

Introduction

This application note describes the ispPAC80, an In-System Programmable (ISP[™]) Analog Circuit from Lattice Semiconductor, and the filters that it can implement. The ispPAC80 is a fifth-order, continuous-time, lowpass integrated analog filter. The user can implement thousands of analog filters in over seven topologies spanning a 50 kHz to 500 kHz range without external components or clocks. Using PAC-Designer[®] software, a user selects a filter type, views simulated performance and configures the design in-system while the IC is soldered to a printed circuit card. Device configurations can be stored in non-volatile E² memory or accessed in-system for adaptive applications.

Background

The ispPAC80 Programmable Lowpass Filter IC implements a collection of op amps, resistors and capacitors to accomplish fifth-order filters with programmable coefficients. The continuous-time cutoff frequency of the filter can be set anywhere between approximately 50 kHz and approximately 300 kHz to 500 kHz, to a resolution of 0.6% or better. The filters the ispPAC80 implements are well-suited for anti-aliasing filters when performing Analog-to-Digital conversion and reconstruction for Digital-to-Analog converters, as well as other complicated filter networks. The 1x10⁹ ohm high-impedance differential inputs allow for improved common-mode rejection, and the differential outputs allow the use of higher-quality circuitry following the filter. Both the differential offset and the common-mode offset are trimmed to be under 1 mV. The differential resistive load is spec'ed as low as 300 ohms and the differential capacitive load is spec'ed to 100 pF for best THD. These values are good for most applications in this frequency range. In addition, the ispPAC80 has a dual-configuration memory, so that it can save configurations for two completely different filters. This can often reduce the components in a multi-filter system, allowing for test modes or other system improvements.

The ispPAC80 contains a differential-input instrumentation amplifier (IA) with selectable gains of 1, 2, 5 or 10, and a multi-amplifier differential filter PACblock that

includes a differential-output summing amplifier (OA). The gain settings and capacitor values are configurable through non-volatile E²CMOS[®] cells on-chip. The device configuration is set by PAC-Designer[™] software and downloaded to the device via a JTAG download cable.

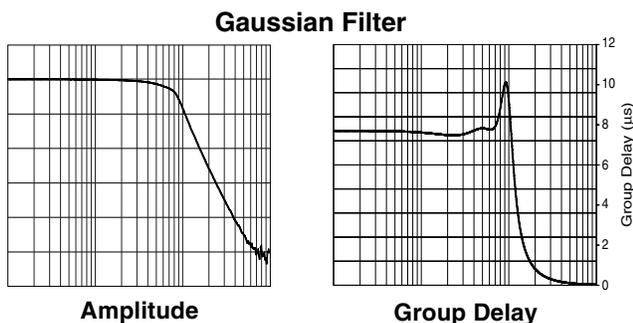
General Configuration

PAC-Designer supports simulation and programming the ispPAC80 with any fifth order lowpass filter and the integrated filter database provides thousands of filters of these types: Gaussian, Bessel, Butterworth and Legendre filters, as well as two Linear Phase Equiripple Delay Error filters, three Chebyshev and 12 Elliptic filters with various ripple factors. Other filter types are realizable with an ispPAC80 and can be entered by programming the individual components. Contact Lattice Applications for more information regarding additional filter types.

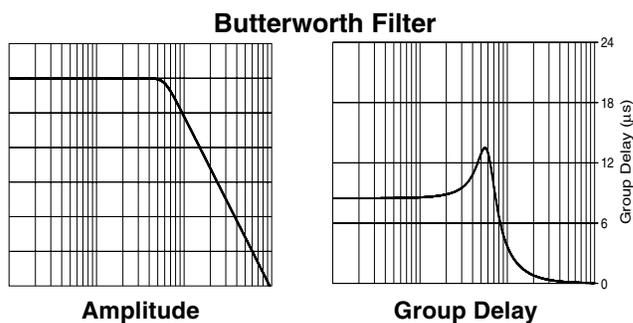
To simplify the selection of the proper filter type, the filters below are arranged by damping coefficient, from lower to higher values. The lower values are good for phase response and its derivative, group delay characteristics, while the higher damping coefficient values are good for amplitude response. The final group of filters utilizes a mixed pole-zero response, which favors a sharp amplitude response, with four different values of ripple spread out over 3 fo/fs combinations. The following page lists these responses with a brief comment on the advantages of each filter, followed by sections discussing each filter type in more detail.

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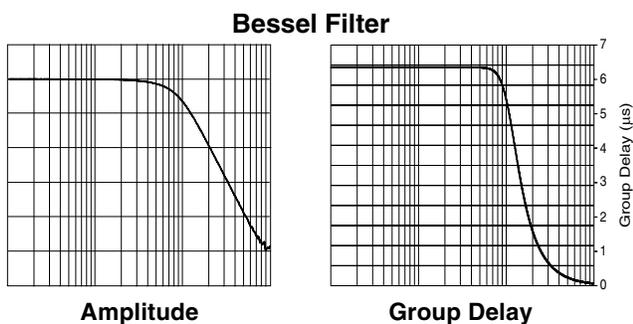
Figure 1. Filter Summary



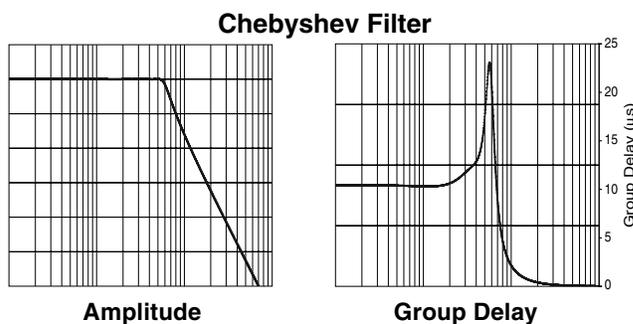
- Very linear (but not perfect) phase response
- Slowest transitional band



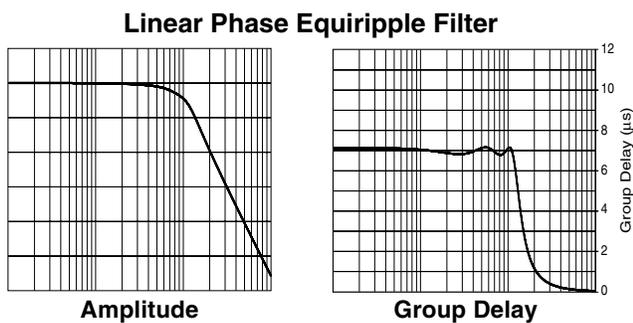
- Maximally flat amplitude



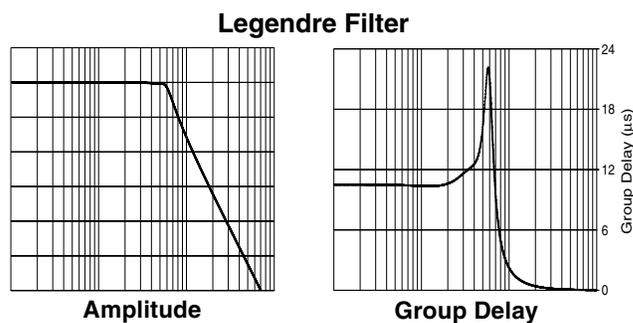
- Perfect phase response



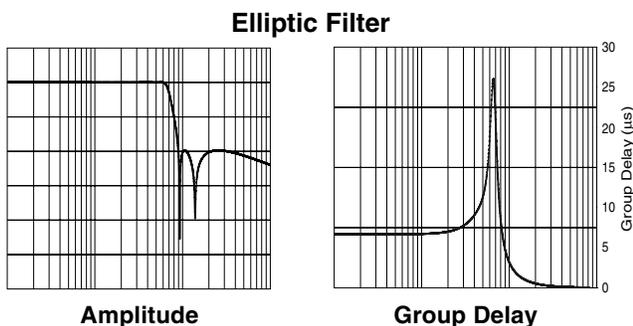
- Equal ripple in the passband



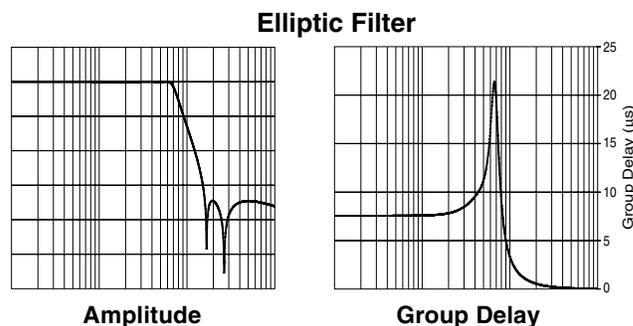
- Wider linear phase band than Bessel



- Mix of Butterworth passband and Chebyshev transition band



- Equiripple passband and stopband, 0.1dB 1.3 ratio



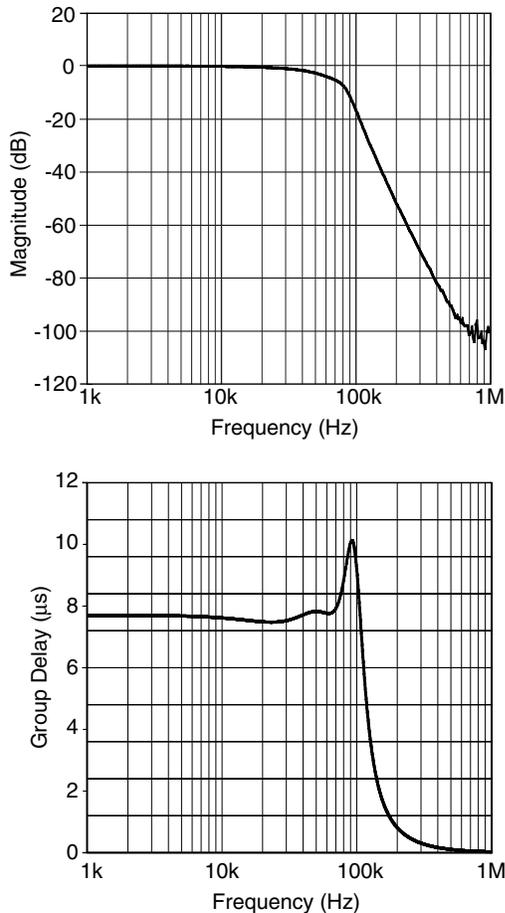
- Equiripple passband and stopband, 0.1dB 2.7 ratio

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Specific Configurations I

The first series of filters have an all-pole response and are optimized for better phase response and its derivative, group delay characteristics, than for amplitude characteristics. All of these filters have maximum ispPAC80 cutoff frequencies of 300 kHz.

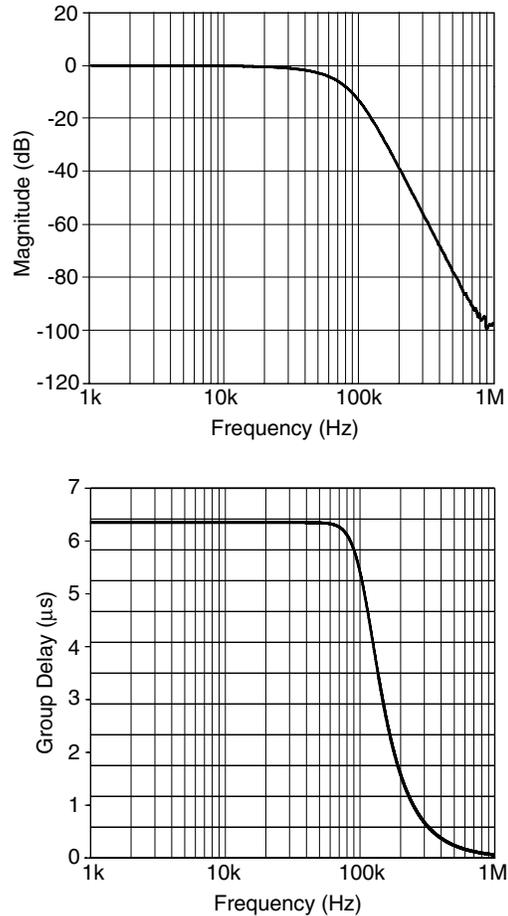
Figure 2. Gaussian Filter



Gaussian filters, as a group, are a general family of filters whose phase-response characteristics are not well-known. Gaussian filters are similar to the Bessel filter, except that the phase response is not as linear as the Bessel for a given number of poles, and the selectivity is not as sharp. The Gaussian response is represented by an exponential formula, which has a rounder top in the passband than the Bessel, and a more gradual slope in the transition band. This shape has nearly ideal phase characteristics. For those looking for better amplitude response, the importance of this shape cannot be fully appreciated, since the rate of increase of attenuation versus frequency of Gaussian, as well as Bessel and Linear Phase Equiripple Delay filters, is fairly low.

Gaussian filters are primarily used in areas such as pulse systems, where, if the various frequencies are not delayed equally, dispersion results and the output for a pulsed input is distorted.

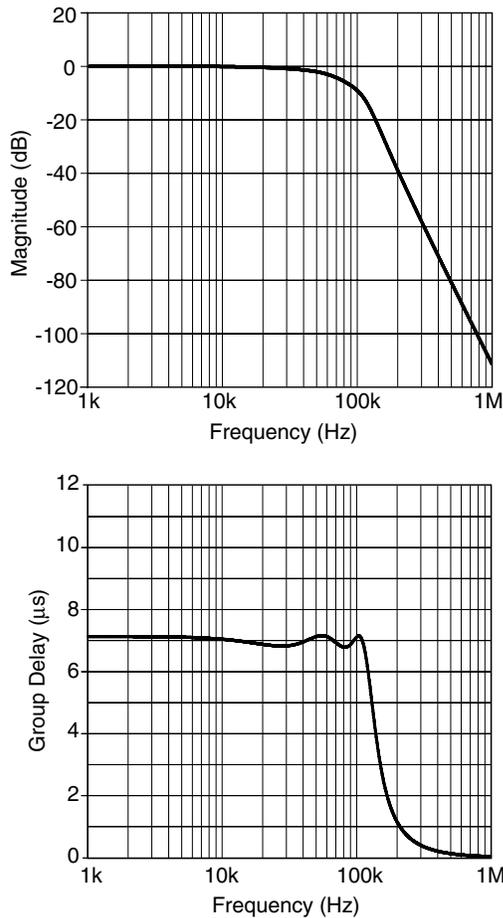
Figure 3. Bessel Filter



The Bessel filter is sometimes called the maximally flat delay filter. The Bessel transfer function (also known as the Thomson function) has been optimized to obtain a linear phase, which implies a maximally flat delay in the passband. The Bessel poles lie on a unit circle where the vertical spacing between the poles is equal. The step response has essentially no overshoot or ringing, however the frequency response is much less selective than in the other filter types (other than Gaussian). That is, it has a less round top in the passband than the Gaussian, but a slightly steeper slope in the transition band. This makes it nearly ideal for pulse response. The Bessel filter is recommended for applications where the transient response is the primary consideration.

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Figure 4. Linear Phase Filter

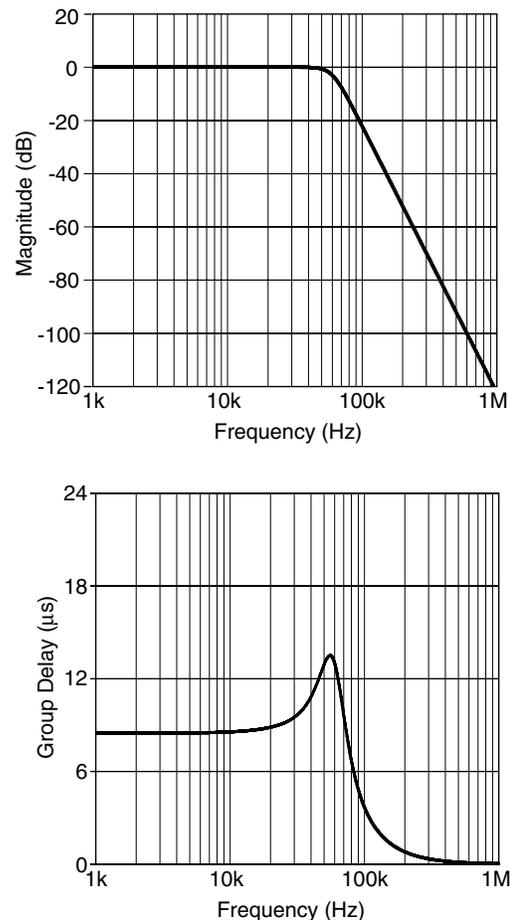


Linear Phase filters with equiripple delay error are somewhat of a special case. The Chebyshev function (equiripple amplitude, to be discussed in a moment) is considered by some people to be a better approximation to an ideal amplitude curve than is the Butterworth filter, because it is more efficient at using the poles while adding a slight amount of ripple. Likewise, an equiripple approximation to linear phase will be more efficient than the Bessel filter because of the slight ripple in its delay. Linear phase can be approximated to within a given delay ripple error of ϵ degrees. For the same number of poles, the equiripple-delay approximation results in a longer region of linear phase and, consequently, a constant delay over a larger interval than the Bessel approximation. Also, the amplitude response is superior to the Bessel response far from cutoff. (In the transition region and below cutoff, both approximations have nearly ideal responses.) As the error in the delay ripple ϵ is increased, the ripple will eventually become visible. The step response also has slightly more overshoot than the Bessel filter.

Specific Configurations II

The next series of filters are still all-pole networks, but they are optimized for good amplitude response instead of good phase response. Their maximum cutoff frequencies in the ispPAC80 are 500 kHz.

Figure 5. Butterworth Filter



The Butterworth filter is known for its maximally-flat amplitude response, including flat response all the way to zero frequency. This filter has an all-pole response with equal-angle roots on the unit circle (whereas the Bessel had equal spacing between the poles). The attenuation at 1 radian/second is -3 dB and it increases at 6 dB for each additional pole. This filter has both moderate attenuation steepness and acceptable transient characteristics. Element values are more practical and less critical than for most other filter types, so the Butterworth has become one of the most-often-used filters. In the ispPAC80, the minimum cutoff frequency for the Butterworth filter is 54 kHz.

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Figure 6. Chebyshev Filter

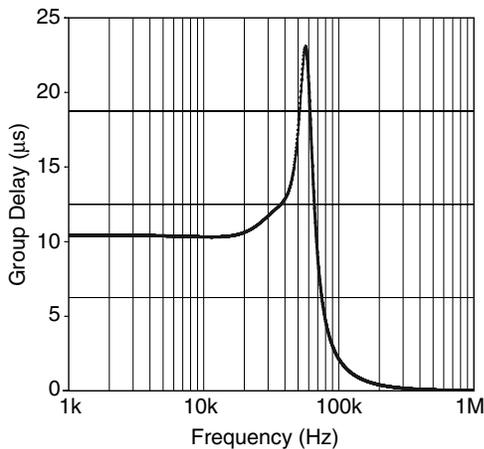
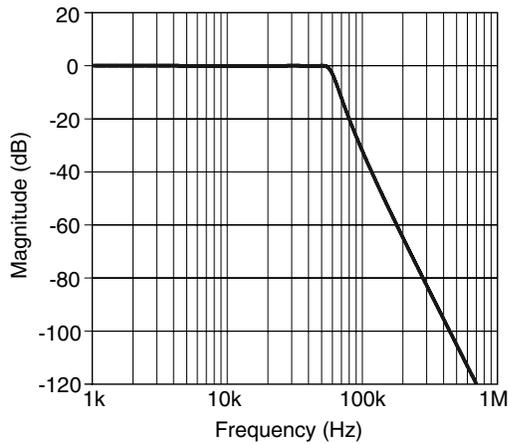
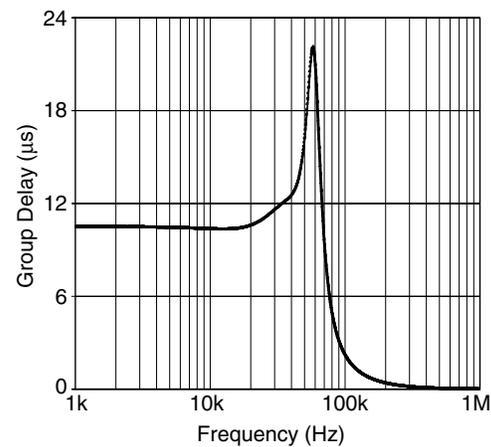
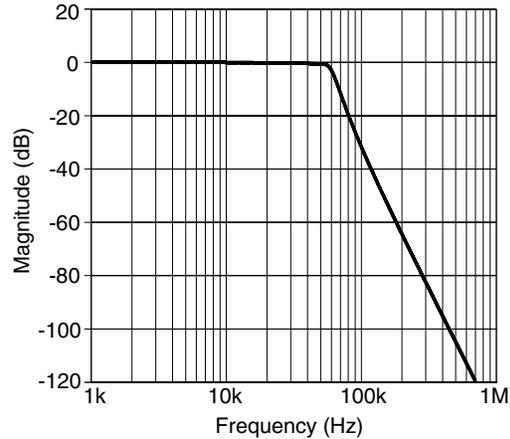


Figure 7. Legendre Filter



Chebyshev filters have poles that lie on an ellipse instead of a circle. This gives the passband amplitude response evenly-spaced ripples, and the filters have an attenuation at 1 radian/second equal to that ripple. Chebyshev filters are sometimes called equiripple filters because they are derived from the equiripple function. They have a more rectangular frequency response in the region near cutoff than does the Butterworth filter, at the expense of allowing ripples in the passband. They also have more delay variation in their passband. Since the ispPAC80 has fifth-order filters, these odd-order Chebyshev filters have zero relative attenuation at DC. (The even-order Chebyshev filters have uneven start and stop ripples, requiring non-matched source and load resistors). These filters are particularly useful where amplitude frequency response is the major consideration. They provide the maximum rate of roll-off of any all-pole transfer function for a given order.

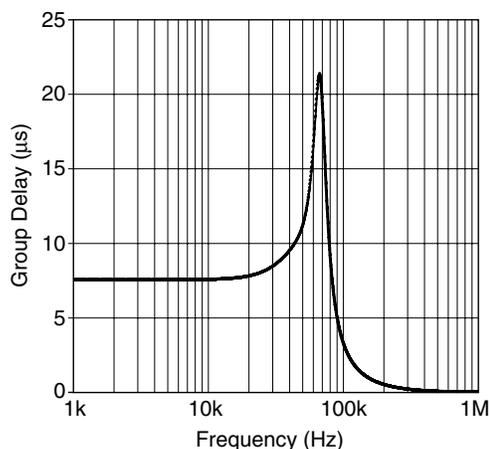
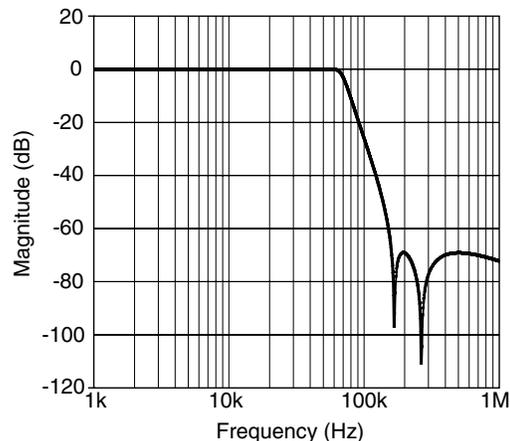
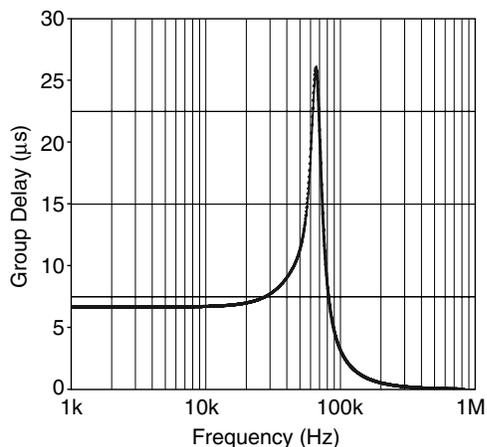
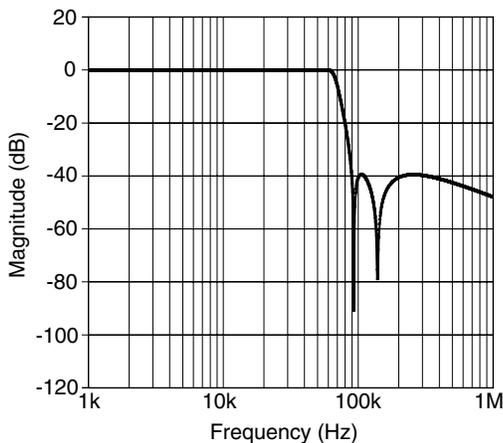
Legendre filters have passband amplitude characteristics approximately equal to a Butterworth filter with 0.1 dB ripple, but a transition region rolloff that is more like a Chebyshev filter. Thus they have a good combination of amplitude response and phase response. They are not symmetrical (a similar characteristic shared by the Gaussian family of filters). A five-pole Legendre filter will have a 31 dB/octave cutoff. Many people consider the Legendre filters to be a good combination of sharp amplitude characteristics with reasonable phase response, even though values have a slight frequency-response droop before rolling off.

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Specific Configurations III

All of the above filters are all-pole networks. They exhibit infinite rejection only at the extreme edge of the stopband. The Elliptic family of filters adds in-band zeroes to give even tighter amplitude response, at the expense of passband phase response and stopband return lobes. The maximum cutoff frequency of these filters in the ispPAC80 is at least 500 kHz.

Figure 8. Elliptic Filters



Elliptic filters, sometimes called Cauer filters, have zeros as well as poles at finite frequencies. The location of poles and zeros in the passband and stopband creates equiripple behavior similar to the Chebyshev filters, except that now the ripple is in both the passband and the stopband. Finite transmission zeros in the stopband reduce the transition region so that extremely sharp roll-off characteristics can be obtained, at the expense of stopband return lobes. The introduction of these zeros allows the steepest rate of descent theoretically possible for a given number of poles. These transition bands have an attenuation at 1 radian/second equal to the ripple. Comparison of five-pole Butterworth and Elliptic filters shows a much more rapid rate of descent in the transition region for the Elliptic filters. This response can usually be obtained with fewer filter sections than other filter types. The maximum value of each return response in the stopband is equal to A_{min} . The usual notation for elliptic filters is as follows: $cc\ n\ \rho\ \theta$, where cc represents complete Cauer, n is the filter order, ρ is the reflection

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Table 1. Filter Type Comparison

Filter Type	Passband Gain	Stopband Gain	Band Edge Selectivity	Transition Bandwidth	Passband Delay
Gaussian	Monotonically Decreasing	Monotonically Decreasing	Low	High	Almost Maximally Flat
Bessel	Monotonically Decreasing	Monotonically Decreasing	Low	High	Maximally Flat
Linear Phase, Equiripple Error	Equiripple in Phase (Better than Bessel)	Monotonically Decreasing	Low	High	Constant with Ripple ϵ
Butterworth	Max. Flat	Monotonically Decreasing	Medium	Medium	No Ripple Increases
Legendre	Monotonically Decreasing	Monotonically Decreasing	High	Medium	Barely Detectable
Chebyshev	Equiripple	Monotonically Decreasing	High	Low	Ripple Increases
Elliptic	Equiripple	Equiripple	Highest	Lowest	Ripple and Increases

coefficient and θ is the modular angle. The angle θ determines the steepness of the filter and is given as $\theta = \sin^{-1} 1/\Omega_s$. Higher values of θ also give larger stopband reflections, which may or may not be desirable.

Table 1 is a comparison of filter types.

Summary

The list of filters in this application note is intended to guide the user in making a reasonable choice as a starting point. Because the PAC-Designer simulator can simulate up to four different filters, the user can compare various designs to see which has the best combination of benefits for a given project. The ispPAC80 filter database offers four choices for good phase response, plus many choices for excellent amplitude response, including 12 choices for heightened amplitude response (Elliptic). It also has the ability to model and simulate more than these choices if there is a different response that is needed. From among these, there should be an excellent filter response for almost all combinations of filter parameters.

Technical Support Assistance

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