Electronic FILTER CIRCUITS

PART 3

by Ray Marston

Ray Marston takes an in-depth look at active C-R filter circuits in the concluding part of this 3-part series.

C-R Active Filters

An active filter is a circuit that combines passive C-R networks and one or more amplifier or op-amp stages, to form a filter that can either out-perform normal C-R filters or can give a performance that is unobtainable from purely passive networks. A good selection of practical test-gear-orientated active filters are described in the next few pages. All these circuits are shown designed around standard 741 op-amps and operated from dual 9V supplies, but they will, in fact, work with virtually any normal op-amp, and from any supply voltages within the op-amp's operating range. If the circuits are to be used above a few tens of kHz, wide-band op-amps should be used.

The two most basic types of active filter are the 1st-order low-pass and high-pass types shown in Figures 1 and 2. These are simple adaptations of the passive types shown in Part 1 of this series, but each have their output buffered by a unity-gain non-inverting amplifier, to give a low-impedance output with a –3dB crossover frequency (f_c) of $^{1}/_{(2\pi RC)}$, and an output slope of 6dB/octave (= 20dB/decade). With the component values shown, each circuit has an fC value of 1kHz. Note that the input signal to the low-pass circuit must provide an effective DC path to ground.

Each of the above two filter circuits uses a single C-R stage, and is known as a '1st-order' filter. Figure 3 shows the practical circuit and formula of a maximally-flat (Butterworth) unity-gain 2nd-order low-pass filter with a 10kHz break frequency. Note that the '2C' capacitor is subjected to unity-gain bootstrapping from the op-amp's output. This circuit's output falls off at a rate of 12dB/octave beyond 10kHz, and is thus about 40dB down at 100kHz, and so on. To alter the break frequency, change either the R or the C value in proportion to the frequency ratio relative to Figure 3; reduce the values by this ratio to increase the frequency, or increase them to reduce the frequency. Thus, for 4kHz operation, increase the R values by a ratio of 10kHz/4kHz, or 2·5 times.

A minor snag with the circuit shown in Figure 3 is that one of its 'C' values should ideally be precisely twice the value of the other, and this can result in some rather odd component values. Figure 4 shows an alternative 2nd-order 10kHz low-pass filter circuit that overcomes this snag and uses equal component values. Note here, that the op-amp is designed to give a voltage gain of 4·1dB via R1 and R2, and thus gives greater than unity bootstrapping to one of the filter's capacitors.

Figure 5 shows how two of these 'equal component' filters can be cascaded to make a 4th-order low-pass filter with a slope of 24dB/octave. In this case, gain-determining resistors $^{R1}/_{R2}$ have a ratio of 6·644, and $^{R5}/_{R4}$ have a ratio of 0·805, giving an overall voltage gain of 8·3dB. The odd values of R2 and R4 can be made by series-connecting standard 5% resistors.

Figures 6 and 7 show unity-gain and 'equal component' versions, respectively, of 2nd-order 100Hz high-pass filters, and Figure 8 shows a 4th-order 100Hz high-pass filter. The operating frequencies

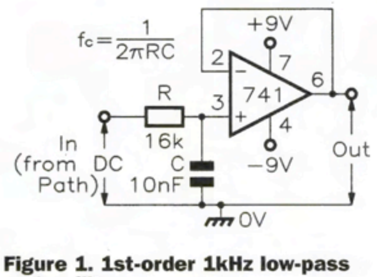

Figure 1. 1st-order 1kHz low-pass active filter.

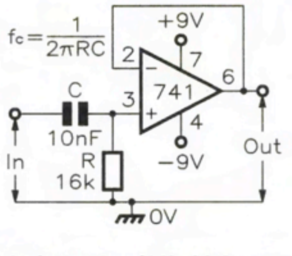

Figure 2. 1st-order 1kHz high-pass active filter.

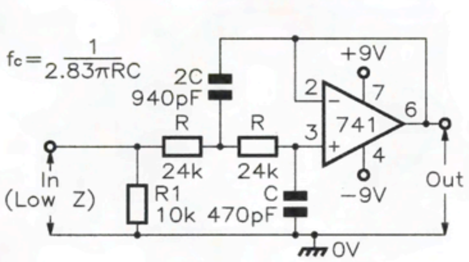

Figure 3. Unity-gain 10kHz 2nd-order low-pass active filter.

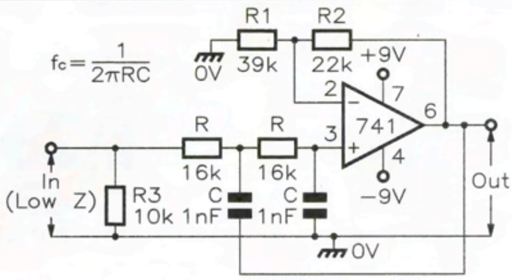

Figure 4. 'Equal components' version of the 10kHz 2nd-order low-pass filter.

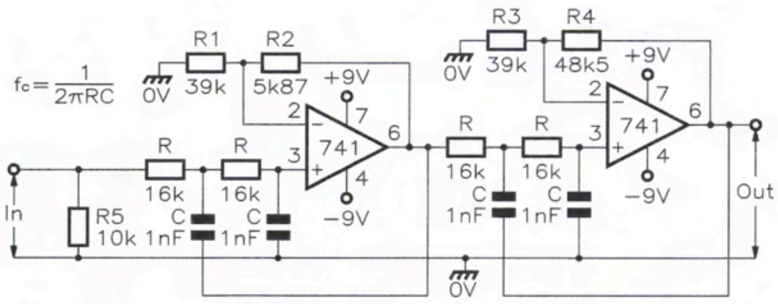

Figure 5. 4th-order 10kHz low-pass filter.

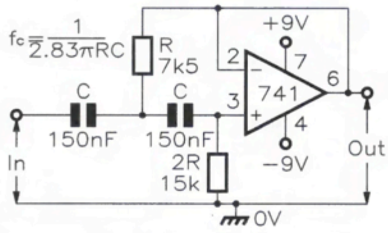

Figure 6. Unity-gain 2nd-order 100Hz high-pass filter.

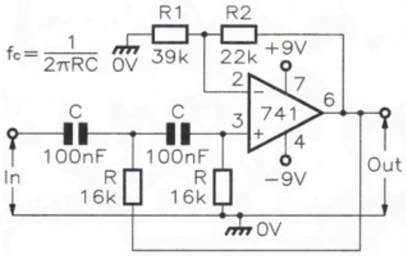

Figure 7. 'Equal components' version of 100Hz 2nd-order high-pass filter.

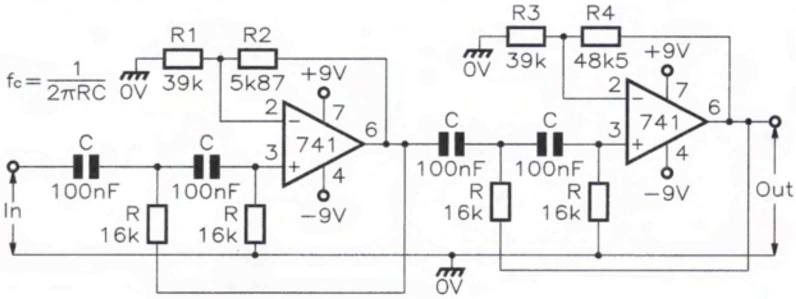

Figure 8. 100Hz 4th-order high-pass filter.

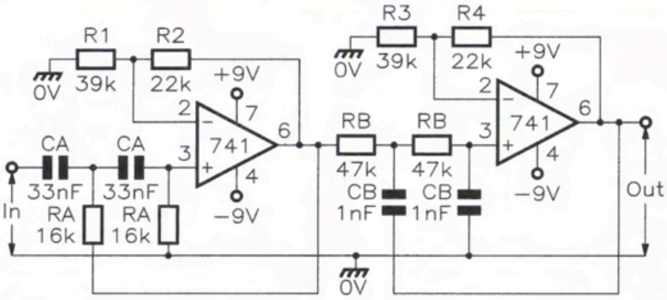

Figure 9. 300Hz to 3·4kHz band-pass filter with 2nd-order response.

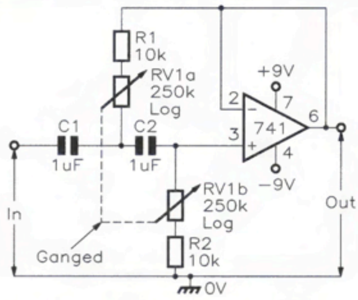

Figure 10. Variable high-pass filter, spanning 23·5 to 700Hz.

of these circuits, and those of Figures 4 and 5, can be altered in exactly the same way as in the Figure 3 circuit, i.e., by increasing the R or C values to reduce the break frequency, or vice-versa.

Finally, Figure 9 shows how the Figure 7 high-pass and Figure 4 low-pass filters can be wired in series to make (with suitable component value changes) a 300Hz to 3·4kHz 'speech' range bandpass filter that gives 12dB/octave of rejection to all signals outside of this range. In the case of the high-pass filter, the 'C' values of Figure 7 are reduced by a factor of three, to raise the break frequency from 100 to 300Hz, and in the case of the low-pass filter, the 'R' values of Figure 4 are increased by a factor of 2·94, to reduce the break frequency from 10 to 3·4kHz.

Variable Active Filters

The most useful type of active filter is that in which the crossover frequency is fully and easily variable over a fairly wide range, and Figures 10 to 12 show three practical examples of 2nd-order versions of such circuits.

The circuit shown in Figure 10 is a simple development of the high-pass filter of Figure 6, but has its crossover frequency fully variable from 23·5 to 700Hz via RV1. Note in this circuit, that the resistive arms of the C-R networks have identical values (unlike Figure 6), so this design does not give maximally-flat 'Butterworth' operation, but nevertheless, gives a very good performance. This circuit can, in fact, be used as a high quality turntable disc (record) 'rumble' filter; 'fixed' versions of such filters usually have a 50Hz crossover frequency.

The Figure 11 circuit is a development of the high-pass filter of Figure 3, but has its crossover frequency fully variable from 2·2 to 24kHz via RV1, and again, does not give a maximally-flat 'Butterworth' performance. This circuit can, in fact, be used as a high quality 'scratch' filter; 'fixed' versions of such filters usually have a 10kHz crossover frequency.

Figure 12 shows how the above two filter circuits can be combined to make a really versatile variable high-pass/low-pass or rumble/scratch/speech filter. The high-pass crossover frequency is fully variable from 23·5 to 700Hz via RV1, and the low-pass value is fully variable from 2·2 to 24kHz via RV2.

Tone and Notch Filters

Excellent active C-R tone filters, with very high effective 'Q' values, can be made by using twin-T or Wien networks in the feedback loops of suitable op-amp circuits. A 1kHz twin-T design has already been described in Figure 15 of Part 1 of this series. Figure 13 shows the practical circuit of a 1kHz Wien bridge based tone or 'acceptor' filter. The Q of this circuit is variable via the 10kΩ variable resistor, R2. Note that this circuit becomes an oscillator if R2 is reduced too far (to less than twice the R1 value).

The basic twin-T notch filter has a very low Q. The filter's Q, and thus, the notch 'sharpness', can be greatly increased by incorporating the twin-T in the feedback network of an active filter. There are two standard ways of doing this. The first way is to use the shunt feedback technique shown in Figure 14, in which the input signal is fed to the twin-T via R1, and an amplified and inverted version of the filter's output is fed back to the filter's input via R2, which has the same value as R1. Figure 15 shows the practical circuit of a 1kHz version of this type of active filter.

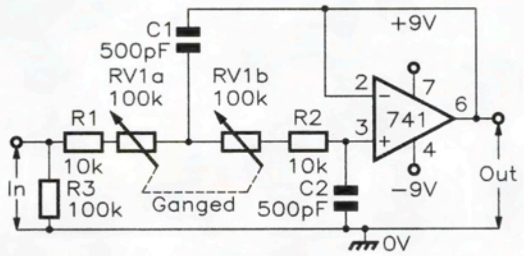

Figure 11. Variable low-pass filter, spanning 2·2 to 24kHz.

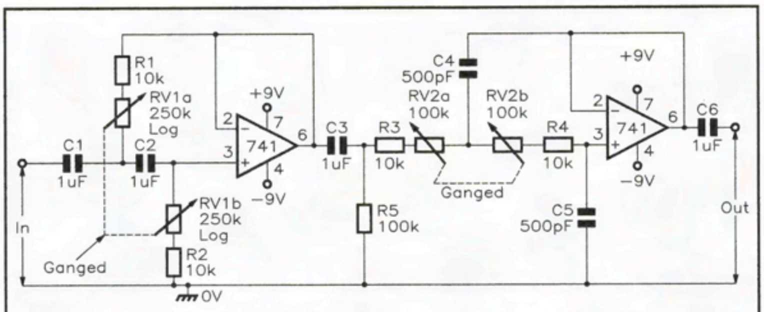

Figure 12. Variable high-pass/low-pass or rumble/scratch/speech filter.

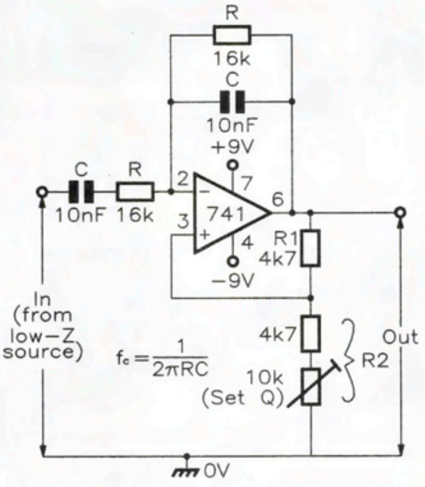

Figure 13. Wien bridge based 1kHz high-Q tone filter.

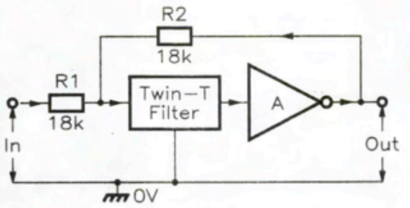

Figure 14. Basic twin-T notch filter using shunt feedback.

The network's null point can be adjusted via the 1kΩ variable resistor.

The second (and more modern) Q-boosting method is the bootstrapping technique, which has already been described and shown in basic form in Figure 12 of Part 1 of this series. Figure 16 shows a practical example of a 1kHz variable-Q version of such a circuit. The twin-T's output is buffered by the upper op-amp (a unity-gain voltage follower), and part of the buffered output is tapped off via RV3 and fed to the bottom of the twin-T (as a bootstrap signal) via the lower op-amp (another unity-gain voltage follower). When RV3's slider is set to the lowest (ground) point, the network has zero bootstrapping, and the circuit acts like a standard twin-T filter with a Q of 0·24. When RV3's slider is set to the highest point, the network has heavy bootstrapping, and the filter has an effective Q of about 8 and provides a very sharp notch. The filter's centre-frequency can be trimmed slightly via RV1, and the null point can be adjusted via RV2, which should be a multi-turn type.

A THD (Distortion) Meter

The bootstrapped twin-T notch filter can be used as the basis of an excellent total harmonic distortion (THD) or 'distortion' meter. Here, the filter's notch is tuned to the basic frequency of the input test signal, and totally rejects the fundamental frequency of the signal but gives zero attenuation to the signal's unwanted harmonics and mush, etc., which appear at the filter's output; the output signals must be read on a true rms volt or millivolt meter. Thus, if the original input signal has a rms amplitude of 1,000mV, and the nulled output has an amplitude of 15mV, the THD value works out at 1·5%.

Figure 17 shows the practical circuit of a high-performance 1kHz THD meter. This filter's Q is set at a value of 5 via the 820Ω-10kΩ divider, to give the benefits of easy tuning combined with near-zero second harmonic (2kHz) signal attenuation. The input signal to the filter is variable via RV3, and the filter's tuning and nulling are variable via RV1 and RV2, respectively. SW1 enables either the filter's INPUT or its DISTorted output to be fed to an external true rms meter; note that the meter feed line incorporates a 10kHz low-pass filter, to help reject unwanted 'noise' signals and give a truer reading of THD.

To use the Figure 17 THD meter, first set SW1 to the INPUT position, connect the 1kHz input test signal, and adjust RV3 to set a convenient (say 1V) reference level on the true rms meter. Next, set SW1 to the DIST position, adjust the input frequency for an approximate null, then trim RV1 and RV2 alternately until the best possible null is obtained. Finally, read the nulled voltage value on the meter and calculate the distortion factor on the basis of:

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

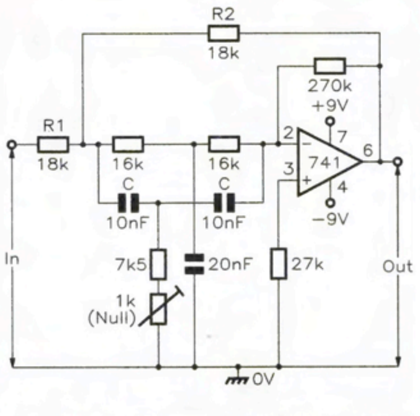

Figure 15. Practical 1kHz twin-T notch filter with shunt feedback.

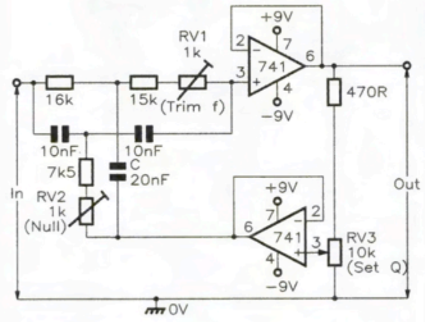

Figure 16. 1kHz variable-Q bootstrapped twin-T notch filter.

Figure 17. 1kHz THD (distortion) meter circuit.