

CD&A Active Filters

by Derek Lockhart

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SUBMISSION ID	82965385	CHARACTER COUNT	14938



8th February 2018

An Investigation into Active Filters
and
The Design and Analysis of a
Butterworth Filter System

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1. Abstract

An investigation in to active filter design. Focusing on a bandpass Butterworth active filter a signal will be generated with induced noise. A Butterworth active bandpass filter will be designed to reject the noise signals and pass the desired signal with minimal distortion. Alternative active filter designs discussed, and a comparison made to the Butterworth design.

2. Introduction

This paper shall analyse the properties of active filters, Hickman[1] explains that conventional passive filters using resistors, capacitors and inductors become rather large and expensive, particularly at audio frequencies, mainly due to the physical size of inductors at such low frequencies. Using active filters removes the need to use inductors. Horowitz and Hill[2] expand on this, explaining that inductors in filters tend to have range of undesirable qualities including resistance and magnetic pickup that will interfere with the filters design as well as being cumbersome large at the audio frequencies.

3. Problem

Minoru et al [3] describes that all signals during transmission collect noise that that will affix to the transmitted signal. Meng et al [4] state that should this noise rise to a significant level with respect to the desired signal then corruption will occur. These errors can be corrected by error correction techniques, however, as Gao et al explain [5] this can be greatly aided by filtering out noise before demodulation. In this example we shall be removing two noise source signals from a desired signal, one above the desired frequency and one below.

4. Solution

The inclusion of two noise source frequencies, one above and one below, the desired frequency necessitates the use of an active bandpass filter. Several designs for active filters are available to use, this paper shall consider the Butterworth filter. As described by Zeng and Allred [6], the Butterworth filter is designed such that it will have minimal ripples in the pass band with an acceptable level of ripples at the transition (Gibbs Phenomenon). This is a compromise choice which has less Gibbs ripple than a Chebyshev filter [7] and a better roll-off rate than the Bessel filter design [8].

Given that the requirement in this case is for a bandpass filter, a single stage will be insufficient for the task, both a high pass filter (HPF) and a low pass filter (LPF) will be required to make the bandpass filter (BPF).

In its simplest form, an active filter uses an Op-amp to amplify the output of a simple RC filter [9], and are predominately used in the audio frequency range. The Butterworth design used in this example is capable of a roll-off rate of 20dB/Decade per pole [10]. Floyd and Buchla [11] define a pole as the number of simple RC filters used that allow signals to bypass the op-amp to ground. Each pole that is added improves the roll-off of the active filter and therefore its performance.

5. Method

This task is to recover a 64kHz signal from a mixed signal that contains two noise frequencies of 16kHz and 115kHz, all signals shall be at $0.2V_{rms}$. The Proteus signal generators used for the noise signals are not set by V_{rms}

therefore: $V_{rms} = \frac{1}{\sqrt{2}} * V_{peak}$ $V_{rms} = 0.707 * V_{peak}$ $V_{rms} / 0.707 = V_{peak}$
 $0.2V_{rms} / 0.707 = 0.282V_{peak} = 0.564V_{peak\ to\ peak}$

5.1 Predicted noise and signal

The individual signals and the predicted complex waveform that they will produce when added are shown below in Figures 1-4.

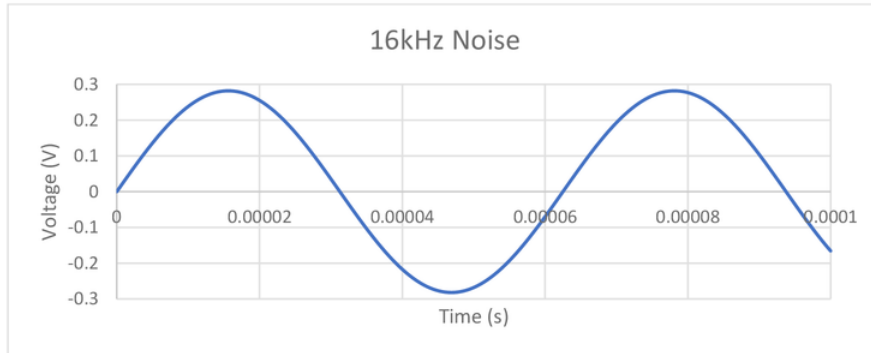


Figure 1 16kHz Noise signal

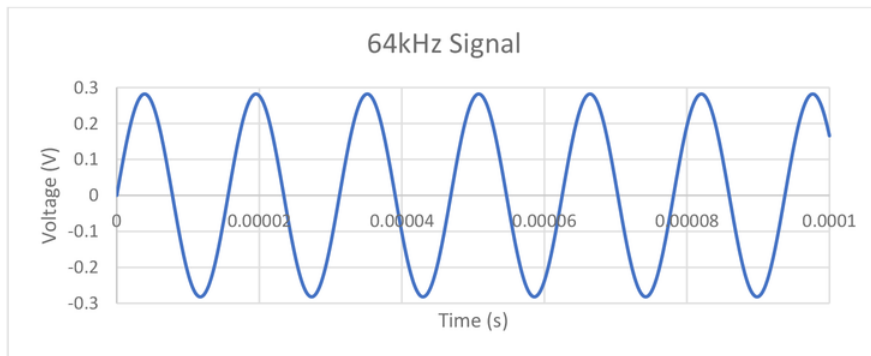


Figure 2 64kHz Desired signal

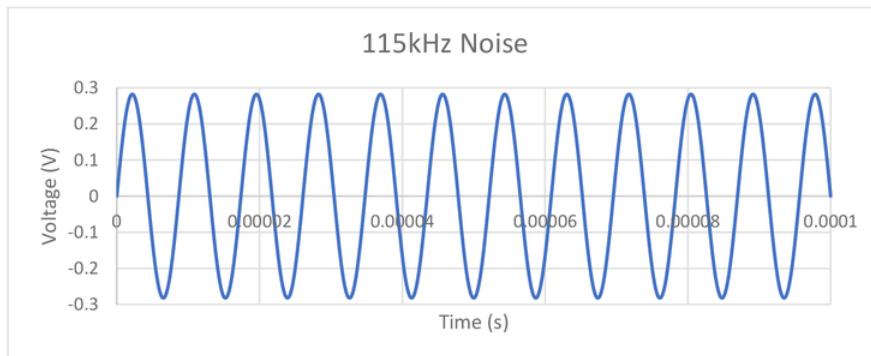


Figure 3 115kHz Noise signal

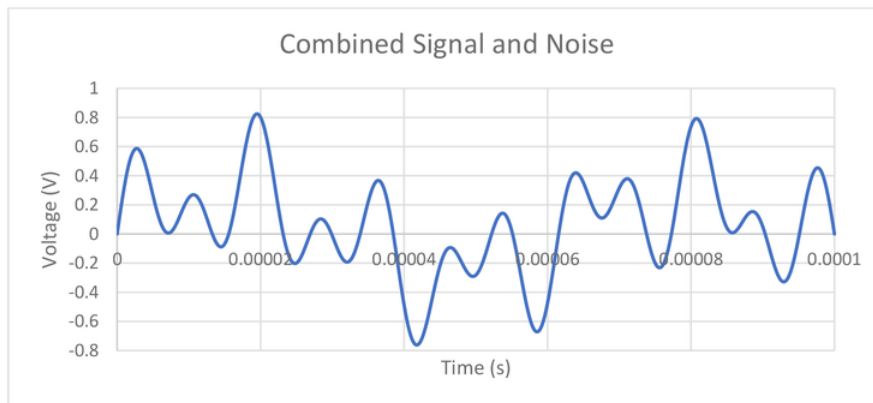


Figure 4 Combined waveform of desired signal plus noise

5.2 Proteus signal generation

The Proteus signal generation setup is shown below in figure 5. It can be seen that V1 and V2 noise generators are set to $0.564V_{\text{peak to peak}}$ and the 64k signal has been set to $200mV_{\text{rms}}$.

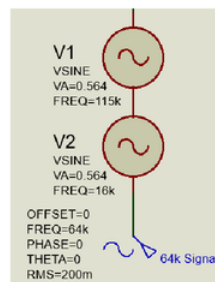


Figure 5 Proteus signal generation

The signals generated by this circuit are shown below in figure 6. It can be seen that they are identical to the predicted values and form previously shown in figures 1-4.

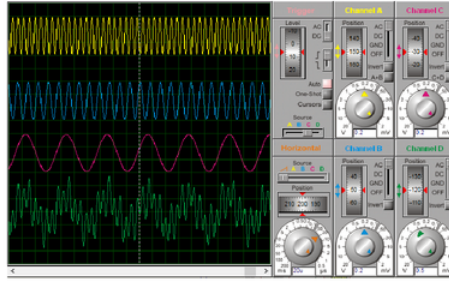


Figure 6 Generated signal waveforms

Channel A (Yellow Trace) shows the 115kHz noise signal. Channel B (Blue Trace) shows the 64kHz wanted signal. Channel C (Pink Trace) shows the 16kHz noise signal. Channel D (Green Trace) shows the combined signal.

5.3 Filter Calculations

To meet the requirement to recover the 64kHz signal and reject both the low and high frequency noise signals a BPF shall be used, to create this we shall use a LPF to reject the high frequency noise, and similarly, use a HPF to reject the low frequency noise.

5.3.1 LPF

The individual filters require a cut-off frequency to be calculated, this cut-off frequency needs to lie between the high frequency noise at 115kHz and the wanted signal at 64kHz, Chen et al[12] define the geometric centre frequency as the mathematical midpoint between two frequencies and is calculated as follows:

$$F_{Geo} = \frac{F_1 + F_2}{2} \quad F_{Geo} = \frac{64\text{kHz} + 115\text{kHz}}{2} = \frac{179\text{kHz}}{2} = 89.5\text{kHz}$$

Mandal and Modal [13] define a filter cut-off frequency as the point at which the filter reduces the signal level by 3dB. Therefore, the LPF cut-off frequency of 89.5kHz will create a 3dB reduction in signal level by this frequency point,

the Butterworth filter design will continue to roll-off at 20dB per decade per poll and all frequencies beyond this point.

5.3.2 HPF

The geometric centre is the of the HPF is calculated in a similar way as shown below:

$$F_{\text{centre}} = \frac{F_1 + F_2}{2} \quad F_{\text{centre}} = \frac{16\text{kHz} + 64\text{kHz}}{2} \quad \frac{80\text{kHz}}{2} = 40\text{kHz}$$

Again, this means that the Butterworth filter will produce a 3dB reduction in signal level by this frequency point and continue to roll-off at 20dB per decade per poll at all frequencies below this point, this also equates to 6dB per octave[11].

5.4 Gain

Figure 7 below, shows the Butterworth filter in a high pass configuration, the gain of the circuit is calculated using the equation

$$A_f = 1 + (R_f/R_1)$$

In the circuit in Figure 7 the gain would be calculated as

$$A_f = 1 + (R_{38}/R_{37})$$

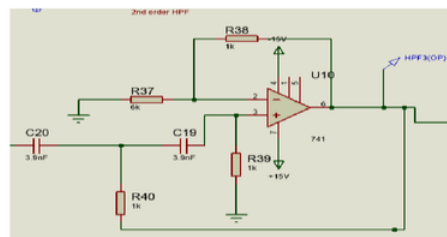


Figure 7 2nd Order Butterworth high pass filter

It can therefore be seen that the minimum gain of the Butterworth active filter in the passband will always be greater or equal to one[14], due to the multiple stages that will be used then the overall gain of the circuit could quickly increase beyond desire and should be managed more strictly as the number of stages grow.

In this circuit the gain shall initially be kept low and then adjusted in the latter stages to keep the system output within reason.

5.5 Component Selection

The ideal cut off frequencies of 40kHz and 89.5kHz may not be perfectly achievable with real world components therefore a compromise must be reached with what is economically possible.

The cut off frequency is calculated using a transposition of the equation

$$f_{\text{cutoff}} = \frac{1}{2 \times \pi \times RC}$$

Picking a reasonable value for a capacitor at 3.9nF gives a resistor value of 456Ω for the LPF, the closest common resistor value is 470Ω. Using these common component values will adjust the cut-off frequency to 86.827kHz. The ideal resistor value of 456Ω could be made using multiple smaller resistors, e.g. 390Ω+56Ω+10Ω=456Ω, in this case 470Ω will suffice.

Using the same capacitor value for the HPF gives a resistor value of 1020Ω, the closest common value of 1kΩ gives a cut-off of 40.808kHz. It should be noted that some sources suggest using minimum resistor values of 1kΩ - 10kΩ[15][16].

Using the calculated figures, a Butterworth active filter circuit was designed and is shown below in figure 8.

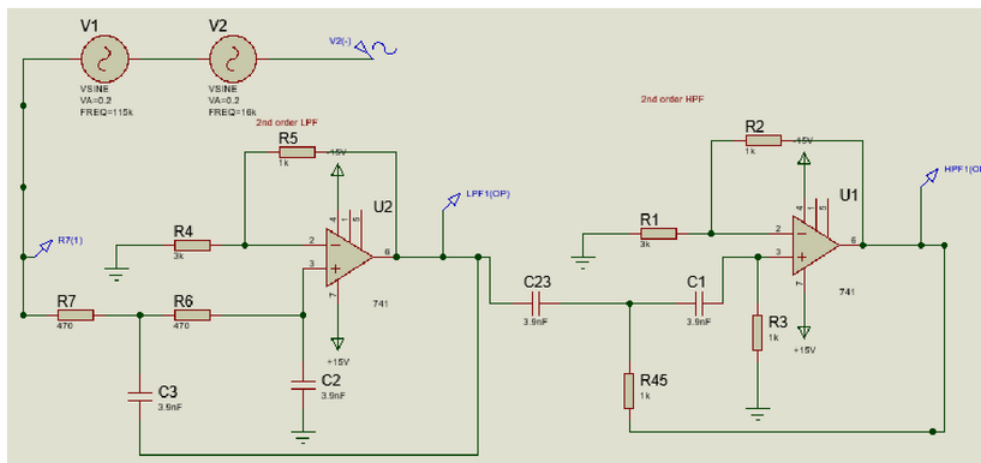


Figure 8 4th Order Butterworth bandpass filter

5.6 LPF Development

The response of this circuit is shown below in Figure 9

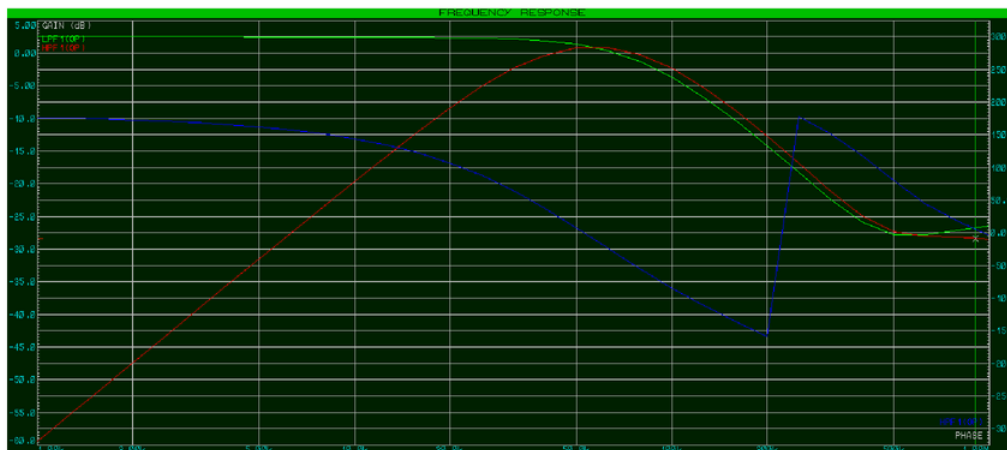


Figure 9 Butterworth bandpass filter response

It can be seen in Figure 9 above that the output of the LPF (Green Trace) passes a point -3dB from the peak level at approximately 85kHz, this follows the theoretical calculated cut-off.

The blue trace in figure 9 shows the phase response of the Butterworth filter that can be seen to be non-linear, this is typical of the Butterworth filter and again falls between the responses of the Chebyshev and Bessel filters[17].

The slope of this trace can be measured as rolling off at 10.53dB in the octave between 100kHz and 200kHz.

The 115kHz signal can be seen to be rejected, although it is not at small enough level to meet the specification of -30dB, the 115kHz signal can be measured at -5.75dB with respect to (wrt) the desired 64kHz signal.

The combined output shown in Figure 7 (Red Trace) shows the output from the HPF rejecting the 16kHz noise signal by 12.4dB wrt the wanted 64kHz signal.

Therefore, it shall require multiple stages of both LPF's and HPF's to meet the -30dB specification for the rejection of the noise signals.

It can also be seen that the combined output is at a higher than the LPF output by 1.3dB due to the gain of the HPF, again this is due to the gain of the Butterworth filters in use being greater than 1.

Using replica LPF's the circuit was extended and repeatedly tested to demonstrate the number of orders required to meet the -30dB specification.

Figure 10 below shows the output.

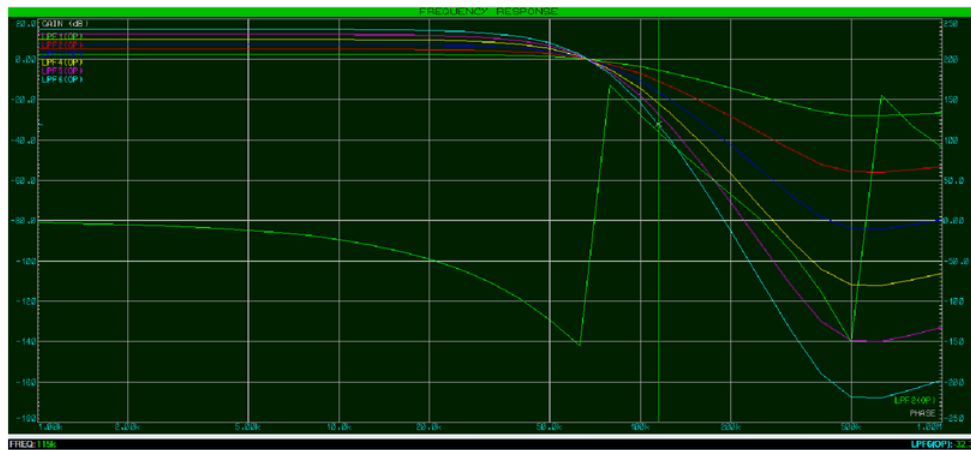


Figure 10 Response of multiple Low Pass Filter stages

Misplaced apos.

Six second order LPF's, a 12th order filter, bring the noise rejection to -32.3dB, this -32.3dB rejection exceeds the design specification. To ascertain if the specification can be met with an 11th order filter, the final stage can have a single pole removed to make it a 1st order active filter. The new output is shown below in figure 11.

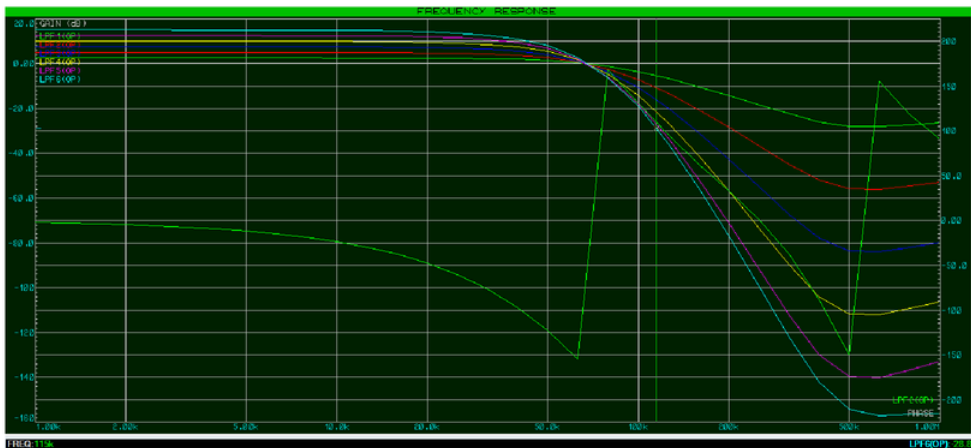


Figure 11 Response of 11th order Low Pass Filter

It can be seen that the 11th order filter does not meet the specification and the 12th order LPF will be required.

5.7 HPF Development

The HPF was added to the system and incrementally extended to find the number of stages and orders required. The outputs are shown below in figure 12.

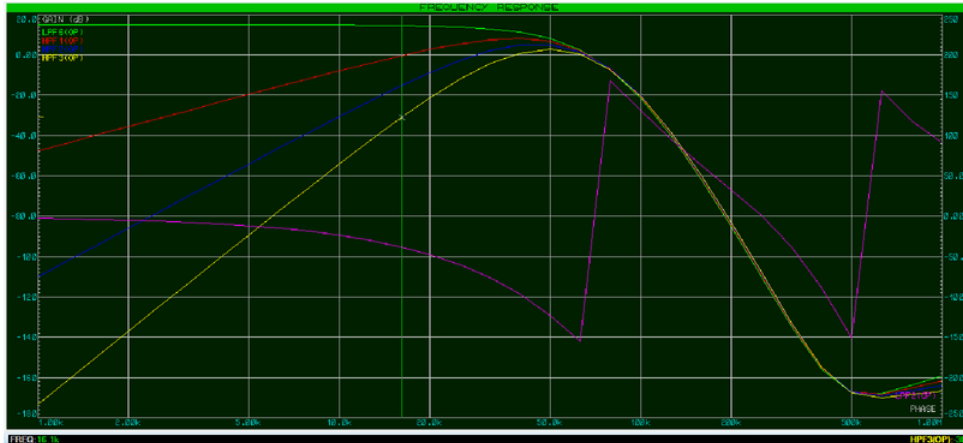


Figure 12 Response of 6th order HPF succeeding 12th order LPF

It can be seen from figure 12 that the noise signal is rejected by greater than 30dB after only 3 stages of 2nd order HPF's. It must be noted that the signal only just meets this specification and therefore an extra stage could be considered to allow some tolerance.

An extra stage was added, and the output shown in figure 13 below.

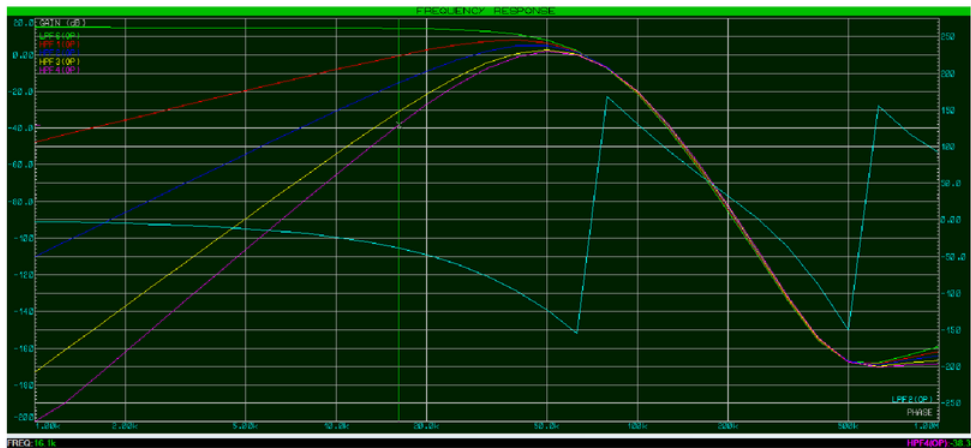


Figure 13 Response of 7th order HPF succeeding 12th order LPF

5.8 Overall System

With the design specification met of rejecting both the high and low frequency noise signals to -30dB met.

The gain of the overall system could now be adjusted to provide a zero gain/loss level of 0dB wrt the system input, however, as can be seen in figure 13, the added gain of the HPF stage has increased the level of the 115kHz noise signal to above the -30dB mark. This could be corrected by adjusting the gain of the Op-amp, though this would also affect the signal level of the 64kHz signal. Therefore, an extra single stage was added to the LPF to correct this change. The new output spectrum is shown below in figure 14.

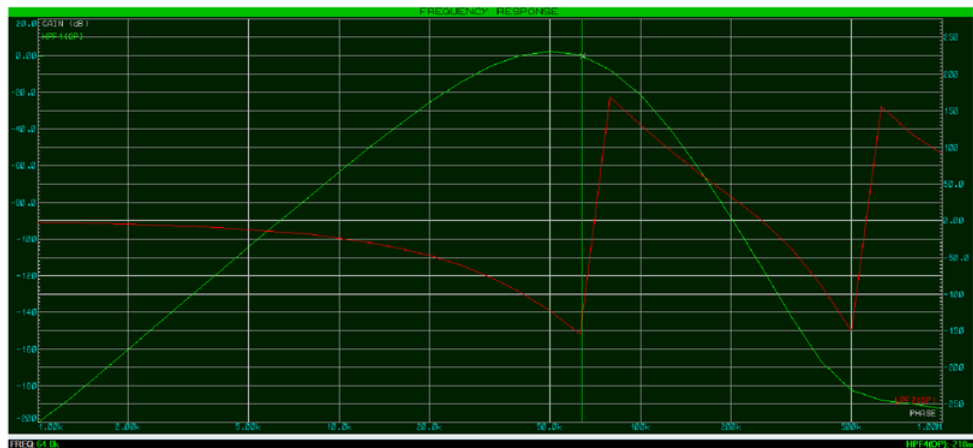


Figure 14 response of completed Bandpass filter

The completed Butterworth bandpass active filter circuit can be seen below in figure 15.

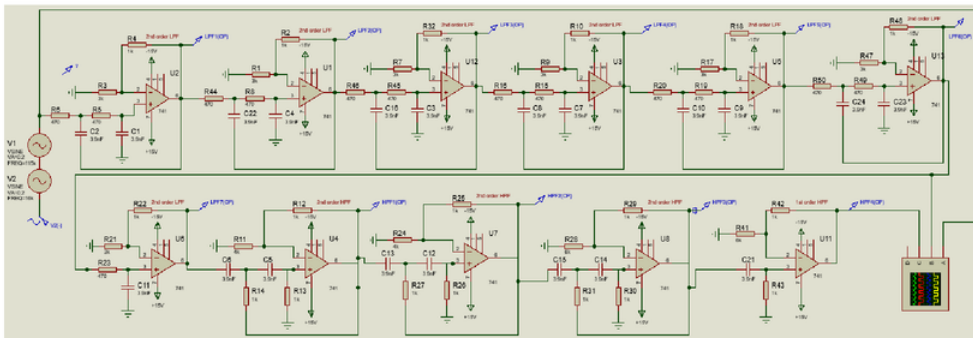


Figure 15 Completed Butterworth bandpass filter

The output of the completed circuit can be seen in figure 16 along with the input waveform for comparison.

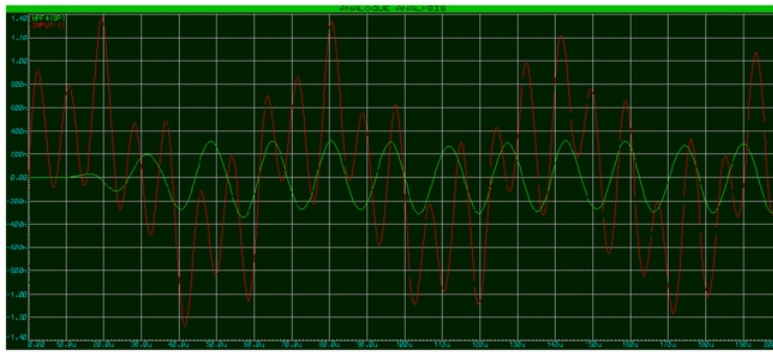


Figure 16 Comparison of filter input and output

The recovered 64kHz signal shows to be stable and without distortion within 100 μ s of start-up.

A simulated digital oscilloscope was also used to compare the input and output waveforms along with the output waveform from the LPF only, this is shown in figure 17 below.

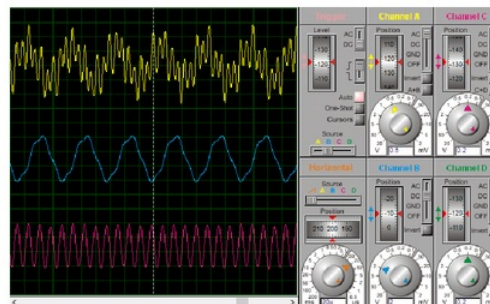


Figure 17 Comparison of input, midpoint and output waveforms

It can be seen from this display that after the LPF (Blue Trace) the output is of a greater magnitude than would otherwise be expected, this is due to the greater gain used in the LPF as opposed to the HPF.

6. Conclusion

The Butterworth filter response is dictated by the components surrounding the op-amp and the RC network poles dictate the cut-off frequency at which rejection takes serious effect. The configuration of the RC components dictates whether each RC network generates a LPF or a HPF. The relative values of the feedback resistors determine the gain of the op-amp and therefore of the circuit. The number of consecutive stages determine the ultimate roll-off rate of stopband signal rejection.

The Butterworth filter design is a compromise to provide a flat pass band and minimal ripple whilst retaining a good roll-off rate, however, due to the proximity in frequency of the high and low pass filters then in this case the flat response in the pass band cannot be observed.

2 The cut-off frequency in this paper was geometrically centred. This was possible since there proved to be a sufficient gap between the desired frequency and the noise frequencies. Should there be insufficient space then the cut-off frequency could have been adjusted, in this case the LPF frequency gap was almost a full octave, should this have been less the cut off could have been nearer to the noise, this would push the desired signal further into the stable region of the pass band, the trade off to this would be the requirement for more filter stages being required to sufficiently attenuate the noise signal.

Should more stages be added to a Butterworth filter, although we are improving response we are also adding gain, in this paper the gain of the circuit was not managed perfectly in the it was found that an excess amount of gain was applied in the LPF that required counteracting in the HPF that followed, this is difficult in a circuit that by design has a minimum gain of 1.

Further it is noted that during research it was found that the recommended values for components in audio filters are of a higher value than those used in this paper.

The phase, roll-off and pass band stability of the Butterworth filter, in all cases, falls between the Chebyshev and Bessel filters, and would seem to be a sensible generic filter choice, particularly for those application that require a stable ripple free passband and transition.

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GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

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Comment 1

Gain?

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Misplaced apos.

Misplaced apostrophe:

An apostrophe can function to indicate a possessive when accompanied by an -s ("the book that belongs to Roy" = "Roy's book"). For words that already have an -s at the end, just adding the apostrophe will do ("the team belonging to the boys" = "the boys' team"). Certain exceptions to this rule apply, and possessive personal pronouns ("like ours," "yours," "hers," "his," "its") are possessive already and therefore do not take an apostrophe. It is always wrong to use a possessive apostrophe to simply make a word plural.

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**Comment 2**

Do you think that choosing the cut-off points of your filters closer to the signal frequency could have reduced the number of filter stages you needed to meet the design specification? - Could you have used less components?

**Comment 3**

that

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DEREK LOCKHART**72.90****RESEARCH-INFORMED LITERATURE**

Excellent selection of source material referenced.
Outstanding knowledge of research-informed
literature embedded in the work.

8.5**KNOWLEDGE AND UNDERSTANDING**

You have shown an excellent knowledge and
understanding of the main concepts and key
theories.

18.75

ANALYSIS



Sound, logical, analytical thinking; synthesis and evaluation. You mentioned the phase of the signal in the pass-band but not any implications this may have on a wider scale. On the whole a very good piece of work.

20.4

PRACTICAL APPLICATION AND DEP.



A good application of the common methods. Would have liked a more visual

16.25

SKILLS FOR PROFESSIONAL PRAC.



Can communicate with an exceptionally high level of professionalism. Work is exceptionally coherent, very fluent and is presented professionally.

9