ACTIVE FILTERS

Active filters are circuits using resistors, capacitors, and amplifiers, usually op-amps, to allow only selected frequencies to pass from the filter's input to its output. These frequency-selective circuits are used to boost or attenuate certain frequencies in audio circuits, electronic music generators, seismic instruments, communications circuits, and in research to study the frequency components of such diverse signals as brain waves and mechanical vibrations. Active filters are used in almost every area of electronics, so they are worth our attention.

BASIC FILTER DEFINITIONS

A filter, whether active or passive (containing no amplifiers), allows a certain portion of the frequency spectrum to pass through to its output. The filter is classified by which portion of the frequency spectrum it passes.

Low-pass filters allow frequencies from dc up to some selected cutoff frequency, f_c, to pass through and attenuate all frequencies above f_c, as shown in Figure 1*a*. The range of frequencies from zero to f_c is called the *passband*. The range of frequencies above f_b is called the *stop band*. The range of frequencies from f_c to f_b is called the *transition region*. The rate at which attenuation changes in the transition region is an important filter characteristic. The frequency at which the output voltage of the filter drops to a value of 0.707 of its value in the passband (or has dropped 3 dB) is the cutoff frequency, f_c. The frequency at which the output voltage is 3 dB above the stop band value is f_b.

A high-pass filter attenuates all frequencies up to f_c and passes all frequencies above f_c up to the frequency limit of the high-pass filter. A high-pass frequency characteristic is shown in Figure 1*b*.

A band-pass filter, as illustrated in Figure 1*c*, passes all frequencies between a lower cutoff frequency, f_1, and an upper cutoff frequency, f_2. All frequencies below f_1 and above f_2 are attenuated. The frequency ranges from f_1' to f_1, and f_2 to f_2' are the transition regions. The center frequency (f_o) is considered to be the geometric mean of f_1 and f_2 and is found from the following equation:

$$f_o = \sqrt{f_1 f_2} \tag{8-1}$$

A band-reject filter attenuates all frequencies between f_1 and f_2 and passes all other frequencies as shown in Figure 1*d*. A band-reject filter with a narrow band of attenuated frequencies is called a *notch filter*. Band-reject filters are useful for eliminating undesired frequencies, such as 60 Hz, from audio systems.

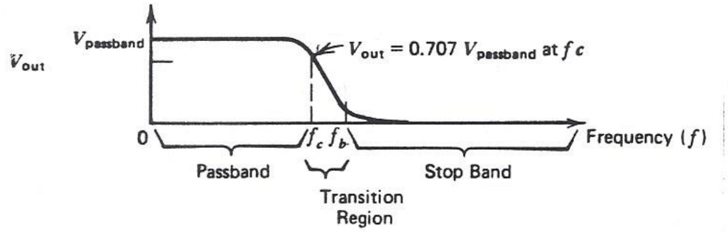
Advantages of Active Filters

Passive filters are constructed from inductors, capacitors, and resistors. In the frequency range in which active filters are useful, most passive filters require large, heavy, costly inductors and attenuate frequencies in the passband (even though the stop-band frequencies are attenuated more). The inductors used in passive filters have winding resistance, core losses, and interwinding capacitance that cause them to behave far from ideally.

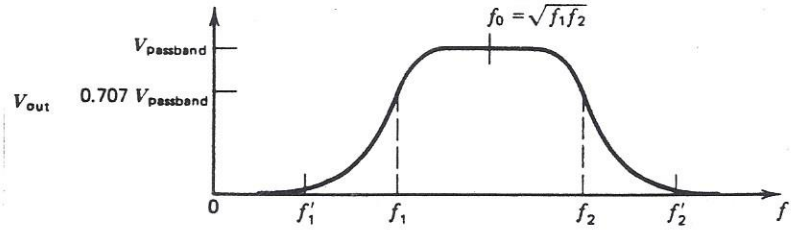
The advantages of active filters over passive filters are:

1. They use resistors and capacitors that behave more ideally than do inductors.
2. They are relatively inexpensive.
3. They can provide gain in the passband and seldom have any severe loss (as do passive filters).
4. The use of op-amps in active filters provides isolation from input to output. This allows active filters to be easily cascaded to obtain higher performance.
5. Active filters are relatively easy to tune.
6. Very low frequency filters can be constructed using modest value components.
7. Active filters are small and light.

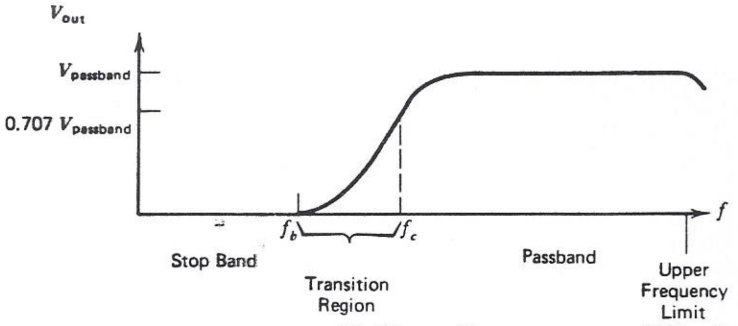
Active filters do have some disadvantages. They require a power supply and are limited in maximum frequency to the highest operating frequency of the op-amp. This limits most op-amp active filters to a few megahertz at most. With discrete amplifiers this frequency can be exceeded. As manufacturers improve the frequency response of op-amps, the upper frequency limit of active filters will be extended.



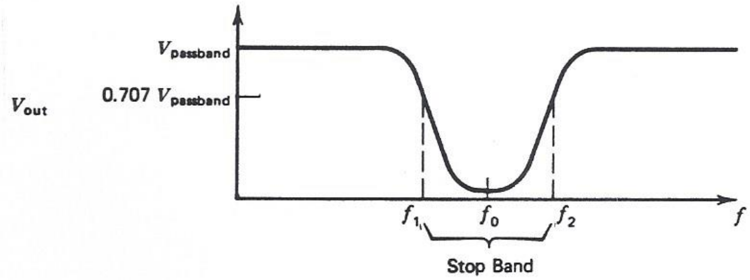
(a) Low-pass filter



(c) Band-pass filter



(b) High-pass filter



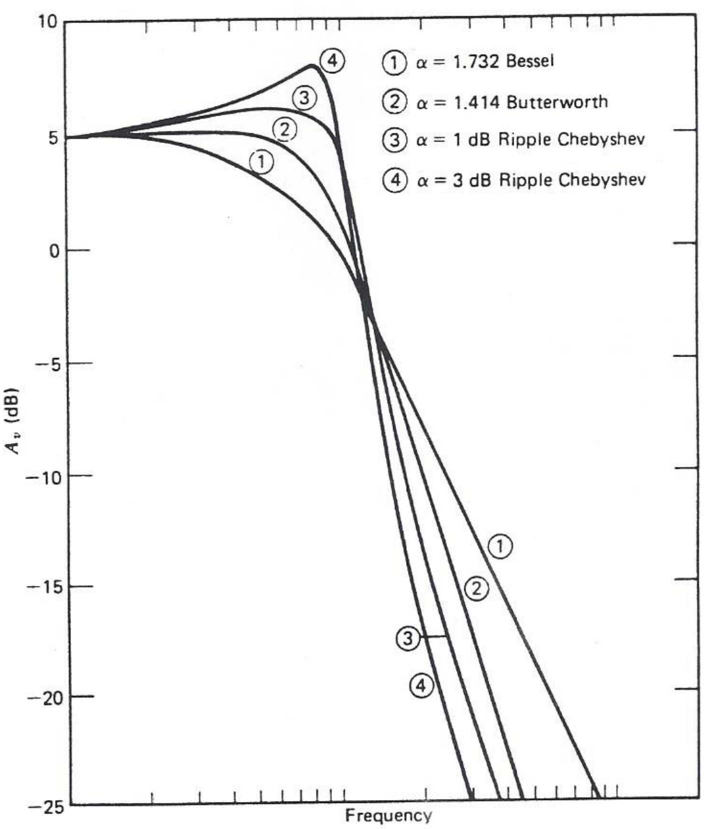
(d) Band-reject filter

Some Definitions

Damping factor, α

The damping factor sets the shape of the transition region and the overshoot of the pass-band response near the transition region. Thus the damping factor sets the shape of the filter's response and the type of filter. A second-order Butterworth filter will have a damping factor (α) of 1.414; a 3 dB ripple second-order Chebyshev will have $\alpha = 0.766$.

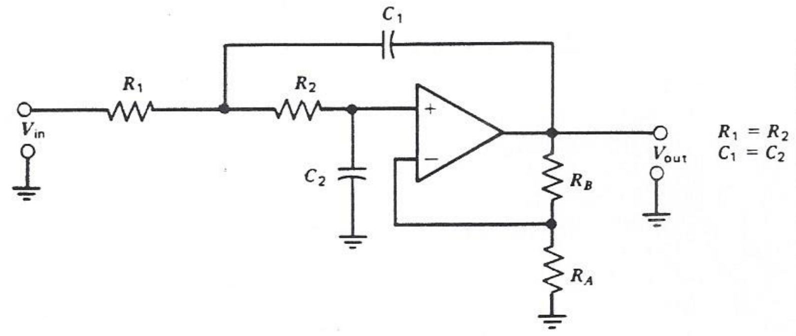
A Bessel filter, a Butterworth filter, and a Chebyshev filter might all have the same schematic, differing only in component values. The damping factor sets the filter response. Several low-pass responses with different damping factors are shown in Figure



Sallen and Key (VCVS)

VCVS stands for voltage-controlled voltage source. The op-amp in these circuits is used as a VCVS. The Sallen and Key low-pass and high-pass second-order active filter circuits, shown in Figure , , are popular, inexpensive, and easy to adjust. In each circuit each RC provides 6 dB/octave of transition region attenuation change. Since there are two RC circuits, R_1C_1 and R_2C_2, the circuits shown are second order. In the low-pass circuit, R_1C_1 and R_2C_2 are integrators. In the high-pass circuit, R_1C_1 and R_2C_2 are differentiators. R_A and R_B set the damping factor. The feedback from the amplifier through C_1 in the low-pass filter and R_1 in the high-pass filter provides the response shape near the passband edge. If $R_1 = R_2$ and $C_1 = C_2$, the components of this filter are easy to calculate.

The Sallen and Key filters must have a fixed gain as R_A and R_B set the damping factor, therefore the filter type.

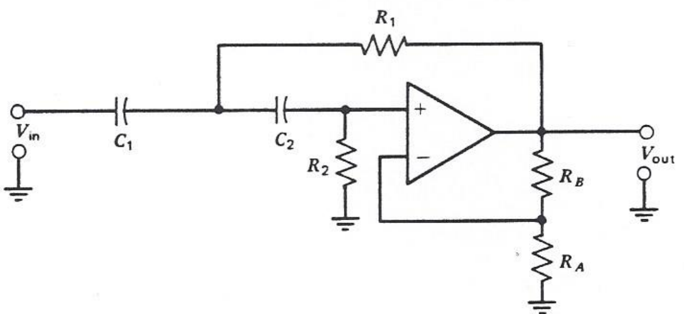


(a) Second-order low-pass filter

$$\omega_c = \frac{1}{(R_1R_2C_3C_4)^{1/2}}$$

or

$$f_c = \frac{1}{2\pi(R_1R_2C_3C_4)^{1/2}}$$



(b) Second-order high-pass filter

$$\omega_c = \frac{1}{(R_3R_4C_1C_2)^{1/2}}$$

or

$$f_c = \frac{1}{2\pi(R_3R_4C_1C_2)^{1/2}}$$

Sallen and Key active filters.

Sallen and Key Equal Component

Since this is the equal component filter, $R_1 = R_2$ and $C_1 = C_2$. Begin by choosing a filter type and f_c. The procedure is as follows:

1. Look up the $f_{(3\,dB)}/f_c$ ratio from Table 8-1 for the selected filter type. Calculate f_c if $f_{(3\,dB)}/f_c \neq 1$.

$$f_c = f_{(3\,dB)}/\text{ratio}$$

2. Select C and calculate R from

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

where

$$R = R_1 = R_2$$
$$C = C_1 = C_2$$

Repeat this step if necessary until a reasonable value of R is found.

3. Select the damping factor from Table 8-1 for the type of filter chosen.
4. Choose an appropriate value of R_A. Often it is convenient to let $R_A = R$. Calculate R_B from

$$R_B = (2 - \alpha)R_A$$

5. Calculate passband gain from

$$A_p = (R_B/R_A) + 1$$

SECOND-ORDER FILTER DAMPING FACTORS AND $f_{(3\,dB)}/f_c$

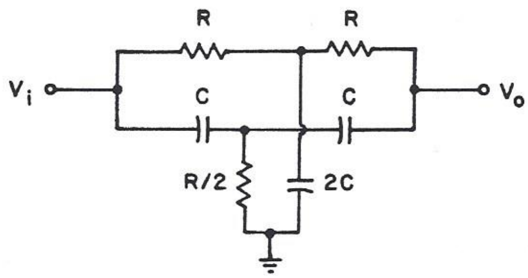
Filter Type	α	$f_{(3\,dB)}/f_c$
Butterworth	1.414	1.00
Bessel	1.732	0.785
Chebyshev		
0.5 dB ripple	1.578	1.390
1 dB ripple	1.059	1.218
2 dB ripple	0.886	1.074
3 dB ripple	0.766	1.000

Low pass $f_c = f_{(3\,dB)}/\text{ratio}$
High pass $f_c = f_{(3\,dB)}\ (\text{ratio})$

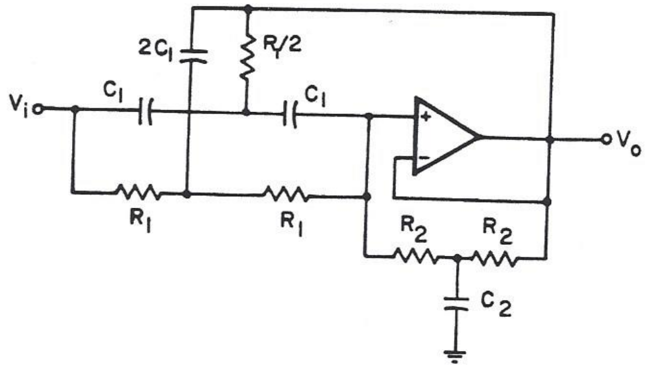
where

$f_{(3\,dB)}$ = desired 3 dB cutoff frequency
f_c = frequency used in calculations
ratio = $f_{(3\,dB)}/f_c$ from table

Notch Filters



The twin-T filter.



Active notch filter.

The notch, or band reject filter, is often designed into audio and instrumentation systems for the rejection of a single frequency, such as 60-Hz power line frequency hum. Perhaps the best-known notch filter, although a passive filter, is the twin-T (sometimes spelled "twin-tee") filter, shown in Figure.

For the twin-T circuit, the null frequency* is given by

$$\omega_n = 1/RC$$

or

$$f_n = 1/2\pi RC$$

With almost perfect matching of the six components, the twin-T filter is theoretically capable of almost infinite rejection at the null frequency. However, using experimenter-grade components, you should expect the rejection, or null depth, to be only 30 to 40 dB.

Since this course is about active filters, we can place the twin-T network in an op amp circuit, as shown in Figure, to form an active notch filter. The Q is found from

$$Q = R_2/2R_1 = C_1/C_2$$

Since the op amp is basically connected as a voltage follower, the passband voltage gain is unity.