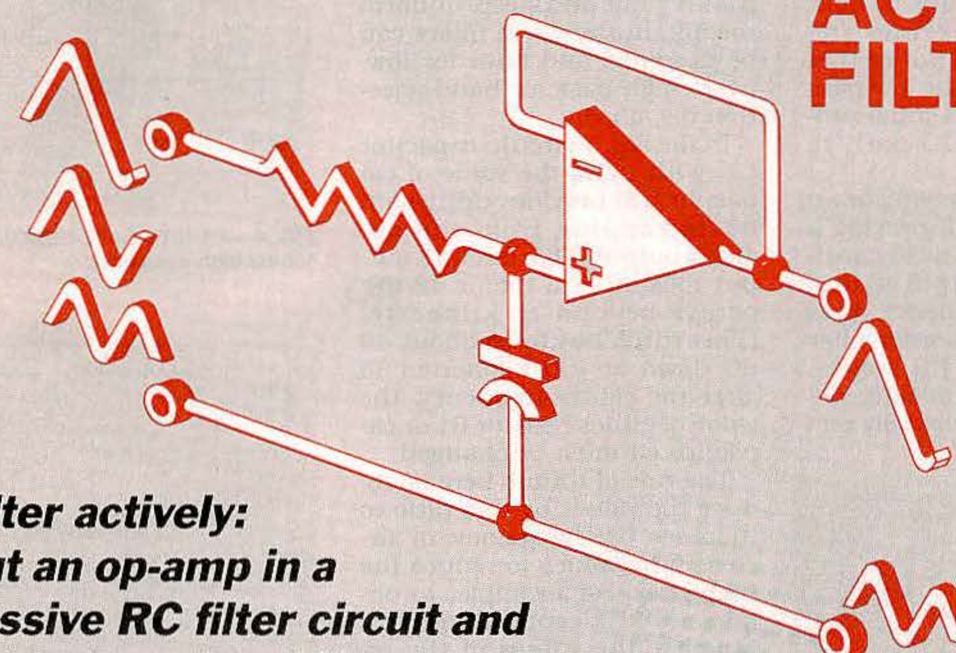
ACTIVE FILTERS



Filter actively: Put an op-amp in a passive RC filter circuit and get better signal filtering.

RAY MARSTON

YOU CAN BOOST THE PERFORMANCE of any resistive-capacitive filter by combining it with one or more operational amplifiers. The result is an active filter that can do things passive filters can't do.

An active filter is a filter that contains a device which supplies signal gain; the op-amp performs that function in all of the circuits presented here. The schematics in this article will permit you to carry out many interesting experiments. Moreover, the circuits can also be put to work in original projects that you design.

All of the active filters discussed in this article include the industry-standard μA741 operational amplifier. It operates from a dual power supply that can provide both the +9- and −9-volt DC needed to power it.

The μA741 was first introduced many years ago by National Semiconductor. Now a true commodity or "jellybean" IC, it is widely second-sourced and readily available throughout the world under such labels as the AD741, CD741, LM741, RM741, and SG741, as well as the μA741. There are also many modifications of the 741 indicated by suffixes to these standard designations.

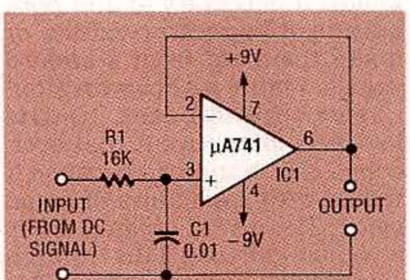


FIG. 1—AN ACTIVE FIRST-ORDER, LOW-pass filter for 1-kHz signals.

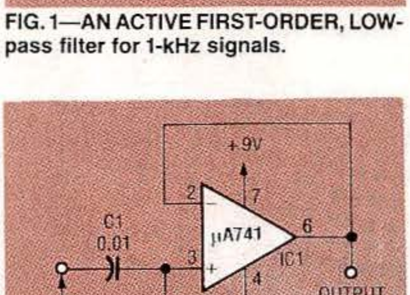


FIG. 2—AN ACTIVE FIRST-ORDER high-pass filter for 1-KHz signals.

Dual versions of the 741, such as the 1458, will also work in the circuits described here. Another widely second-sourced device, it is available under such labels as CA1458, LM1458, and MC1458. However, the circuits presented here will also work with most commodity op-amps, provided that they are supplied with their required voltages. If you want active filters for frequencies above a few tens of kilohertz, select a wide-bandwidth op-amp such as the high-speed, dual JFET-input LF353, also widely second-sourced.

The two most basic active-filters, low-pass and high-pass, shown in Figs. 1 and 2, are known as *first-order* filters because each has a single resistive-capacitive stage. These filters are simple modifications of the passive filters described in the article on RC filters in the June Issue of *Electronics Now* starting on page 57.

However, each of these active filters is buffered by a unity-gain, non-inverting op-amp to give a low-impedance output with a −3 dB crossover frequency (f_c) of $1/(2\pi RC)$, and an output slope of 6 dB/octave or 20 dB/decade.

With the component values shown with Figs. 1 and 2, both filters will have a center frequency (f_c) of 1 kHz. Notice that the input signal to the low-pass filter shown in Fig. 1 must provide an effective DC path to ground.

Figure 3 is a schematic for an active filter that will provide a very flat, unity-gain, second-order, low-pass output with a 10-kHz center frequency. It is known as a second-order filter because of its two RC stages, and as a *Butterworth* filter because it exhibits a virtually rectangular attenuation curve. These filters have flat response characteristics in their band-pass regions and steep, uniform rolloffs. Butterworth filters can be designed and built for low-pass, high-pass, or band-rejection response.

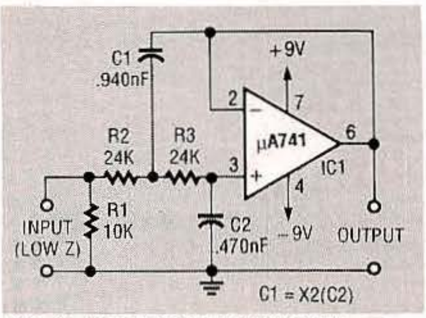


FIG. 3—AN ACTIVE UNITY-GAIN, second-order low-pass (Butterworth) filter for 10-kHz signals.

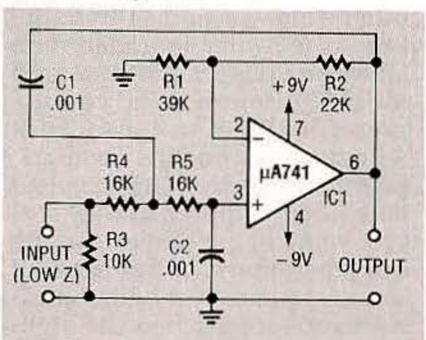


FIG. 4—AN EQUAL COMPONENTS second-order low-pass filter for 10-kHz signals.

In the Fig. 3 circuit, capacitor C1 (with twice the value of capacitor C2) provides unity-gain bootstrapping from the op-amp's output. This circuit's output rolls off at a rate of 12 dB/octave beyond 10 kilohertz. (This turns out to be about 40 dB down at 100 kilohertz.) To alter the center frequency, the value of either resistor R1 or capacitor C1 must be changed.

The rule of thumb here is: reduce the values by this ratio to increase the frequency, or increase the values to reduce the frequency. For example, to obtain a 4-kHz center frequency, increase the values of the resistors by the ratio of 10 kHz/4 kHz, or by a multipler of 2½. The formula for determining center frequency (f_c) for the circuit in Fig. 3 is:

$f_c = 1/2.83\pi RC$

A minor drawback in the Fig. 3 filter design is that capacitor C1 must be precisely twice the value of C2. That requirement makes it necessary to find non-standard capacitor values or make them up from standard values. Figure 4 shows an alternative second-order, 10-kHz low-pass filter circuit that overcome, that handicap because it works with capacitors of equal value. The μA741 op-amp offers a voltage gain of 4.1 dB through resistors R1 and R2. This yields greater than unity bootstrapping for one of the filter's two input capacitors.

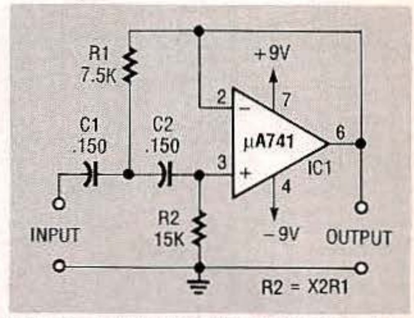


FIG. 6—A UNITY-GAIN, SECOND-order, 100-Hz high-pass filter.

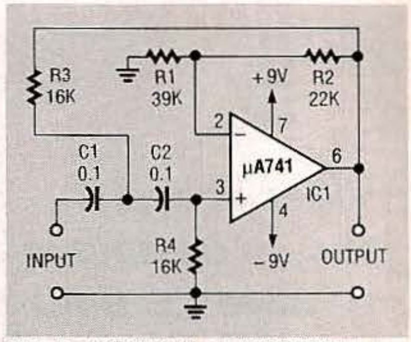


FIG. 7—AN EQUAL COMPONENTS second-order 100-Hz high-pass filter.

Figure 5 shows how two filter circuits with equal-component values can be cascaded to make a fourth-order, low-pass filter with a rolloff of 24 dB/octave. In this example, if the 39 K value of gain-determining resistor R1 is divided by the 5.87 K value of resistor of R2, a ratio of 6.644 is obtained. Also, if the value of 39 K resistor R3 is divided by the 58.5 K value of resistor R4, a ratio of 0.805 is obtained. The center frequency of this circuit is determined by the standard formula.

The cascaded combination in Fig. 5 provides an overall voltage gain of 8.3 dB. The non-standard resistor values of R2 and R4 can be obtained by connecting two standard 5% resistors in series to equal the desired value. The center frequencies of the filters shown in Figs. 4 and 5 can be altered in the same way that was discussed for Fig. 3.

Figure 6 is the schematic for a unity-gain, second-order, 100-kHz filter. Its center frequency is determined by the formula:

$f_c = 1/(2.83\pi RC)$

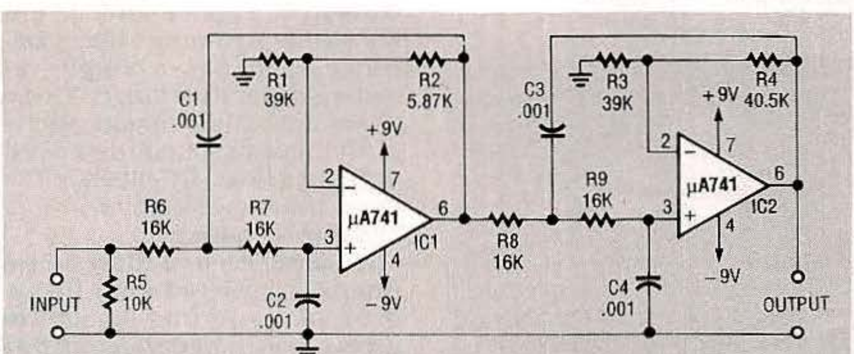


FIG. 5— A FOURTH-ORDER LOW-PASS FILTER for 10-kHz signals.

change reduces the center frequency from 10 kHz to 3.4 kHz.

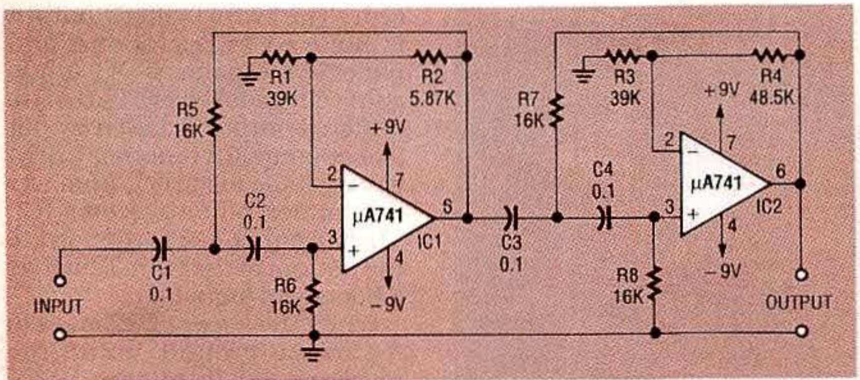


FIG. 8—A FOURTH-ORDER HIGH-PASS FILTER for 100-Hz signals.

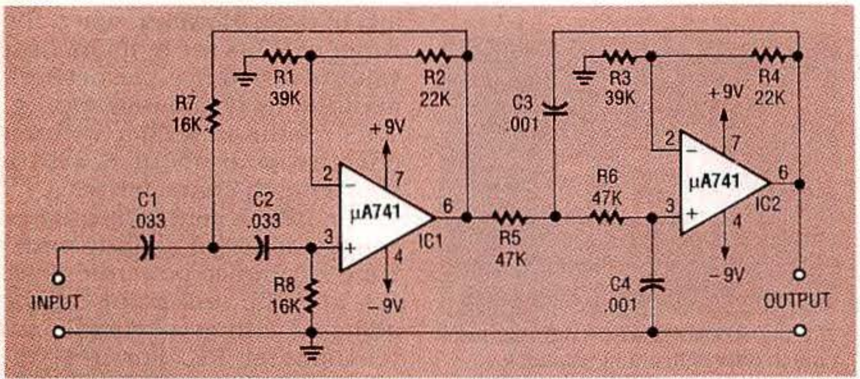


FIG. 9—A SECOND-ORDER BANDPASS FILTER with a range of 300 Hz to 3.4 kHz.

Figure 7 is the schematic for an equal-value components version of the Fig. 6 second-order 100-kHz filter. However, its center frequency is determined by the standard formula. The operating frequencies of both of these filters can also be changed in the way that was discussed for Fig. 3.

Figure 8 shows a fourth-order, 100-Hz highpass filter. Finally, Fig. 9 illustrates how the high-pass filter of Fig. 7 and low-pass filter of Fig. 4 are connected in series to form a 300-Hz to 3.4 kHz, audio-range bandpass filter. It offers 12dB/octave rejection to all signals outside of that passband. Notice, however, that certain changes must be made in component values for this circuit to work. In the front end high-pass filter based on Fig. 7, the values of C1 and C2 were reduced by ⅓ to 0.33µF to raise the center frequency to 300 Hz from 100 Hz. In the back end low-pass filter based on Fig. 4, resistor R3 was deleted and the values of resistors R4 and R5 were increased by a factor of 2.94 from 16 K to 47 K. That change reduces the center frequency from 10 kHz to 3.4 kHz.

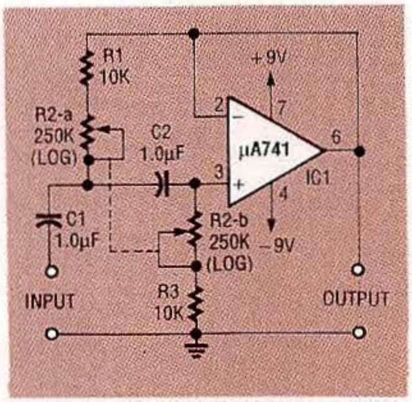


FIG. 10—A VARIABLE HIGH-PASS filter that covers the 23.5- to 700-Hz. band.

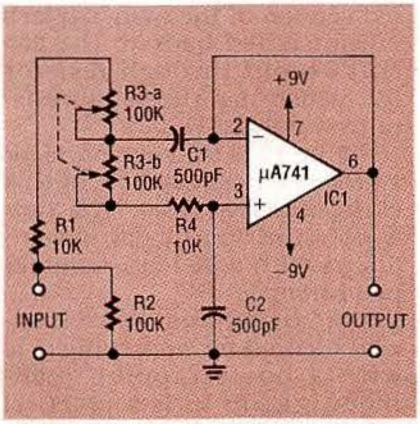


FIG. 11—A VARIABLE LOW-PASS filter that covers a 2.2- to 24-kHz band.

Variable active filters

The most useful active filter is one that offers a wide frequency range with an easy-to-change crossover frequency. Figures 10 to 12 are schematics for three useful second-order filters that meet that criteria.

The circuit in Fig. 10 is a simple modification of the high-pass filter in Fig. 6. However, by varying dual trimmer potentiometer R2, a crossover frequency with a range of 23.5 Hz to 700 Hz can be obtained. Notice that, unlike the situation in Fig. 6, the resistive value of the upper arm of the filter (R1 +R2-a) equals the resistive value of the lower arm (R2-b +R3).

Unfortunately, this modification detracts from the virtually flat Butterworth characteristic curve, although it still provides very good filter performance. This circuit will work as a high quality filter for removing turntable motor "rumble" in LP disc players. Moreover, fixed versions of this filter can be expected to exhibit a 50-Hz crossover frequency.

The schematic in Fig. 11 is a modification of the high-pass filter in Fig. 3. However, trimmer potentiometer R3 permits its crossover frequency to be fully variable from 2.2 kHz to 24 kHz. Although this modification detracts from a truly flat Butterworth characteristic, this filter can, nevertheless, function as a high quality filter for the removal of scratch noises in LP disc players. Fixed versions of this filter typically have a 10-kHz crossover frequency.

Figure 12 illustrates how the filter circuits of Figs. 10 and 11 can be combined to make a truly versatile, variable high-pass/low-pass or rumble/scratch/audio filter. Trimmer potentiometer R2 varies the high-pass crossover frequency from 23.5 to 700 Hz, while trimmer capacitor R7 varies the low-pass value from 2.2 to 24 kHz.

Tone and notch filters.

High-performance active RC tone filters with high effective Q

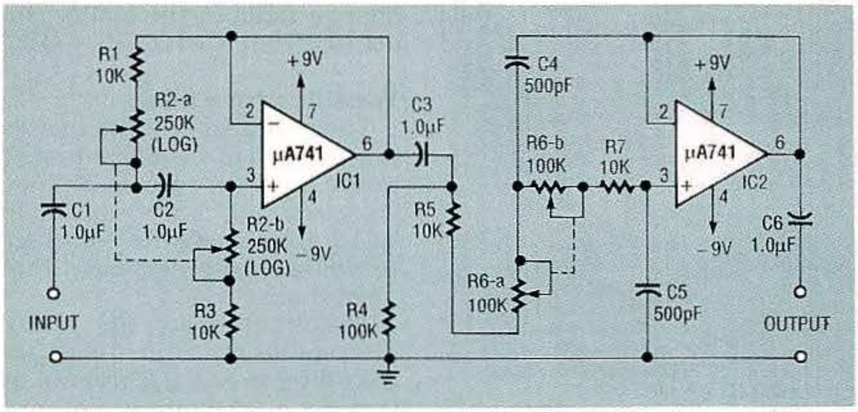


FIG. 12—A VARIABLE HIGH-PASS/LOW-PASS OR RUMBLE/SCRATCH audio filter.

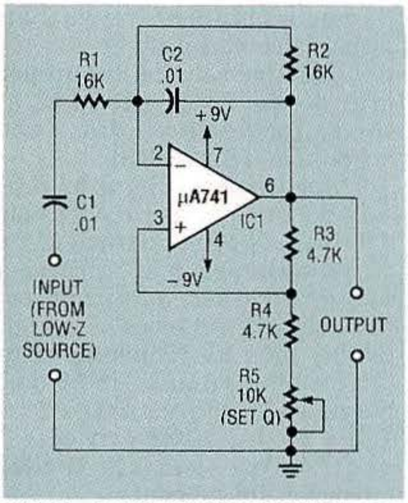


FIG. 13—A HIGH-Q TONE FILTER based on the Wien bridge for 1-kHz tones.

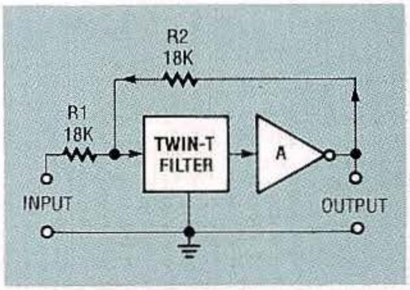


FIG. 14—A DIAGRAM FOR A BASIC twin-t notch filter with shunt feedback.

values can be made with twin-T or Wien networks in the feedback loops of op-amps. Figure 13 shows a useful 1-kHz tone or acceptor filter based on the Wien-bridge circuit. The Q of this filter can be varied by fixed resistor R4 in series with 10K SET Q trimmer potentiometer R4. Caution: this circuit will oscillate if the wiper on R4 is positioned so that the value of R4 is less than twice the value of R3.

The basic twin-T notch filter has a very low Q. The filter's Q and the sharpness of its notch characteristic can be increased by including the twin-T in the feedback network of an active filter. There are two conventional ways to do this.

The first is to organize the circuit in a general shunt feedback arrangement as shown in Fig. 14. The input signal is fed to the twin-T filter through resistor R1 before it is amplified by amplifier A. The amplified and inverted version of the twin-T filter's output is fed back to the circuit's input through resistor R2, which has the same resistance value as R1.

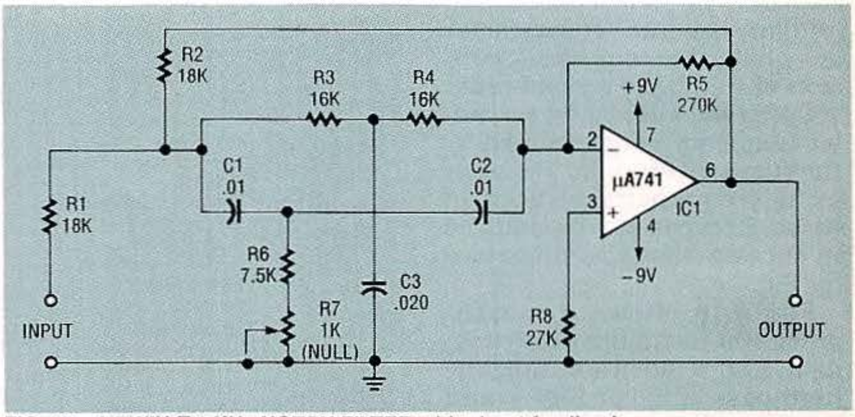


FIG. 15—A TWIN-T 1-KHz NOTCH FILTER with shunt feedback.

Figure 15 is the schematic for 1-kHz practical example of this class of active filter. The network's null point can be adjusted with 1 K NULL trimmer potentiometer R7.

The second (and more modern) method for improving Q is with a bootstrapping technique. Figure 16 is a practical schematic for a 1-kHz variable-Q version of that circuit concept. The twin-T filter's output is buffered by operational amplifier IC1 (organized as a unity-gain voltage follower). Part of its buffered output is taken by pin 3 of op-amp IC2 (another unity-gain voltage follower), from SET Q trimmer potentiometer R7. The output of IC2 is then fed to the bottom of the twin-T filter as a bootstrap signal.

When the wiper of R7 is set to its lowest (ground) point, the network exhibits zero bootstrapping, and the circuit acts like a standard twin-T filter with a Q of 0.24. However, when the wiper of R7 is set to its highest value of resistance, the network exhibits heavy bootstrapping. This results in a filter with an effective Q of about 8 with a sharp notch characteristic.

The filter's center-frequency can be adjusted slightly with TRIM F trimmer pottentiometer R3, and the null point can be adjusted with NULL trimmer potentiometer R6. For best results, trimmer R6 should be a multiturn unit.

Building a THD meter

The bootstrapped twin-T notch filter can function as a total harmonic distortion or THD meter. With the filter's notch tuned to the basic frequency of the input test signal, the filter totally rejects the fundamental frequency of the signal, and applies zero attenuation to the signal's unwanted harmonics. The output signals must be measured on a true RMS voltmeter.

If the original input signal

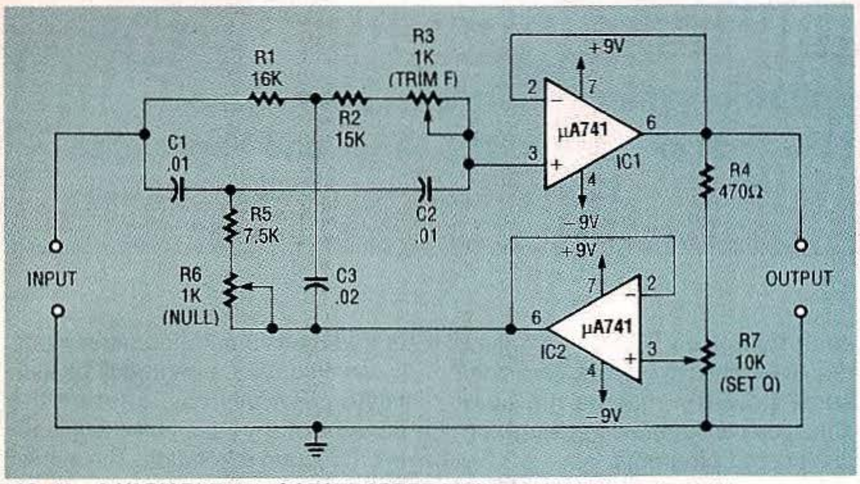


FIG. 16—A VARIABLE-Q, BOOTSTRAPPED TWIN-T NOTCH filter for 1 kHz.

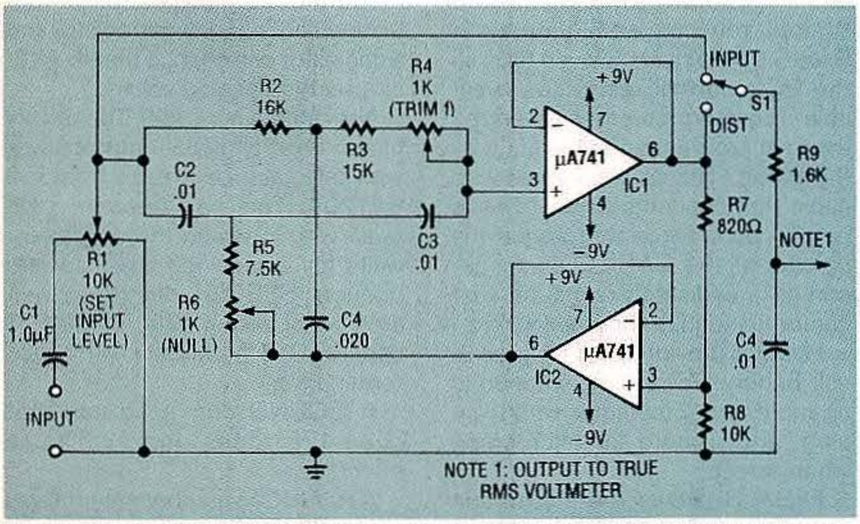


FIG. 17—THE SCHEMATIC FOR A 1-kHz TOTAL HARMONIC DISTORTION (THD) meter circuit.

has an RMS amplitude of 1000 millivolts, and the nulled output has an amplitude of 15 millivolts, the ratio of output signal to input signal multiplied by 100 gives a THD of 1.5 %.

Figure 17 is a schematic for a high-performance, 1-kHz THD meter. In this circuit, the filter's Q is set at a value of 5 by the voltage divider formed by 820-ohm resistor R7 in series with the 10 K resistor R8.

The input signal to the filter can be varied with 10 K SET INPUT LEVEL trimmer capacitor R1, and the filter's tuning and nulling can be varied by NULL trimmer potentiometer R6. Switch S1 permits the circuit to be switched to either the filter's INPUT or distorted (DIST) output. Either output can be fed to an external true RMS voltmeter.

To make a measurement with the THD meter shown in Fig. 17, set switch S1 to its INPUT position, connect the 1-kHz input test signal, and adjust R1 to set a convenient (1- or 2-volt) reference level with the true RMS voltmeter switch.

Then set S1 in the DIST position, adjust the input frequency for an approximate null, and adjust trimmer potentiometers R4 and R6 alternately until you obtain the best possible null. Read the nulled voltage and calculate the distortion factor from the formula:

$$THD\ (\%) = (V_{DIST} \times 100)/V_{IN}$$

Studying and building filter circuits should give you some new insights into the way operational amplifiers can enhance the effectiveness of passive filter circuits. Ω