Designing active analog filters in minutes

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Introduction

Active analog filters can be found in almost every electronic circuit. Audio systems use filters for frequency-band limiting and equalization. Designers of communication systems use filters for tuning specific frequencies and eliminating others. To attenuate high-frequency signals, every data-acquisition system has either an anti-aliasing (low-pass) filter before the analog-to-digital converter (ADC) or an anti-imaging (low-pass) filter after the digital-to-analog converter (DAC). This analog filtering can also remove higher-frequency noise superimposed on the signal before it reaches the ADC or after it leaves the DAC. If an input signal to an ADC is beyond half of the converter's sampling frequency, the magnitude of that signal is converted reliably; but the frequency is modified as it aliases back into the digital output.

A low-pass, high-pass, band-pass, or band-stop filter can be efficiently designed with the WEBENCH® Filter Designer software from Texas Instruments (TI). This application replaces TI's FilterPro™ and the former National Semiconductor's WEBENCH Active Filter Designer software. It uses the approach of these programs and formulas verbatim when generating active filters. But it goes beyond these two programs by allowing in-depth adjustments to filter variables, optimizing the filter, finding appropriate TI operational amplifiers (op amps) for the filter circuits, and providing SPICE simulation capability.

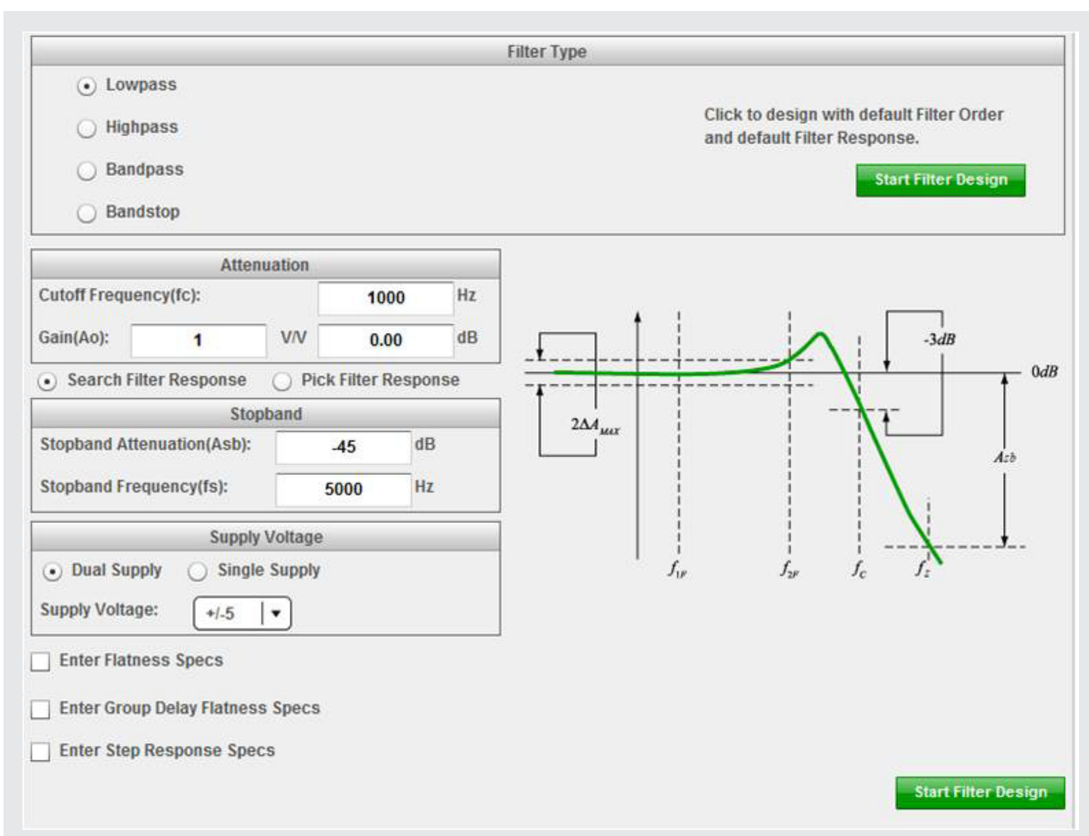
Key design parameters for a low-pass analog filter

The frequency-domain specifications of a low-pass analog filter include four fundamental parameters:

- fc, the filter's –3-dB cutoff frequency
- Ao, the gain of the filter
- Asb, the stop-band attenuation
- fs, the frequency of the intercept to the stop-band attenuation

These parameters are shown in WEBENCH Filter Designer's Filter Type window in Figure 1. The frequency span from DC to the cutoff frequency (fc) is the pass-band

Figure 1. WEBENCH® Filter Designer's key analog-filter parameters

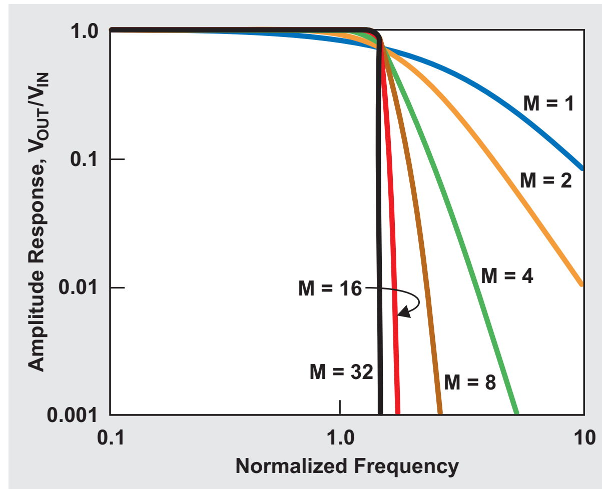


region. The magnitude of the response in the pass band is Ao in Figure 1. The response in the pass band can be flat with no ripple, as it is with a Butterworth or Bessel filter. Conversely, a Chebyshev filter has a ripple up to the cutoff frequency. The magnitude of the ripple error of a Chebyshev filter is $2\Delta A_{MAX}$.

As the response of the filter goes beyond fc, it falls through the transition band to the stop-band region. The filter approximation (Butterworth, Chebyshev, Bessel, etc.) determines the bandwidth of the transition band and the order (M) of the filter. The number of poles in the transfer function determines the filter order. For instance, if a filter has three poles in its transfer function, it is a third-order filter.

Generally, the transition band becomes smaller when more poles are used to implement the filter design, as shown in Figure 2 for a Butterworth low-pass filter. Ideally, a low-pass, anti-aliasing filter should perform with a "brick-wall" style of response, with an extremely small transition band. Practically speaking, this is not the best approach for an anti-aliasing solution. With active-filter design, every two poles require an op amp. For instance, a 32nd-order filter requires 16 op amps, 32 capacitors, and up to 48 resistors.

Figure 2. Increased number of poles in Butterworth filter creates sharper rolloff



Analog filter-approximation types

Figure 3 shows the low-pass-filter types available in the Solutions window from the WEBENCH Filter Designer's Visualizer screen. This screen appears after the user clicks on the Start Filter Design button shown in Figure 1.

The more popular filter-approximation types are the Butterworth, Chebyshev, and Bessel. Filters can be identified by examining amplitude versus frequency domain and amplitude versus time domain.

Butterworth filter

The transfer function of a Butterworth filter consists of all poles and no zeroes and is represented by

$$\frac{V_{OUT}}{V_{IN}} = \frac{Ao}{a_0 s^n + a_1 s^{n-1} + a_2 s^{n-2} \ldots a_{n-1} s^2 + a_n s + 1}.$$

Figure 3. Low-pass-filter types in WEBENCH® Filter Designer

Solutions

Solutions: (7 found)

Select	Filter Response	Color	Order	Max Q	Att (dB)	Passband Ripple (dB)	Group Delay (usec)	Group Delay Flatness (usec)	Settling Time (usec)	Step Response Overshoot (%)
Select	Transitional Gaussian to 6dB	Green	4	1.32	-47.59	0.380	367.676	9.147	1489.356	0.79
Select	Linear Phase 0.05°	Blue	4	1.07	-46.41	0.437	361.873	2.088	1490.866	1.06
Select	Butterworth	Black	4	1.31	-55.91	0.002	448.464	32.576	2717.626	10.82
Select	0.2dB Chebyshev	Yellow	4	2.435	-60.15	0.199	816.477	405.321	4215.482	15.20
Select	Linear Phase 0.5°	Magenta	4	1.34	-48.78	0.317	379.450	16.052	1529.731	1.78
Select	Bessel	Red	5	0.92	-49.26	0.446	385.154	1.83e-4	1169.675	0.77
Select	Transitional Gaussian to 12dB	Aqua	5	1.52	-52.56	0.562	400.004	13.012	1521.612	0.00

Figure 4 shows that the response of a fourth-order, low-pass Butterworth filter is flat in the pass-band portion. The technical term for this characteristic is *maximally flat*. Later it will be shown that the rate of attenuation in the transition band is not as good as with the Chebyshev filter.

Figure 5 shows that the step response of the same fourth-order Butterworth filter has some overshoot and ringing in the time domain. If the filter order were higher, this overshoot would also be higher. If this filter is used after a multiplexer, its settling time should be considered.

Figure 4. Frequency response of fourth-order, low-pass Butterworth filter

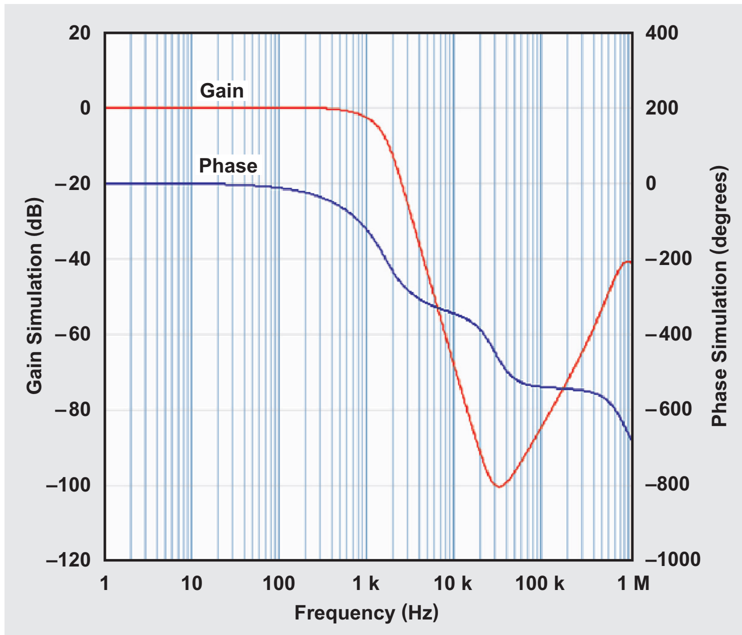
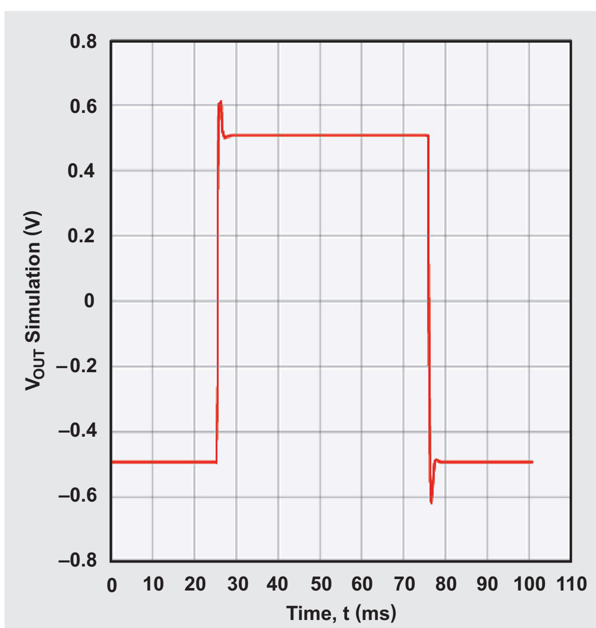


Figure 5. Step response of fourth-order, low-pass Butterworth filter



Chebyshev filter

The transfer function of the Chebyshev filter is similar to the Butterworth filter only in that it has all poles and no zeroes:

$$\frac{V_{OUT}}{V_{IN}} = \frac{Ao}{a_0 + a_1 s + a_2 s^2 + \ldots a_{n-1} s^{n-1} + s_n}$$

Figure 6 shows that the frequency response of a fourth-order, low-pass Chebyshev filter has a 0.2-dB ripple in the pass-band region. The pole placement in the circuit design determines this ripple. In general, an increase in ripple magnitude lessens the width of the transition band.

The ripple magnitude of $2\Delta A_{MAX}$ (Figure 1) theoretically can be as large or as small as desired. A high-ripple magnitude generally results in more error in the pass-band region but a faster attenuation in the transition band.

The rate of attenuation in the transition band is steeper than for a Butterworth filter. For instance, to meet the transition bandwidth of a third-order Chebyshev with a 0.5-dB ripple, a fourth-order Butterworth filter is required. Although with the Chebyshev filter there is ringing in the pass-band region, the stop band is devoid of ringing.

The step response of a fourth-order, low-pass Chebyshev filter with a 0.2-dB ripple has a fair degree of overshoot and ringing (Figure 7).

The overshoot and ringing phenomena are a consequence of the phase response in the frequency domain. Recall that the Fourier analysis of a step response (or square wave) shows that a square wave can be constructed by adding odd harmonic sinusoidal signals. Consequently, the higher frequencies from the step input arrive at the output of the filter before the lower frequencies. This is called a *distortion group delay*. This group delay in seconds is calculated as

$$\frac{\text{Change in phase/Change in frequency}}{360}.$$

Figure 6. Frequency response of fourth-order, low-pass Chebyshev filter

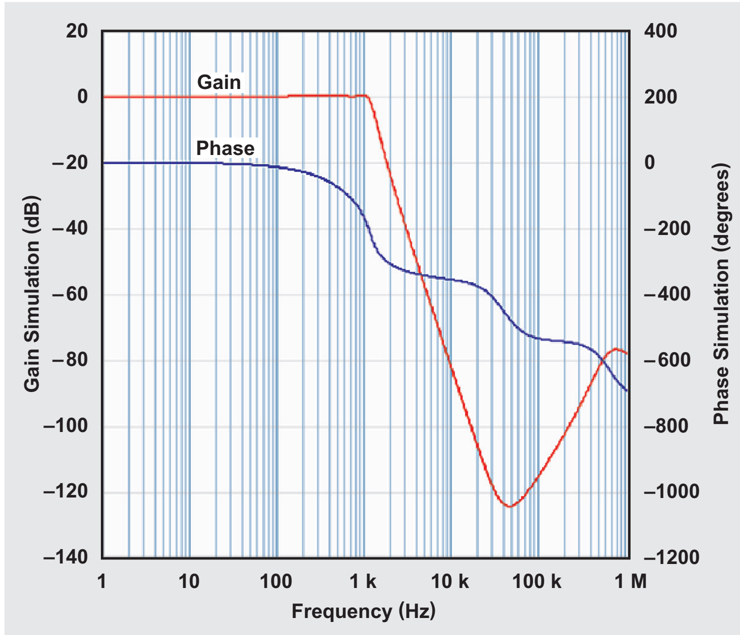
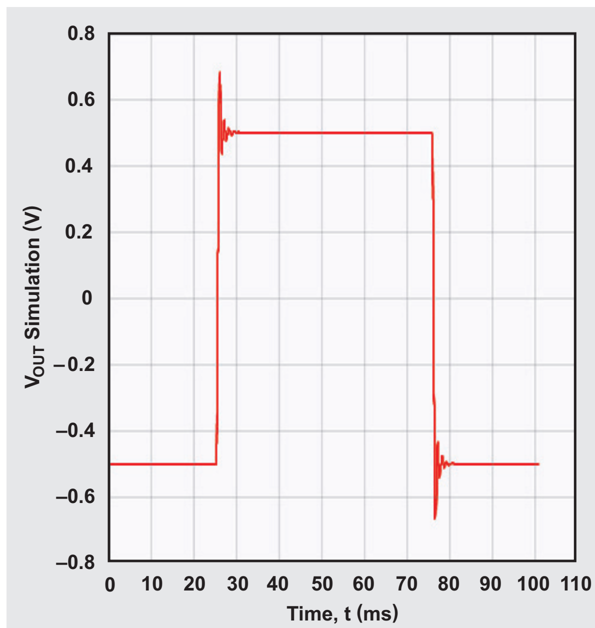


Figure 7. Step response of fourth-order, low-pass Chebyshev filter



Comparison of filter-approximation types

For low-pass filters, the type of filter approximation affects the frequency response before and beyond the filter's cut-off frequency. Since the inverse of frequency (in hertz) is seconds, the filter type inversely impacts the time domain. Table 1 compares low-pass Butterworth, Chebyshev, and Bessel filters in the frequency domain (pass-band and transition regions) and the time domain (step response).

Table 1. Comparison of filter-approximation types

FILTER TYPE	PASS BAND	TRANSITION REGION	STEP RESPONSE
Butterworth	Maximally flat magnitude response in the pass band	Steeper than Bessel, but not as good as Chebyshev filter	Some overshoot and ringing, but less than the Chebyshev filter
Chebyshev	Ripple in the pass band	Steeper than Butterworth and Bessel filters	Fair degree of overshoot and ringing
Bessel	Flat magnitude response in the pass band	Slower than Butterworth and Chebyshev filters	Very little over-shoot or ringing as compared to Butterworth and Chebyshev filters

Getting started with WEBENCH Filter Designer

TI's Filter Designer lets engineers design, optimize, and simulate complete multistage active-filter solutions within minutes. Optimized filter designs can be created with a selection of TI op amps and passive components from TI's vendor partners.

The Filter Designer software can be accessed at www.ti.com/webenchfilters-aaj along with a quick tutorial. A filter can be selected from low-pass, high-pass, band-pass, and band-stop types. Performance constraints for attenuation, group delay, and step response can be specified if desired, and there are a variety of filter responses to choose from, such as Chebyshev, Butterworth, Bessel, linear phase, and transitional Gaussian. The filter response best suited for the design is determined by optimizing for pulse response, settling time, lowest cost, pass-band ripple, and stop-band attenuation.

Sallen-Key or multiple feedback topologies are design options for each filter stage, and the best op amps for the design are chosen by evaluating gain bandwidth versus current versus cost and other parameters. The resistor/capacitor tolerances can be specified as ideal, 0.5, 1, 2, 5, 10, or 20%. Experimenting with user-defined capacitor seed values adjusts the range of resistor values in the filter design. Filter topologies can also be optimized for sensitivity, lowest cost, and smallest footprint.

The design can then be analyzed by running SPICE electrical simulation with the option for a closed-loop frequency response, a step response, or a sine-wave response. The input conditions of these options can be adjusted in order to evaluate different output results.

References

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