FILTER DESIGN

Tim Orr tackles the subject of Active Filters.

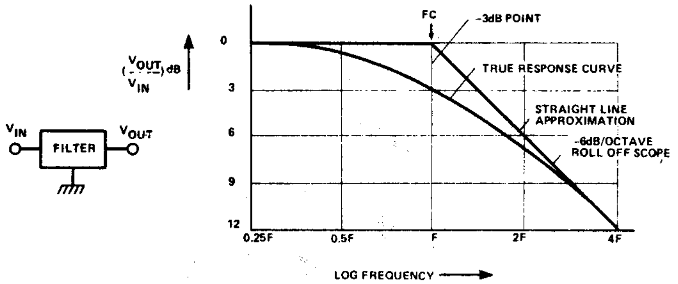


Fig. 1. Frequency response of a first order low pass filter.

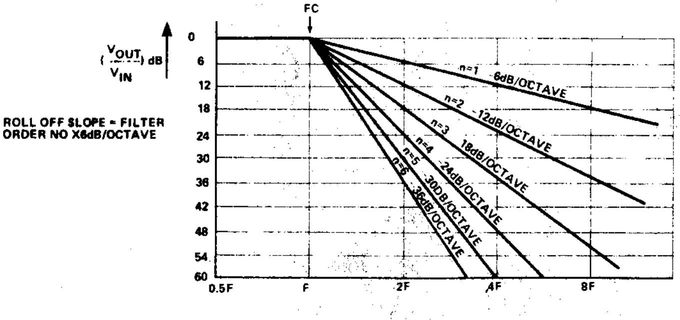


Fig. 2. Filter roll-off slopes. As n increases so does the roll-off.

THE FREQUENCY RESPONSE plot of a first order low pass filter (Fig. 1) reveals several important features. The break frequency Fc, is defined as the point at which the output signal is attenuated by 3dB. The curve than approximates to a –6dB/octave roll off slope. By using a straight line approximation it is easy to calculate attenuations caused by the filter. For example, an 8kHz sinewave filtered by a 1kHz first order lowpass filter will be attenuated 18dB, a reduction in level of almost one-tenth. The calculation is simple; 8kHz is 3 octaves above 1kHz. The filter attenuates at 6dB per octave, therefore the final attenuation is

3 x 6 = 18dB.

To increase the roll of slope, the filter order must be increased, figure 2. When constructing high order filters, it is necessary to assemble them out of smaller filter sections each having different Q factors. A high order filter constructed from sections all having the same Q factor will have a very 'unabrupt' frequency response curve, which is generally not what is required.

A simple first order filter (Fig. 3) merely requires a resistor, a capacitor and a voltage follower. A second order filter (Fig. 4) requires two RC networks. This circuit has a 'flattest amplitude' response (when it has a Q of 0.7) and is often referred to as a Butterworth response. The response may be modified by altering the Q factor, but in all the following examples a Butterworth response has been chosen. This design is known as a 'unity gain Sallen and Key' filter. The Q factor is determined by the ratio of the two timing capacitors. This often leads to a circuit design which employs non-preferred capacitor values as can be seen in the three filters by a process known as scaling. For instance, if the required break frequency is 5kHz, then the resistors, or the capacitors in the filter should be reduced by a factor of five. If say the filter in figure 5a had to be redesigned to operate

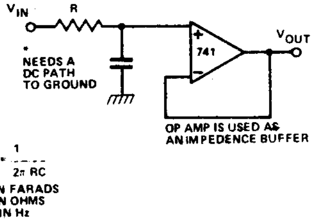


Fig. 3. Simple first order low pass filter.

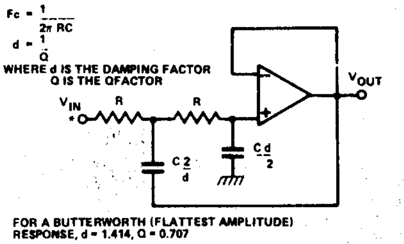


Fig. 4. Second order unity gain Sallen and Key low pass filter.

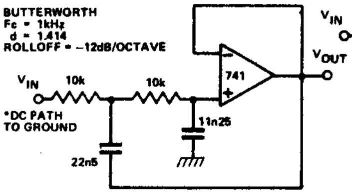


Fig. 5a. Second order low pass filter 1kHz.

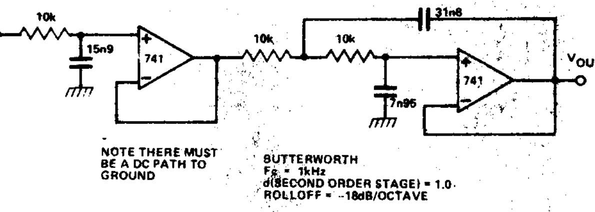


Fig. 5B. Third order low pass filter, 1kHz.

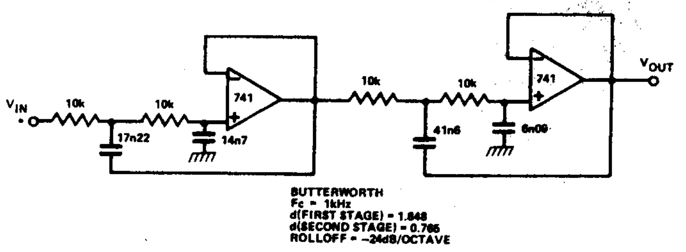


Fig. 5c. Fourth order low pass filter, 1kHz.

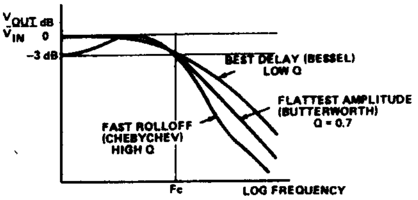


Fig. 6. Frequency response versus Q factor.

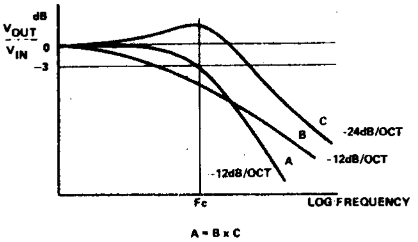
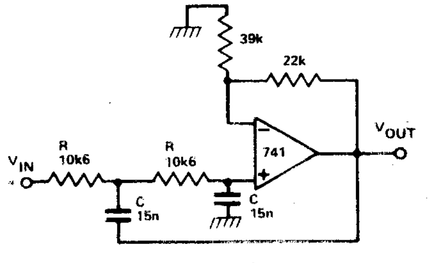


Fig. 7. Combining high and low Q factors.

50Hz,then the required component changes would be to change the 10k resistors to 40k. Active filters generally employ op amps and so care should be taken so as not to operate them near to their bandwidth limit, which would cause the filter response to be degraded. A 741, for instance, should not be used for frequencies above 50kHz.

Figure 6 shows the effect of varying Q in a low pass filter. Generally, the response that is wanted is the 'flattest amplitude' curve. A fourth order filter (Fig. 5c) is constructed from a low Q and high Q filter. The overall response of this filter is seen in figure 7. Note that the flattest amplitude curve (A) is made up out of the product of curves B and C. The peak in the high Q curve (C) is flattened out by the droop of the low Q curve (B).

The problem of having different and unpreferred capacitor values is greatly reduced by using an 'equal component' design, figure 8a, b, c. The Q factors are controlled by the gain of the op amp and so the capacitor values are all the same. Note that these filters provide a voltage gain which is in fact the product of the DC gains of each amplifier. Frequency scaling can be performed by modifying the R and/or the C components. Capacitors generally are available in E6 or E12 values, whereas resistors can be obtained in the E24 series, and so it is usually much easier to scale the R components, keeping them within the range 1k to 100k. Low pass filters find many uses in audio processing and are often used in data acquisition systems (fig. 9). The high pass filter (fig. 10) is exactly complementary in operation to the low pass device. The unity gain Sallen and Key structure is seen in figure 11 with calculated values for second, third and fourth order filters in figure 12a, b, c. Also there are calculated values for 'equal component' realizations in figure 13a, b, c.

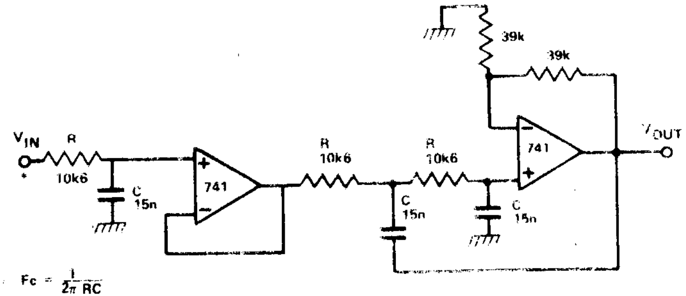


$F_c = \frac{1}{2\pi RC}$
COMPONENT TOLERENCE = 10%
ROLLOFF SLOPE = −12dB/OCTAVE

Fig. 8a. Second order low pass filter, 1kHz.

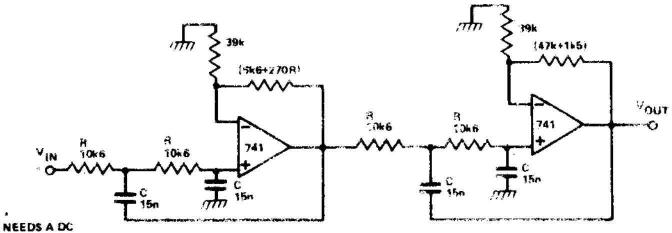
The band pass response is defined in figure 14. This can be realized with a single op amp circuit, the multiple feedback band pass filter, figure 15. Calculated values are seen in the chart of figure 16. The maximum Q should be kept below a value of 20 at 1kHz, otherwise the filter may become unstable and oscillate. Frequency scaling may be performed by multiplying the R or the C components with a constant. High Q, high frequency operation is not possibile with this design because the op amp runs out of bandwidth.

The state variable filter (fig. 17) overcomes this problem by using the bandwidth of three op amps. Q factors of several hundred at 1kHz are ob-



$F_c = \frac{1}{2\pi RC}$
COMPONENT TOLERENCE = 10%
ROLLOFF SLOPE = 18dB/OCTAVE

Fig. 8b. Third order low pass filter, 1kHz.



FOR C. USE SIEMENS B32560 TYPES
$F_c = \frac{1}{2\pi RC}$
COMPONENT TOLERENCE = 5%
ROLLOFF SLOPE = 24dB/OCTAVE

Fig. 8c. Fourth order low pass filter, 1kHz.

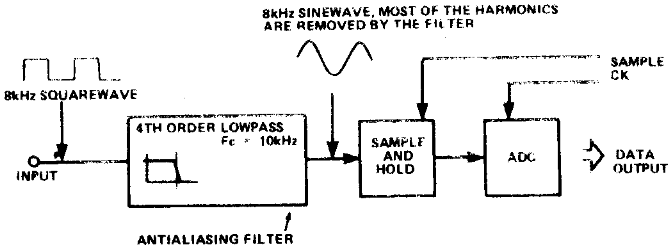


Fig. 9. Use of a low pass filter in an ADC system.

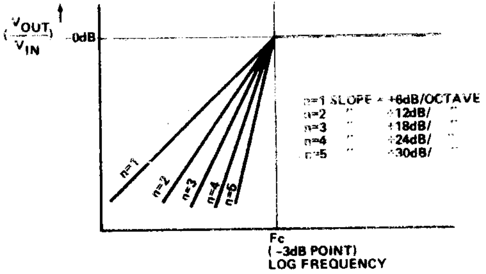
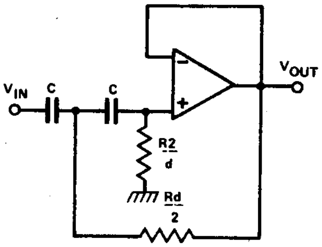


Fig. 10. Frequency response of different orders of high pass filter

tainable with this circuit. It also produces four outputs; high, low, band pass and notch, making it a very versatile design. The frequency may be scaled by altering the R or the C components and also the Q factor is separately programmable and is invariant with frequency. The all pass filter (fig. 18) has a flat frequency response, which in itself is of no use at all. However, it does suffer a 180° phase shift as a function of frequency. By cascading two stages (fig. 19) it is possible to obtain a 180° phase shift at the frequency Fc. This phase shifted signal when mixed with the original will give a notch response due to the cancellation of the two signals.



$Fc = \frac{1}{2\pi RC}$

$d = \frac{1}{Q}$

WHERE d IS THE DAMPING FACTOR
Q IS THE Q FACTOR
FOR A BUTTERWORTH (FLATTEST AMPLITUDE) RESPONSE, d = 1.414 AND Q = 0.707

Fig. 11. Unity gain Sallen and Key high pass filter.

d = 1.414
ROLLOFF = +12dB/OCTAVE

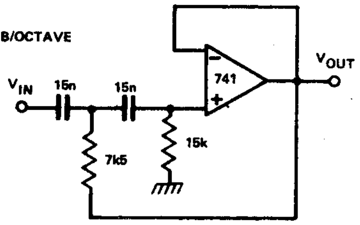
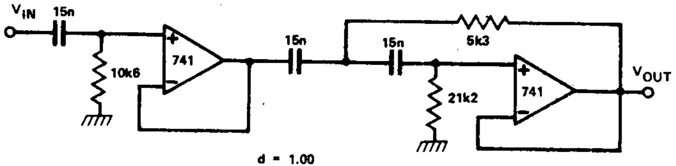


Fig. 12a. Second order Butterworth 1kHz high pass filter.



d = 1.00
(SECOND ORDER STAGE)
ROLLOFF = +18dB/OCTAVE

Fig. 12b. Third order Butterworth 1kHz high pass filter.

d(FIRST STAGE) = 1.848
d(SECOND STAGE) = 0.765
ROLLOFF = +24dB/OCTAVE

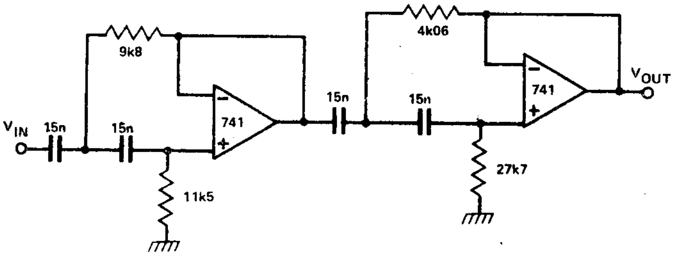


Fig. 12c. Fourth order Butterworth 1kHz high pass filter.

EQUAL COMPONENT HIGHPASS
COMPONENT TOLERENCE = 10%
ROLLOFF = +12dB/OCTAVE

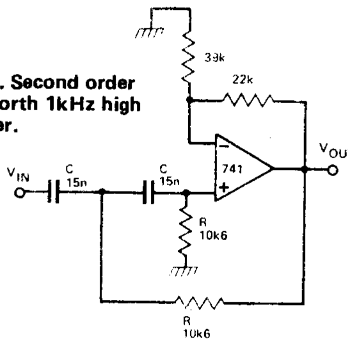
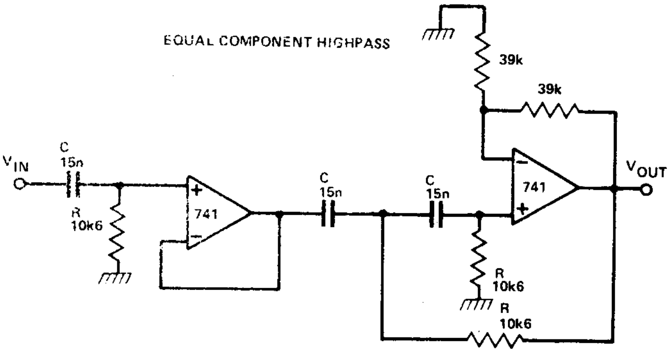
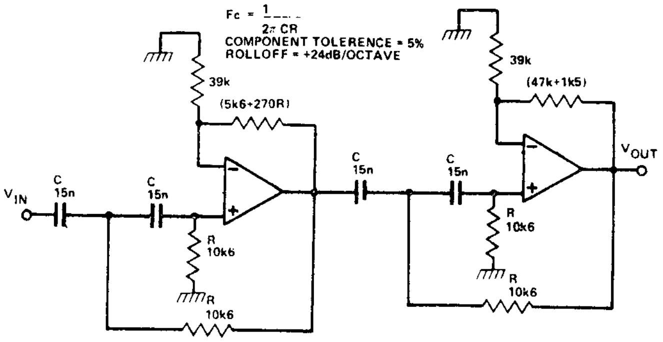


Fig. 13a. Second order Butterworth 1kHz high pass filter.



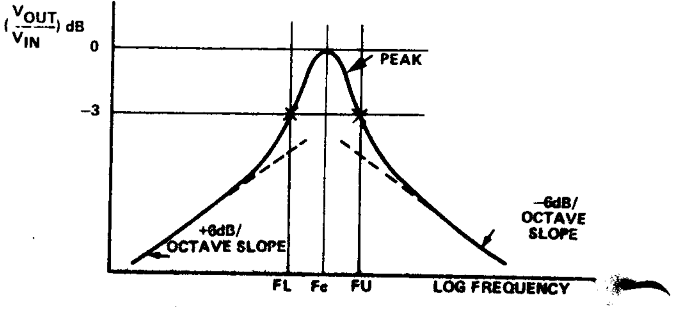
$Fc = \frac{1}{2\pi CR}$
COMPONENT TOLERENCE = 10%
ROLLOFF = +18dB/OCTAVE

Fig. 13b. Third order Butterworth 1kHz high pass filter.



$Fc = \frac{1}{2\pi CR}$
COMPONENT TOLERENCE = 5%
ROLLOFF = +24dB/OCTAVE

Fig. 13c. Fourth order Butterworth 1 kHz high pass filter



FC = CENTRE FREQUENCY
FU = UPPER -3dB POINT
FL = LOWER -3dB POINT

FU–FL = BANDWIDTH (FBW)
$Q = \frac{FC}{FBW}$

Fig. 14. Band pass response (single pole).

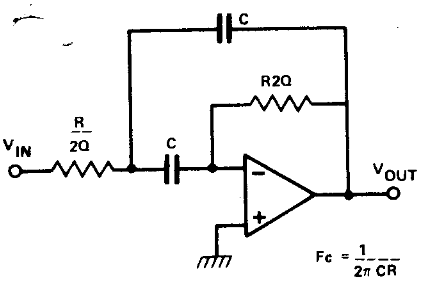


Fig. 15. Single pole multiple feedback bank pass filter.

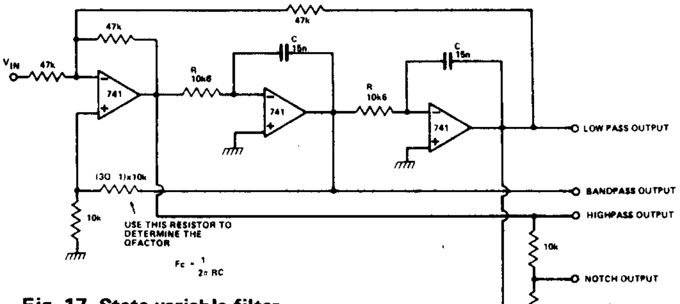
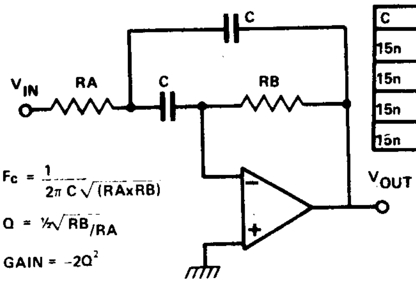
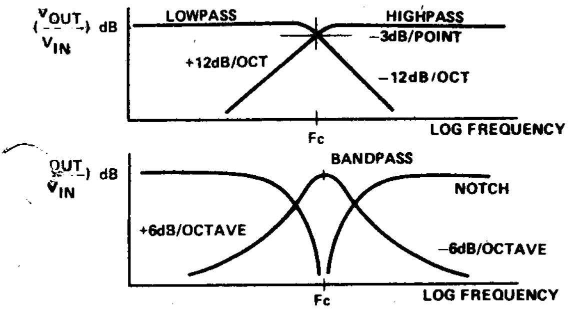


Fig. 17. State variable filter.



C	RA	RB	Fc	Q	GAIN
15n	10k6	10k6	1kHz	0.5	x 0.5
15n	5k305	21k22	1kHz	1.0	x 2.0
15n	2k652	42k44	1kHz	2.0	x 8.0
15n	1k326	84k88	1kHz	4.0	x32.0

Fig. 16. Multiple feedback filter selection chart.



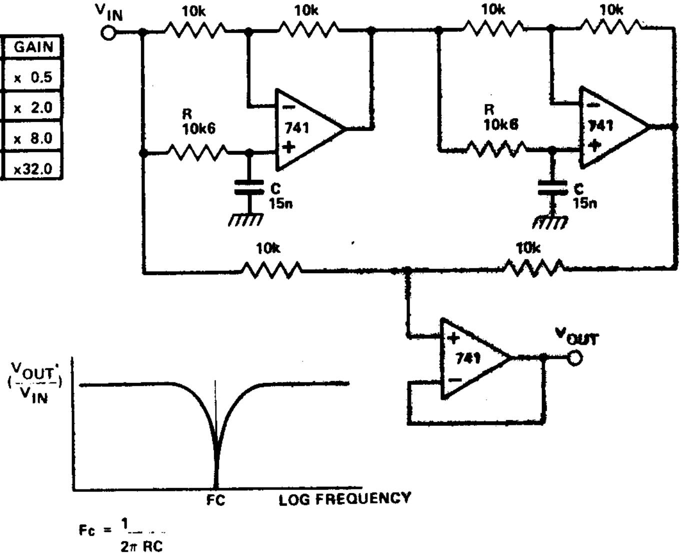


Fig. 19. Notch filter using all pass sections.

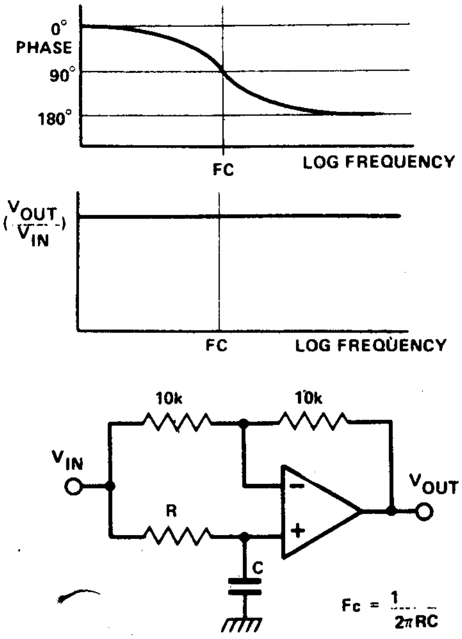
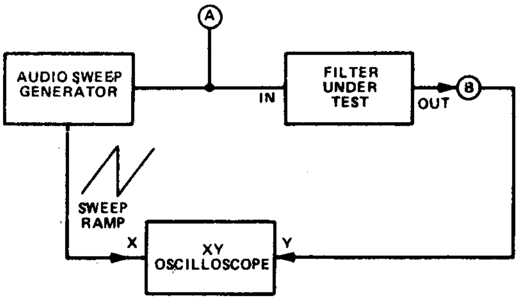


Fig. 18. All pass filter.



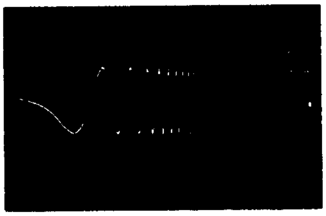


Fig. 20. Testing filter design with an oscilloscope. 'Scope traces' from points A and B are shown left (A above, B below).

Testing active filters is very easy if you have a swept sinewave generator and an XY oscilloscope (fig. 20). The frequency response appears as a linear amplitude versus log frequency display. It is generally possible to sweep five times a second, which gives an almost continuous display and allows you to see immediately the effect of any changes that you make to the filter. ●