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SALLEN-KEY LOW-PASS FILTER DESIGN PROGRAM

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Although low-pass filters are vital in modern electronics, their design and verification can be tedious and time consuming. The Burr-Brown FilterPro™ program makes it easy to design unity-gain low-pass active filters. The program supports the most commonly used all-pole filters: Butterworth, Chebyshev, and Bessel.

Butterworth—maximally flat magnitude. This filter has the flattest possible pass-band magnitude response. Attenuation is –3dB at the design cutoff frequency. Attenuation above the cutoff frequency is a moderately steep –20dB/decade/pole. The pulse response of the Butterworth filter has moderate overshoot and ringing.

Chebyshev—equal ripple magnitude. (Sometimes translated Tschebyscheff or Tchevysheff). This filter response has steeper attenuation above the cutoff frequency than Butterworth. This advantage comes at the penalty of amplitude variation (ripple) in the pass-band. Unlike Butterworth and Bessel responses, which have 3dB attenuation at the cutoff frequency, Chebyshev cutoff frequency is defined as the frequency at which the response falls below the ripple band. For even-order filters, all ripple is above the 0dB DC response, so cutoff is at 0dB—see Figure 1a. For odd-order filters, all ripple is below the 0dB DC response, so cutoff is at –(ripple) dB—see Figure 1b. For a given number of poles, a steeper cutoff can be achieved by allowing more pass-band ripple. The Chebyshev has even more ringing in its pulse response than the Butterworth.

Bessel—maximally flat delay, (also called Thomson). Due to its linear phase response, this filter has excellent pulse response (minimal overshoot and ringing). For a given number of poles, its magnitude response is not as flat, nor is its attenuation beyond the –3dB cutoff frequency as steep as the Butterworth. It takes a higher-order Bessel filter to give a magnitude response similar to a given Butterworth filter, but the pulse response fidelity of the Bessel filter may make the added complexity worthwhile.

SUMMARY

Butterworth

Advantages—Maximally flat magnitude response in the pass-band.
Disadvantages—Overshoot and ringing in step response.

Chebyshev

Advantages—Better attenuation beyond the pass-band than Butterworth.
Disadvantages—Ripple in pass-band. Even more ringing in step response than Butterworth.

Bessel

Advantages—Excellent step response.
Disadvantages—Even poorer attenuation beyond the pass-band than Butterworth.

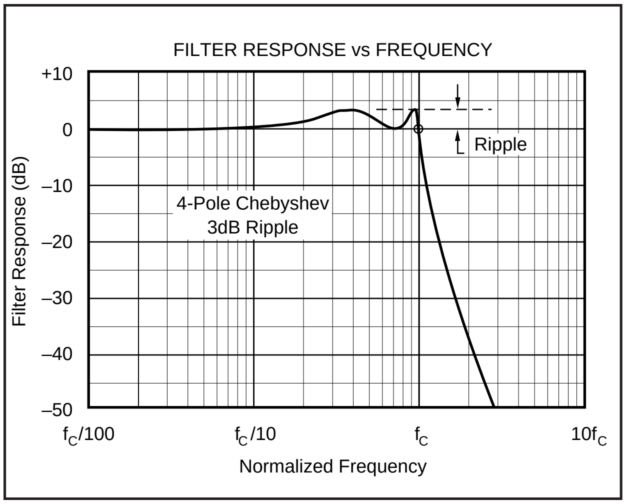

FIGURE 1a. Response vs Frequency of Even-Order (4-pole), 3dB-Ripple Chebyshev Filter Showing Cutoff at 0dB.

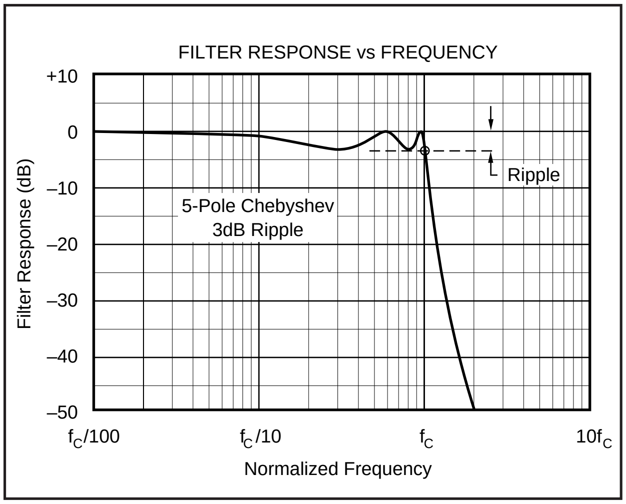

FIGURE 1b. Response vs Frequency of Odd-Order (5-pole), 3dB-Ripple Chebyshev Filter Showing Cutoff at –3dB.

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Even-order filters designed with this program consist of cascaded sections of Sallen-Key complex pole-pairs.

Odd-order filters contain an additional real-pole section. Figures 2 to 5 show the recommended cascading arrangement. Lower Q stages are placed ahead of high Q stages to prevent op amp output saturation due to gain peaking. The program can be used to design filters up to 7th order.

USING THE FilterPro™ PROGRAM

With each data entry, the program automatically calculates values for 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.

RESISTOR VALUES

The program automatically selects standard capacitor values and calculates exact resistor values for the filter you have selected. In the "1% display" option, the program calculates the closest standard 1% resistor values. To select standard 1% resistor values, use the arrow keys to move the cursor to the **Display** menu selection. Then press <**ENTER**>. Because the program selects the closest 1% resistor for one resistor in each pole-pair, and then calculates the exact value for the second resistor before selecting the closest 1% value for the second resistor, it produces the most accurate filter design that can be implemented with 1% resistors.

Using the "Scale Resistors" menu option allows you to scale the computer-selected resistor value to match the application. The default value of 10kΩ is suggested for most applications.

Higher resistor values, e.g. 100kΩ, 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. However, noise due to the resistors will be increased by the square-root of resistor increase.

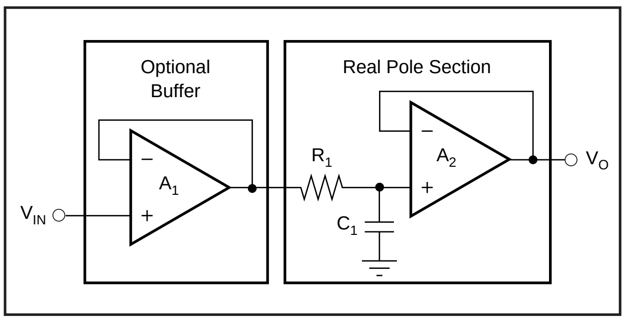

FIGURE 2. Real Pole Section (unity-gain, first-order Butterworth) $f_{-3dB} = 1/(2\pi R_1C_1)$

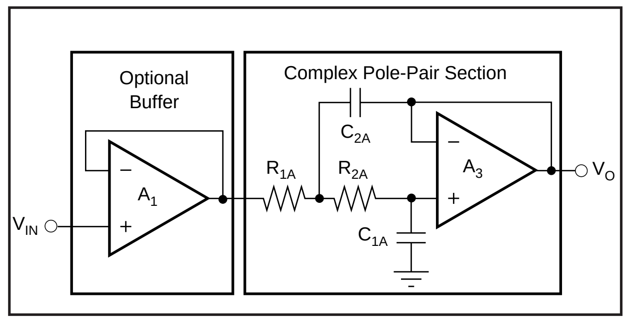

FIGURE 3. Second-Order, Unity-Gain, Low-Pass Filter Using Sallen-Key Configuration for Complex Pole-Pair.

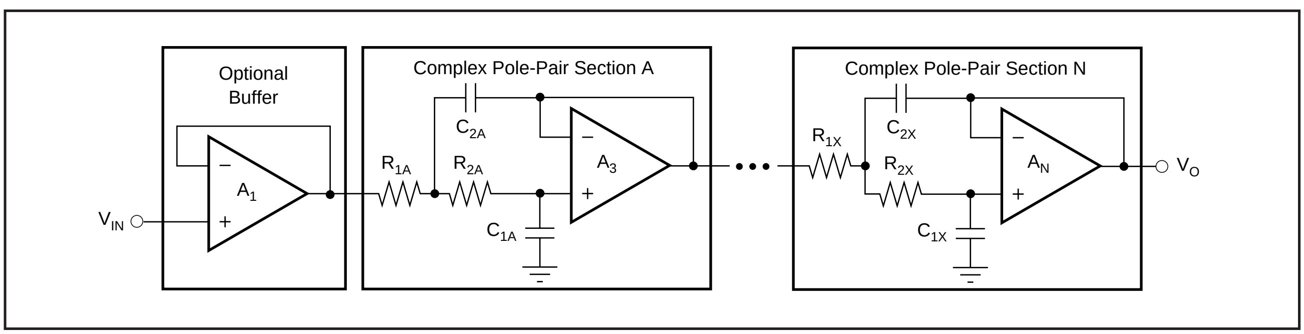

FIGURE 4. Even-Order, Unity-Gain, Low-Pass Active Filter Using Cascaded Sallen-Key Complex Pole-Pairs.

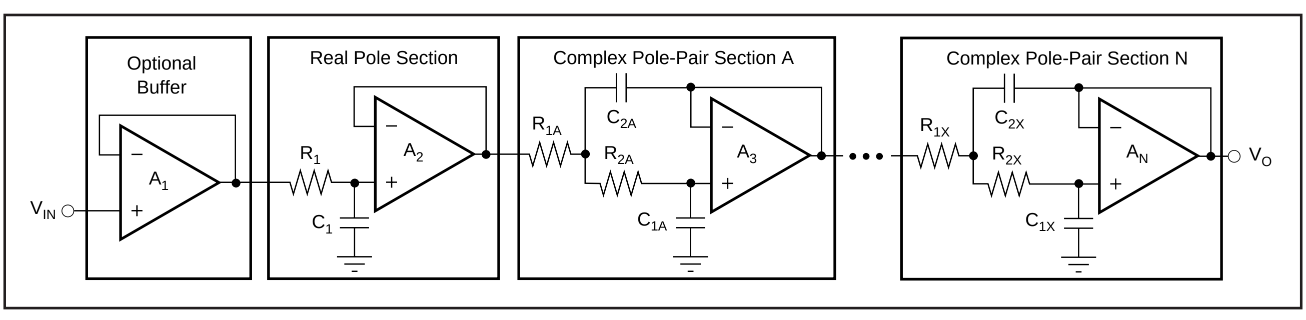

FIGURE 5. Odd-Order, Unity-Gain, Low-Pass Active Filter Using One Real Pole Followed by Cascaded Sallen-Key Complex Pole-Pairs.

Lower resistor values, e.g. 500Ω, are a better match for high-frequency filters using the OPA620 op amp.

Capacitor Values

Compared to resistors, capacitors with tight tolerances are more difficult to obtain and can be much more expensive. Using the "capacitor menu" option allows you to enter actual measured capacitor values. The program will then select exact or closest standard 1% resistor values as before. In this way, an accurate filter response can be assured with relatively inexpensive components.

If the common-mode input capacitance of the op amp used in a filter section is more than approximately 0.25% of C_1, it must be considered for accurate filter response. A capacitor menu option allows you to change the values of program-selected capacitors as explained earlier. To compensate for op amp capacitance, simply add the value of the op amp common-mode input capacitance to the actual value of C_1. The program then automatically recalculates the exact or closest 1% resistor values for accurate filter response.

Op Amp Selection

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

In a low-pass filter section, maximum gain peaking at f_n (the section's natural frequency) is very nearly equal to Q. As a rule of thumb, for a unity-gain Sallen-Key section, the op amp bandwidth should be at least $100 \cdot Q^3 \cdot f_n$. For a real-pole section, op amp bandwidth should be at least $50 \cdot f_n$. For example, a 20kHz 5-pole Butterworth filter needs a 8.5MHz op amp in the Q = 1.62 section.

To aid in selection of the op amp, a program option can display f_n and Q for each section. Press <**ENTER**> in the Display option of the menu. Although Q is formally

Attach Disk Sleeve Here.

Call (602) 741-3978 to down-load a DOS-compatible executable file. Down-load the FILTER1 file from the components, analog circuit functions area. File transfers are supported by XMODEM, Kermit, ASCII and Sealink protocols. Communications settings are 300/1200/2400 baud, 8-N-1.

Or,

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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.

The slew rate of the op amp must be greater than $\pi \cdot V_{Op\text{-}p} \cdot$ FILTER BANDWIDTH for adequate full-power response. For example, a 100kHz filter with 20Vp-p output requires an op amp slew-rate of at least 6.3V/µs. Burr-Brown offers an excellent selection of op amps which can be used for high performance active filters. The guide below lists some good choices.

OP AMP SELECTION GUIDE, (IN ORDER OF INCREASING SLEW RATE.)

T_A = 25°C, V_S=±15V, specifications typ, unless otherwise noted, min/max specifications are for high-grade model.

OP AMP MODEL	BW typ (MHz)	FPR (1) typ (kHz)	SR typ (V/µs)	V_{OS} max (µV)	V_{OS}/dT max (µV/°C)	NOISE at 10kHz (nV/√Hz)	C_{CM} (3) (pF)
OPA177	0.6	3	0.2	10	±0.1	8	1
OPA27	8	30	1.9	25	±0.6	2.7	1
OPA2107(2) dual	4.5	280	18	500	±5	8	4
OPA2604(2) dual	10	400	25	2000	±5 typ	10	10
OPA602(2)	6	500	35	250	±2	12	3
OPA404(2) quad	6	500	35	1000	±3 typ	12	3
OPA627(2)	16	875	55	100	±0.8	4.5	7
OPA620 (V_S = ±5V)	300	16MHz (5Vp-p)	250	500	±8 typ	2.3 (at 1MHz)	1

NOTES: (1) Unless otherwise noted, FPR is full power response at 20Vp-p as calculated from slew rate. (2) These op amps have FET inputs. (3) Common-mode input capacitance.

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 vs 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.

THE UAF42 UNIVERSAL ACTIVE FILTER

For other filter designs, consider the Burr-Brown UAF42 Universal Active Filter. It can easily be configured for a wide variety of low-pass, high-pass, or band-pass filters. It uses the classical state-variable architecture with an inverting amplifier and two integrators to form a pole-pair. The integrators include on-chip 1000pF, 0.5% capacitors. This solves one of the most difficult problems in active filter implementation—obtaining tight tolerance, low-loss capacitors at reasonable cost.

Simple design procedures for the UAF42 allow implementation of Butterworth, Chebyshev, Bessel, and other types of filters. An extra FET-input op amp in the UAF42 can be used to form additional stages or special filter types such as band-reject and elliptic. The UAF42 is available in a standard 14-pin DIP. For more information about the UAF42 request Burr-Brown Product Data Sheet PDS-1070**.**

EXAMPLES OF FILTER RESPONSE

Figures 6a and 6b show actual measured magnitude response plots for 5th-order 20kHz Butterworth, 3dB Chebyshev and Bessel filters designed with the program. The op amp used in all filters was the OPA627. As can be seen in Figure 5, the initial roll-off of the Chebyshev filter is fastest and the roll-off of the Bessel filter is the slowest. However, each of the 5th-order filters ultimately rolls off at –N • 20dB/decade, where N is the filter order (–100dB/decade for a 5-pole filter).

The oscilloscope photographs show the step response for each filter. As expected, the Chebyshev filter has the most ringing, while the Bessel has the least.

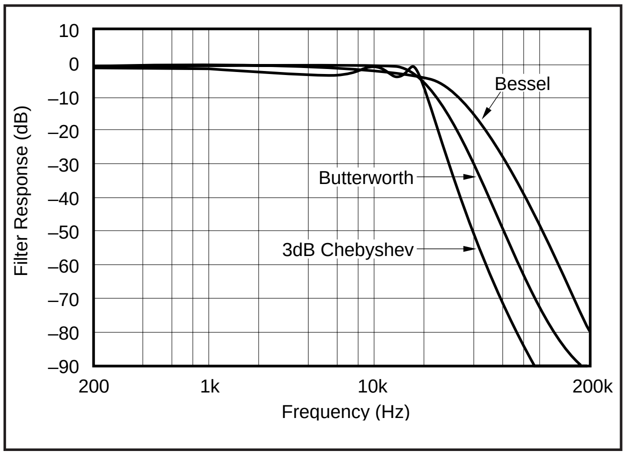

FIGURE 6a. Gain vs Frequency for 5th-Order 20kHz Butterworth, 3dB Chebyshev, and Bessel Unity-Gain Low-Pass Filters Showing Overall Filter Response.

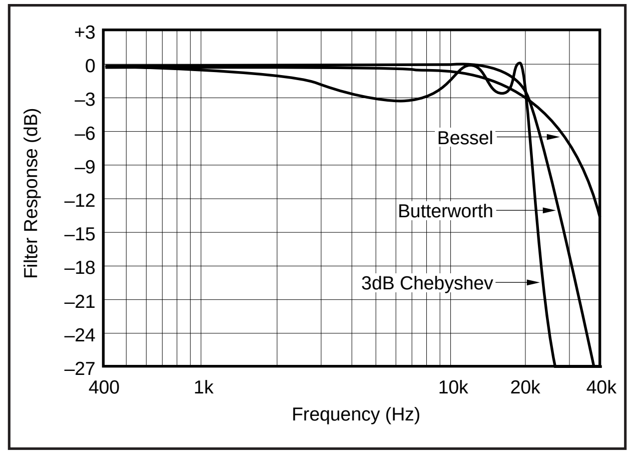

FIGURE 6b. Gain vs Frequency for 5th-Order 20kHz Butterworth, 3dB Chebyshev, and Bessel Unity-Gain Low-Pass Filters Showing Transition Band Detail.

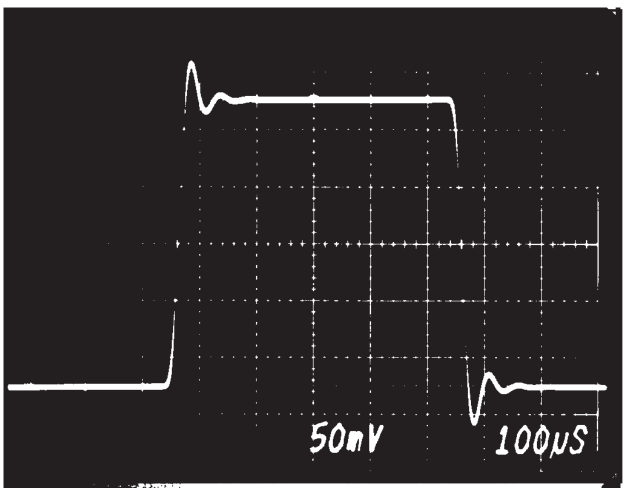

FIGURE 7. Step Response of 5th-Order 20kHz Butterworth Low-Pass Filter.

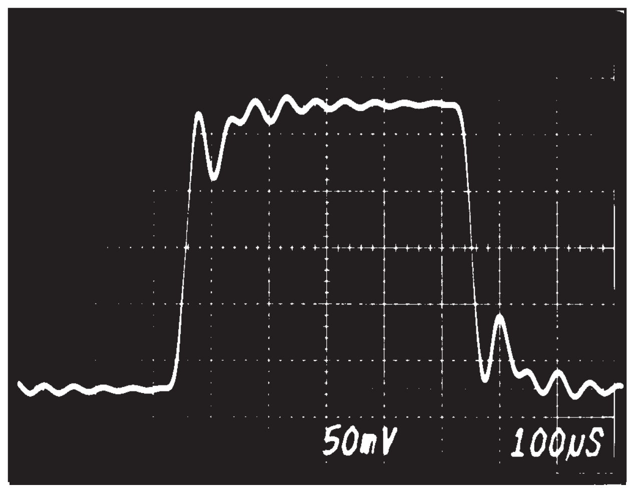

FIGURE 8. Step Response of 5th-Order 20kHz 3dB Ripple Chebyshev Low-Pass Filter.

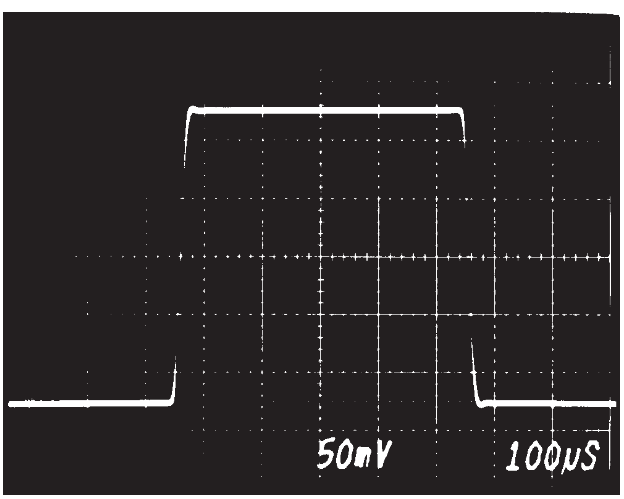

FIGURE 9. Step Response of 5th-Order 20kHz Bessel Low-Pass Filter.

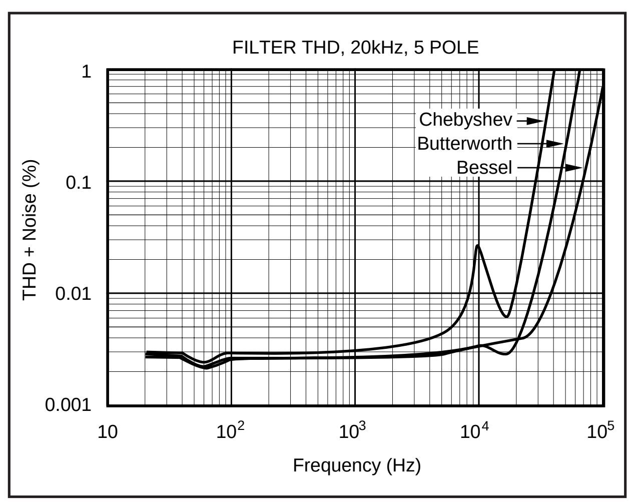

FIGURE 10. Measured Distortion for the Three 20kHz Low-Pass Filters.