WORKING WITH OTA's

The LM13600 is a second-generation dual Operational Transconductance Amplifier that can be used as a voltage-controlled amplifier, resistor, filter, or oscillator. In this article we'll show you how.

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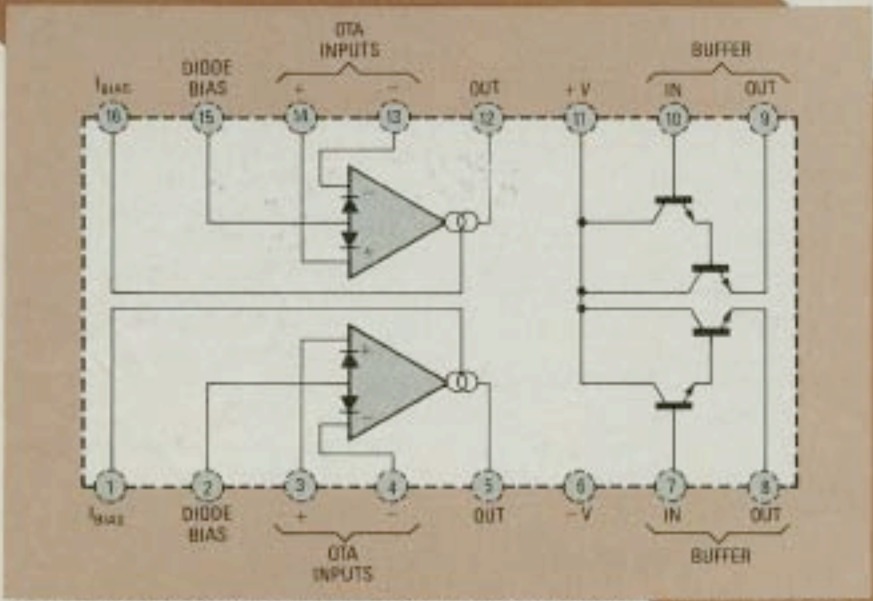

FIG. 1—PIN CONNECTIONS of the LM13600 dual OTA are as shown. You can also see how each IC contains two OTA's.

LAST TIME (MAY 1988) WE DISCUSSED THE basic operating principles of the CA3080 *O*perational *T*ransconductance *A*mplifier (OTA), and showed how it can be used to make various types of voltage- or current-controlled amplifiers and micro-power Schmitt triggers, comparators, and oscillators. However, the CA3080 has relatively high distortion and an unbuffered high-impedance output.

In this article we will introduce you to an improved second-generation OTA; the LM13600. That device is actually a dual OTA, as shown by the pinout of Fig. 1. The package also incorporates linearizing diodes that greatly reduce signal distortion, and a coupled output-buffer stage that can provide a low-impedance output.

The two OTA's of the LM13600 share common supplies, but are otherwise fully independent. All elements are integrated on a single chip, so both OTA's have closely matched characteristics (transconductance values are typically matched within 0.3 dB), making the IC ideal for use in stereo applications. The commercial version of the LM13600 can be powered from a split supply of up to 18 volts, or a single-ended supply of up to 36 volts.

Linearizing diodes

Figure 2 shows a basic connection diagram for one of the OTA's in the LM13600. Basically, that OTA is almost identical to the one in the CA3080, except for the addition of linearizing-diodes D1 and D2. Those are integrated with Q1 and Q2, and have characteristics that are matched to the base-emitter junctions of Q1 and Q2. In use, equal low-value resistors R1 and R2 are wired between the inputs of the differential amplifier and ground. Bias-current I_D is fed to those resistors from the positive supply via R3, D1, and D2. Since D1 and D2 have identical characteristics, and since R1 and R2 have equal values, bias current, I_D, divides equally between R1 and R2.

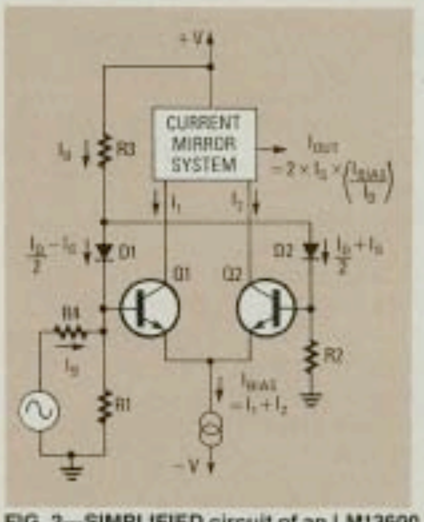

FIG. 2—SIMPLIFIED circuit of an LM13600 OTA shows one of the more basic ways of using the IC.

The circuit's input voltage is applied via R4, which has a large value relative to R1, and generates an input signal current of I_S. That signal current feeds into R1 and generates a voltage across it, reducing D1's current to a value of $(I_D/2) - I_S$. Since I_D is constant, the D2 current rises to $(I_D/2) + I_S$. Consequently, the linearizing diodes apply a heavy negative feedback to the differential amplifier and substantially reduce the signal distortion. If I_S is small relative to I_D, the output current of the circuit is equal to $2 \times I_S \times (I_{BIAS}/I_D)$. The gain of the circuit can be controlled either by I_{BIAS} or I_D. In use, I_D and I_{BIAS} should both be limited to a maximum of 2 mA.

The graph of Fig. 3 shows typical distortion levels of the LM13600 at various peak-to-peak input voltages, with and without the use of the linearizing diodes. At a 30-mV input, the distortion is below 0.03% with the diodes, and 0.7% without them. At a 100-mV input, the distortion is roughly 0.8% with the diodes, and 8% without them.

Controlled-impedance buffers

Figure 4 shows the internal circuit of each half of the LM13600. The two

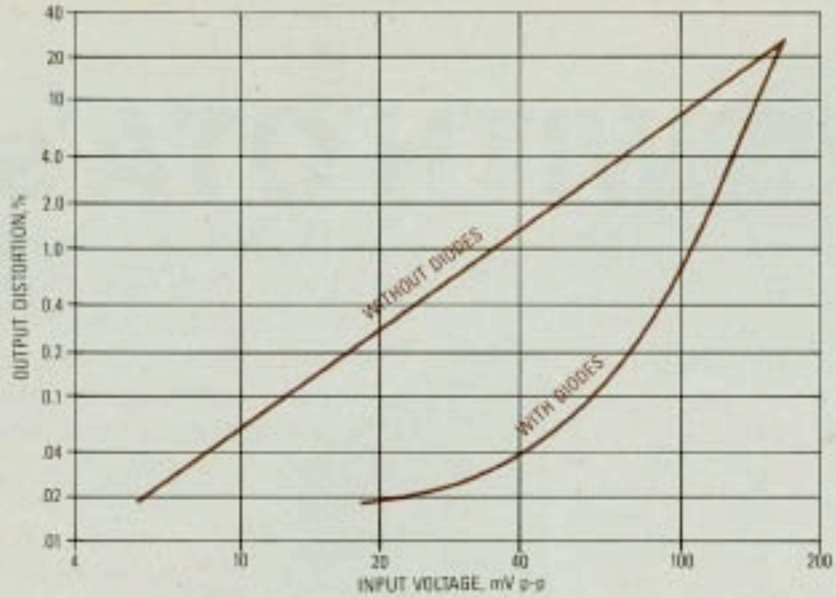

FIG. 3—TYPICAL DISTORTION LEVELS of the LM13600 OTA, with and without the use of the linearizing diodes.

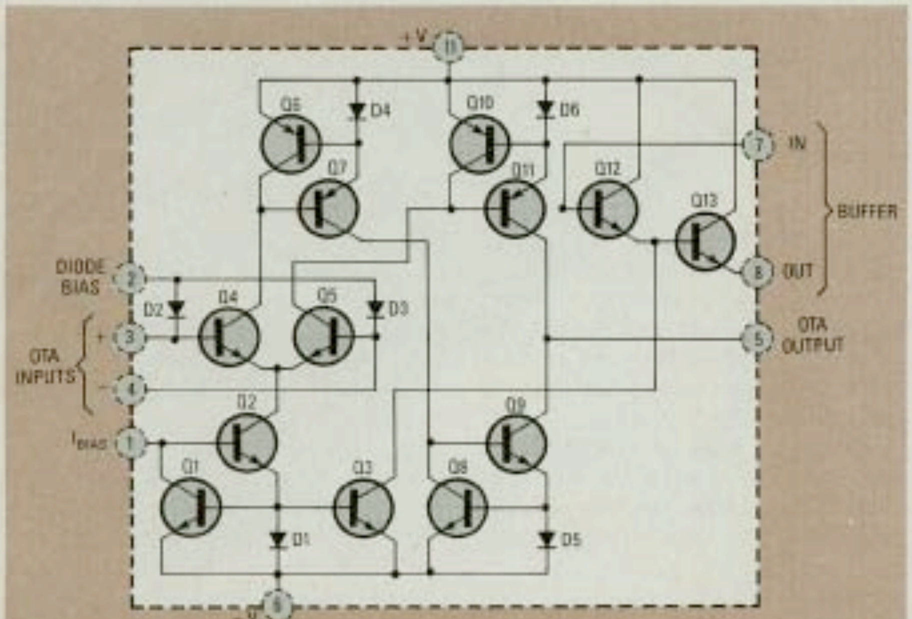

FIG. 4—INTERNAL CIRCUIT of one half of the LM13600 dual OTA. Each LM13600 IC contains two of these circuits.

output transistors (Q12 and Q13) are connected for use as a controlled-impedance Darlington emitter-follower buffer stage. When the base of Q12 is connected to the output of the OTA, and the emitter of Q13 is connected to the negative supply (−V) via a suitable load resistor, the buffer makes the OTA's high-impedance output signal available at a low-impedance level. The output current of each buffer stage should be limited to 20 mA maximum. Note that the output of the buffer stage is about 1.2 volts (two base-emitter voltage drops) below the output-voltage level of the OTA, so the buffer should not be used in precision DC-amplifier applications.

VCA circuits

Figure 5 shows the circuit of a *V*oltage-*C*ontrolled *A*mplifier (VCA) using half of an LM13600 IC. The input signal is fed to the non-inverting terminal of the OTA via current-limiting resistor R4. The high-impedance output of the OTA is loaded by R5, which determines the peak amplitude of the output signal. The output signal is available at a low-impedance level via the buffer stage, which is loaded via R6.

The circuit in Fig. 5 is powered from dual 9-volt supplies. The current I_D is fixed at about 0.8 mA via R1, but I_{BIAS} is variable via R7 and an external gain-control voltage. When the gain-control voltage is at the negative-supply level of −9 volts, I_{BIAS} is zero and the circuit has an overall gain of −80 dB. When the gain-control voltage is at the positive-supply value of +9 volts, I_{BIAS} reaches a value of roughly 0.8 mA, and the circuit has a gain of roughly 1.5. The gain is fully variable within those limits via the gain-control input. The circuit is a non-inverting amplifier, since the input signal is fed to the non-inverting input of the OTA. It can be used as an inverting amplifier by feeding the input signal to the OTA inverting input instead.

Because the two halves of the LM13600 have closely matched characteristics, the IC is ideal for use in stereo-amplifier applications. Using both halves of an LM13600 you can make two amplifiers like the one in Fig. 5. Then, if you connect both gain-control inputs together, and feed them from a single gain-control voltage and current-limiting resistor, you'll have a voltage-controlled stereo amplifier.

The VCA circuit of Fig. 5 can be used as an amplitude modulator or 2-quadrant multiplier by simply feeding the carrier signal to the OTA input, and the modulation signal to the gain-control input. If desired, the gain-control pin can be DC-biased so that a carrier output is available while no AC-input signal is applied. Figure 6 shows a practical example of an inverting-amplifier circuit of that type. The AC-modulation signal modulates the amplitude of the carrier-output signal.

Figure 7 shows how one half of an LM13600 can be used as a ring modulator or 4-quadrant multiplier. In that circuit, there is no carrier output when the modulation voltage is at ground level, but increases when the modulation voltage moves positive or negative with respect to ground. When the modulation voltage is positive, the carrier-output signal is inverted relative to the carrier input; and when the modulation voltage is negative, the carrier output is non-inverted.

The circuit in Fig. 7 is similar to the circuit in Fig. 6, except that the component values shown are suited for operation from a dual 15-volt supply, and that I_{BIAS} is adjustable via R7. The OTA's output (inverted relative to the input signal) feeds into the one end of R5, and at the same time the input signal feeds directly into the other end of R5. Potentiometer R7 is adjusted so that when the modulation input is tied to ground, the overall gain of the OTA is such that its output current exactly balances (cancels) the carrier input current to R5. Under that condition the circuit has no carrier output. When the modulation input goes positive, the OTA's gain increases and its output signal exceeds that caused by the carrier input to R5, so an inverted output signal is generated. Conversely, when the modulation input goes negative, the OTA's gain decreases and the carrier input to R5 exceeds the output of the OTA; therefore, a non-inverted output signal is generated.

Offset biasing

The circuits in Figs. 5–7 are shown with the OTA's input biased by fixed-value 47O-ohm resistors wired between the two input terminals and ground. In practice, that simple arrangement may cause the circuit's DC level at the output to shift slightly when the gain-control input (I_{BIAS}) is varied between its minimum and maximum value. If desired, that level-shifting effect can be eliminated by adding a presettable offset-adjust control, as shown in Fig. 8. Potentiometer R4 enables the relative values of the biasing resistors, R2 and R3, to be varied over a limited range. To adjust the offset bias, reduce I_{BIAS} to zero, note the DC level of the output signal, and then increase I_{BIAS} to maximum and adjust R4 for the same DC-output level.

AGC amplifier

Figure 9 shows how to make an Automatic Gain Control (AGC) amplifier in which a 100:1 change in the input-signal amplitude causes only a 5:1 change in the output amplitude. In that circuit, I_{BIAS} is fixed by R4, and the output signal is available directly across R5. The output buffer is fed from the output of the OTA and is used as a signal rectifier. The rectified output of the buffer is smoothed via R6 and C2, and used to apply the I_D current to the linearizing diodes of the OTA. However, no significant I_D current is generated until the OTA's output goes high enough to turn on the Darlington buffer and the linearizing diodes. An increase in I_D reduces the OTA's gain, and negative feedback holds the output at a steady level.

The basic gain of the amplifier in Fig. 9, with no I_D current, is 40. Therefore, with an input signal of 30 mV p-p, the OTA's output of 1.2 volts p-p is not enough to generate an I_D current, so the OTA operates at full

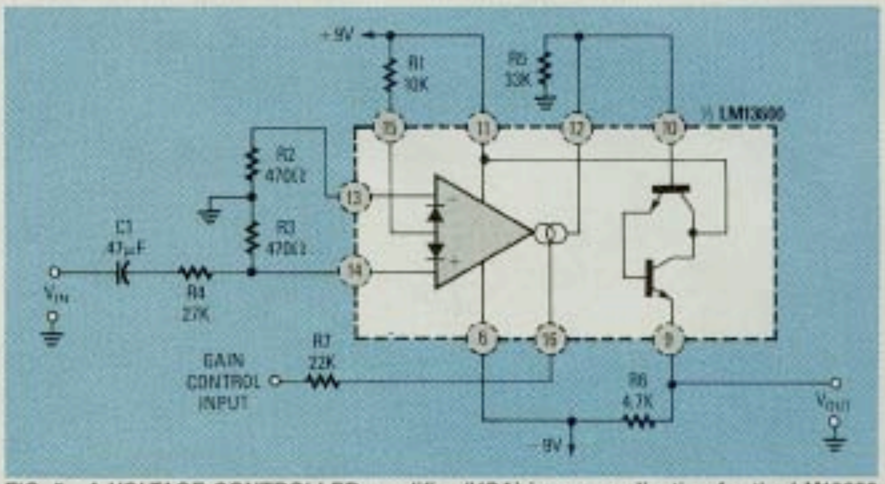

FIG. 5—A VOLTAGE-CONTROLLED amplifier (VCA) is one application for the LM13600. The LM13600 is also well suited for use as a stereo amplifier because it contains two matched amplifiers.

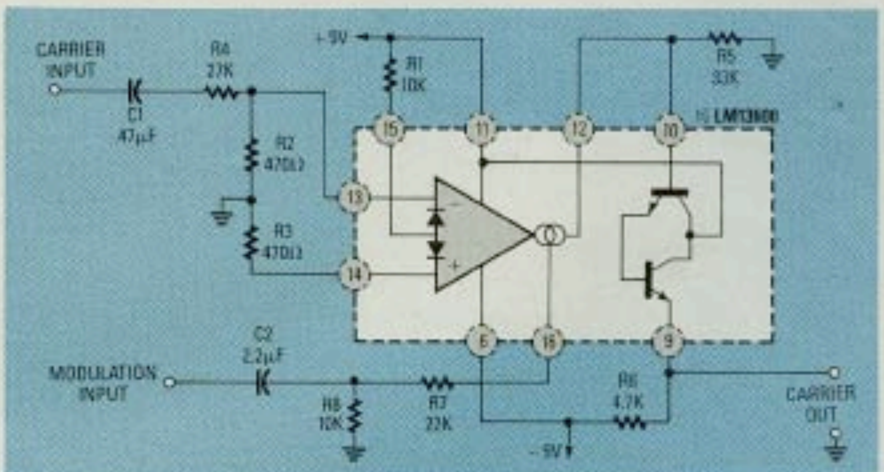

FIG. 6—AN AMPLITUDE MODULATOR or 2-quadrant multiplier can be made using one half of the LM13600.

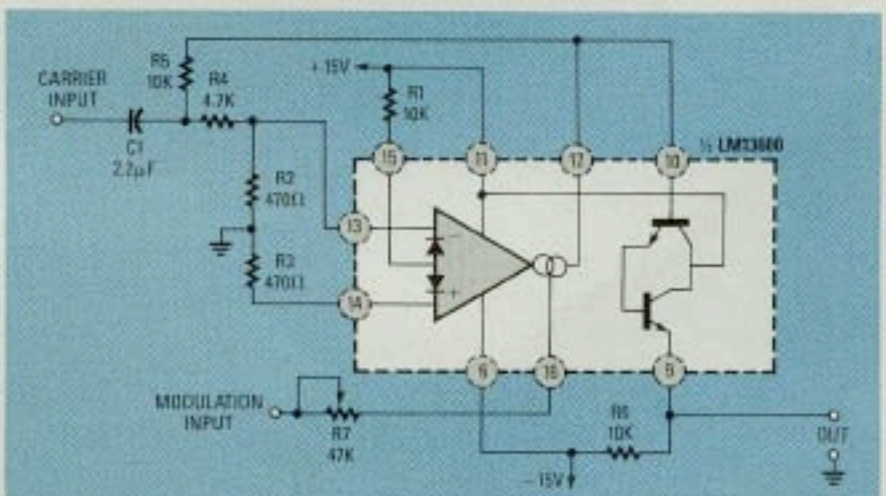

FIG. 7—THE CIRCUIT SHOWN HERE is a ring modulator or 4-quadrant multiplier.

gain. With an input of 300 mV, however, the OTA's output is enough to generate a significant I_D current, and the circuit's negative feedback automatically reduces the output level to 3.6 volts p-p, giving an overall gain of 11.7. With an input of 3 volts, the gain falls to 2 (an output of 6 volts p-p). The circuit thus has a 20:1 signal compression over that range.

Voltage-controlled resistors

One unusual application of the LM13600 is as a *V*oltage-*C*ontrolled *R*esistor (VCR), using the circuit shown in Fig. 10. The basic theory is as follows: An AC signal applied to the R_X terminals feeds into the inverting terminal of the OTA via C1, the output-buffer transistors, and the R5/R_A attenuator. The OTA will then generate an output current that is proportional to V_{IN} and I_{BIAS}. Therefore, because R = V/I, the R_X terminal functions as an AC resistor whose value is determined by I_{BIAS}.

The effective resistance between the R_X terminals of the circuit in Fig. 10 equals $(R5 + R_A)/(gm \times R_A)$, where gm (transconductance) is approximately $20 \times I_{BIAS}$. That formula can be approximated as $R_X = R5/(I_{BIAS} \times 20R_A)$. Using the component values shown, R_X equals approximately 10 megohms when it has an I_{BIAS} current of 1 µA, and 10 kilohms when it has an I_{BIAS} current of 1 mA.

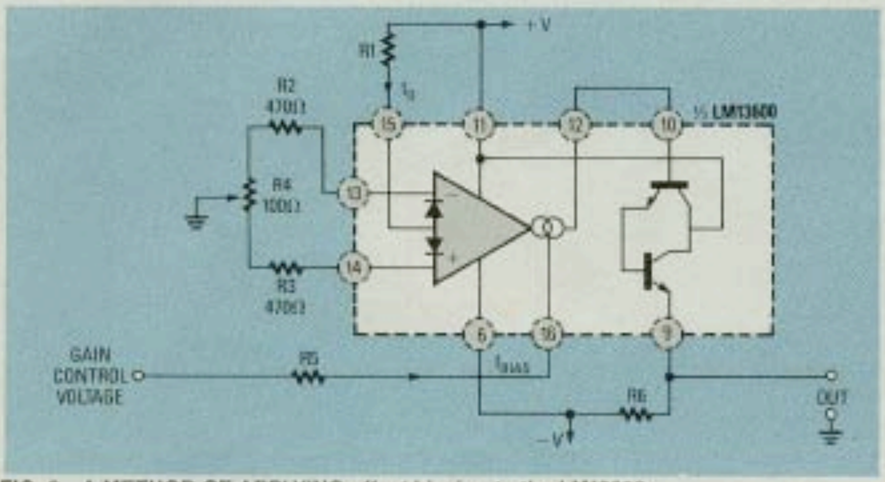

FIG. 8—A METHOD OF APPLYING offset biasing to the LM13600.

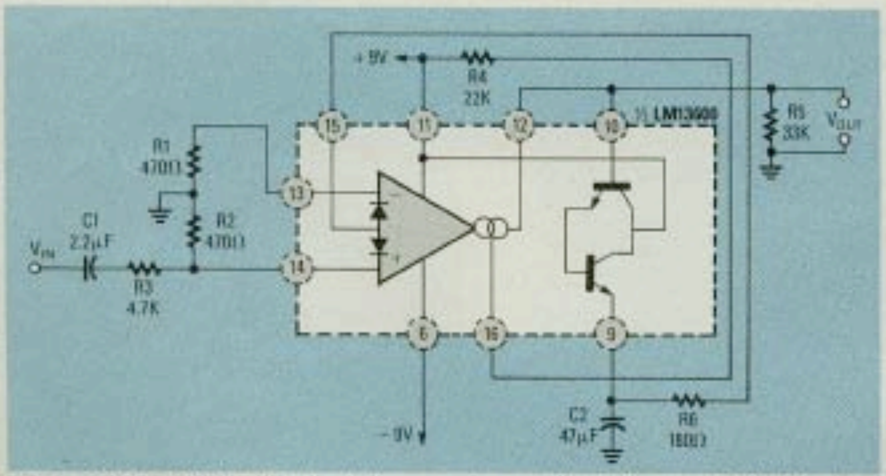

FIG. 9—AN AGC AMPLIFIER adjusts its own gain according to the magnitude of the input signal.

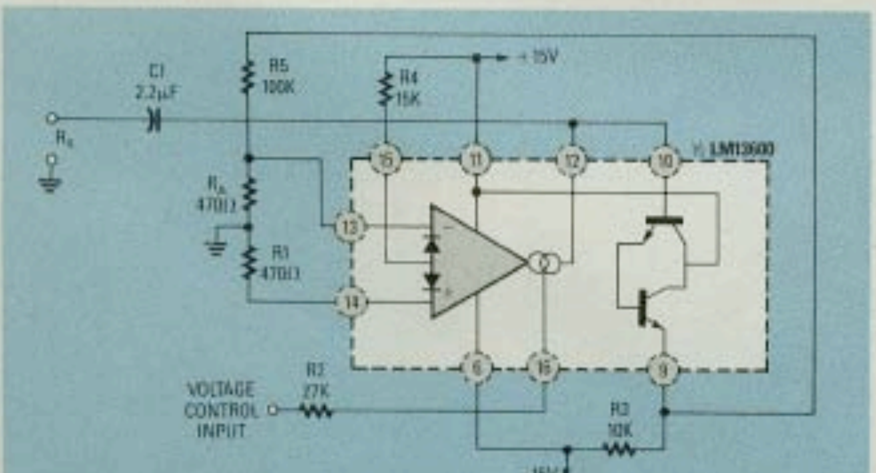

FIG. 10—A VOLTAGE-CONTROLLED RESISTOR can be used as an electronically-controlled resistor.

Voltage-controlled filters

A voltage-controlled low-pass filter can be implemented by using one half of an LM13600 in the configuration shown in Fig. 11. In that circuit, the values of R5, C2, and I_{BIAS} control the cut-off frequency (f_O) of the filter. The input signal is applied to the non-inverting terminal of the OTA via voltage-divider network R1/R2. The OTA's output signal is "followed" by the buffer stage and fed back to the inverting terminal via an identical voltage-divider network, R5/R_A. The basic OTA operates as a non-inverting amplifier with a gain of R5/R_A, but because the input signal to the OTA is applied via a voltage divider with a value equal to R5/R_A, the overall circuit operates as a unity-gain voltage follower.

At low frequencies, C2 has a very high impedance and is able to be fully charged by the OTA's output current, so the circuit operates as a voltage follower as was previously described. As the frequency increases, C2's impedance decreases and is no longer able to be fully charged by the OTA's output current, so the output signal starts to attenuate at a rate of 6-dB-per-octave. The cut-off point of the circuit, defined as the point where the output falls by 3 dB, occurs when $X_C/20I_{BIAS}$ equals R5/RA, as shown by the formula in the diagram (gm is approximately equal to $20 \times I_{BIAS}$). With the component values that are shown in Fig. 11, the filter's cut-off

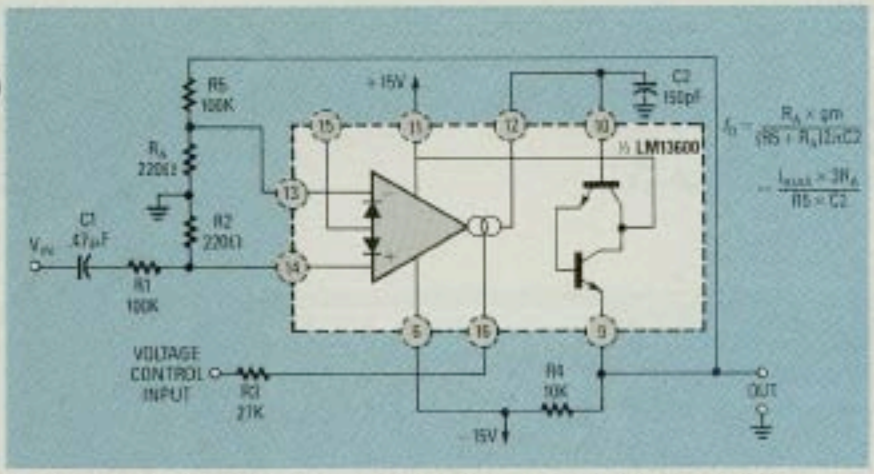

FIG. 11—A VOLTAGE-CONTROLLED LOW-PASS filter covering 45 Hz to 45 kHz.

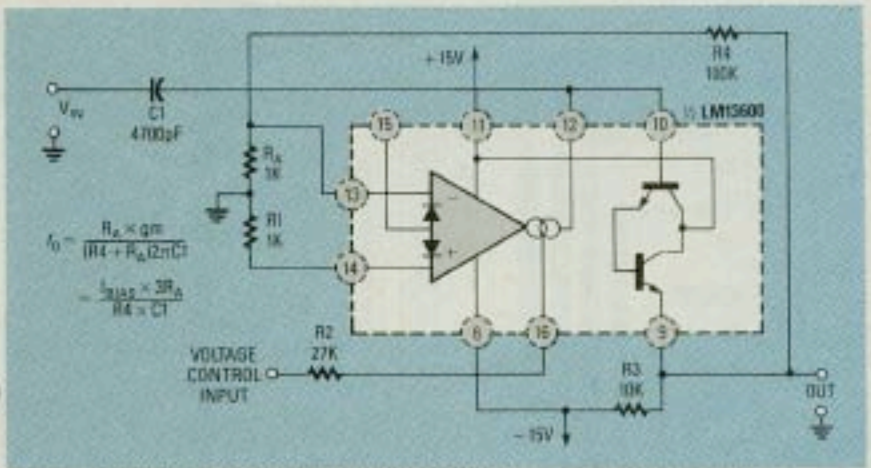

FIG. 12—A VOLTAGE-CONTROLLED HIGH-PASS filter covering 6 Hz to 6 kHz.

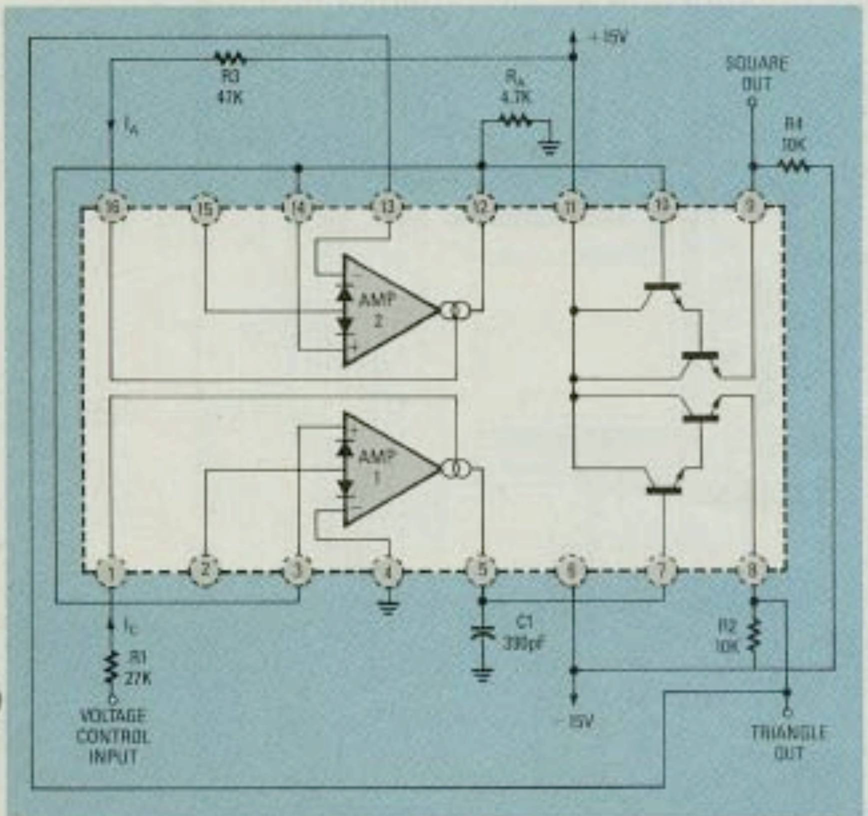

FIG. 13—A COMBINATION TRIANGLE-SQUARE-WAVE VCO covering 200 Hz to 200 kHz.

point occurs at about 45 Hz with an I_{BIAS} of 1 μA, and at 45 kHz with an I_{BIAS} of 1 mA.

A similar principle can be used to make a voltage-controlled high-pass filter. As shown in Fig. 12, that circuit has cut-off frequencies of 6 Hz when it has an I_{BIAS} current of 1 μA, and 6 kHz when it has an I_{BIAS} current of 1 mA.

Voltage-controlled oscillators

To conclude this look at the LM13600 operational transconductance amplifier, Fig. 13 shows how to use the IC as a *V*oltage-*C*ontrolled *O*scillator (VCO). The circuit uses both halves of the LM13600, and simultaneously generates both triangle and square waves.

To understand the operating theory of the circuit, assume initially that capacitor C1 is negatively charged and that the square-wave output signal has just switched high. Under that condition a positive voltage is developed across R_A, which is fed to the non-inverting terminals of the two amplifiers. That voltage causes amp 1 to generate a positive output current, equal to bias current I_C, that flows into C1 and generates a positive-going linear ramp voltage.

The ramp voltage is then fed to the inverting terminal of amp 2 via the Darlington buffer stage, until it eventually equals the voltage on the non-inverting terminal, at which point the output of amp 2 starts to swing in a negative direction. That initiates a regenerative switching action, and at that moment, the signal at the square-wave output terminal abruptly goes negative.

In that new state, a negative voltage is generated across resistor R_A, causing amp 1 to generate a negative output current equal to I_C, causing capacitor C1 to discharge until its voltage equals that of R_A, at which point the square-wave output switches high again.

The process repeats over and over again, making available a triangle waveform at R2 and a square wave at R4. The frequency of those waveforms is variable via the voltage-control input; that input is what controls the value of I_C. With the component values shown, the circuit then generates a frequency of about 200 Hz when the I_C bias current is 1 μA, and 200 kHz when the bias current is 1 mA. R-E