Operational Amplifiers Part II of VI
How Do You Choose the Right Amplifier for Your Low-Pass Filter?

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The task of selecting the correct single-supply op amp for an active low-pass filter (LPF) circuit can appear overwhelming as you read any op amp data sheet, and view all of the specifications. For instance, there are 24 dc and ac electrical specifications in Microchip's 5-MHz, single-supply, MCP6281/2/3/4 data sheet. But in reality there are only two specifications that you should initially consider. Once you have chosen your amplifier, based on those two specifications, there are two additional ones that you should consider before reaching your final decision. This article will identify these key specifications and give guidelines on how to select the right amplifier for your filtering circuit.

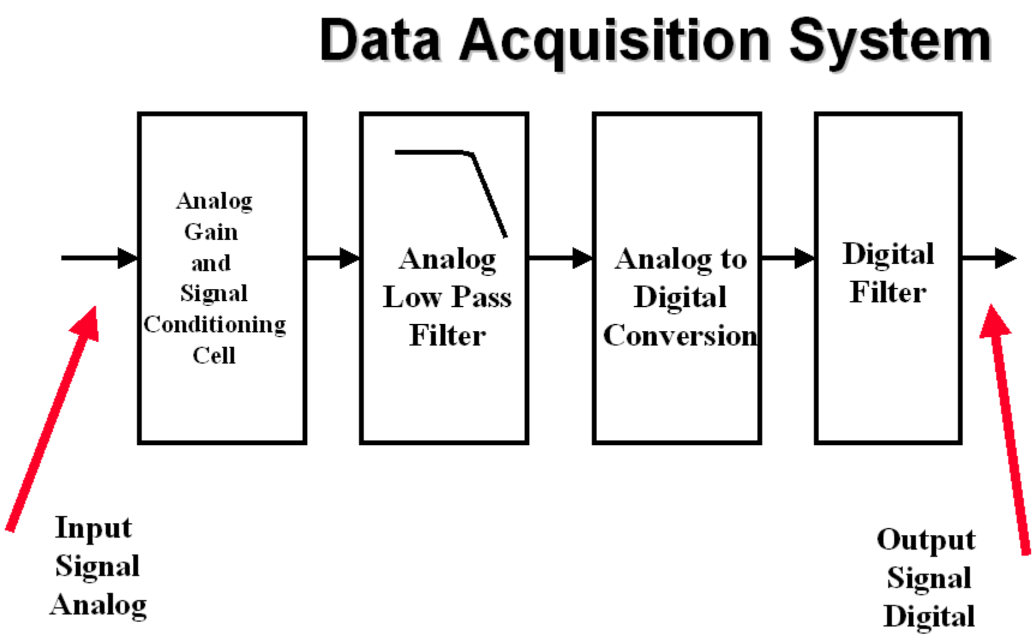

Fig. 1: A typical data acquisition system starts with an analog gain stage followed by an anti-aliasing LPF which feeds the ADC, producing a digital representation of the analog input. The digital output can be further filtered in the digital domain

Analog filters can be found in almost every electronic circuit. Audio systems use them for pre-amplification and equalization; in communication systems, filters are used to tune in specific frequencies while eliminating others. But if an analog signal is digitized (see Fig. 1) low-pass filters are almost always used to prevent aliasing errors from out-of-band noise and interference. Analog filtering can remove higher frequency noise superimposed on the analog signal before it reaches the ADC. In particular, this includes low-level noise, as well as extraneous noise peaks. Any signal that enters the ADC is digitized. If the signal is higher than half of the sampling frequency, the magnitude of that signal is converted reliably, but the frequency is modified as it aliases back into the digital output.

You can use a digital filter to reduce the noise after digitizing the signal, but keep in mind the rule of thumb: “Garbage in will give you garbage out.”

The most common topologies for second-order, active LPFs are shown in Figs. 2 and 3. The non-inverting Sallen-Key low-pass filter (Fig. 2) is designed so that the input signal is not inverted. A gain option is implemented with R_1 and R_2. If you want a dc gain of +1 V/V, the two resistors should be of equal value. In a second-order, Multiple Feedback configuration (Fig. 3), the input signal is inverted around the reference voltage, V_{REF}. If a higher order filter is needed, both of these topologies can be cascaded.

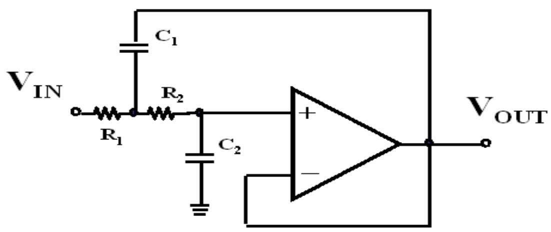

Fig. 2: Second-order Sallen-Key LPF implementation with dc unity gain of +1 V/V

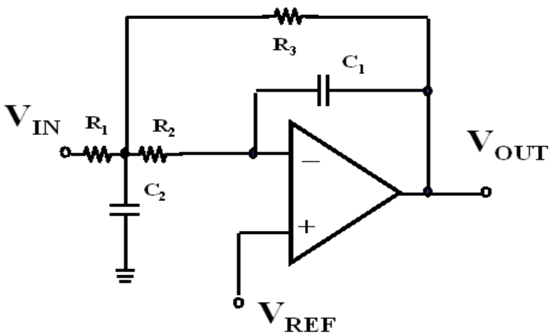

Fig. 3: Second-order Multiple-Feedback LPF implementation with -1 V/V dc gain

The two key specifications that you should initially consider when designing with either of these topologies is gain bandwidth product (GBWP) and slew rate. Prior to the selection of the op amp, you need to determine the filter cut-off frequency (f_C), the frequency where your filter starts to attenuate the signal. Sometimes, in literature, you will find that this is called the pass-band frequency. Once this is done, Microchip's filter design software program, FilterLab analog filtering software tool (available at no cost at http://www.microchip.com), can be used to determine the capacitor and resistor values.

Since you have already defined your cut-off frequency, selecting an amplifier with the right bandwidth is easy. The closed-loop bandwidth of the amplifier must be at least 100 times higher than the cut-off frequency of the filter. If you are using the Sallen-Key configuration and your filter gain is +1 V/V, the following formula should be used:

$$GBWP \geq 100\ f_C$$

If you are using the Multiple-Feedback configuration, the following formula should be used:

$$GBWP \geq 100 (-G_{CLI} + 1) f_C$$

where, G_{CLI} is equal to the inverting gain of your closed-loop system

As an example, a Sallen-Key low-pass filter circuit, configured with a corner frequency of 10 kHz and a gain of +1 V/V would require that the GBWP of the amplifier be greater than 1 MHz. Since the GBWP of the MCP6281/2/3/4 amplifier is 5 MHz (typical), this amplifier could be used in that filter circuit.

In addition to paying attention to the bandwidth of your amplifier, the slew rate should be evaluated in order to ensure that your filter does not create signal distortions. The slew rate of an amplifier is determined by internal currents and capacitance. When large signals are sent through the amplifier, the appropriate currents charge these internal capacitors. The speed of this charge is dependent on the value of the amplifier's internal resistances, capacitances and currents. In order to ensure that your active filter does not enter into a slew condition you need to select an amplifier such that:

$$\text{Slew rate} \geq 2\pi \ V_{OUT(P-P)} f_C$$

where, $V_{OUT\ P-P}$ is the expected peak-to-peak output voltage swing below f_C

Going back to our previous example, the application requires an output peak voltage of ~5 V in a single-supply environment. This performance level would dictate that the amplifier that is used in the LPF has a slew rate that is equal to or greater than 0.314 V/µsec. The specified Slew Rate of the MCP6281/2/3/4 family of amplifiers is 2.5 V/µsec exceeding the required conditions for this filter.

There are two second-order specifications that affect your filter circuit, input common-mode voltage range (V_{CMR}), for the Sallen-Key circuit and input bias current (I_B). In the Sallen-Key configuration, V_{CMR} will limit the range of your input signal, while I_B describes the amount of current going in or out of the input pins of the amplifier. If you are using the Sallen-Key filter (Fig. 2, again) the input bias current of the amplifier will conduct through R_2. The voltage drop caused by this error will appear as an input-offset voltage and input-noise source. But more critically, high input bias currents in the nano or microampere range may motivate you to lower the resistor values in your circuit. When you do this you will have to increase the capacitors in order to meet your filter cutoff frequency requirements. Large capacitors may not be a very good option, however, because of cost, accuracy and size. Generally, filters with lower-corner frequencies will require a CMOS amplifier instead of its bipolar amplifier counterpart.

If you follow these simple guidelines you will find that designing a successful LPF is not that difficult and you will quickly have a working circuit.

Recommended References:

AN699 *"Anti-Aliasing, Analog Filters for Data Acquisition Systems,"* Bonnie C. Baker, Microchip Technology Inc.

FilterLab, Analog filtering software tool at: http://www.microchip.com