

Butterworth Filter Design

by Nathan Davies

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Butterworth Filter Design

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Abstract



The circuit created in this assignment was an active Butterworth bandpass filter which from the specification was to have a low cutoff frequency of 35KHz, a high cutoff frequency of 170KHz and a wanted signal of 61KHz. This report contains the method and results found during the research and creation of the circuit which in the end achieved the specification of creating an active filter that has a low and high cutoff frequency at -30dB and to not use the normal Sallen & Key method to achieve this goal.

Introduction

The aim of the assignment was to create an active filter that would be capable of removing noise from a noise corrupted signal on Proteus. The signal would be comprised of three sinusoidal waves: a high frequency, a low frequency and a wanted signal. These frequencies were to be taken from my student number which is 1706135 these frequencies were required to have an amplitude of 0.2Vrms and have the same starting phase. The final filtered signal is required to demonstrate at least a 30dB reduction at the high and low frequencies. The second requirement for this assignment was to not use a Sallen & Key topology but to research other types of active filters to use in the creation of the filter.

Filters and topologies

Filters are a type of circuit that are used normally in signal analysis to remove or reduce the amount of noise in a noise corrupted filter for example radio stations use these filters to remove useful analogue data such as a presenter's voice or music from a carrier wave, or to remove unwanted sound in the form of noise from the wave [1]. This unwanted noise comes from multiple of places such as within the circuit or from natural noise as it's travelling through the atmosphere.

There are two main types of filters used which are passive and active. Passive filters are linear circuits that use resistors, capacitors and inductors they are called passive filters because they don't contain any active components within the circuit [2]. The way passive filters work is that inductors block the high frequency signal while the capacitors block the low frequency signal the number of these components within the circuit determines the order of the filter [2].

Active Filters are analogue circuits that use active components to filter out unwanted noise. Normally the active component they use is an opamp (operational amplifier) of which the 741 opamp is typically used [1]. This component replaces the use of inductors as a cheaper and more precise component. The type of filter used in this assignment is an active filter this is because it is more precise than a passive filter and more parameters can be changed easily while keeping the same values such as the Q value and the gain of the circuit [1].

There are three subtypes of filters that can be used to remove unwanted noise from a signal these three are called High Pass, Low Pass and Band Pass filters. These different subtypes of filters determine what frequencies are allowed through and which ones are blocked. For the spec of the assignment one of the requirements was to create a filter that was not of a Sallen & Key topology. Through research it was found that a Butterworth filter uses only 2 resistors and two capacitors in its design this is shown on the next couple of pages where more in-depth research into the different filter subtypes is done.

Low Pass

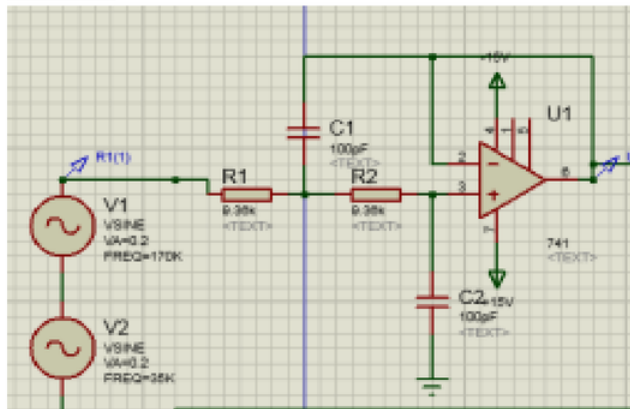


Figure 1 a Butterworth Low pass filter

The screenshot above shows a Butterworth low pass filter. A low pass is a type of filter that filters out all the high frequencies and only allows low frequencies through up to a determined cutoff frequency. As can be seen in the screenshot the circuit is made up of two resistors and two capacitors and an opamp [5]. As the signal from V1 and V2 enters the circuit it passes through the resistors which control the gain of the wave then through the capacitors which are set to specific values to allow frequencies up to 170KHz to pass through and to block any higher frequencies.

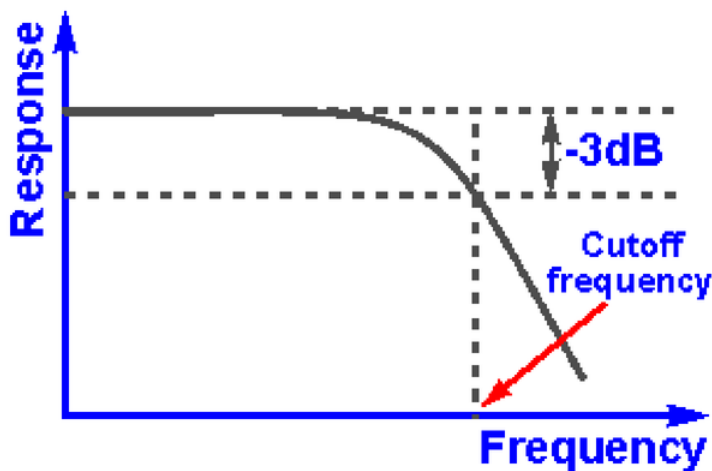


Figure 2 typical output for a Low pass filter [5]

The graph above shows a representation of a typical low pass filter output. As can be seen the filter allows low frequencies through up to a certain point the cutoff frequency then slowly blocking frequencies. This curve that can be seen is the results of the capacitors discharging which means that having no curve in the result is impossible without a perfect filter.

High Pass

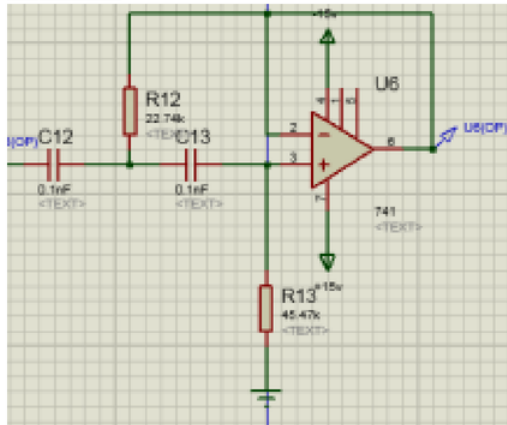


Figure 3 a Butterworth High pass filter

The screenshot above shows the opposite of a low pass filter which is a high pass filter. A high pass is a type of filter that filters out all the low frequencies and only allows high frequencies through up to a determined cutoff frequency [4]. As can be seen above the circuit is similar to a low pass in architecture, containing two resistors and two capacitors but the orientation of the components has switched. As the signal from V1 and V2 enters the circuit it passes through the capacitors which control gain within the circuit then through the resistors which are set to specific values to begin allowing frequencies through at around 35KHz and block off any frequencies below this cutoff point.

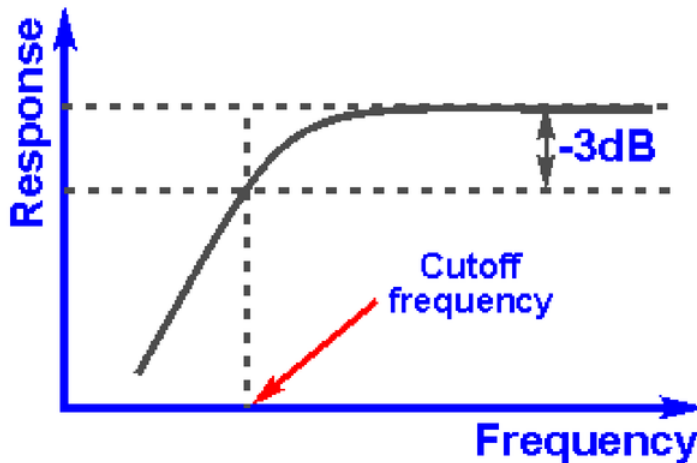


Figure 4 typical output for a High pass filter [4]

The graph above shows a representation of a typical high pass filter output. As can be seen the filter blocks off low frequencies up to a point the cutoff frequency then slowly allowing high frequencies through until the gain is equal to 0. If the filter in use was a perfect filter there would be no curve present in the graph and the graphs response would be an almost straight line on the cutoff frequency.

Band Pass

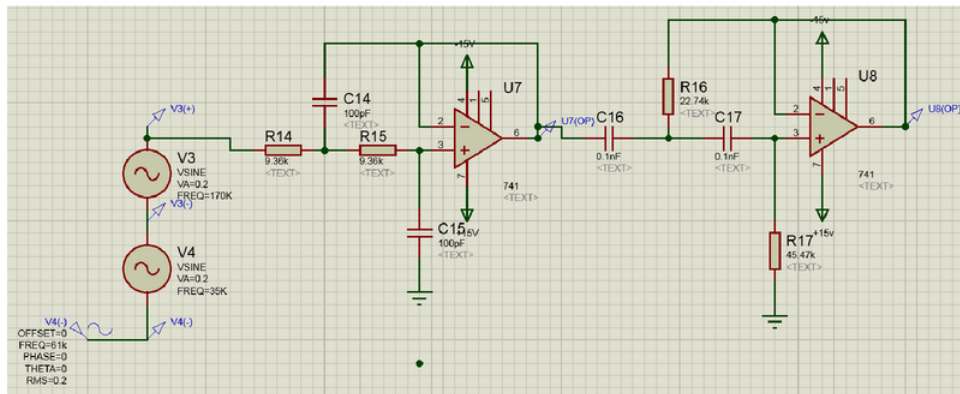


Figure 5 a Butterworth Bandpass filter

The screenshot above shows a Butterworth bandpass filter. A band pass filter is a combination of a low pass filter and a high pass filter to create a filter that cuts off frequencies around a certain frequency. These cutoff frequencies are determined by the cutoff frequencies of the low and high pass filters, with the high pass being the low cutoff and the low pass being the high cutoff point. As the signal from V1 and V2 comes into the circuit it passes through the lowpass filter allows all frequencies up till a cutoff point this low pass signal then goes through the high pass filter to have the low frequencies removed up until the high passes cutoff frequency.

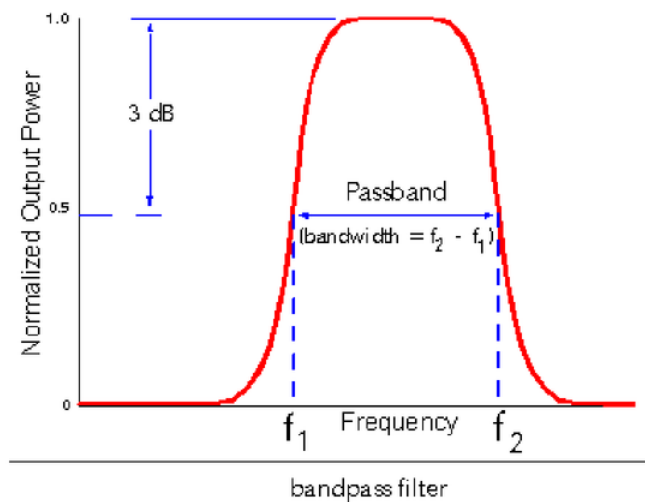


Figure 6 typical output for a band pass filter [6]

The graph above shows a representation of a typical bandpass filter output. As can be seen from the graph above because a bandpass filter is a combination of a lowpass and a high pass filter the graph shows two slopes at near each cutoff frequencies this shows that only a select amount of frequencies is being allowed through the circuit.

Method / Results

This section of the report contains the equations used with in the assignment and the results gathered during the assignment. For the circuit to work correctly and meet the specification of having the cutoff frequencies be at -30dB each a number of each filter had to be added to the final circuit design this number is the order of the circuit, this was found out through trial and error by adding and subtracting filters from the order in the end an 8th order filter was found to give the ideal response. In the assignment brief it stated that the values used for the high, low and wanted frequencies were to be taken from my student number with the student number being 1706135. Below is a table created to show how the student number was broken up and what values corresponded with which frequency.

Frequency Type	Value
High Frequency	170KHz
Wanted Frequency	61KHz
Low Frequency	35KHz

High Pass filter

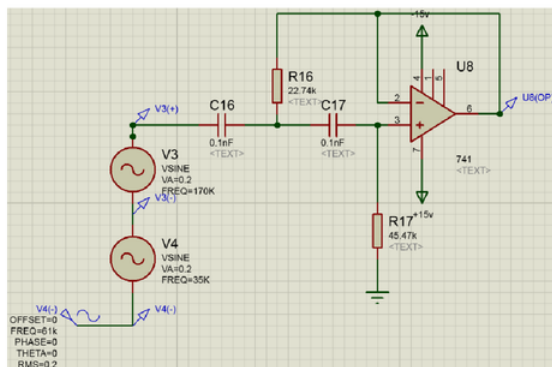


Figure 7 a Butterworth High pass filter

Above shows a picture of a working Butterworth high pass filter created in Proteus. This was created by first researching the topology of a Butterworth filter then calculating the values for each component. For the calculations because both the resistor values and capacitor values were unknown it was decided a standard capacitor value was to be picked and the resistor value was to be calculated. The equations used in the calculation of the components is found below:

$$R1 = \frac{1}{2\pi FC}$$

$$R1 = \frac{1}{2\pi \times 35 \times 10^3 \times 0.1 \times 10^{-6}}$$

$$R1 = 45.47284088\Omega$$

$$R1 = 45.47\Omega \text{ to 2.d.p}$$

R1 has been multiplied by 1000 to reduce the amount of filters needed within the circuit so the new value of R1 = 45.47KΩ 2.d.p.

$$R2 = \frac{R1}{2}$$

$$R2 = \frac{45.47284088 \times 10^3}{2}$$

$$R2 = 22.73642044 \times 10^3 \Omega$$

$$R2 = 22.74 \times 10^3 \Omega \text{ to } 2.d.p$$

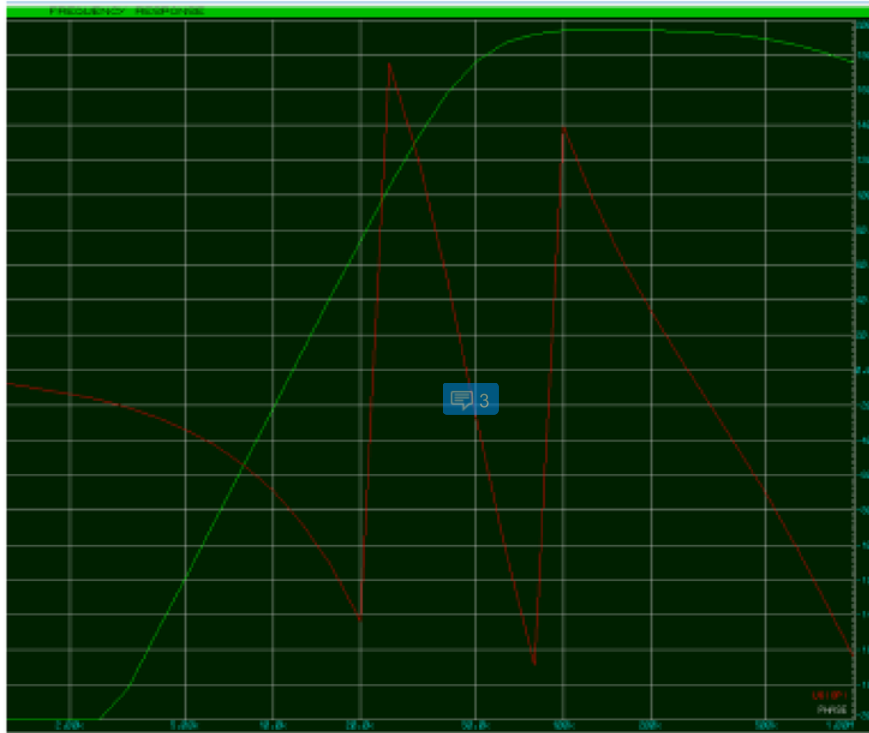


Figure 8 output of the Butterworth High pass

The graph above shows the resultant output of the wave for the high pass filter designed using the calculations. As can be seen it follows the shape of a typical high pass filter found in figure 3. The graph also shows that around the cutoff frequency of 35KHz the slope is around -3dB . The red line on the graph indicates the phase within the graph. As can be seen the phase slowly decreases until 20KHz then sharply rises until it peaks at the cutoff frequency of 35KHz. It then continues this trend of sharply increasing and decreasing until around 100KHz where the phase decreases gradually until the end of the graph

Low Pass Filter

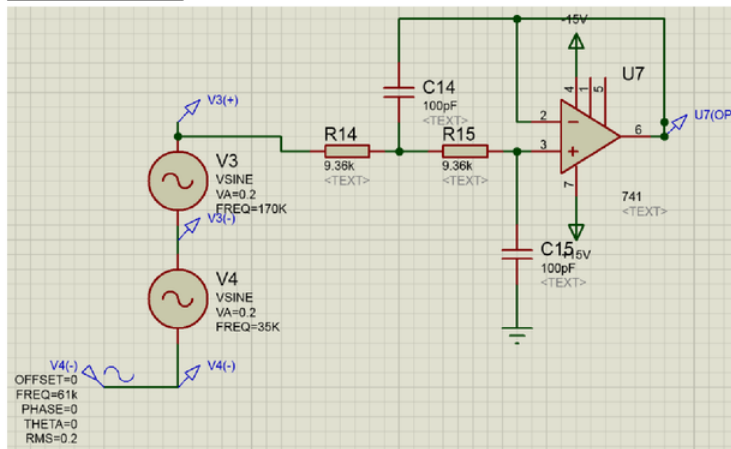


Figure 9 a Butterworth Low pass filter

Above shows a working Butterworth low pass filter created in Proteus. As with the low pass It was created by first researching the topology of the filter then calculating the component values. For this circuit again, all component values were unknown so it was decided that a standard resistor value was to be picked and then the resistor value was to be calculated. Also for this circuit a capacitor value different to the high pass filters capacitor was chosen. The equations used in the calculation of the components can be found below:

$$R1 = \frac{1}{2\pi FC}$$

$$R1 = \frac{1}{2\pi \times 170 \times 10^3 \times 100 \times 10^{-9}}$$

$$R1 = 9.362055476 \times 10^3 \Omega$$

$$R1 = 9.36 \times 10^3 \Omega \text{ to 2.d.p.}$$

R1 has been multiplied by 1000 to reduce the amount of filters needed within the circuit so the new value of R1 = 9.36KΩ to 2.d.p.

$$C2 = \frac{C1}{2}$$

$$C2 = \frac{100 \times 10^{-9}}{2}$$

$$C2 = 50 \times 10^{-9}$$

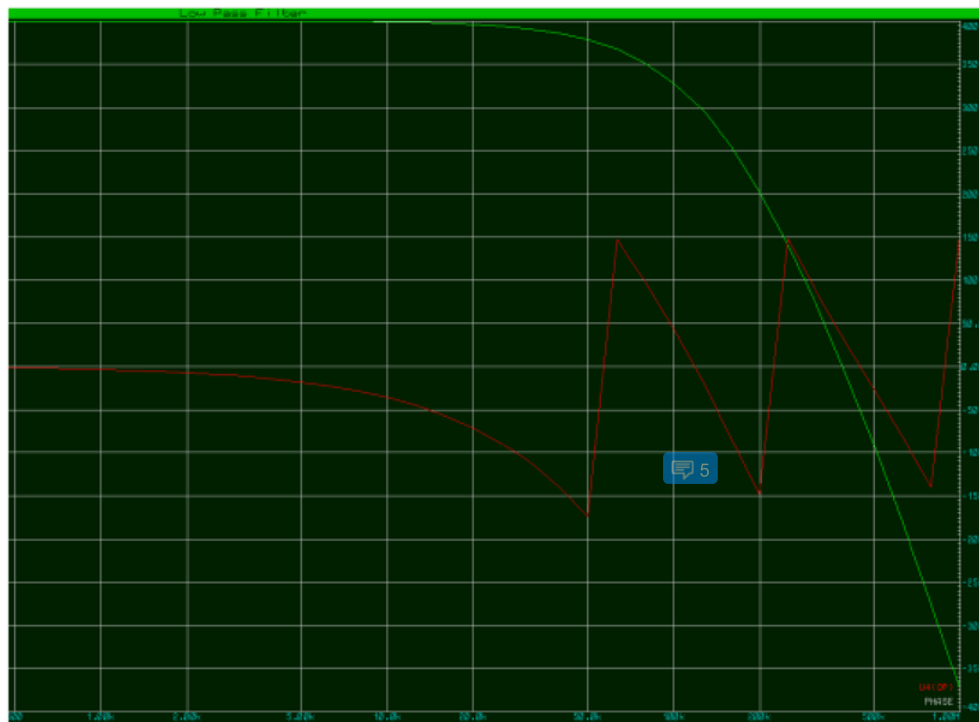


Figure 10 output of the Butterworth Low pass filter

The above graph shows the resultant output of the wave for the Low pass filter designed using the calculations. As can be seen by the graph it follows the shape of a typical low pass filter as can be seen in figure 2. The also shows that the cutoff frequency of 170KHz is around the -3dB mark on the graph this is where the cutoff frequency is supposed to be. Also a red line can be seen on the graph this indicates the phase with in the graph. As can be seen the phase slowly decreases until around 50KHz then sharply rises until it peaks around 61KHz this trend continues onwards until the end of the graph.

Band Pass Filter

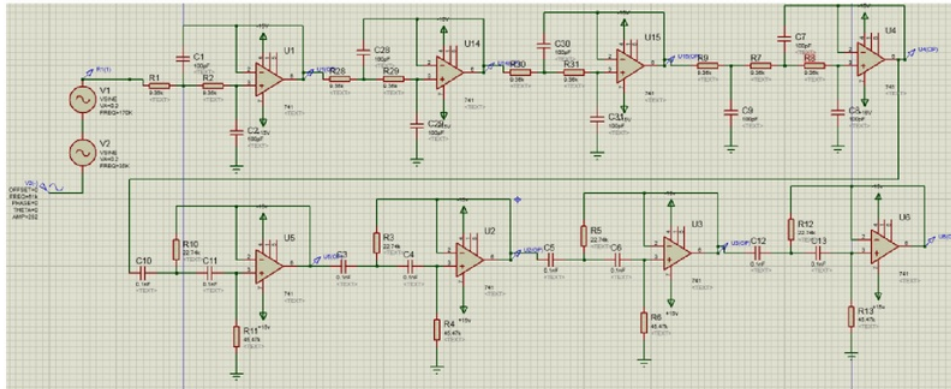


Figure 11 a Butterworth Bandpass filter

Above shows a working Butterworth bandpass filter created in Proteus. As with any bandpass filter, the filter is a combination of a low pass filter and a high pass filter. For this circuit the values for the previous low and high pass filters were used to complete this circuit. The only two equations used in this circuit were to calculate the centre frequency and the bandwidth of the curve these equations can be seen below:

$$f_0 = \sqrt{f_h \times f_l}$$

$$f_0 = \sqrt{170 \times 10^3 \times 35 \times 10^3}$$

$$f_0 = 77.1362431 \times 10^3 \text{ Hz}$$

$$f_0 = 77.14 \text{ KHz to } 2. \text{ d. } 0$$

$$\beta = f_h - f_l$$

$$\beta = 170 \times 10^3 - 35 \times 10^3$$

$$\beta = 135 \times 10^3 \text{ Hz}$$

$$\beta = 135 \text{ KHz}$$

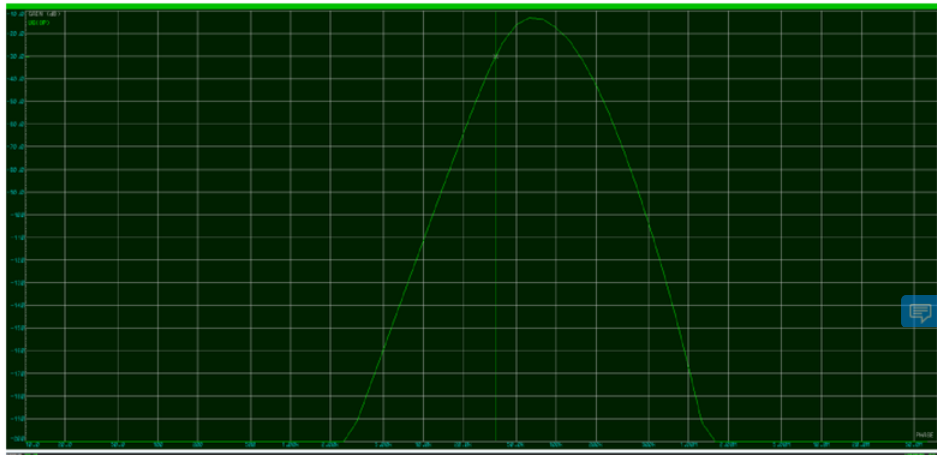


Figure 12 Low cutoff Band pass output

7 Above shows the output wave from the bandpass circuit with the low cutoff values indicated by the green vertical line. As can be seen by the shape of the graph it follows the shape of a typical bandpass filter output found in figure 6. Also seen in this is that the cut off and wanted frequencies of 35KHz and 170KHz are within this curve which shows that the graph is in the correct position.

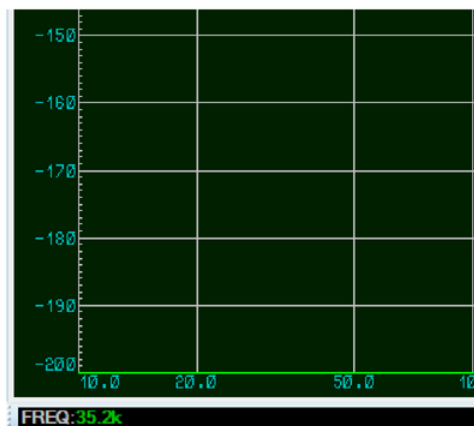


Figure 14 Low cutoff frequency

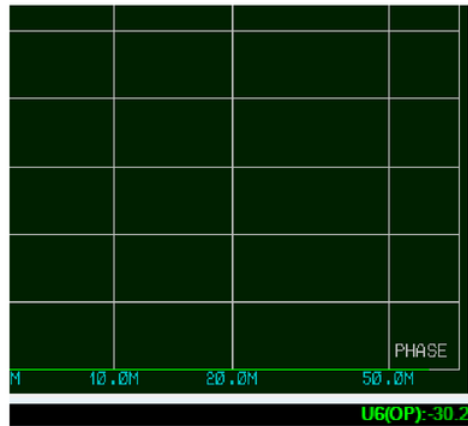


Figure 13 Value of decibels

The two screenshots above show close up of the low cut off frequency value and the value of decibel it is at on the graph. As can be seen from these screenshots the low cutoff value of 35KHz is within the range of 30dB as stated in the spec. This shows that the high pass filter is working correctly and that it meets the specification.

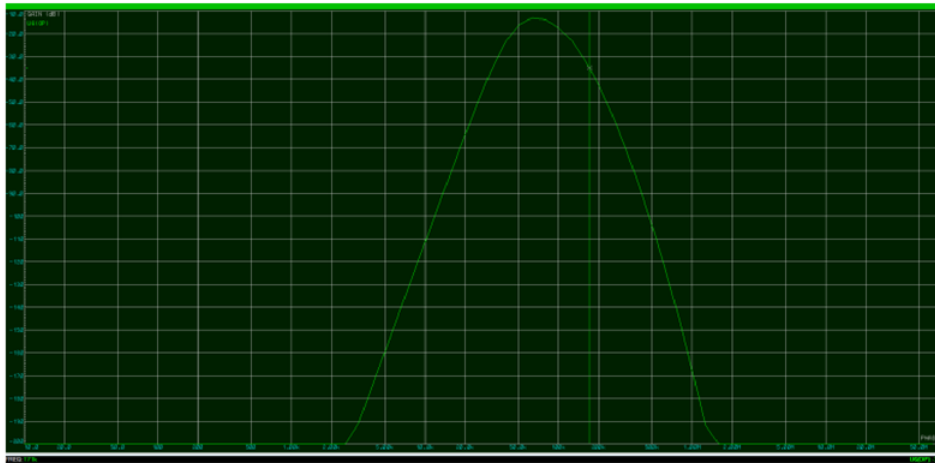


Figure 15 High cutoff Band pass output

The graph above shows the same bandpass filter output but with the high cutoff frequency of 170KHz selected shown by the vertical green line on the graph.

8

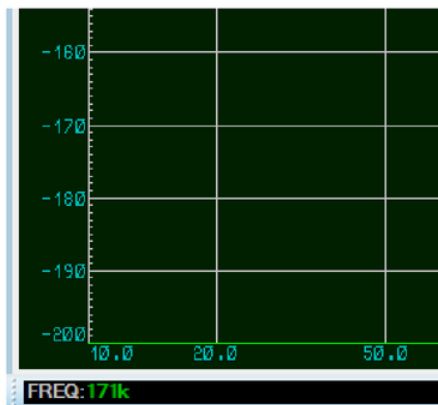


Figure 17 High cutoff frequency

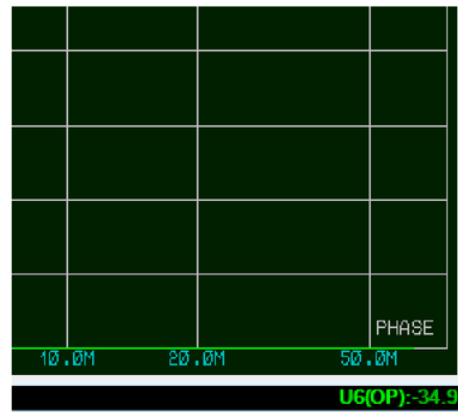


Figure 16 Value of decibels

9

The two screenshots above show close up of the high cutoff frequency and its corresponding decibel value on the graph. As can be seen by these screenshots the high cutoff frequency is about 5 dB more than the required amount specified within the spec. This could probably be resolved by either adding in another 2nd order filter or if that filter reduced it too much add in a 1st order filter.

Analogue Response

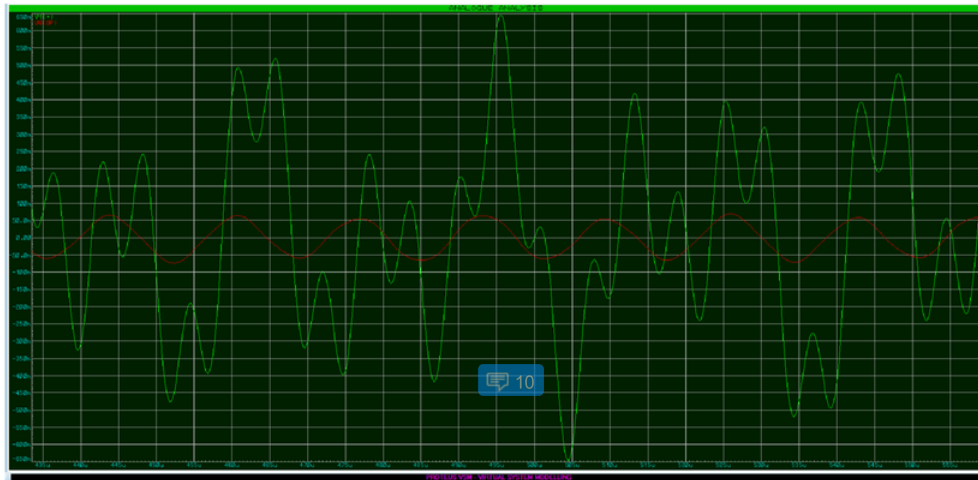


Figure 18 Analogue response input and output

Above is a graph that shows the analogue response of the input signal and the resultant output signal of the bandpass circuit with the green line representing the input and the red line representing the output. As can be seen on the graph the green line has a lot of added noise into it. This is because the input is a combination of three sinusoidal waves which are a high frequency of 170KHz, a low frequency of 35KHz and a wanted signal of 61KHz which induce noise within the wave and causes the different amplitudes within it. The red line as you can see is has no noise in it and perfectly follows the shape of a normal sine wave with constant amplitude. This shows that the bandpass filter is working correctly as it is filtering out noise and is normalising the amplitude to a single value.

Analysis of results

As can be seen from the results from this experiment the overall shape of each filter follows the typical shape of their respective filter and that each of the cutoff frequencies meet the required decibel levels mention in the spec. With the low cutoff being -3dB with in the high pass filter and achieving a -30dB level within the bandpass filter. And the high cutoff frequency achieving a -3dB response within the low pass filter and a -34.9dB response within the bandpass filter.

Conclusion

In conclusion the Butterworth bandpass circuit design and tested in this report performs to what the specification asked for, with the spec being to create a bandpass filter that was not in the sallén & key topology and to have an end cutoff frequency response of -30dB. If the assignment was to be done again it could be done with a different filter topology or by using more 3rd or 2nd order filters within the design.

References

- [1] Wikipedia, "Active Filters," [Online]. Available: https://en.wikipedia.org/wiki/Active_filter.
- [2] L. A. Electronics, "Passive Filters," [Online]. Available: http://www.learnabout-electronics.org/ac_theory/filters81.php.
- [3] Wikipedia, "Butterworth Filter," [Online]. Available: https://en.wikipedia.org/wiki/Butterworth_filter.
- [4] R. Electronics, "Active op amp high pass filter circuit," [Online]. Available: http://www.radio-electronics.com/info/circuits/opamp_high_pass_filter/op_amp_highpassfilter.php.
- [5] R. Electronics, "Active op amp low pass filter," [Online]. Available: http://www.radio-electronics.com/info/circuits/opamp_low_pass_filter/op_amp_lowpassfilter.php.
- [6] s. o. cosmos, "Band pass filter," Songs of cosmos, [Online]. Available: http://www.songsofthecosmos.com/encyclopedia_of_modern_music/B/band-pass_filter.html.

Butterworth Filter Design

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

55/100

PAGE 1

PAGE 2

PAGE 3



Comment 1

These were meant to be the frequency of the noise components corrupting your signal, not the cutoff frequencies of your filter.

PAGE 4

PAGE 5

PAGE 6

PAGE 7



Comment 2

Multiplying a filter component value will not decrease the required filter order, it will only change the cut-off frequency of that filter

PAGE 8



Comment 3

graph axis labels unreadable.

PAGE 9



Comment 4

Capacitor?

PAGE 10



Comment 5

Graph axis labels unreadable

PAGE 11

PAGE 12



Comment 6

graph axis labels unreadable



Comment 7

This line is not visible on the graph

PAGE 13



Comment 8

line not visible on graph



Comment 9

decibels is a unit used to measure many things. You should use gain or attenuation instead.

PAGE 14



Comment 10

output trace and axis labels unreadable

PAGE 15

PAGE 16

GRADING FORM: SMU GENERIC_GJ

NATHAN DAVIES

55

RESEARCH-INFORMED LITERATURE



Inclusion of a wide range of research-informed literature, including sources retrieved independently.

6.5

Very good use of referencing conventions, consistently applied.

KNOWLEDGE AND UNDERSTANDING



Evidence of basic knowledge and understanding of the relevant concepts and underlying principles. You seem to confuse some terminology and omit certain details.

12

ANALYSIS



Evidence of some logical, analytical thinking and synthesis. Valid conclusions if somewhat brief.

15.9

PRACTICAL APPLICATION AND DEP.



A good application of a range of methods, materials, tools and/or techniques. Evidence of some innovation and creativity. It would have been nice to see a more graphical approach to the design of your filters.

15.5

SKILLS FOR PROFESSIONAL PRAC.



"Can communicate effectively in a suitable format, but may have minor errors. Mostly coherent work and is in a suitable structure. Your graphs have let you down as they mostly have unreadable axis labels or illegible traces.

5.1