FREQUENCY
DEVICES™, INC.

Introduction to Active Filters

Electronic Filters

An Electronic Filter is a device that is used to separate a signal that you want from some other signal or signals that you do not want or to separate signals of different frequency. An example of a simple electronic filter is the device that takes the output from a stereo amplifier and separates the low frequencies to go to the woofer speaker and the high frequencies to go to the tweeter speaker. Another example is a low pass filter used in the output of a transmitter to only allow the desired signal pass and attenuate the harmonics.

Active Filters

A Passive Filter uses inductors capacitors and resistors in combination to create the filter. An Active Filter uses amplifiers (usually operational amplifiers) along with resistors and capacitors to do the filtering. Inductors, which can be large and bulky, are not needed. Using operational amplifiers (or op-amps) allows you to easily make many different kinds of filters.

Filter Shapes

There are four main filter shapes: Low Pass, High Pass, Band Pass, and Band Reject (or Band Stop). As the name implies the low pass shape only allows low frequencies to pass and high frequencies are attenuated. See Figure 1 for the frequency response of a typical low pass filter frequency response.

The High pass is the opposite of a low pass in that high frequency signals are passed and low frequencies are attenuated.

The Band Pass filter allows a narrow band of signals to pass at its center frequency and rejects signals above and below that frequency. See Figure 2 for an example of a band pass filter frequency response.

The Band Reject filter is the opposite of the Band Pass in that it only attenuates signals at the center frequency of the filter.

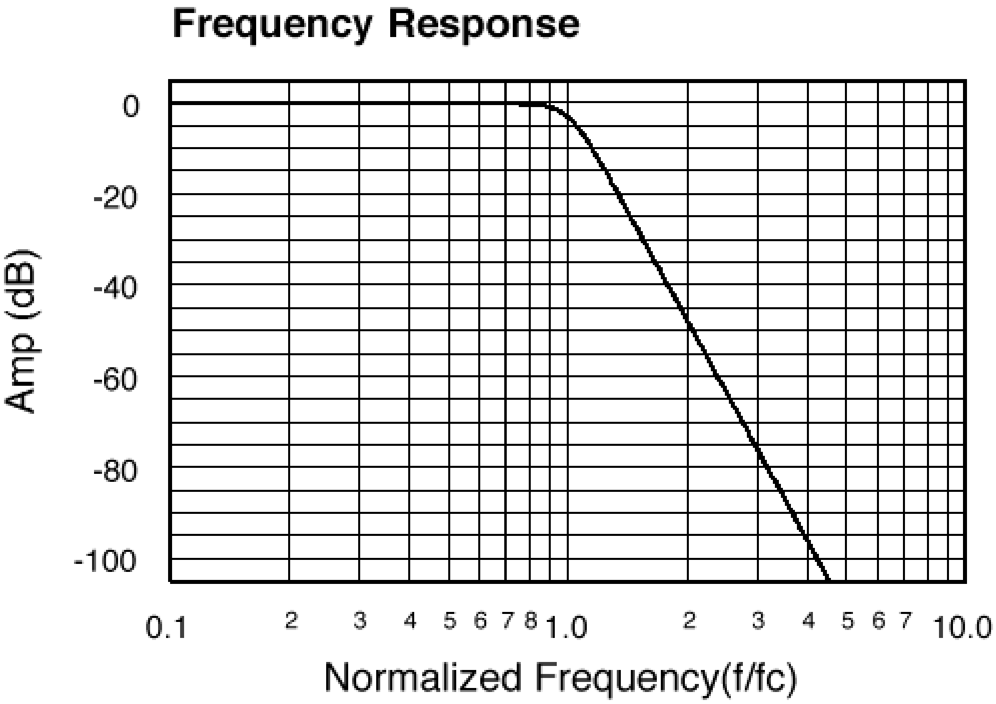

Figure 1 - Low pass Filter

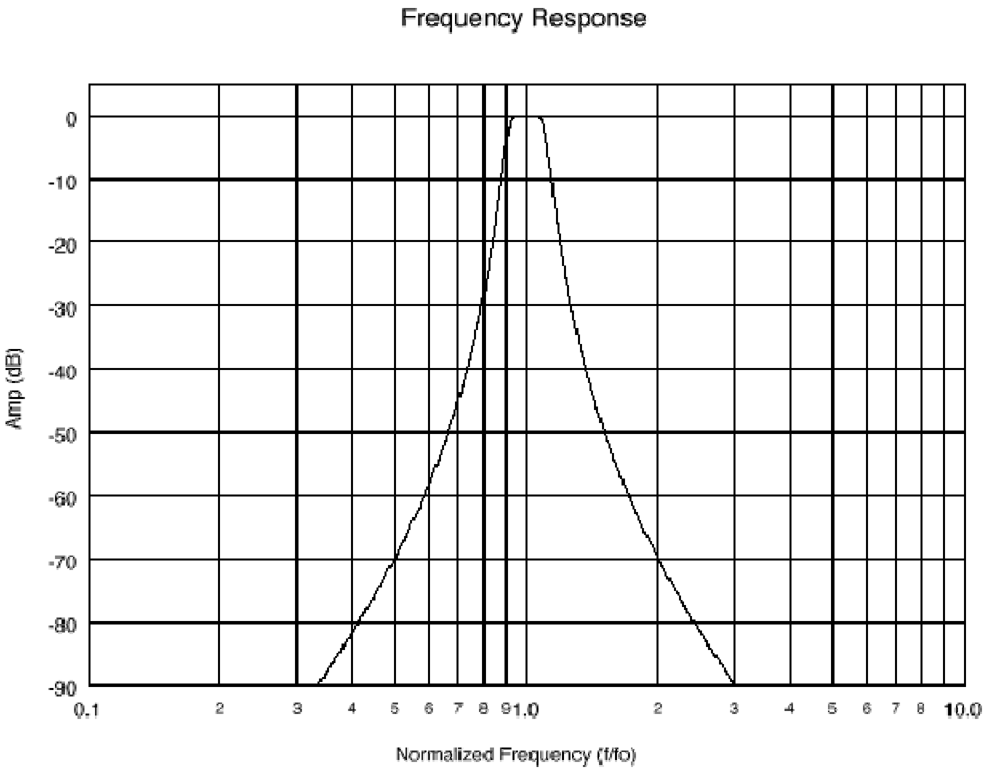

Figure 2 - Band pass Filter

Amplitude Response

Amplitude Response is defined as the ratio of the output amplitude to the input amplitude versus frequency and is usually plotted on a log scale as shown in Figure 3**.** Note how the steepness of the transition band slope (roll-off) increases as the number of poles increase. In the Butterworth Filter shown in Figure 3 the two-pole filter attenuates by 12 dB every time you double the frequency. The four-pole by 24 dB, the six-pole by 36 dB and the eight-pole attenuates by 48 dB every time you double the frequency. The more poles in the active filter the more attenuation at a given frequency in the stop band.

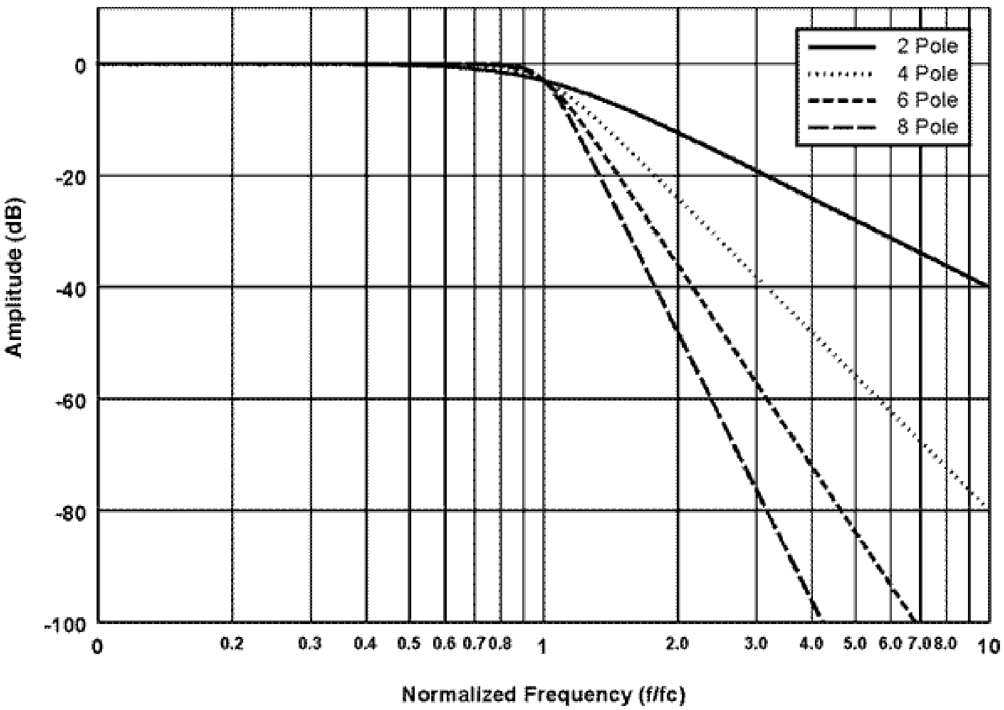

Figure 3 - 2, 4, 6, and 8 Pole Butterworth low pass

Normalization

The figures in this paper show frequency responses that are normalized to 1. The frequency axis on the response plot is scaled so that the corner or ripple frequency is always one Hertz instead of the actual intended corner or ripple frequency. This allows one normalized curve to represent any filter that would have the same response shape. To convert a normalized amplitude response curve to a curve representing a filter whose corner frequency is not at one Hertz, multiplying any number on the frequency axis by the intended corner or ripple frequency scales the frequency axis.

For example, say you wanted to know what the shape of an eight-pole Butterworth filter like one in figure 1 would be for a center frequency of 225 Hz. You simply multiply all of the normalized numbers in the x-axis of figure 4 by 225. What is shown as 2.0 would be 450 Hz. The attenuation of the filter at 450 Hz then would be about 48 dB. The attenuation at 3.0 times the frequency, or 675 Hz, would be about 76 dB.

This helps you decide how many pole you need in your filter. In the example above the eight-pole filter attenuates anything at 450 Hz (or at 2.0) by about 48 dB. Moving up the 2.0 line the six-pole filter would only attenuate by about 36 dB, the four-pole by about 24 dB, and the 2 pole by about 12 dB.

Transfer Functions

Transfer functions can be classified into one of two basic categories, **Amplitude Filters** and **Phase Filters**. Amplitude filters are designed for the best amplitude response for a given situation, for example zero ripple in the amplitude response pass-band. Phase filters are designed for desired phase response, such as linear phase with frequency throughout the filter amplitude pass-band.

Amplitude Filters

For many applications the design goal is to approximate ideal "brick wall" frequency response. Probably the most common amplitude filter transfer function is the **Butterworth** which has a maximally flat amplitude response in the pass-band. The amplitude response rolls-off monotonically (uniform slope) as frequency increases in the stop-band. The primary limitation is that Butterworth filters produce slower roll-off than some of the alternative transfer functions.

The **Chebychev** function provides faster roll-off in the transition band than a Butterworth filter would, but at the expense of some variation in the pass-band called ripple. Chebychev stop-band roll-off is monotonic. It is important to note that many designers avoid Chebychev transfer functions in favor of Elliptic alternatives because section Q's are higher for Chebychev’s than with elliptic functions which provide faster roll-off in the transition-band.

Although an **Elliptic** filter achieves faster roll-off than either Butterworth or Chebychev varieties, it introduces ripple in both the pass- and stop-bands. Also, elliptic filter roll-off is not monotonic, eventually reaching an attenuation limit, called the stop-band floor. Elliptic filters involve the use of very high Qs and gains so they can be difficult to build for higher frequencies.

Figure 4 compares the amplitude response of eight-pole Butterworth, 0.1 dB ripple Chebychev, and 0.1 dB ripple, -84 dB stop-band floor Elliptic transfer functions. The curves are normalized to the -3 dB cutoff frequencies.

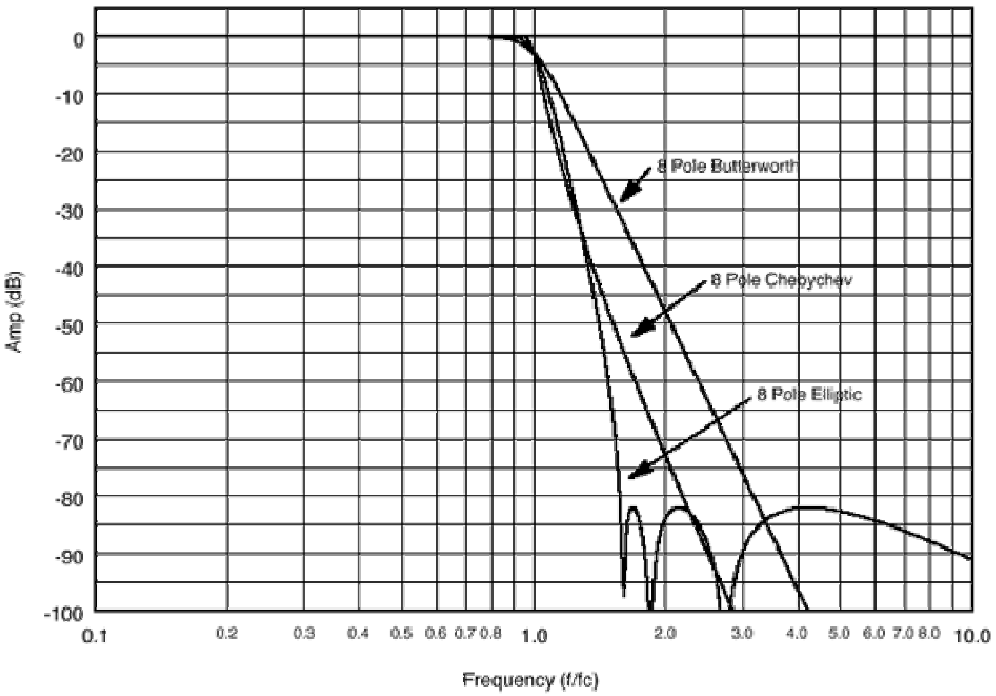

Figure 4

Phase Filters

For some filter applications it is desirable to preserve a transient waveform while removing higher frequency noise components from the signal. If each of the frequency components of the input waveform is phase shifted an amount linearly proportional to frequency, then they remain in the correct time relationship and sum together to create, at the output, the original waveform that was present at the input of the filter, with the higher frequencies components having been removed by the filter. When a filter has phase delay that varies linearly with frequency it is called a **Linear Phase** filter. A linear phase filter has a constant group delay, at least through the pass-band. Amplitude filters provide relatively constant group delay only from 0 Hz to about the mid pass-band frequency range peak near the center frequency.

The most common linear phase filter is based on the **Bessel** functions. Bessel filters provide very linear phase response and little delay distortion (constant group delay) in the pass-band. They show no overshoot in response to step input and roll-off monotonically in the stop-band. They also exhibit much slower attenuation in the transition-band than amplitude filters. Figure 5 presents amplitude and delay response curves for an 8-pole Bessel. Other types of phase filters include, constant-delay (a modified Bessel), equiripple phase, equiripple delay, and Gaussian transfer functions. They either have more pass-band amplitude roll-off for only a small improvement in phase linearity or only slightly less roll-off in the pass-band at the expense of degrading the phase linearity.

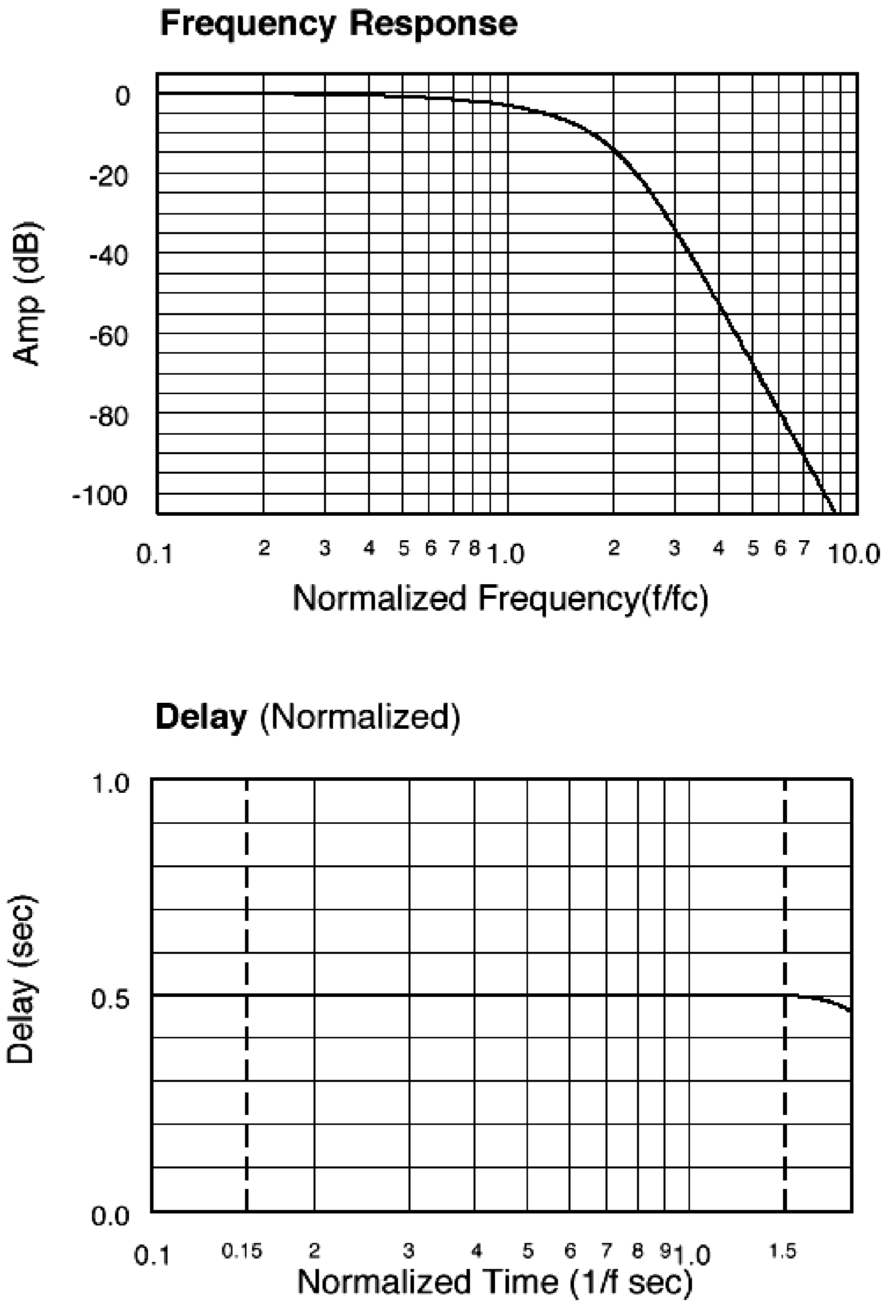

Figure 5

Compensated Filters

Some applications require filters offering the sharp roll-off characteristics of amplitude-type filters and the linearity of phase-type transfer functions. Two techniques, amplitude equalization and delay equalization, are available to achieve these ends. Both add complexity to filter design, and have theoretical and practical limits.

Amplitude equalization modifies the amplitude response of phase filters to produce a filter that is sometimes called a C**onstant Delay** filter. Improving the transition-band roll-off rate, however, does not come free. Adding equalization also introduces a small amount of step-input overshoot, and roll-off is no longer monotonic; that is, compensation introduces a stop-band floor. This technique can achieve a factor-of-two improvement in Bessel roll-off to a -80 dB floor, comparable to Butterworth-filter performance. For comparison, Figure 6 shows the amplitude response of an 8-pole Bessel, an 8-pole, 6-zero constant delay, and an 8-pole Butterworth response

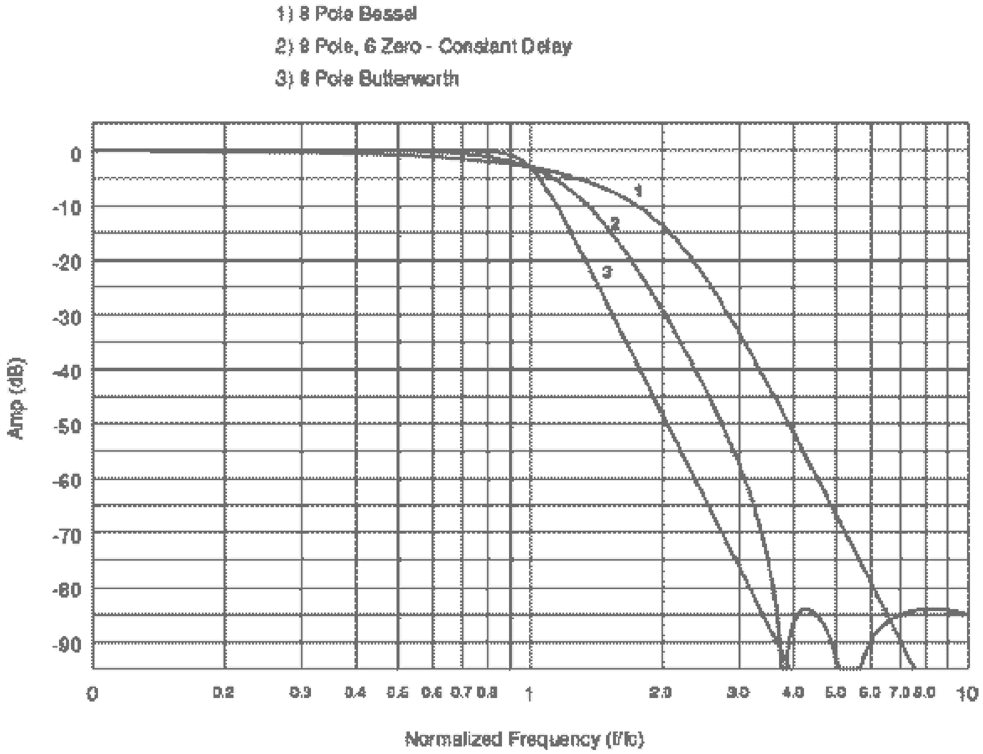

Figure 6

Step Response

Step response for amplitude type filters may exhibit substantial overshoot (ringing) when presented with a sudden change in voltage amplitude at the filter input. See Figure 7 for typical 8 pole transfer function step response curves.

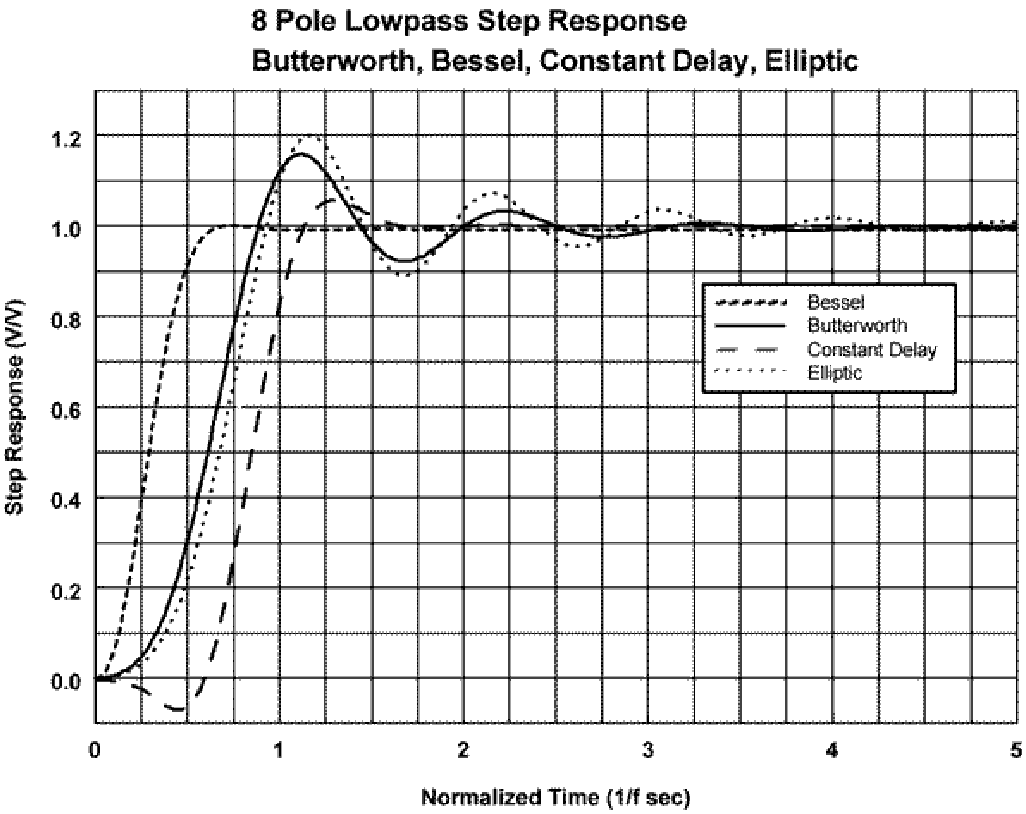

Figure 7

Phase Response

All filters introduce a time delay between the filter input and output terminals. This delay can be represented as a phase shift if a sine wave is passed through the filter. The extent of phase shift depends on the filter's transfer function. For most filter shapes, the amount of phase shift changes with the input signal frequency. The normal way of representing this change in phase is through the concept of Group Delay, the derivative of the phase shift through the filter with respect to frequency.

Group Delay

Group Delay is the phase slope on a linear phase vs. frequency plot**.** Figure 5 compares the group delay of some typical phase response curves.

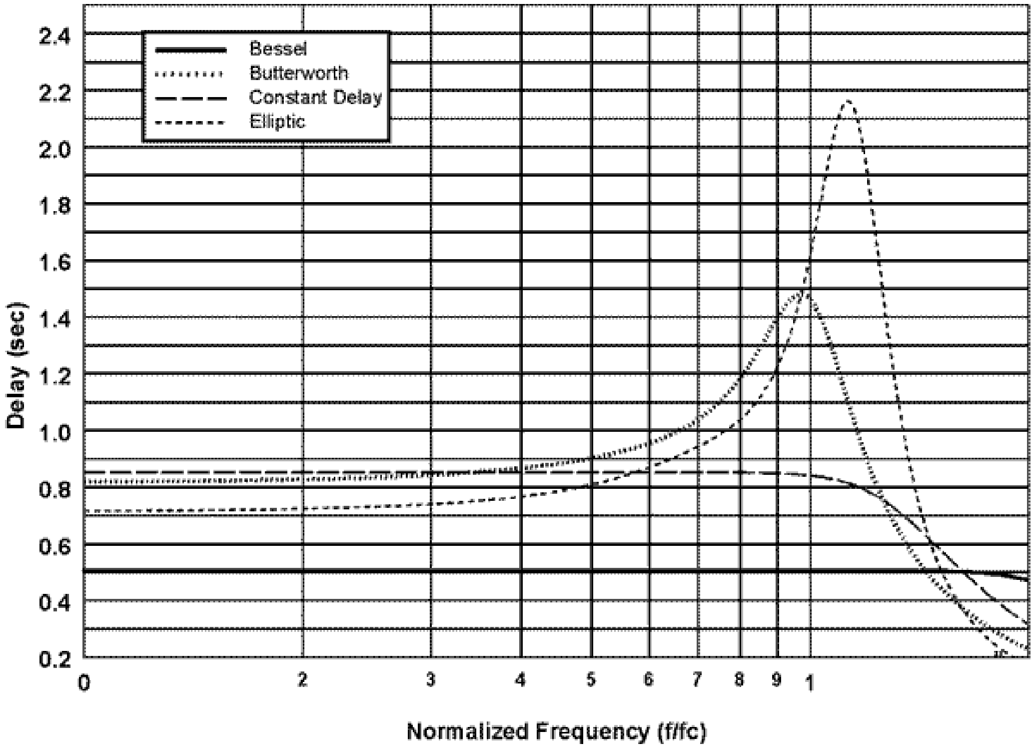
Bessel
Butterworth
Constant Delay
Elliptic
Delay (sec)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
2
3
4
5
6
7
8
9
1
Normalized Frequency (f/fc)

Figure 5

Frequency Devices Inc.

Frequency Devices was founded in 1968 to provide electronic design engineers with analog signal solutions and engineering services. FDI today designs and manufactures standard and custom signal conditioning, signal processing and signal analysis solutions utilizing analog, digital and integrated analog/digital technology. By addressing a wide array of signal processing needs, Frequency Devices continues to provide state-of-the-art solutions to the rapidly changing electronics industry. From prototype to production, we design and manufacture products to agreed-upon performance specifications, utilizing the latest technologies.

FDI has focused our talents on precision performance while minimizing size which allows us to offer our customers some of the smallest, most precise, and cost-effective signal-processing products available anywhere. By integrating our superior technology into instrumentation products, we also provide compact precision bench-top, laboratory and system solutions.

At the heart of our solutions lie our analog technologies. Frequency Devices' ability to identify the design weaknesses of each design approach and integrate their strengths to achieve a desired performance objective through the use of layout techniques, packaging skills and intellectual property results in analog, digital and mixed signal solutions that provide superior performance. This superior performance of Frequency Devices' solutions has earned the company a place:

- On the international space station where its active filter modules are used as anti-aliasing filters in Boeing's Active Rack Isolation System (ARIS),
- At the LIGO observatory (a joint development program affiliated with California Institute of Technology, Massachusetts Institute of Technology and the National Science Foundation), providing high resolution, low noise real-time data processing digital-to-analog conversion that integrated precision analog design with state-of-the-art 24-bit digital conversion,
- And on numerous OEM, R & D, and test system applications in the health, space, defense, science, engineering, and technology segments of the precision data acquisition markets.

These applications represent only a few examples of the myriad alternatives that Frequency Devices offers to enhance the processing accuracy of analog, digital and mixed-signal systems.

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