Filters for Data Transmission

Bruce Carter

ABSTRACT

The process of filtering an analog signal removes all frequencies above or below a corner frequency, passing only a band of frequencies, or rejecting a band of frequencies. When digital signals are filtered, however, a totally different set of constraints applies. This application note gives the designer a set of tools for implementing a filter that is the best compromise of interference rejection and preserving the timing of data signal harmonics.

1 Introduction

Analog filtering has an unspoken assumption that the desired signal is composed of primarily of a single sinusoidal component, or a range of non-critical sinusoidal components. There are many applications, however, that involve the filtering of data. The previous assumptions no longer apply, and the designer must adopt new techniques for a successful filter design.

Data transmission is best done differentially, so that common mode components can be eliminated. This is not to say that data transmission cannot be done in a single-ended manner, through coaxial cable, etc. Interference, however, is much more of an issue in a single-ended system. For example: a common question that Texas Instruments receives is how to implement a 60-Hz notch filter. The correct answer is to urge the customer to use differential transmission, which would inherently reject 60 Hz. This note will exclusively show differential circuit examples.

2 The Harmonic Nature of Data

While a sine wave is composed of only one frequency component, more complex waveforms are composed of many frequency components. These frequency components form the final waveform when added together. Any continuous time, T-periodic waveform x(t) can be described mathematically as a Fourier series[1,2] of individual sine waves. The general form of the Fourier series is:

$$x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty}\left(a_k \cos(k\omega_0 t) + b_k \sin(k\omega_0 t)\right)$$

Where:

Fundamental frequency $\omega_0 = \frac{2\pi}{T}\,\text{rad}/\text{sec}$

The Fourier series of a square wave is:

$$x(t) = \sin(\omega_o t) + \frac{\sin(3\omega_o t)}{3} + \frac{\sin(5\omega_o t)}{5} + \ldots + \frac{\sin(N\omega_o t)}{N}$$

This means that a square wave is an infinite series of odd harmonics, summed together to create the square shape. Obviously, if a square wave is to be transmitted without distortion, all of the harmonics - out to infinity - must be transmitted.

Figure 1 shows the first 999 harmonics of a 0-dB 1-MHz square wave. As with any square wave, there are no even harmonics, only odd. Because the frequency axis is logarithmic, the harmonics from 1 to 999 appear to crowd closer together as the frequency is increased from 1 MHz to 1 GHz. Harmonics above 1 GHz will continue to follow a –20 dB per decade slope.

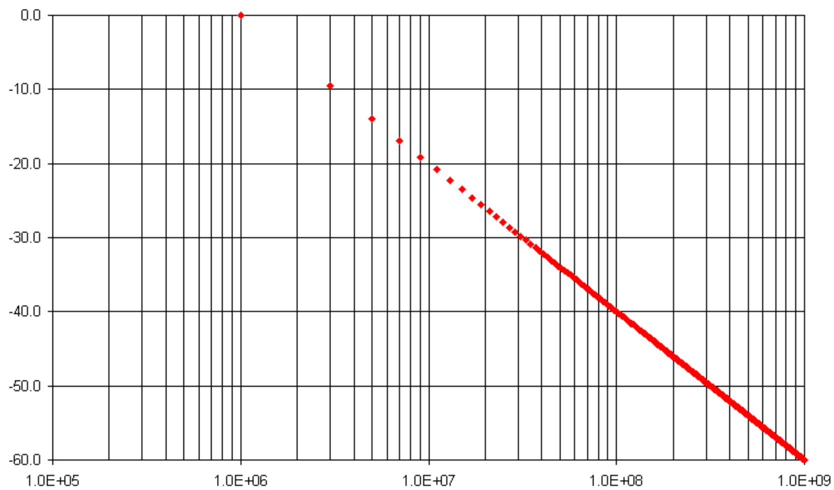

Figure 1. The Spectrum of a 1-MHz Square Wave

Any filter function must take the harmonic structure of the wave into account. The removal or modification of any harmonic will affect the shape of the waveform. Modification includes amplitude, phase, and timing (group delay) of each and every harmonic. Modifying higher order harmonics will have less effect on the shape of the waveform than modifying lower order harmonics, but the effect will be right at the corners of the waveform. When filtering a square wave or any other data format, it is the job of the designer to decide what harmonics must be passed and what can be eliminated.

In subsequent figures, harmonics will be shown in blue, and harmonics above the 11th are not shown – they will crowd together to the point that they would produce continuous blue under the blue diagonal line that frames the other harmonics.

3 Filtering Data

This section presents several options for filtering data.

3.1 Low Pass Filtering Data

Low pass data filtering affects the harmonic content of the waveform, because, by definition, it eliminates higher order harmonics.

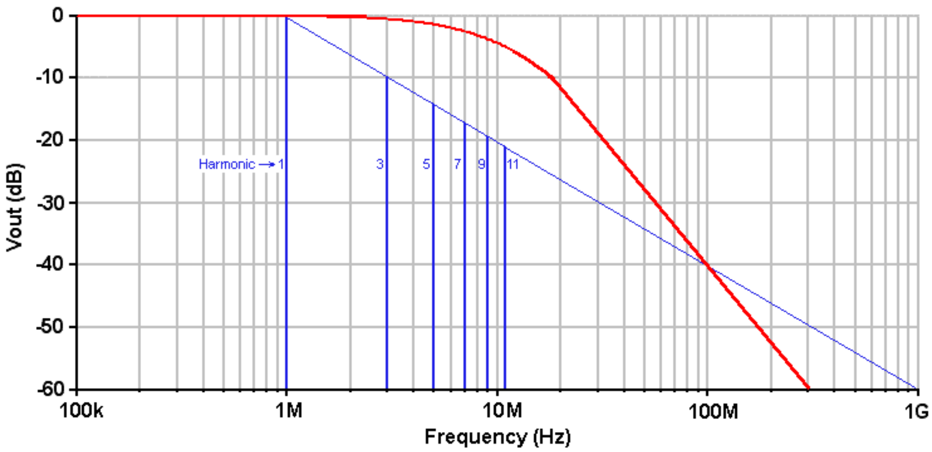

Figure 2. Low Pass Filtering of a 1-MHz Square Wave

Interfering frequencies must be much higher in frequency than the fundamental frequency. If the system requires that third, fifth, or even higher harmonics must be passed, the 3 dB corner frequency must be above these harmonics; 3, 5, 7 or more times the fundamental frequency. Figure 2 shows a low pass filter response with a corner frequency between the 9th and 11th harmonics. Note that there is significant attenuation of the 5th and 7th harmonics as well, which produces rounding in the final waveform. The resulting waveform looks something like Figure 3:

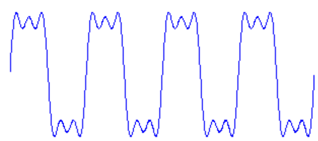

Figure 3. Square Wave Approximation

Fourier synthesis[3] allows the user to play with Fourier harmonics and how they affect the shape of the waveform.

An imperfect waveform may be acceptable to the designer - it depends on the timing of the leading and trailing edge of the waveform. The elimination of harmonics results in rounding of the edges, and therefore delays in the leading and trailing edges of the digital signal. The residual ripple in the high and low sections of the waveform must not trigger logic level changes at the next digital stage. Of more importance, however, is that the harmonics that are passed are not delayed. An early or late harmonic can change the timing of data. The shape of the waveform must be preserved.

One of the designer’s jobs is to select a 3 dB corner frequency that eliminates interference, but does not adversely affect system performance by attenuating harmonics that are crucial to system timing. The designer also has to insure that all of the harmonics are phase shifted by the same amount, and arrive at the output of the filter at the same time. The designer, who is used to the Butterworth response, must choose another type of filter response.

3.1.1 Types of Filter Response

The filter designer has several types of filter response from which to select. Low pass filter responses are shown in Figure 4:

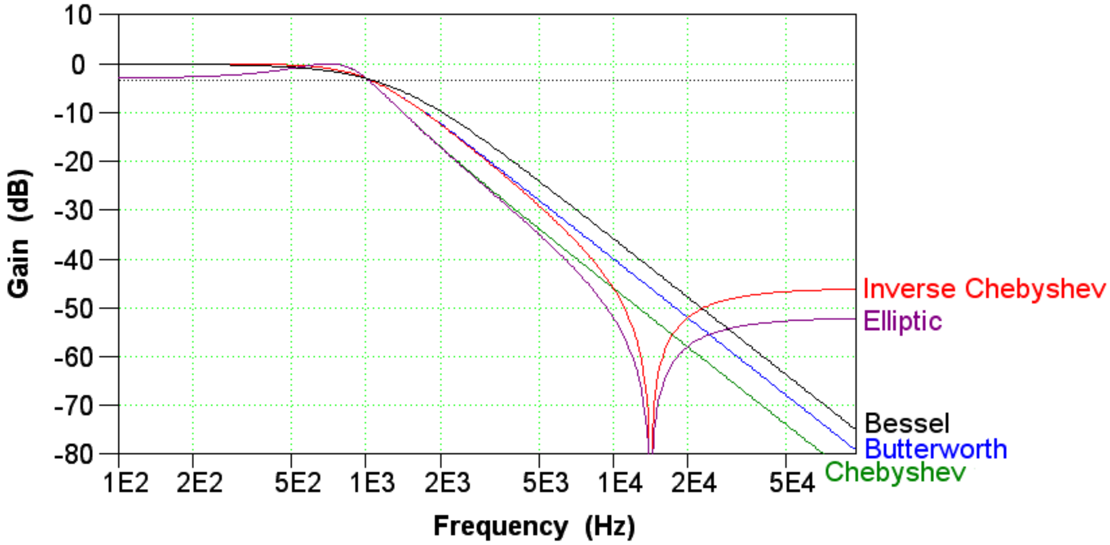

Figure 4. Filter Amplitude Responses

All of these response characteristics roll off 3 dB at the corner frequency (in this case 10 kHz). After that, they all differ:

- Butterworth is the most popular response. It has no ripple in the pass or stop. There is a single set of component ratios that produces a Butterworth response.
- Chebyshev response has more roll off than Butterworth, and it has ripple in the pass band.
- Inverse Chebyshev response has ripple in the stop band, and therefore has a lot of rejection near the corner frequency, but the rejection *bounces back*, and there is some passage in the stop band.
- Elliptical response combines the characteristics of Chebyshev and inverse Chebyshev, having ripple in the pass band and in the stop band. Like the inverse Chebyshev, the stop band rejection has some bounce back.
- Bessel response has less rolloff in the stop band than the other types, and is not as flat in the pass band. Therefore, it has not been a very popular filter response.

The designer might ask, "why use a filter response that is not as *good* as the others?" But the definition of *good* might be surprising! Bessel response has a characteristic that is extremely important to certain types of filter applications - constant group delay response.

IMPORTANT CONCEPT

Constant group delay is essential for data transmission.

3.1.2 Amplitude Roll Off or Group Delay?

The emphasis for most designers is the degree of roll-off - just how much was needed, and just how close the corner of the filter could be placed to the passband without negatively affecting the signal content. A Bessel filter, however has (almost) flat group delay in the passband:

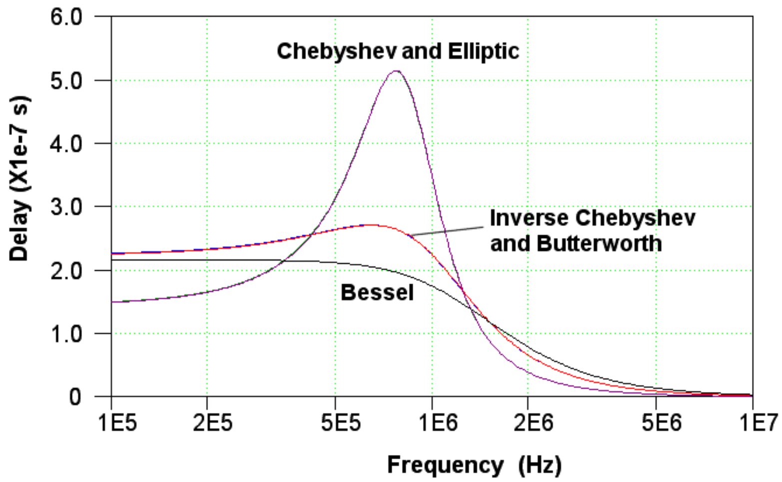

Figure 5. Filter Group Delay

Designers know much about the amplitude response of the filter. That, after all, determines what frequencies are passed, and what frequencies are stopped. Designers are only vaguely aware of the implications for the phase of the signal, and even less about group delay. There are few CAD programs that even address the group delay of a filter circuit.

3.1.3 Group Delay - Defined

Group delay is defined as:

The propagation time delay of the envelope on an amplitude modulated signal as it passes through a filter. Group delay is proportional to the change in slope of the phase shift response versus frequency curve[4].

Defined mathematically[5]:

$$D(\omega) = -\frac{d}{d\omega}\Theta(\omega)$$

Where:

$\Theta(\omega)$ is the phase shift in radians

$D(\omega)$ is the group delay

3.1.4 Group Delay – Its Effect on Data Streams

Constant group delay is the characteristic of Bessel filters that makes them valuable to digital designers. Very few filters are designed with square waves in mind. Most of the time, the signals filtered are sine waves, or close enough that the effect of harmonics can be ignored. If a waveform with high harmonic content is filtered, such as a square wave, the harmonics can be delayed with respect to the fundamental frequency, especially if a Butterworth or Chebyshev response is used. A Bessel response should be selected to avoid delaying the harmonics. Referring back to Figure 2, the group delay of a Butterworth filter is longest at the corner frequency, meaning that the 7^{th} and 9^{th} harmonics are delayed longer than the fundamental (1^{st}), 3^{rd}, 5^{th}, 11^{th} to infinity). While a low pass characteristic may only round the square wave edges and produce a little ripple in the high and low portions, changing the delay of harmonics as well can wreak havoc with the structure of the wave, producing peaking or nulls at the edges of the waveform.

It may be painful for a designer to live with less rolloff, or put in multiple Bessel filter stages to increase the rolloff. Regrettably, this is the price of preserving signal harmonic content.

Fortunately, the designer may have an alternative – see notch filtering.

3.1.5 Designing the Filter

Figure 6 shows the circuit for a low pass filter. The best filter topology to use for differential low pass filters is the Multiple Feedback (MFB). The designer should:

- Select a corner frequency based on harmonic content desired in the waveform.
- Select a value of capacitor. This is the value for C1, and it also gives the value of C2, because the ratio of two is known.
- Calculate the starting resistor value “R”
- R1, R2, and R3 can then be calculated from the ratios below.
- The filter can be scaled up or down in frequency linearly by changing component values, if the ratios are preserved.

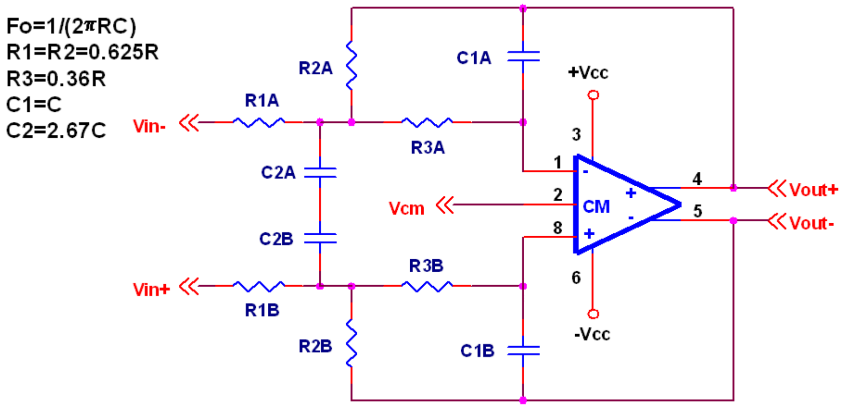

Figure 6. Differential Low Pass Filter

3.2 High Pass Filtering Data

The simplest type of data filtering is high pass filtering. High pass filters can be used when low frequency interference (such as audio on a DSL signal) is present. A high pass filter is not the most effective way of removing a single frequency, however. For single frequencies, use a notch filter.

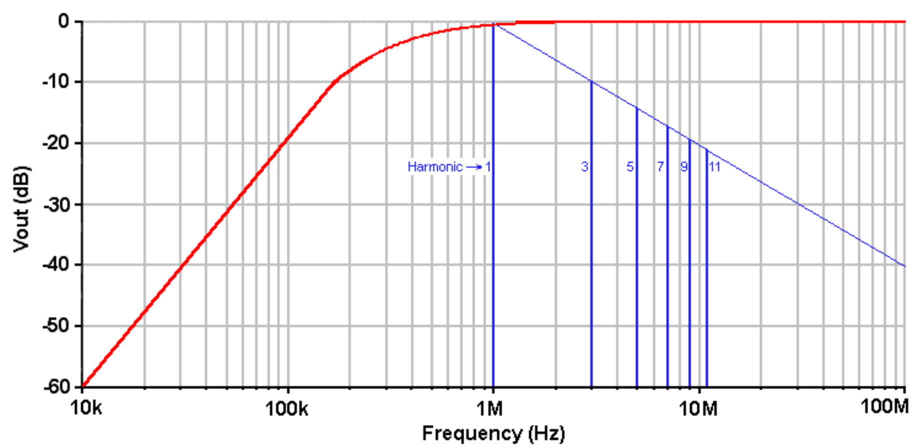

Figure 7. High Pass Filtering a Square Wave

The only challenge for the designer is to select a corner frequency such that the fundamental is only slightly affected by the low frequency rolloff. The designer is strongly encouraged to use the Bessel MFB high pass filter of Figure 8.

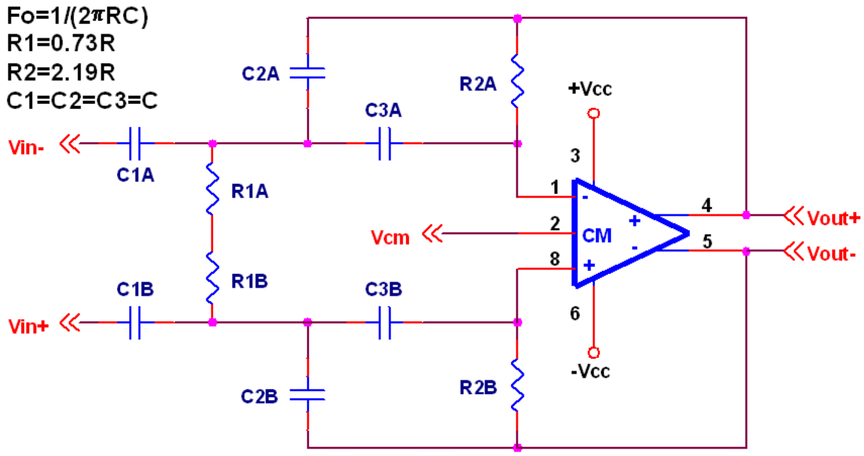

Figure 8. Differential Bessel High Pass Filter

The design procedure for the differential high pass filter is similar to that employed for the differential low pass filter.

3.3 Notch Filtering Data

If:

- The fundamental signal is at a fixed frequency.
- The interfering signal is at a single fixed frequency that does not coincide with a harmonic.
- The interfering signal is below the fundamental, or not so far above it that it is difficult to resolve from important signal harmonics.

Then a high-Q notch filter can be used to eliminate it.

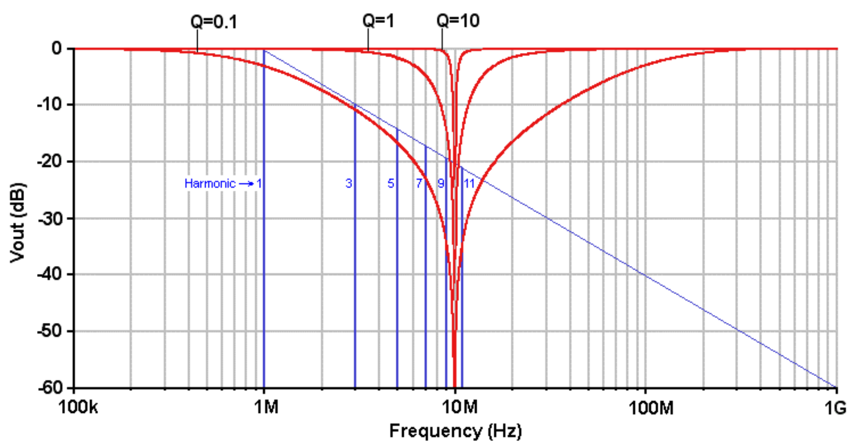

Figure 9. Notch Filtering a 1-MHz Square Wave With 10-MHz Interference

Superimposed on the spectrum of the square wave are the characteristics of a 10-MHz notch filter with various values of Q. Because the harmonics are so closely spaced, only a notch filter with a Q of 10 or above can eliminate 10-MHz interference without adversely affecting square wave harmonics. Even a Q of ten produces some attenuation of the 9^{th} and 11^{th} harmonics.

The designer should make sure that the harmonics affected by the notch filter are not critical to the shape of the waveform. Unfortunately, the group delay of a notch filter is maximum near the notch. The harmonics near the center frequency are delayed with respect to the other harmonics.

Figure 10 shows the schematic diagram for a differential notch filter. The design procedure is similar to that of the low pass and high pass filter. The designer is cautioned, however, that the bandwidth of the amplifier used for high Q notch filters must be higher than the normal 40-dB headroom rule to avoid slew rate limitations on notch depth.

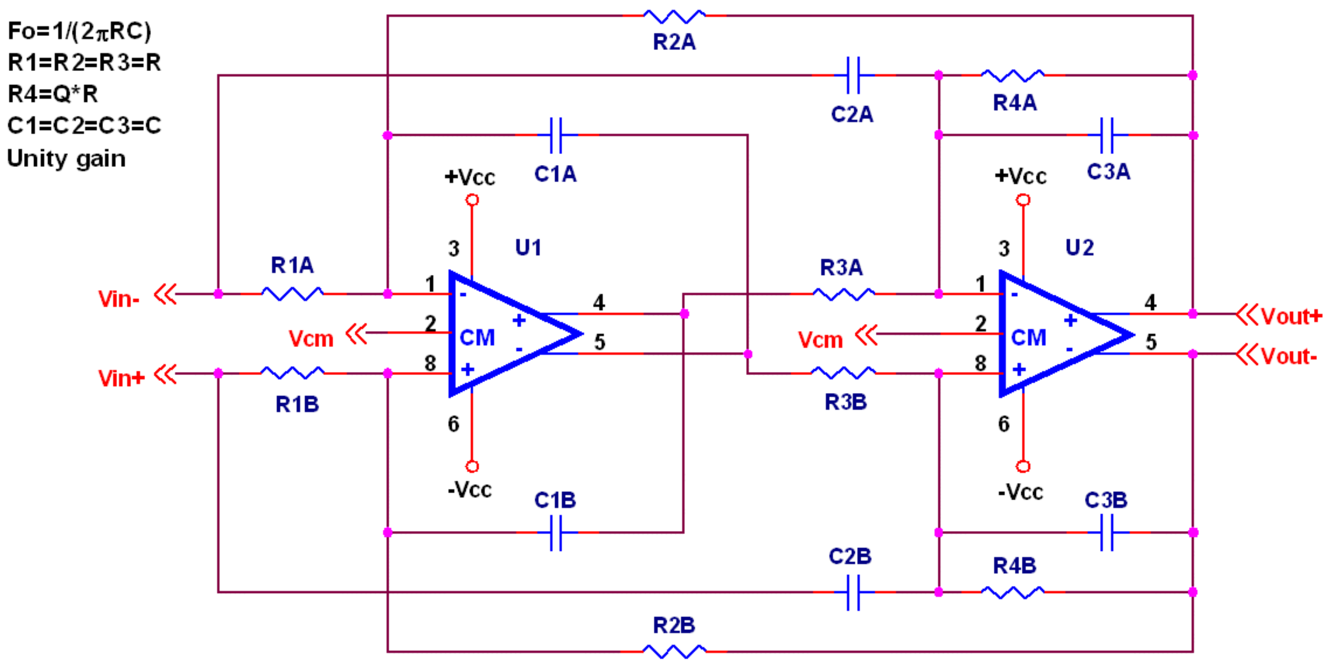

Figure 10. Differential Notch Filter

A very common question that repeatedly comes up is how to reject 60 Hz. Differential data transmission should eliminate it, but if not, the following circuit can be used:

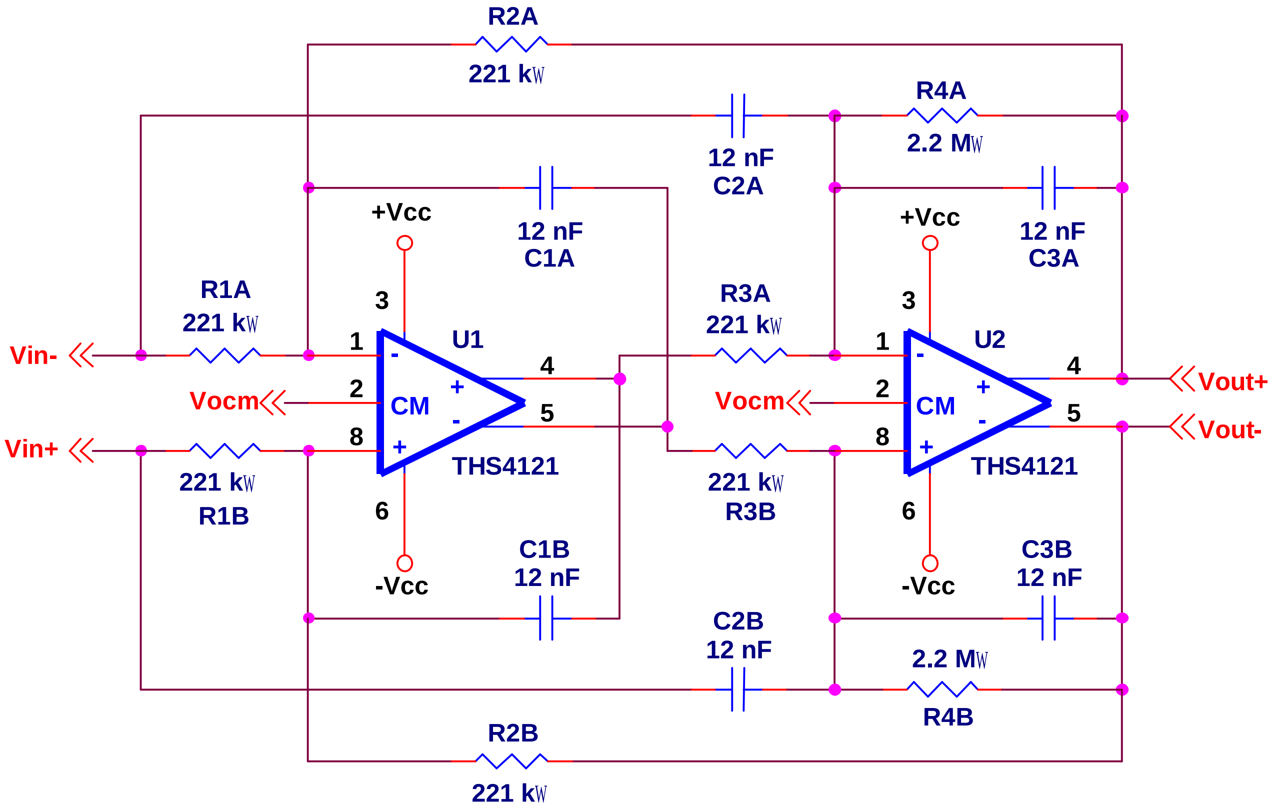

Figure 11. 60-Hz Notch Filter

3.4 Bandpass Filtering Data

Bandpass filters used for data transmission are never of the high-Q variety, as a broad range of harmonics must be passed. Therefore, the filter should be formed by cascading a high pass filter stage with a low pass filter stage.

4 Conclusions

Filtering data streams involves a knowledge of the harmonic content of the waveform involved. The designer should consider a Bessel filter response, due to its relatively constant group delay characteristics. Low pass filtering is much more destructive to harmonic content than high pass filtering. Notch filtering can be considered for single interfering tones.

5 Reference URLS

1. http://www.jhu.edu/~signals/fourier2/: Fourier series
2. http://www.phy.ntnu.edu.tw/java/sound/fourier/fourier.html: Fourier series
3. http://www.phy.ntnu.edu.tw/java/sound/sound.html: Fourier synthesis demonstration
4. http://www.klmicrowave.com/groupdelay.html: Group delay
5. http://www-ccrma.stanford.edu/~jos/filters/Phase_Delay_Group.html: Group delay

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