

Anyone who builds or experiments with electronics circuits has at one time or another been faced with the problem of removing unwanted frequencies from the signal of interest. In most cases, a simple low-pass, high-pass, bandpass, or band-reject filter will suffice. Such filters are great for blocking entire bands of frequencies, but what do you do when the offending frequency is within the band of interest?

I recently encountered just such a dilemma while experimenting with a circuit that was designed to operate below 500 Hz. Because of the circuit's design parameters, a 60-Hz, AC-hum problem soon became apparent. Aside from 60-Hz, AC hum, interfering in-band signals can also be induced by oscillators, motors, or other signal-generating devices used in (or near) the circuit. The signals from such sources are often difficult to suppress, particularly if the interfering signals are of greater power than the frequencies that they intrude upon, or if errors were made in laying out the circuit. One way to eliminate unwanted in-band interference is with a notch filter.

Notch Filters. A notch filter is functionally similar to a bandstop or band-reject filter in that it is designed to arrest a particular band of frequencies. But unlike the bandstop/reject filter, the notch filter has a very narrow rejection band. Its rejection band is focused around the center frequency (f_C) of the circuit. The frequency response for a notch filter is shown in Fig. 1. The bandwidth (BW) of such a filter is the difference between the frequencies at the two -6 dB points (f_L and f_H) when the out-of-notch response is at the reference 0-dB point. The filter's bandwidth is given by: $f_H - f_L$.

The sharpness or "Q" of a notch filter—a measure of the narrowness of the filter's bandwidth—is defined as the ratio of the center frequency (f_C) to bandwidth. The Q of a notch filter is given by:

$$Q = \frac{f_C}{BW} \quad (1)$$

For instance, a notch filter that's centered on 60 Hz and has -6 dB points at 58 and 62 Hz (a 4 Hz bandwidth) has a Q of 60/4 or 15.

The notch filter does not entirely remove the offending signal; instead, it greatly suppresses the

offending signal, thereby reducing its presence in the affected band of frequencies. The degree of suppression, called the notch depth (see Fig. 1), is defined by the ratio of the gain of the circuit at an out-of-notch frequency (e.g., f_{0B}) to the gain at the notch frequency. Assuming that the input signal levels at both frequencies are equal, the notch depth can be calculated from the output voltages of the filter at the two different frequencies using:

$$\text{Notch Depth} = 20 \log_{10} \left(\frac{V_{fc}}{V_{ob}} \right) \quad (2)$$

Notch depths of -40 to -60 dB are relatively easy to achieve with proper circuit design and component selection.

Twin-Tee Filter Networks. One of the most popular forms of notch filter is the twin-tee filter. An example of a twin-tee filter is shown in Fig. 2. As its name implies, the circuit is comprised of a pair of T-networks. In our example, the T-networks consist of C1/C3/R2 and R1/R3/C2. The center frequency of the network is given by:

$$f_C = \frac{1}{2\pi} \sqrt{\frac{C1 + C3}{(C1)(C2)(C3)(R1)(R3)}} \quad (3)$$

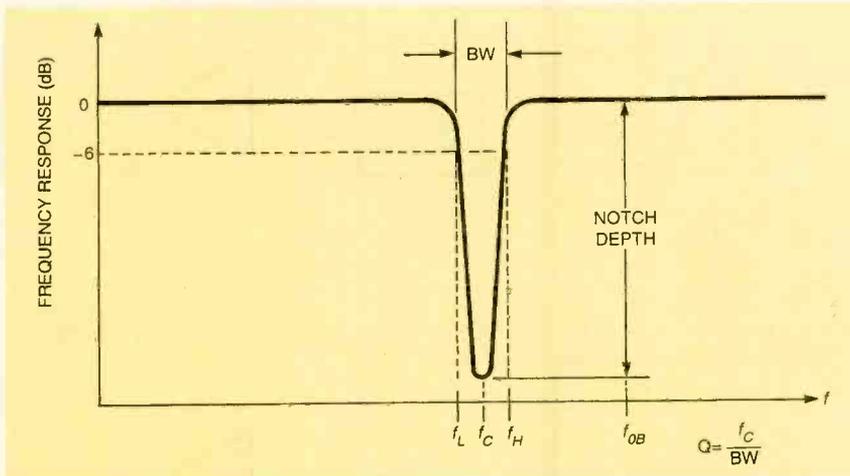
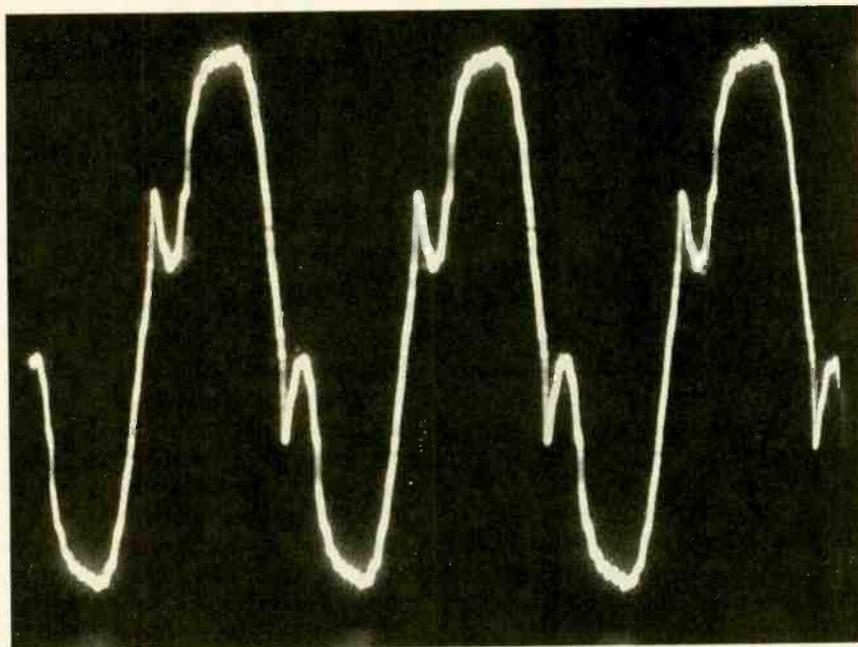


Fig. 1. The frequency response for a notch filter is shown here. The function of the notch filter is similar to that of a bandstop or band-reject filter. But unlike the bandstop/reject filter, which is designed to block a whole range of frequencies, the notch filter has a very narrow rejection band.



Here is an example of the 60-Hz hum found in one of my projects and recorded on an oscilloscope.

That expression can be simplified by adopting a convention that calls for the following relationships: $C1 = C3 = C$; $R1 = R3 = R$; $C2 = 2C$; and $R2 = R/2$. If that convention is adopted, then the equation can be reduced to:

$$f_C = \frac{1}{2\pi RC} \quad (4)$$

where f_C is the filter's center frequency in hertz (Hz), R is resistance in ohms, and C is capacitance in farads. Be sure to use the right units when working the problems, i.e., 10,000 ohms for 10 kilohms or 1×10^{-9} for 0.001 μF .

In designing a filter, it is wise to first select a capacitor value and then calculate the required resistance. That's done because there are many more standard resistance values than capacitance values. Besides potentiometers can be easily used to trim the values of resistances; it is more difficult to use trimmer capacitors for the same purpose. For 60-Hz filters, some common values for resistor R and C are:

CAPACITANCE (μF)	RESISTANCE (Ω)
0.001	2,652,582
0.01	265,258
0.15	17,684

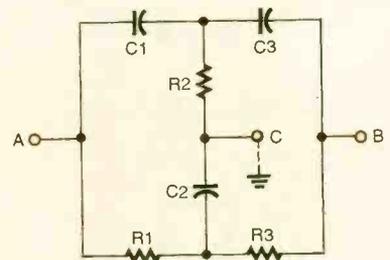


Fig. 2. The twin-tee filter (shown here), one of the most popular forms of notch filter, is comprised of a pair of T-networks, one consisting of $C1/C3/R2$ and the other built around $R1/R3/C2$.

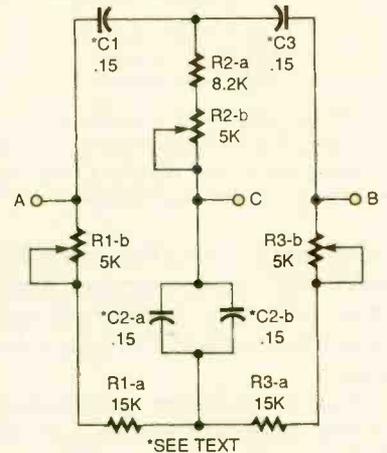


Fig. 3. Here is a 60-Hz twin-tee notch filter that uses potentiometers to tune the filter's central frequency.

There are two factors that govern the notch depth of the twin-tee filter. One of the factors is the values of the components; they must be very close to the calculated values. The other determining factor is that the two filters must be closely matched to one another. For example, let's say that a 60-Hz notch filter was assembled using 0.15- μF -capacitor and 17,684-ohm resistor values, and that the capacitors were randomly selected from among a group of a dozen or so good-quality units, while the resistors were 18k, 5% metal-film units. The notch depth at 60 Hz was only 10 dB, but at 58 Hz, it was 48 dB. Obviously, there was a mismatch, which caused a significant shift in notch frequency.

Now let's suppose that a second filter was built using the same values. In this case, the 0.15- μF capacitors were selected from about 20 on hand. In order to match the capacitors as close as possible, each was measured using a capacitance

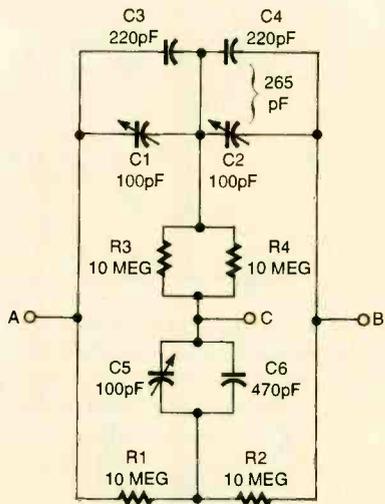


Fig. 4. Another form of adjustable circuit is shown here. This one differs from the one in Fig. 3 in that it uses trimmer capacitors rather than potentiometers as the adjustable element.

meter. The reason for that was to find those that closely matched each other, and only incidentally how close they come to the calculated value.

Errors in the mean capacitance of the selected group can be trimmed out using a potentiometer instead of resistors in the twin-tee network. Figure 3 shows a 60-Hz twin-tee notch filter wherein potentiometers are used to tune the filter's central frequency. Each potentiometer in that circuit must be adjusted several times to null the output signal, stopping when there is no further suppression of the output signal.

An oscilloscope or AC voltmeter, along with a well-calibrated signal source, can be used to check the operation of circuit. If you are unsure as to the accuracy of the signal source, a frequency counter can be used to monitor the signal-source output. (Keep in mind that in our example, a shift of only 2-Hz produced a 38-dB difference in notch depth!)

Another form of adjustable circuit is shown in Fig. 4. Although, it is similar to the circuit in Fig. 3, this one uses trimmer capacitors rather than potentiometers as the adjustable element. In the Fig. 4 circuit, four capacitors (two fixed and two variable, C1-C4) combine to form an equivalent capacitance of 265 pF. The capacitor combination allows the circuit to be adjusted above

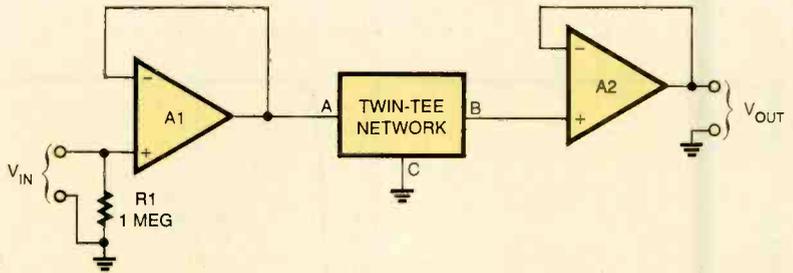


Fig. 5. Shown here is a basic active twin-tee filter. In this circuit, the basic twin-tee network is cascaded with input- and output-buffer amplifiers.

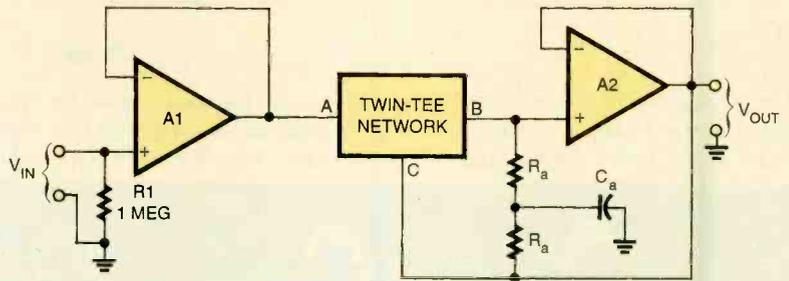


Fig. 6. Altering the active twin-tee circuit as shown here produces a filter circuit with superior characteristics.

and below the design value by a margin sufficient to cancel out any tolerance problems.

The 10-megohm resistors specified should be matched to each other using an ohmmeter. Again, the goal is to match the resistor values as close as possible to each other, and only incidentally close to the design value. It is desirable that the resistance values be exactly equal; failing that, they should be as closely matched as possible. The difference between their mean value and the design value can then be trimmed out via the variable capacitor.

The performance of the twin-tee filter can be vastly improved by incorporating one or more op-amps into the filter's design, turning the basic circuit into an active twin-tee filter.

Active Twin-Tee Notch Filters.

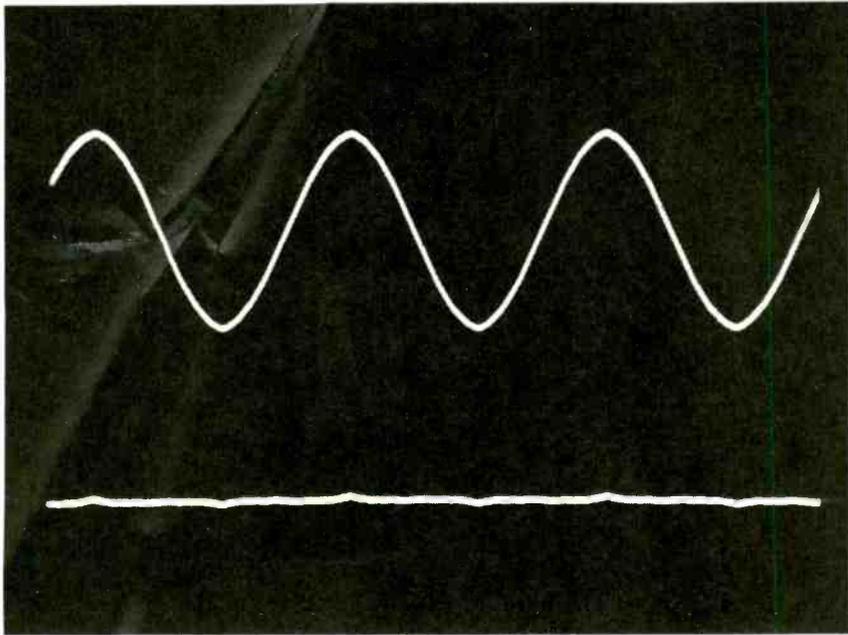
Active filters are simply filter networks that use one or more active devices (such as op-amps) in their design. Figure 5 shows a basic active twin-tee filter, wherein the basic twin-tee network is cascaded with input- (optional) and output- (required) buffer amplifiers. Note that in Fig. 5 and subsequent active twin-tee filter schematics, the "twin-tee" net-

works, which are identical to the previous networks, are shown as functional blocks for the sake of simplicity. Be aware that points "A," "B," and "C" represent the same positions as in the previous illustrations. The buffer amplifiers, both of which are configured as unity gain, non-inverting voltage followers, isolate the filter network from the outside world. For low-frequency applications, 741, 1458, and similar devices can be used. For higher frequency applications—i.e., circuits with an upper cut-off frequency above 3 kHz—non-frequency-compensated devices, such as the CA-3130 or CA-3140, can be used.

Altering the active twin-tee circuit in Fig. 5 as shown in Fig. 6 produces a filter circuit with superior characteristics. In the Fig. 6 circuit, port-C of the twin-tee network (the common point) is connected to the output terminal of the output buffer amplifier. There is also a feedback network consisting of two resistors (R_a) and a capacitor (C_a). The values of R and C in the twin-tee network are found from Eq. 4, while the values of R_a and C_a are found from:

$$R_a = 2RQ \quad (5)$$

and



Shown here is the input (upper) and output (lower) traces for a signal that was on a frequency of precisely 60 Hz.

FOR FURTHER READING

IC User's Casebook

Joseph J. Carr
Howard W. Sams & Co.
(Indianapolis, IN, 1988);
Cat. No. 22488

Integrated Electronics

Harcourt, Brace, Jovanovich
Technology Publications
(San Diego, CA, 1990)

IC Op-Amp Cookbook

Walter G. Jung
Howard W. Sams & Co.
(Indianapolis, IN, 1974)

Handbook of Operational Amplifier Circuit Design

David F. Stout and Milton Kaufman
McGraw-Hill
(New York, 1976)

5. Select R_Q : $R_Q = 2QR = (2)(8)(265,392 \text{ ohms}) = 4.24 \text{ megohms}$.

6. Select $C_Q = C/Q = 0.01 \mu\text{F}/8 = 0.0013 \mu\text{F}$.

When the circuit in Fig. 6 was built using the twin-tee network of Fig. 3, with potentiometers for adjustments, the null was close to -48-dB deep.

Figure 7 shows two variations on the Fig. 6 circuit. Figure 7A shows the addition of a notch-depth control (R_2), consisting of a 5k potentiometer in a feedback loop connected between the output of amplifier A2 and the input port of the twin-tee network. An active twin-tee filter with variable Q control is shown in Fig. 7B. In that circuit, a non-inverting follower (A3) is connected in the feedback loop in place of R_Q and C_Q . The Q of the notch is set by the position of R1, the 10k potentiometer. The Q of that circuit can be adjusted from 1 to 50.

Other Approaches. The twin-tee filter is not the only possible approach to making a notch filter. In Fig. 8A we see a circuit (in block form) in which the responses of a high-pass filter (HPF) and a low-pass filter (LPF) are overlapped. The two filters, which may be active filters in their own right, are connected in parallel, with their outputs summed together in a two-input inverting follower amplifier (A2). The gain of that circuit is -1, unless the HPF and LPF sections have either gain or loss in their own right.

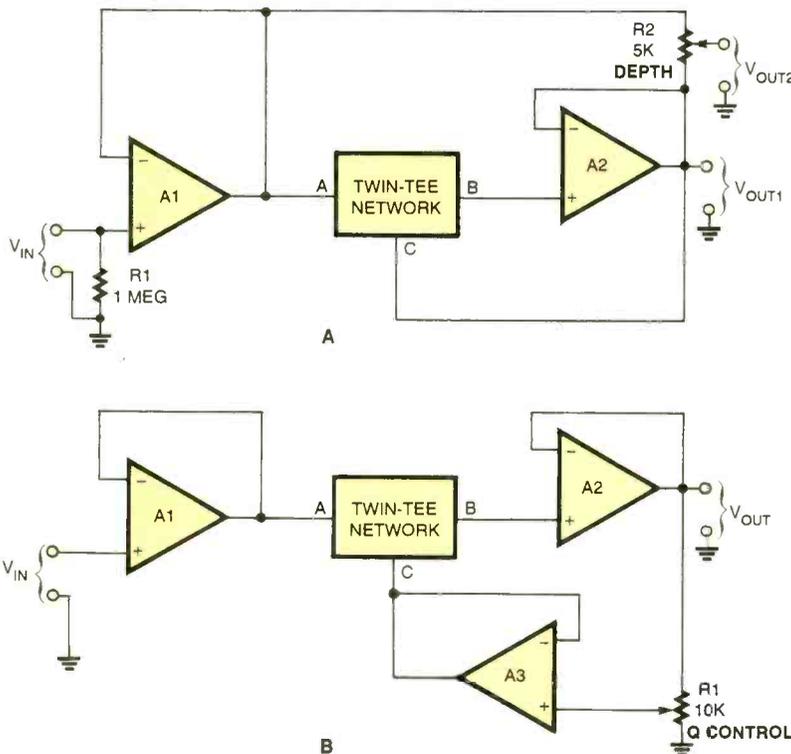


Fig. 7. Shown here are two variations on the circuit in Fig. 6. The circuit in A incorporates an additional notch-depth control; the circuit in B has a feedback loop connected from the output of A2 to the input of the twin-tee network.

$$C_Q = \frac{C}{Q} \quad (6)$$

For example, let's design a 60-Hz notch filter with a Q of 8.

1. Select a trial value for C of $0.01 \mu\text{F}$.

2. Calculate the value of R from Eq. 4, which works out to 265,392 ohms.

3. Calculate $R/2$: $265,392/2 = 132,696 \text{ ohms}$.

4. $C_2 = 2C = (2)(0.01 \mu\text{F}) = 0.02 \mu\text{F}$.

SURFACE-MOUNT

(continued from page 36)

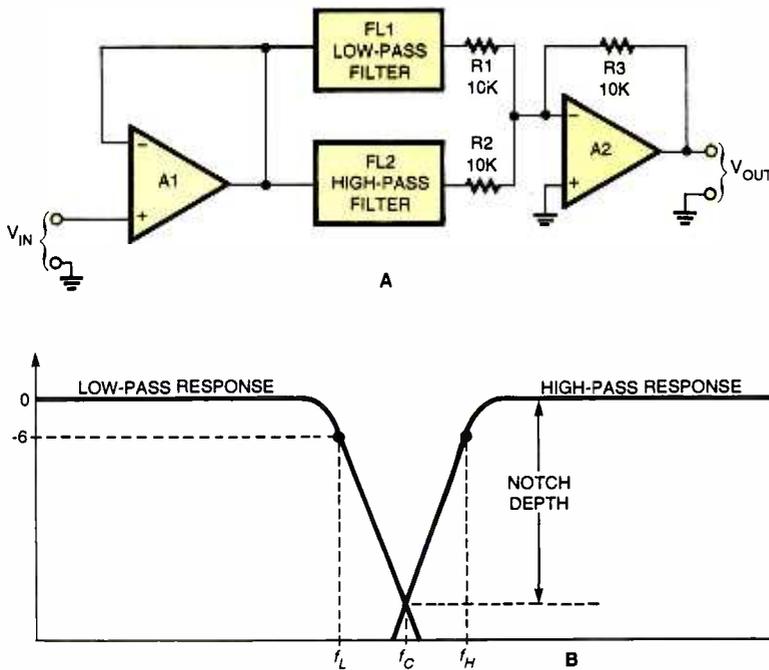


Fig. 8. The twin-tee filter is not the only possible approach to making a notch filter. Shown in A is a circuit that is comprised of both high-pass and low-pass filters, which together function as a notch filter. The overlapping frequency responses of the circuit are shown in B.

The overlapping frequency responses of the circuit are shown in Fig. 8B. The lower notch frequency (f_L) is the -6 dB frequency of the low-pass filter, while the upper notch frequency (f_H) is the -6 dB frequency of the high-pass filter. The depth of the notch is set by the point where the responses of the high-pass and low-pass filters cross.

The notch filter of Fig. 8A is often implemented using a single state-variable filter, because those types of active filters have both low-pass and high-pass outputs.

Another approach to the notch filter is shown in Fig. 9. That circuit is sometimes called the active-inductor, notch filter. The notch frequency for that circuit is set by:

$$f_C = \frac{1}{2\pi\sqrt{R_a R_b C_a C_b}} \quad (7)$$

Equation (7) can be simplified to

$$f_C = \frac{1}{2\pi R \sqrt{C_a C_b}} \quad (8)$$

If the following conditions are met:

$$\frac{R_3}{R_1} = \frac{R_2}{R_a + R_b} = \frac{R_2}{2R} \quad (9)$$

It is possible to use any one of the elements, C_a , C_b , R_a , or R_b , to

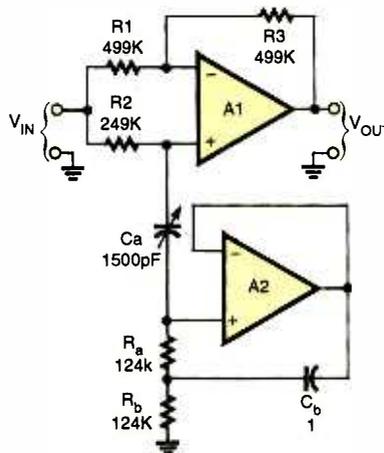


Fig. 9. Sometimes called the active-inductor, notch filter, this variation of the notch filter can be varied via C_a .

tune the filter. In most cases, C_a is made variable and C_b is a large value-fixed capacitor. The 1500-pF variable capacitor can be made by paralleling all sections of a three-section broadcast variable, with a single small fixed or trimmer capacitor.

Conclusion. Unwanted signals, such as 60-Hz interference, as well as other extraneous signals are a pain in the transistor, but they are also quite easy to get rid of using ordinary notch-filter circuits. ■

construction project. At this point, the modules are treated as any other electronics component.

Note: Connections between SIP-7 and the speaker jacks should be handled through twisted wire. For the best performance, single-conductor, shielded cable is recommended for the input and volume controls.

Next, select an enclosure for the project and determine where on the front and rear panels the off-board components will be placed. The project can be housed in a small aluminum enclosure, like RadioShack part #270-253. Place the front-panel components so that they are neat and easily accessible.

The power transformer (T1) was selected, because the combined total-current draw of the modules amounts to less than 100 mA. In addition, the unit's small dimensions allow a smaller enclosure to be used to house the project.

The project can be expanded as you see fit; remember, your imagination is the only limiting factor.

SIP Construction Contest. The applications for the SIPs are really unlimited, and we're very interested in what you are able to come up with. So, we've come up with a little contest. Design some type of audio circuit built around the SIP modules. Send your design to: SIP Contest, **Popular Electronics**, 500 Bl-County Blvd., Farmingdale, NY 11735. If your design is publishable, we'll present your design to our readers and pay the author of the winning entry our regular rates for an article. On the other hand, if your design is presented as a part of a SIP-circuits article, we'll pay each contributor \$50 for their design. If there are similar entries, the one with the earliest postmark will be selected.

Table 1 list the prices for the individual SIPs in kit form or fully assembled. The Parts Lists gives additional SIP ordering information.

Hope you like the Auctioneer's Amplifier project. ■