a music synthesizer to create chime and gong effects.**

Another place that the circuit is especially useful is in audio applications. That's because it produces sounds that are quite similar to those produced by a ring modulator. For example, if two sinewaves are multiplied by the device, the output will be a complex signal composed of the sum and difference frequencies of the two. Such a signal can be used in electronic music-synthesis to create gong and chime effects.

Refer to Fig. 7 now. The two inputs are labeled "X" and "Y" and are set up to accept bipolar 5-volt signals (i.e., 10-volts peak-to-peak). Resistors R8 and R2 form an attenuator and drop the X-input signal to the desired 10-mV level. Resistors R4 and R6 are in series with the Y input. To balance the multiplier you apply a signal to the X input, ground the Y input (O volts), and then adjust R9 for minimum feedthrough. Then, reverse the procedure—apply a signal to the Y input, ground the X input, and adjust R4 for minimum feedthrough.

The output is converted to a voltage by IC2, a 741 op-amp. For more demanding applications, that IC should changed to a BiFET-type op-amp, such as the LF351. Note that this stage not only buffers, but also scales the output suitably—since the circuit is set up to accept bipolar 5V signals the output is scaled so that it equals $-V_XV_Y/5$. That puts the output in the same range as the inputs.

One drawback of this circuit is that only very-low-impedance input sources can be used. That is easy enough to correct, though, by buffering the two inputs. Additionally, the driving sources must be DC coupled. If those limitations are respected, however, the circuit performs very well and is far cheaper to build than any equivalent.

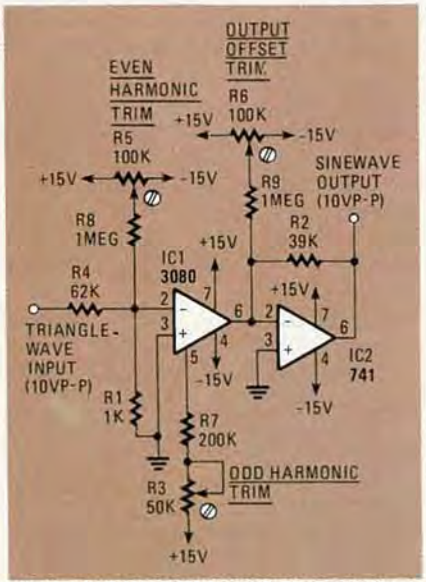

**FIG. 8—IF A TRIANGLEWAVE is fed to the input of this circuit, the output will be a sinewave of the same amplitude. The total harmonic distortion will range from 2% to 4%.**

### Trianglewave-to-sinewave converter

When we looked at the differential pair, we said that the input signal must always be at or below 10 mV for lowest distortion. A circuit that deliberately violates that rule is shown in Fig. 8.

In that circuit, which is a triangulwave-to-sinewave converter, a triangular wave with a value of 10-volts peak-to-peak is applied to the input at R4. Resistors R4 and R1 drop the voltage to about 160-mV peak-to-peak, which is applied to the 3080. Resistor R5 is used to trim the symmetry, which reduces the even-order harmonics. Resistors R7 and R3 form the current source for the 3080, and adjusting R3 has the effect of rounding or flattening the output; the result is that the odd harmonics are reduced. By adjusting R5 and R3, a very close approximation of a sinewave can be obtained. The total harmonic distortion of the circuit will typically range from 2% to 4%. Resistor R6 is used to adjust the output offset.

The output of this circuit will be a sinewave with the same amplitude as the input triangular wave. An important thing to note about the circuit is that it is non-reactive—it uses no capacitors or inductors. Thus it will work over a wide range of frequencies.

As this article has shown, the 3080 operational transconductance amplifier is not only versatile, but quite easy to work with. The equations we've presented, and Ohm's law, are really all it takes to get circuits using that device up and running. Obviously there are many refinements that can be made—correcting for temperature effects, for instance—but they can be tackled later on when you've had more experience with the device. **R-E**