FilterPro™ low-pass design tool

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Introduction

Although low-pass filters are vital in modern electronics, their design and verification can be tedious and time-consuming. The FilterPro program aids in the design of low-pass filters implemented with the multiple feedback (MFB) and Sallen-Key topologies. This article is an introduction to the use and capabilities of FilterPro.

History of FilterPro

In 1991 Burr-Brown released a version of FilterPro as a DOS application by Bruce Trump and R. Mark Stitt. When TI purchased Burr-Brown in 2000, the idea of updating some of Burr-Brown's tools for customer use was proposed, including writing a Windows® version of FilterPro. The source code was written in Q-Basic, and the best path for the upgrade seemed to be Visual Basic®. A new operator interface was developed, and the original computational subroutines were able to be used nearly verbatim.

The major difference between the original FilterPro for DOS and FilterPro for Windows is that all menu-selected windows available in the old version are visible on a single form of the new version. In addition, the new version displays the circuits schematically instead of referring to schematics in the application note.

Easy design of low-pass filters

Once the FilterPro program is started, several parameters must be entered to design a low-pass filter. The cutoff frequency, number of poles, filter type, and filter configuration are the main inputs. Because there are instances where the Sallen-Key filter topology is a better choice, the user can specify either MFB or Sallen-Key topology.

An ideal low-pass filter would completely eliminate signals above the cutoff frequency and perfectly pass signals below it (in the pass-band). In real filters, various trade-offs are made in an attempt to approximate the ideal. Some filter types are optimized for gain flatness in the pass-band, some trade off gain variation (ripple) in the pass-band for steeper roll-off, and still others trade off both flatness and rate of roll-off in favor of pulse-response fidelity. FilterPro supports the three most commonly used all-pole filter types: Butterworth, Chebyshev, and Bessel. Figures 1 and 2 are examples of filters designed by FilterPro that use two of these filter types.

Figure 1. Response vs. frequency of even-order (4-pole), 3-dB-ripple Chebyshev filter

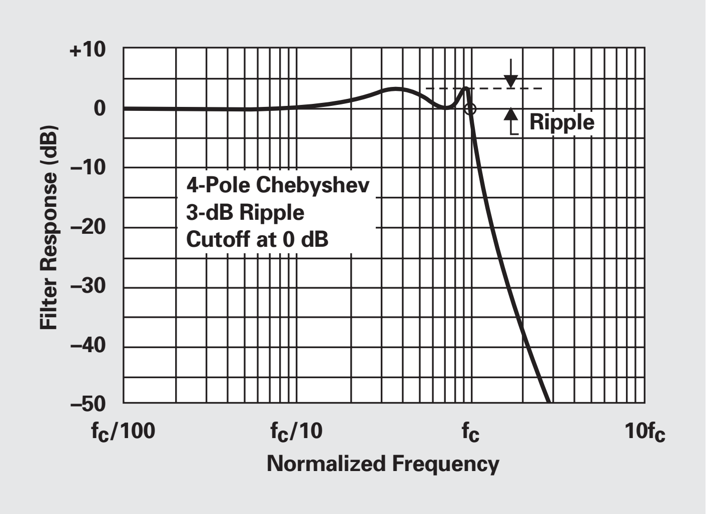
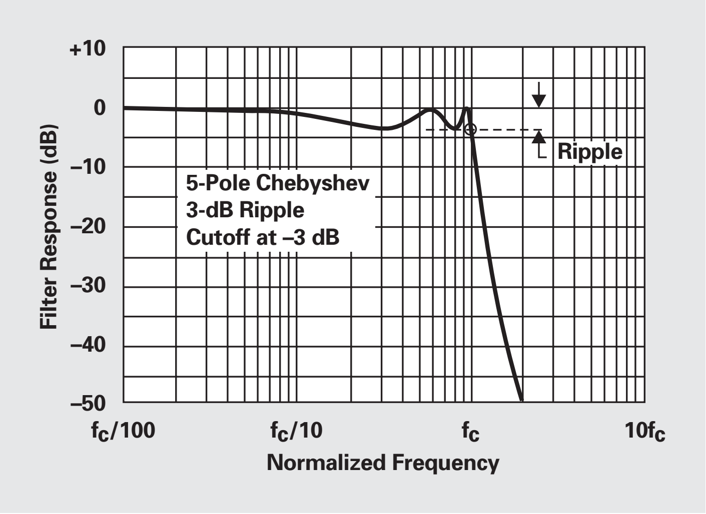


Figure 2. Response vs. frequency of even-order (5-pole), 3-dB-ripple Chebyshev filter



Filter circuits

Even-order filters designed with FilterPro consist of cascaded sections of complex pole pairs. Odd-order filters contain an additional real-pole section. The program automatically places lower-Q stages ahead of higher-Q stages to prevent op amp output saturation due to gain peaking. The program can be used to design filters up to tenth order.

Complex pole-pair circuit

The choice of a complex pole-pair circuit depends on performance requirements. FilterPro supports the two most commonly used active pole-pair circuit topologies. Figures 3–5 show the three different pole-pair schematics.

Figure 3. MFB complex pole-pair section (gain = –R2/R1)

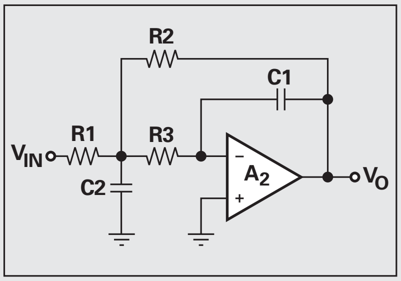


Figure 4. Sallen-Key complex pole-pair section (gain = 1)

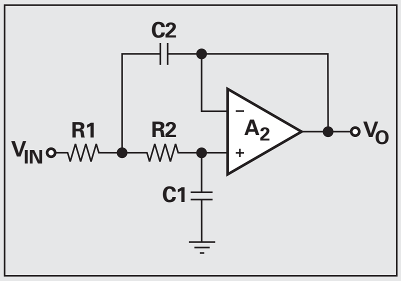
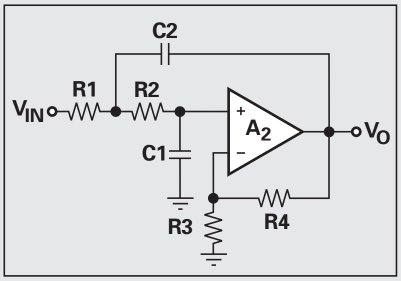


Figure 5. Sallen-Key complex pole-pair section (gain = 1+ R4/R3)



Using the FilterPro program

With each data entry, the program automatically calculates filter performance and values for all filter components. This allows you to use a "what if" spreadsheet-type design approach. For example, you can quickly determine, by trial and error, how many poles are needed for a given roll-off.

Computer requirements

The operating system required for FilterPro for Windows should be Windows 95, NT 3.5, or newer. The display should be configured for at least 800 × 600. It is helpful, but not required, to have a printer (capable of printing a screen dump) available either locally or on a network.

Installation

To install FilterPro on your computer, go to analog.ti.com and, under AMPLIFIERS AND COMPARATORS, click on Engineer Design Utilities. Download FilterPro and then run the setup.exe program from your hard drive.

Getting started

The first time you use the program, you may want to double-click on the FilterPro icon on the desktop. Another way is to select Start, Programs, and FilterPro. The start-up screen shows default values for a 3-pole, 1-kHz Butterworth filter. Figure 6 shows a 9-pole MFB design with a Chebyshev response and a cutoff frequency of 100 kHz. Notice that the ripple is .001 dB. If a higher ripple were entered, the response would be different. For a different filter design, click on the radio buttons and/or enter different values in the Settings frame as follows:

1. Under Circuit Type, choose the pole-pair circuit: Sallen-Key or MFB.
2. Under Filter Type, select Bessel, Butterworth, or Chebyshev.
3. For the Chebyshev filter type, enter the ripple amount in the Ripple box at upper right: 0.0001 dB to 10 dB.
4. In the Poles box, enter the desired number of poles: 1 to 10 (minimum of 2 for Bessel or Chebyshev).
5. In the Cutoff Freq. box, enter the filter cutoff frequency: 1 MHz to 100 MHz.
6. If you want to view the gain/phase response of the current filter design at a particular frequency (the default value is 10 times the cutoff frequency), enter the frequency of interest in the Response Freq. box. The gain/phase values are displayed in the f_n, Q, and Response fields at the lower right of the screen.
7. If you want to change the resistor scaling, enter a value in the R1 Seed box.
8. If you want to change the gain of a section, enter the desired value in the appropriate Gain boxes under Optional Entry. The default value for gain is 1.0 V/V in each section.
9. If you want to choose your own capacitor values, enter them in the appropriate C1 or C2 boxes under Optional Entry.
10. If you want to design with standard 1% resistors instead of exact resistors, click the "1% Resistors" check box.

On-screen prompts to the left of the response graph will guide you in program use. Refer to this article for more detail, if needed.

Program features

To print results

To print results, select the Print menu at the top of the screen. It will display a dialog box that can be used to print the screen. When printing is started, the normal screen size will be increased to include a table containing sensitivity data or component values not shown on the schematic in Figure 6. The larger screen will then be captured and sent to the printer. If the screen is not fully visible due to position or size, only what is visible will be printed.

Sensitivity

Sensitivity is the measure of the vulnerability of a filter's performance to changes in component values. The important filter parameters to consider are natural frequency (f_n) and Q.

f_n sensitivity for both MFB and Sallen-Key

Sensitivity of f_n to resistor, capacitor, and amplifier gain variations is always low for both the Sallen-Key and MFB filter topologies.

$$S_R^f = S_C^f = \pm 0.5\%/\% \text{ and}$$

$$S_K^f = 0, \text{ where}$$

S_R^f, S_C^f, and S_K^f = sensitivity of f_n to resistor, capacitor, and gain variations, respectively.

Q sensitivity

For the MFB topology, sensitivities to Q are also always low, but sensitivities for the Sallen-Key topology can be quite high—exceeding $2KQ^2$. K is the variable used here for op amp gain. At unity gain, the Sallen-Key Q sensitivity to resistor and capacitor variations will always be low. Unfortunately, however, the sensitivity of the unity-gain Sallen-Key pole pair to op amp gain can be high.

Q sensitivity for MFB pole pair

$$S_C^Q = \pm 0.5\%/\%,$$

$$S_R^Q = \pm \frac{R2 - R3 - KR3}{2(R2 + R3 + KR3)} \text{ (MFB complex pole pair), and}$$

$$S_K^Q = \pm \frac{KR3}{R2 + R3 + KR3} \text{ (MFB complex pole pair).}$$

Notice, by inspection, that S_R^Q is always less than ±0.5%/%, and S_K^Q is always less than 1.0%/%.

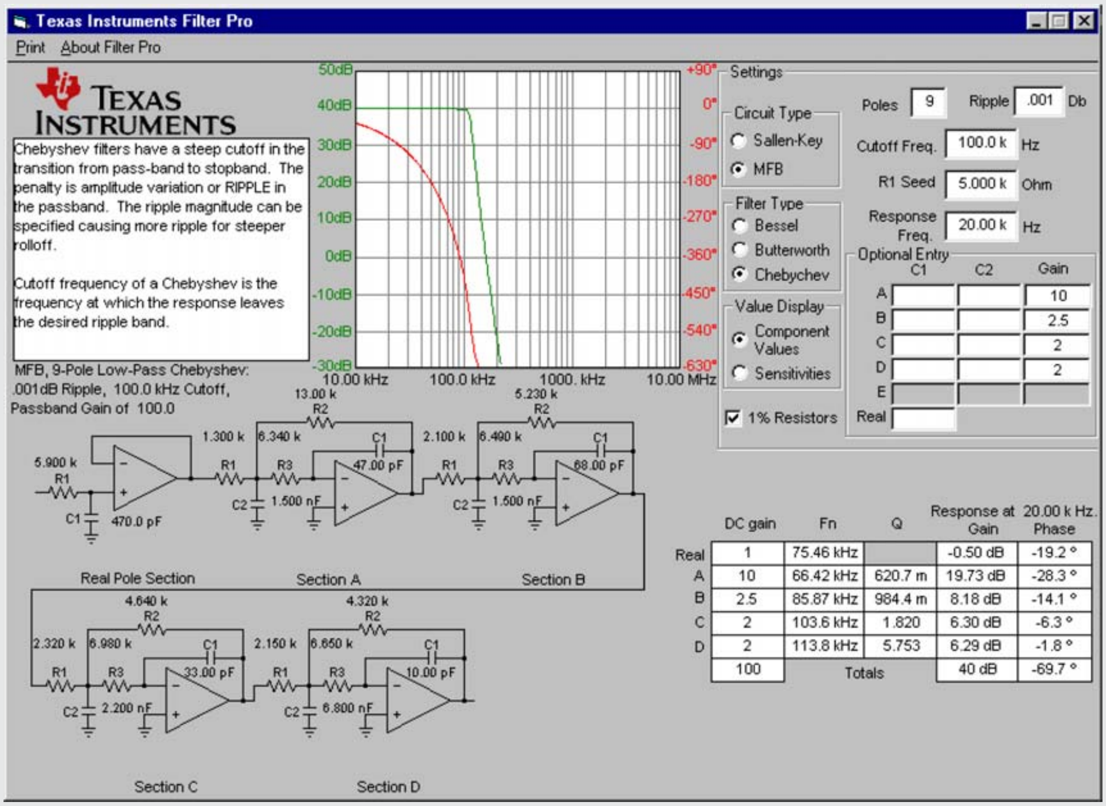
Q sensitivity for Sallen-Key pole pair (gain = 1)

$$S_C^Q = \pm 0.5\%/\% \text{ and}$$

$$S_R^Q = \pm \frac{R1 - R2}{2(R1 + R2)} \text{ (Sallen-Key complex pole pair).}$$

Therefore, S_R^Q is always less than ±0.5%/%.

Figure 6. Screen display of FilterPro showing a 9-pole MFB filter (gain = 40 dB)



Chebyshev filters have a steep cutoff in the transition from pass-band to stopband. The penalty is amplitude variation or RIPPLE in the passband. The ripple magnitude can be specified causing more ripple for steeper rolloff.

Cutoff frequency of a Chebyshev is the frequency at which the response leaves the desired ripple band.

MFB, 9-Pole Low-Pass Chebyshev:
.001dB Ripple, 100.0 kHz Cutoff,
Passband Gain of 100.0

Settings

Circuit Type
○ Sallen-Key
● MFB

Filter Type
○ Bessel
○ Butterworth
● Chebychev

Value Display
● Component Values
○ Sensitivities

☑ 1% Resistors

Poles 9
Ripple .001 Db
Cutoff Freq. 100.0 k Hz
R1 Seed 5.000 k Ohm
Response Freq. 20.00 k Hz

Optional Entry

	C1	C2	Gain
A			10
B			2.5
C			2
D			2
E			
Real			

	DC gain	Fn	Q	Response at 20.00 k Hz. Gain	Phase
Real	1	75.46 kHz		-0.50 dB	-19.2 °
A	10	66.42 kHz	620.7 m	19.73 dB	-28.3 °
B	2.5	85.87 kHz	984.4 m	8.18 dB	-14.1 °
C	2	103.6 kHz	1.820	6.30 dB	-6.3 °
D	2	113.8 kHz	5.753	6.29 dB	-1.8 °
	100	Totals		40 dB	-69.7 °

$S^2 < S_K^Q < 2Q^2S$ (Sallen-Key complex pole pair), where

S_R^Q, S_C^Q, and S_K^Q = sensitivity of Q to resistor, capacitor, and gain variations (%/%), respectively.

K = op amp gain. For the circuit in Figure 3, K = R2/R1. For the circuit in Figure 4, K = 1.0. For the circuit in Figure 5, K = 1 + R4/R3.

Note: FilterPro always selects component values so that unity-gain Sallen-Key S_K^Q will be closer to Q^2 than to $2Q^2$. However, it will allow you to design Sallen-Key pole pairs with high sensitivities (high Qs and gain >> 1). You must make sure that sensitivities to component variations do not make these designs impractical. A feature in the display allows you to view the f_n and Q sensitivities of filter sections to resistor and capacitor variations.

Using the sensitivity display feature

To use the Sensitivity display option, click on the Sensitivity radio button in the Settings frame (see Figure 6). The schematic shows sensitivity of f_n (S^f) and Q (S^Q) to each component for each filter section.

Rather than displaying the derivative with respect to component variations, the program calculates the f_n and Q change for a 1% change in component values. This gives a more realistic sensitivity value for real-world variations.

Using the seed resistor setting

The Seed Resistor setting allows you to scale the computer-selected resistor values to match the application. Move the cursor to the R1 Seed field and enter your *seed* resistor value. The default value of 10 kΩ is suggested for most applications.

When the circuit is in a power-sensitive environment (battery power, solar power, etc.), the value can be increased to decrease power consumption. Some high-speed op amps require lower feedback resistance, so their seed resistor value should be decreased.

Higher resistor values—e.g., 100 kΩ—can be used with FET-input op amps. At temperatures below about 70°C, dc errors and excess noise due to op amp input bias current will be small. Remember, however, that noise due to the resistors will be increased by $\sqrt{n}$ where n is the resistor increase multiplier.

Lower resistor values—e.g., 50 Ω—are a better match for high-frequency filters using the OPA620 or OPA621 op amps.

Using the capacitor option

Compared to resistors, capacitors with tight tolerances are more difficult to obtain and can be much more expensive. The capacitor fields (C1 and C2 boxes under Optional Entry, shown in Figure 6) allow you to enter actual measured capacitor values. In this way, an accurate filter response can be achieved with relatively inexpensive components. Prompts on the left of the screen advise minimum/maximum capacitor entry limits. With each capacitor entry, the program will select the exact or closest standard 1% resistor values as before.

Unless capacitor entries are made, FilterPro selects capacitors from standard E6 values (six values per decade). When values other than E6 are used (E12, measured, etc.), then the appropriate values should be entered.

Input capacitance compensation—Sallen-Key only

If the common-mode input capacitance of the op amp used in a Sallen-Key filter section is more than approximately C1/400 (0.25% of C1), it must be considered for accurate filter response. You can use the capacitor entry fields to compensate for op amp input capacitance by simply adding the value of the op amp common-mode input capacitance to the actual value of C1. The program then automatically recalculates the exact or closest 1% resistor values for accurate filter response. No compensation for op amp input capacitance is required with MFB designs.

Capacitor selection

Capacitor selection is very important for a high-performance filter. Capacitor behavior can vary significantly from ideal, introducing series resistance and inductance, which limit Q. Also, nonlinearity of capacitance versus voltage causes distortion.

Common ceramic capacitors with high dielectric constants, such as “high-K” types, can cause errors in filter circuits. Recommended capacitor types are: NPO ceramic; silver mica; metallized polycarbonate; and, for temperatures up to 85°C, polypropylene or polystyrene.

Using the f_n and Q displays

To aid in selection of the op amp, a feature in FilterPro allows you to view pole-pair sections f_n and Q. The f_n and Q information is also useful when troubleshooting filters by comparing expected to actual responses of individual filter sections.

Op amp selection

It is important to choose an op amp that can provide the necessary dc precision, noise, distortion, and speed.

Op amp bandwidth

In a low-pass filter section, maximum gain peaking is very nearly equal to Q at f_n (the section’s natural frequency). So, as a rule of thumb:

- *For an MFB section:* Op amp bandwidth should be at least 100 × Gain × Qf_n.
- *For high-Q Sallen-Key sections:* A higher op amp bandwidth is required.
- *For a Sallen-Key section:* For Q > 1, op amp gain-bandwidth should be at least 100 × Gain × Q^3f_n. For $Q \leq 1$, op amp gain-bandwidth should be at least 100 × Gain × f_n.
- *For a real-pole section:* Op amp bandwidth should be at least $50f_n$.

Although Q is formally defined only for complex poles, it is convenient to use a Q of 0.5 for calculating the op amp gain required in a real-pole section.

For example, a unity-gain, 20-kHz, 5-pole, 3-dB ripple Chebyshev MFB filter with a second pole-pair f_n of 19.35 kHz and a Q of 8.82 needs an op amp with a unity-gain bandwidth of at least 17 MHz. On the other hand, a 5-pole Butterworth MFB filter with a worst-case Q of 1.62 needs only a 3.2-MHz op amp. The same 5-pole Butterworth filter implemented with a Sallen-Key topology would require an 8.5-MHz op amp in the high-Q section.

Op amp slew rate

For adequate full-power response, the slew rate of the op amp must be greater than $\pi V_{O\ p-p} \times$ Filter Bandwidth. For example, a 100-kHz filter with 20-V_{p-p} output requires an op amp slew rate of at least 6.3 V/ms. Texas Instruments offers an excellent selection of op amps that can be used for high-performance active filters. The Web site mentioned earlier (analog.ti.com) can help you select an appropriate op amp for your application.

Full-power bandwidth

The full-power bandwidth parameter of the op amp should be at least the maximum signal frequency to be passed.

Conclusion

Using FilterPro for Windows, a designer can quickly and accurately develop low-pass filters for many different applications without the need for complex calculations.

Reference

For more information related to this article, you can download an Acrobat Reader file at www-s.ti.com/sc/techlit/*litnumber* and replace *"litnumber"* with the **TI Lit. #** for the materials listed below.

Document Title	**TI Lit. #**
1. "FilterPro™ MFB and Sallen-Key Low-Pass Filter Design Program," Application Report	. . .sbfa001

Related Web site

analog.ti.com

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