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by Michael Morgan

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Introduction

The purpose of this assignment is to carry out in depth research into the design of several active filters. These filters will be designed and simulated on a computer-based program to be able to test the different circuits' responses, against a technical specification for each circuit. The results and circuits will be critically analysed, with the use of theory, for their performance characteristics and will be altered in accordance to meet assignment specification. A rounded conclusion stating what was discovered will follow.

Research into filter design

Active filters are used in modern day circuitry to alter the output frequency of a circuit, in relation to the circuits phase or amplitude however, it will not add any new frequencies (Elprocus, 2020). To achieve this, they use a plethora of different electrical components, such as Op Amps, FET, JETS and transistors, in their thousands, set up in various combinations. As more and more technological devices use active filters more research is put into them. They are used to enhance the capabilities of a device while keeping it compact, flexible in its applications compared to other similar devices (Tokyo Institute of Technology, 2006).

Filter can come in different types, band stop, band pass, low and high pass. Low pass filters block out all the higher end frequencies, while only allowing lower frequencies to pass through, much like a sieve. High pass filters allow larger frequencies through and block the finer frequencies.

Low pass filter work on the basis that if a continuously increasing frequency is applied to a circuit, the circuit will have a frequencies attenuation characteristic, as seen in figure 1. They can simply be made, in a 1st order filter, by connecting a resistor and capacitor in series, this does depend on what order the components are connected. Figure 2 shows the set up of low pas filter with the use of resistors in series with capacitors in parallel and an Op Amp

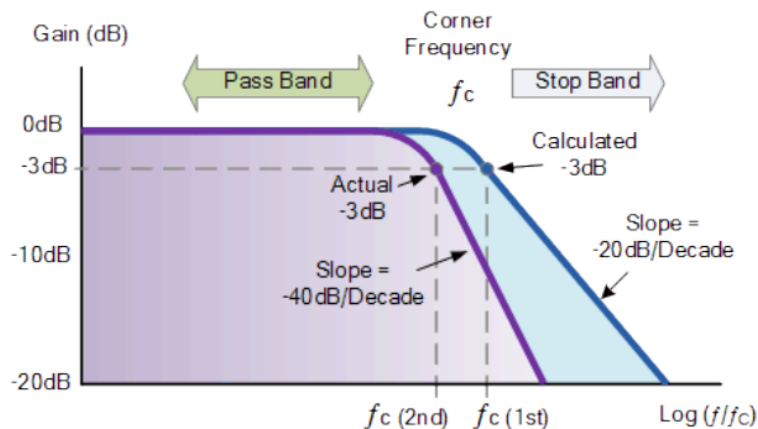


Figure 1: Low pass filter attenuation (Electronic tutorials, 2020)

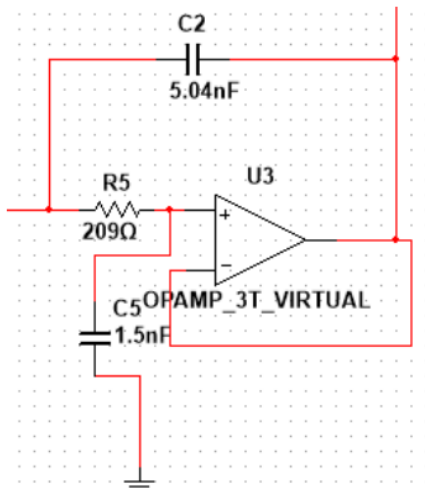


Figure 2: low pass filter configuration

All frequencies can be pass up to a certain point, the cut off frequency, without attenuation, while all the values above are attenuated. A common use of a low pass filter is when rectifiers are used to produce D.C supplies. They introduce a large ripple into the system which is undesirable. Low pass filters are added to smooth out the voltage waveform (J.Bird, 2014).

High pass filters are, as sated before, the opposite of low pass. They allow the desired range above the cut off frequency of a low pass filter to pass through. If a frequency below this is applied to a system, then it will not be allowed to pass. Continually increasing the frequency to above the cur off point and beyond the high pass filter is activated and does not attenuate the frequency anymore. This can be seen in figure 3.

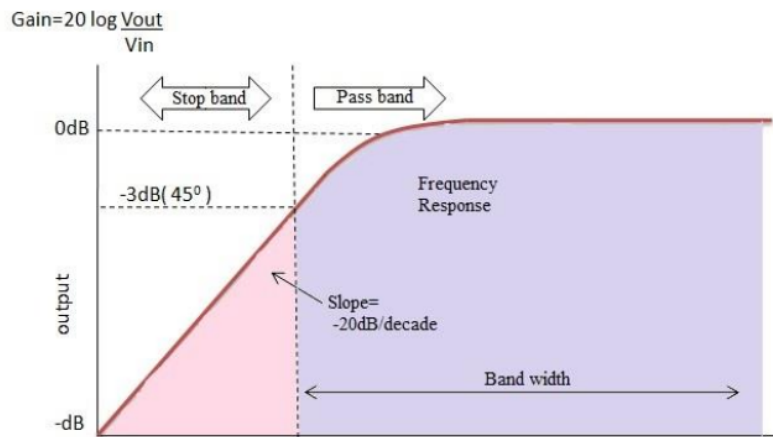


Figure 3: High pass filter attenuation

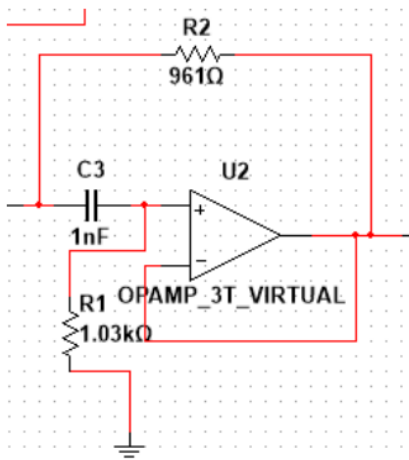


Figure 4: High pass filter configuration

High pass filters are used in audio amplifier applications as coupling capacitors to direct the higher frequencies to a certain type of speaker, while blocking the low end frequencies which will be allowed to pass to other types of speakers (Electronic Tutorials, 2020). Figure 4 shows the configuration, opposite to that of a low pass where the capacitors are in series and resistors in parallel.

There are 3 common types of active filter used in electrical circuits which we must investigate. Butterworth, Chebyshev and Bessel, each filter having its own characteristics and responses. When designing a circuit for filtering there are 3 main considerations, Response, transition between pass and stop and the ability to filter without distortion.

Bessel filters are an analogue linear type of filters which are typically used in radio frequency devices however can be used in audio applications. They are optimised to provide a constant or maximum group or phase delay in a low pass filter band (Electronic Notes, 2020). Due to this they do sacrifice sharpness in their output response and provide a slower transition from low pass to the cut off frequency compared to other filters. However, they provide constant propagation delay, meaning if a certain wave is inputted the output will mimic this with minimal to zero overshoot because all frequencies will be delayed by the same amount (Simon Bramble, 2020). Depending on what order of Bessel filter is used, will depend on the magnitude response of the filter. As you increase the order, the response magnitude increases giving a sharper roll off dB/decade, trending towards zero, seen in figure 5 with minimal ripple equalling less noise.

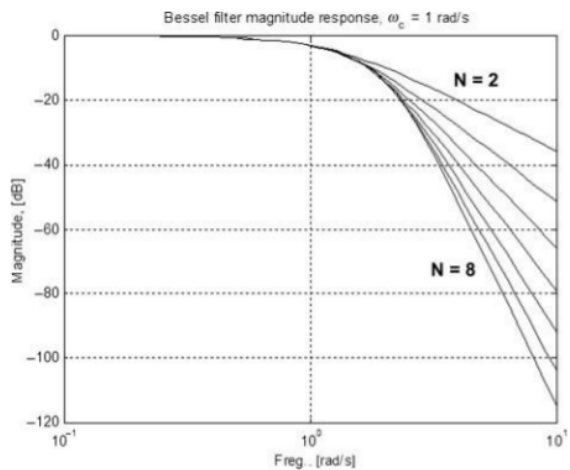


Figure 5: Bessel cut off frequency roll off (Science Direct, 2020)

A Butterworth filter is known as a signal process or conditioning filter, with a key features of a Butterworth filters being its maximal flat response, see figure 5, where it will be as close to 0Hz as possible until the cut off frequency around -3dB. It's roll-off is faster than that of Bessel however not as responsive as Chebyshev. Due to this the butterworth filter is versatile and a good application for audio processing (Simon Bramble, 2020)

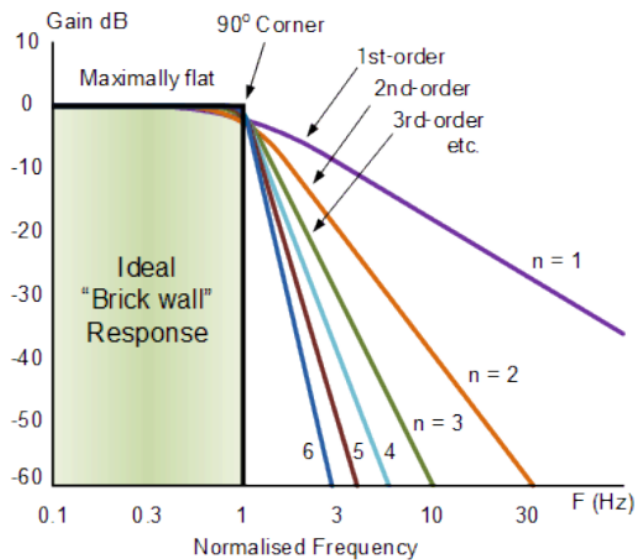


Figure 6: Butterworth filter response (Electronic Tutorials, 2020)

The gain in Db will be stable until the response of the cut off frequency is required. Once again depending on the order of filter will depend on the speed of the response, increase in order will provide a rapider, sharper, response to cut off, trending towards zero. This type of filter also provides an increase in group delay performance and less overshoot. However, this filters idea response in not attainable as it produces an excessive passband ripple (Electronic Tutorials, 2020).

Chebyshev filters are analogue or digital filters used for distinct frequency separation between one band to another, pass and stop. One of its attributes is to reduce the error between the characteristics of the filter and ideal filter. It is also fast roll off due to it being carried out by recursion, calls upon itself, rather than convolution, calling on another function. The cut off frequency occurs when the gain falls to the value of the final ripple (Electronic Notes, 2020). The filter has a steeper roll off dB/Decade compared to that of Bessel and Butterworth, see figure 8. Within the band pass range, the response is rippled, meaning that the gain or dB, changes with frequency. If the ripple in the pass band increases the roll off becomes sharper and vice versa, see figure 7. This then becomes a trade-off between the two depending on what is desired. There are two types of Chebyshev, Type-1 and Type-2. 1- allows the ripple only to occur in the pass band, while 2- Only allows ripple in the stop band (Ele, 2020). These filters are used in numerous applications such as RF conditioning.

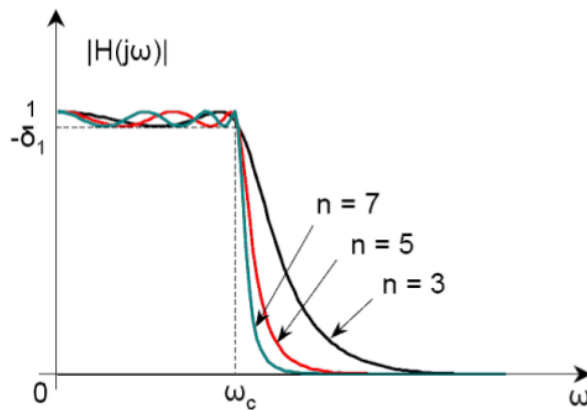


Figure 7: Chebyshev filter response (Reach Gate, 2020)

Each of the 3 filters spoken about has different characteristic, seen in figure 8 which has been spoken about above however they do hold one characteristic between them. Each filter has a 1st stage cut off point with a roll off gradient of 20dB/decade. As you increase the stages e.g. to stage 4, you increase the roll off by 4 to 80dB/decade and so on through the stages. With an increase in order there is a trade off with the amount of gain produced. For Chebyshev the sharpness of the cut off point increases with order increase but it produces larger ripple. Butterworth 2nd order is flatter in the pass band than its first which causes slight distortion.

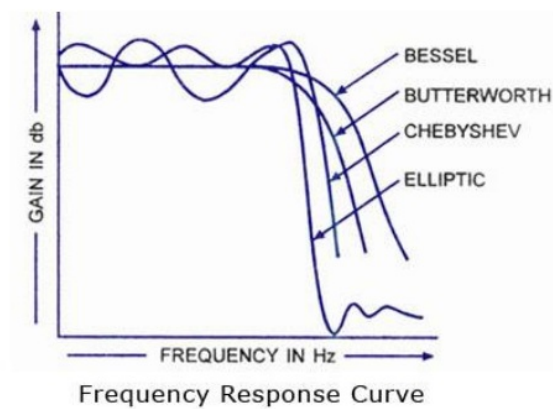


Figure 8: Each filters response curve (Electronics Stack Exchange, 2020)

Filter	Application	Pass band response	Stop Band response	Roll-Off characteristics
Bessel	Audio or radio frequency	Medium gradient, increasing with an increase in order	Flat	Slowest of the 3, increasing with an increase in order
Butterworth	High quality audio, radars, data converting, motion analysis	Maximally Flat	Steady to flat	Sharper than Bessel, and sharper again as you increase in order, not as sharp Chebyshev
Chebyshev	Radio frequency, focusing on signal condition	Rippled	Can be rippled depending on what type	Quickest of the 3, increasing in speed with an increase in order

Figure 9: Comparison table

Figure 9 shows a comparison between the 3 filters investigated. Bessel filters are used in audio applications, with medium gradient response, slightly noisy and slow roll off characteristics, compared to the other two filters. Butterworth filters are used for high quality audio due to their flat pass band, minimal noise distortion and steady to flat roll off response as well as the speed of it. While Chebyshev is used in signal conditioning. Its pass band is rippled however the speed or sharpness of it cut off it's the greatest, meaning it will filter out the frequencies better, but can be rippled if it is type 2. All these filters can be used in a feedback loop system of a control unit. Where feedback is fed into the start of the system, set point, to achieve a steady process value output with minimal distortion.

Design method, choices and calculations

For all of the following 5th order low pass filters filter or the 3 different types of filters, coefficient tables were used to gain values for ai, bi for the 5th order stage (Texas Instruments , 2008).

Bessel 5th order low pass filter.

Stage 1

Frequency= 160 kHz

C1= 1.5nf

$$R_1 = \frac{a_1}{2\pi f_c C_1}$$

$$R1 = \frac{0.6656}{2\pi \times 160k \times 1.5n}$$

R1= 441 Ω

Stage 2

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$

$$\geq \frac{1.5n \times 4 \times 0.4128}{(0.6656)^2} \geq 1.91nF$$

$$C_2 = 1.91nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$

$$R1 = \frac{1.1402 \times 1.91n - \sqrt{(1.1402 \times 1.91n)^2 - 4 \times 0.4128 \times 1.5n \times 1.91n}}{4\pi \times 160k \times 1.5n \times 1.91n} = 359\Omega$$

$$R2 = \frac{1.1402 \times 1.91n + \sqrt{(1.1402 \times 1.91n)^2 - 4 \times 0.4128 \times 1.5n \times 1.91n}}{4\pi \times 160k \times 1.5n \times 1.91n} = 397\Omega$$

Stage 3

$$R1 = \frac{0.6216 \times 5.04n - \sqrt{(0.6216 \times 5.04n)^2 - 4 \times 0.3245 \times 1.5n \times 5.04n}}{4\pi \times 60k \times 2.5n \times 8.4n} = 203\Omega$$

$$R2 = \frac{0.6216 \times 5.04n + \sqrt{(0.6216 \times 5.04n)^2 - 4 \times 0.3245 \times 1.5n \times 5.04n}}{4\pi \times 160k \times 1.5n \times 5.04n} = 209\Omega$$

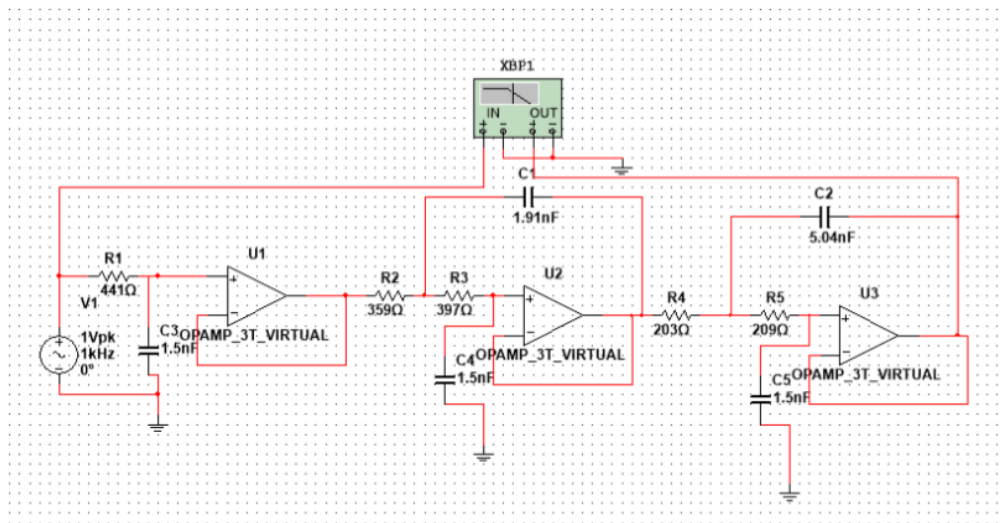


Figure 10: Bessel 5th order

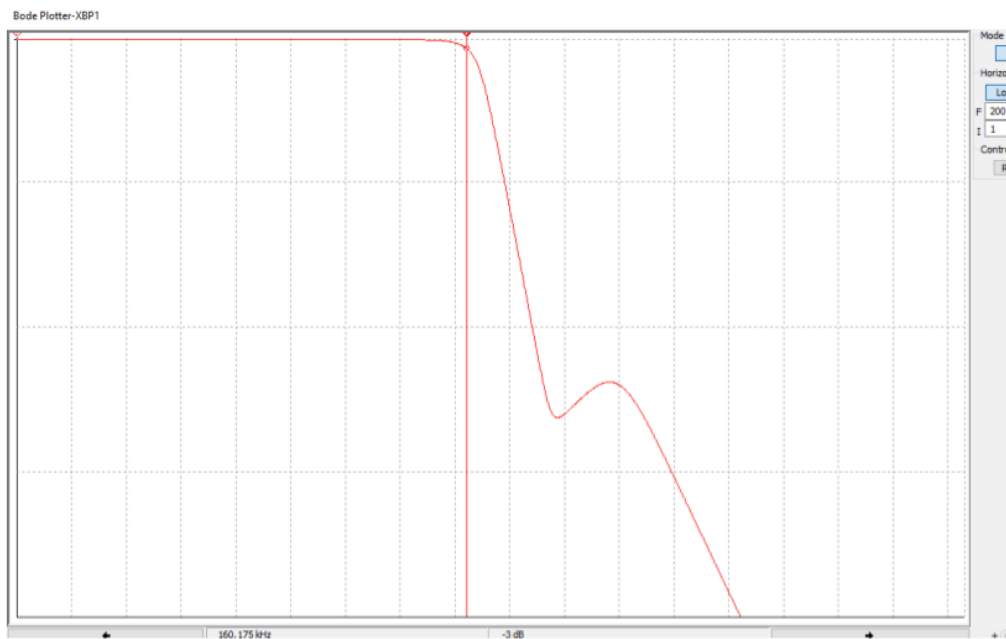


Figure 11: 5th order Bessel cut off frequency

Shows cut-off at -3dB at 160KHz. This is what is expected from the calculated results.

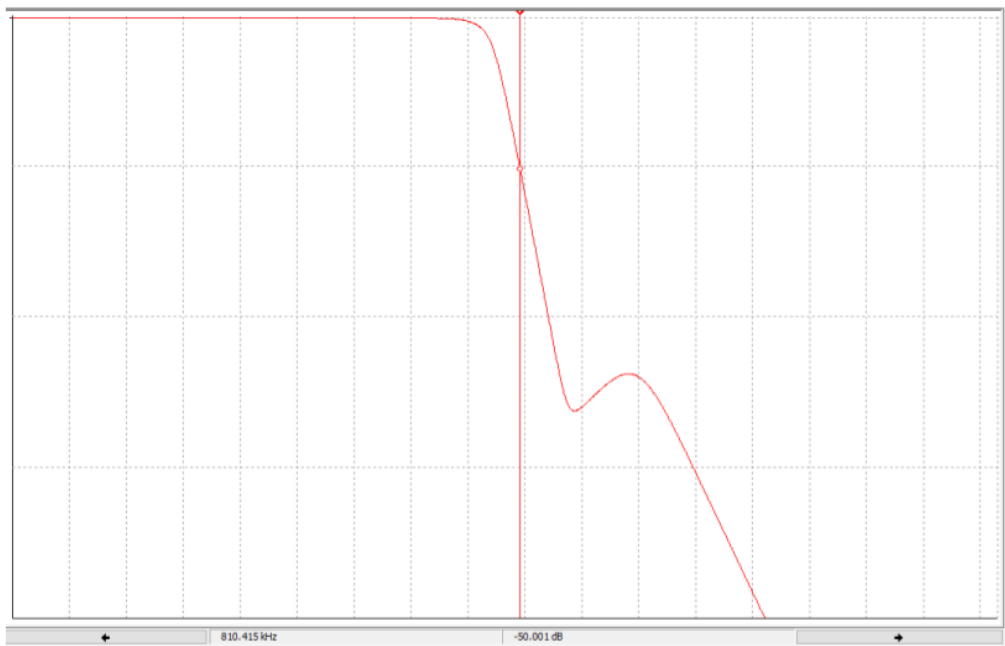


Figure 12: Bessel roll off gradient

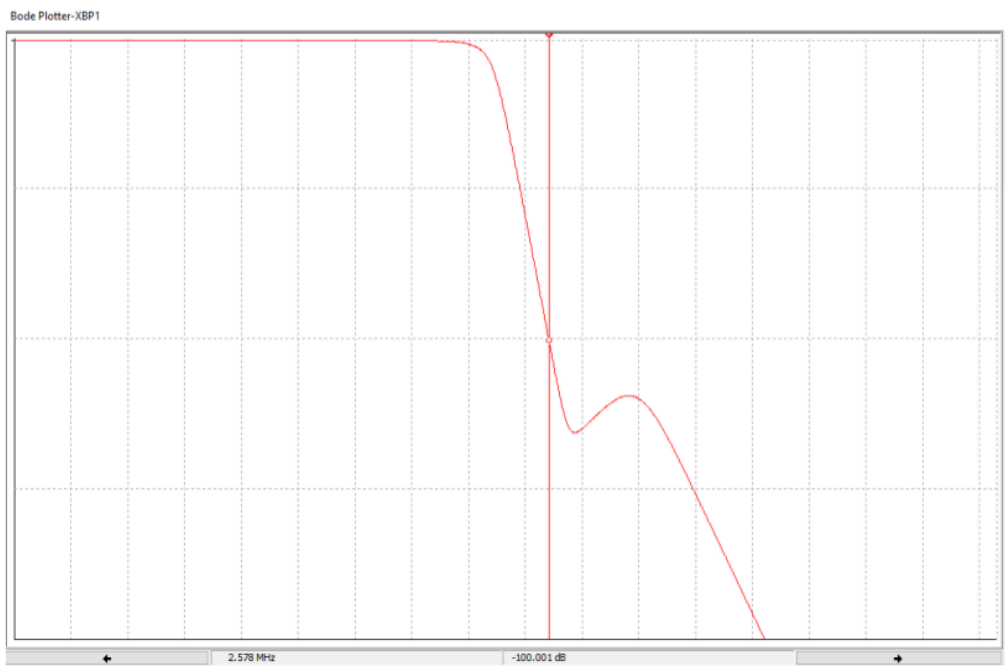


Figure 13: Bessel roll off gradient

Figures 10 & 11 above show that there is a 100dB/Decade roll off. This is seen as each block, grid, equates to half a decade therefor doubling this will prove that there is a 100dB/Decade roll off

gradient for 5th order Bessel. This 100dB/decade roll off is due to the filter being 5th order and will be the same throughout each 5th order filter or different types.

Butterworth 5th order low pass filter

Stage 1

$$C_1 = 0.5nF$$

$$R_1 = \frac{a_1}{2\pi f_c C_1}$$

$$= \frac{1}{2\pi \times 160k \times 0.5n}$$

$$R_1 = 1990\Omega$$

Stage 2

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$

$$\geq \frac{5n \times 4}{(1.618)^2} \geq 0.764nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$

$$R_1 = \frac{1.618 \times 0.764n - \sqrt{(1.618 \times 0.764n)^2 - 4 \times 1 \times 0.5n \times 0.764n}}{4\pi \times 160k \times 0.5n \times 0.764n} = 1600\Omega$$

$$R_2 = \frac{1.618 \times 0.764n + \sqrt{(1.618 \times 0.764n)^2 - 4 \times 1 \times 0.5n \times 0.764n}}{4\pi \times 160k \times 0.5n \times 0.764n} = 1620\Omega$$

Stage 3

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$

$$\geq \frac{5n \times 4}{(0.618)^2} \geq 5.24nF$$

$$C_2 = 5.24nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$

$$R_1 = \frac{0.618 \times 5.24n - \sqrt{(0.618 \times 5.24n)^2 - 4 \times 1 \times 0.5n \times 5.24n}}{4\pi \times 160k \times 0.5n \times 5.24n} = 599\Omega$$

$$R_2 = \frac{0.618 \times 5.24n + \sqrt{(0.618 \times 5.24n)^2 - 4 \times 1 \times 5n \times 5.24n}}{4\pi \times 160k \times 0.5n \times 5.24n} = 630\Omega$$

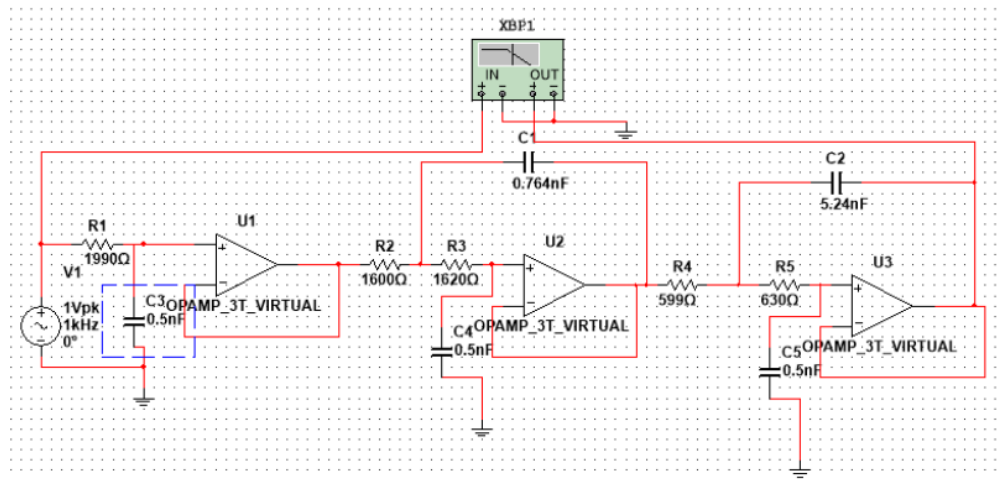


Figure 14: Butterworth 5th order circuit

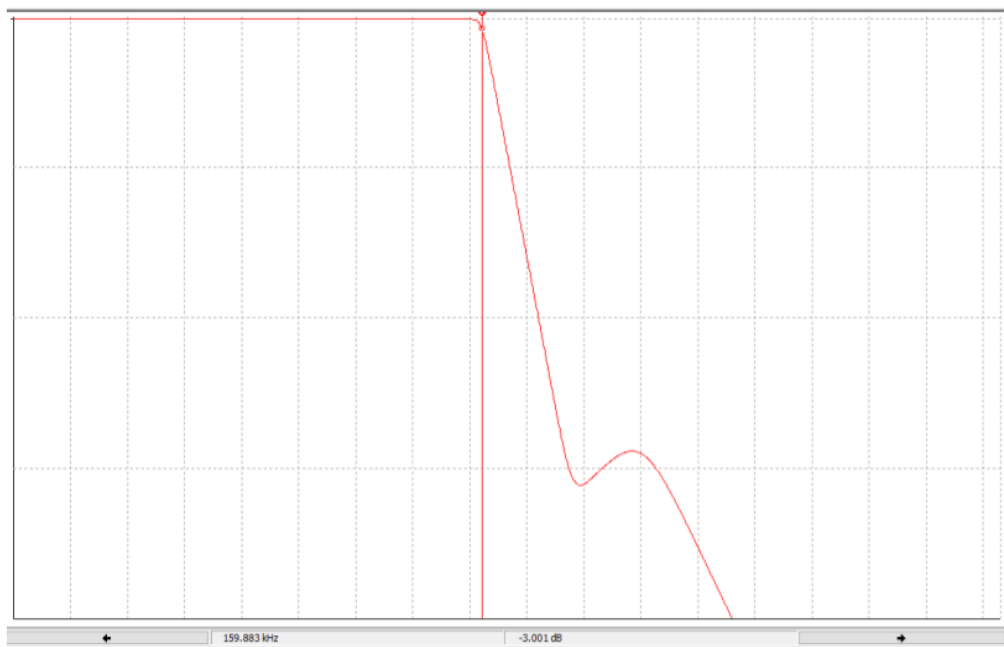


Figure 15: Butterworth cut off frequency

Figure 15 shows the cut off frequency at -3dB being at 160KHz which is what was expected from this filter.



Figure 16: Butterworth roll off gradient

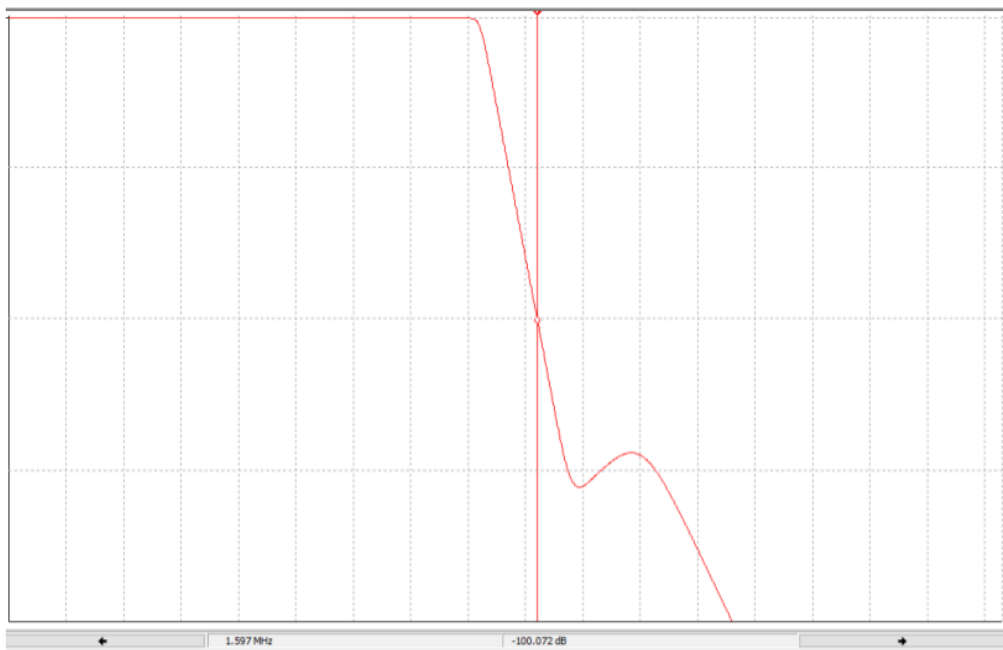


Figure 17: Butterworth roll of gradient

Figures 17 & 18 shows that there is a 100dB/roll off per decade. Each block is 50dB so stretching out the graph will produce a roll off 100/dB/Decade.

Chebyshev 5th order low pass filter

Stage 1

$$R_1 = \frac{a_1}{2\pi f_c C_1}$$
$$= \frac{3.5711}{2\pi \times 160k \times 1.5n}$$

$$R_2 = 2368\Omega$$

Stage 2

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$
$$\geq \frac{1.5n \times 4 \times 2.4896}{(1.1280)^2} \geq 11.74nF$$

$$C_2 = 11.74nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$

$$R1 = \frac{1.1280 \times 11.74n - \sqrt{(1.1280 \times 11.74n)^2 - 4 \times 2.4896 \times 1.5n \times 11.74n}}{4\pi \times 160k \times 1.5n \times 11.74n} = 373\Omega$$

$$R1 = \frac{1.1280 \times 11.74n + \sqrt{(1.1280 \times 11.74n)^2 - 4 \times 2.4896 \times 1.5n \times 11.74n}}{4\pi \times 160k \times 1.5n \times 11.74n} = 375\Omega$$

Stage 3

$$C_2 \geq \frac{C_1 \times 4b}{a^2}$$
$$\geq \frac{1.5n \times 4 \times 1.0814}{(0.1872)^2} \geq 185.15nF$$

$$C_2 = 185nF$$

$$R = \frac{a_i C_2 \pm \sqrt{a_i^2 C_2^2 - 4b_i C_1 C_2}}{4\pi f_c C_1 C_2}$$

$$R1 = \frac{0.1872 \times 185n - \sqrt{(0.1872 \times 185n)^2 - 4 \times 1.0814 \times 1.5n \times 185n}}{4\pi \times 160k \times 1.5n \times 185n} = 63\Omega$$

$$R1 = \frac{0.1872 \times 185n + \sqrt{(0.1872 \times 185n)^2 - 4 \times 1.0814 \times 1.5n \times 185n}}{4\pi \times 160k \times 1.5n \times 185n} = 61\Omega$$

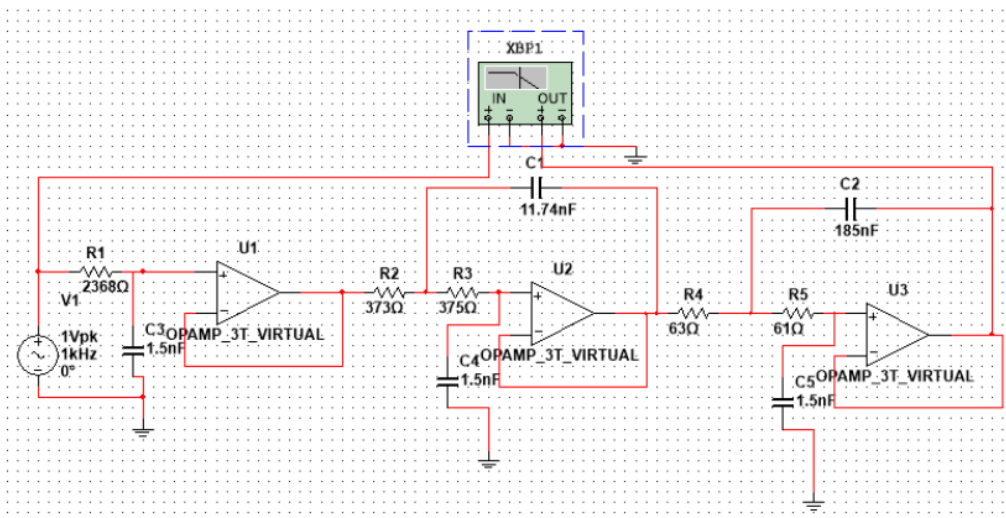


Figure 18: Chebyshev 5th order circuit

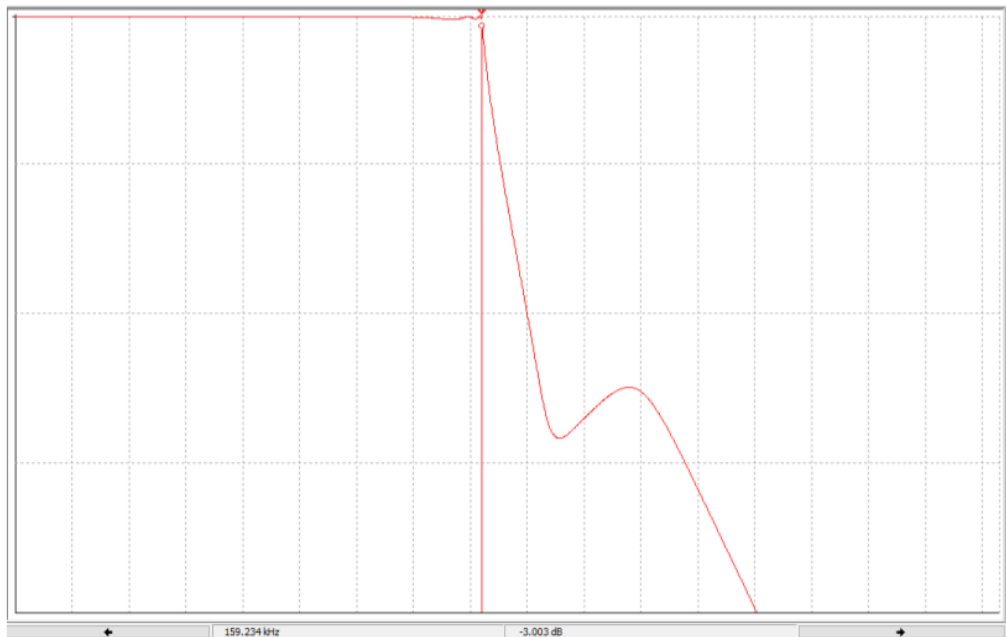


Figure 19: Chebyshev cut off frequency

Figure 19 shows that the cut off occurs at 160kHz at -3dB



Figure 20: Chebyshev roll off gradient



Figure 21: Chebyshev roll off gradient

Figures 20 & 21 above shows that there is a 100dB/decade roll off. This is shown between the two graphs as 50dB/decade however if the graph was stretched out this would equate to 100dB/decade roll off.

Butterworth high pass filters

3rd order high pass Butterworth

Stage 1

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 160k(1n)1} = 995\Omega$$

Stage 2

$$R2 = \frac{1}{2\pi f_c C a_1} = \frac{1}{\pi 160k(1n)1} = 1.98K\Omega$$

$$R3 = \frac{a_1}{4\pi f_c C b_1} = \frac{1}{4\pi 160k(1n)1} = 497\Omega$$

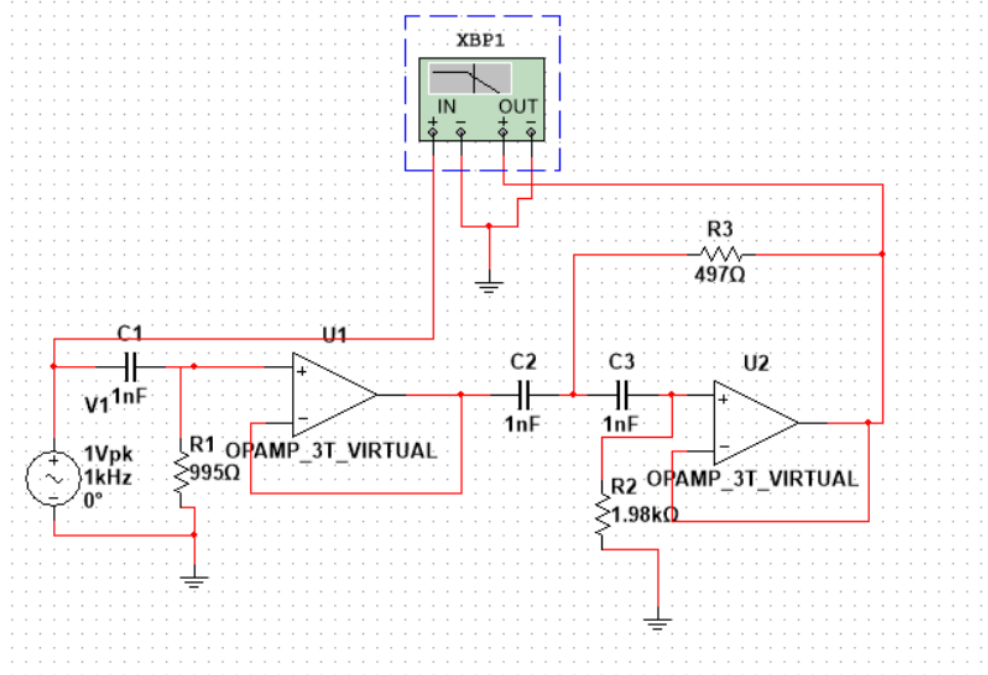


Figure 22: 3rd order Butterworth high pass filter

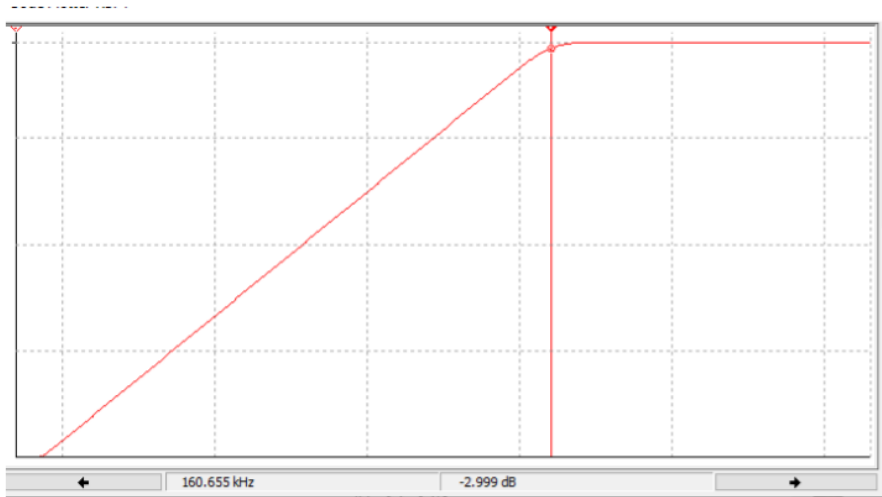


Figure 23: 3rd order Butterworth roll off

-3dB roll off at 160kHz

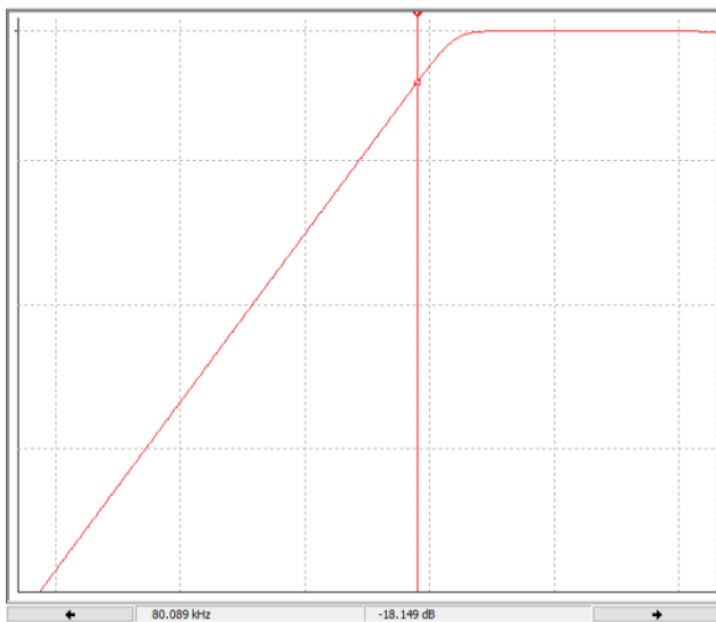


Figure 24: 3rd order Butterworth roll off gradient

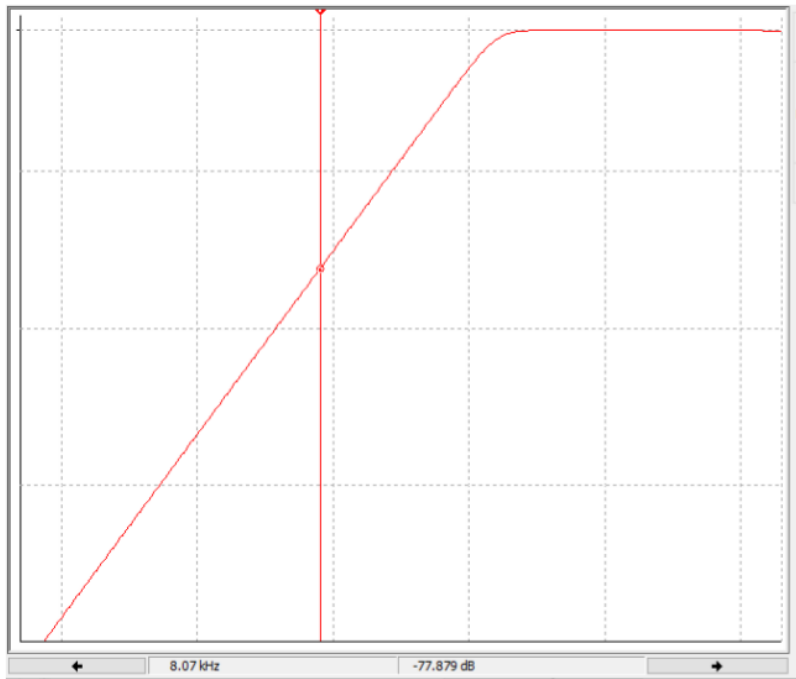


Figure 25: 3rd order Butterworth roll off gradient

Figure 24 & 25 show that there is a -59.7dB/decade roll off. $-77.8\text{dB} - (-18.1)\text{dB} = -59.7\text{dB/decade}$. this is close to what was expected of a 3rd order Butterworth, 60dB/decade roll off, between 80KHz and 8KHz.

6th Order Butterworth

Stage 1

$$R1 = \frac{1}{\pi f_c C a_1} = \frac{1}{\pi 160k(1n)1.9319} = 1.03k\Omega$$

$$R2 = \frac{a_1}{4\pi f_c C b_1} = \frac{1.9319}{4\pi 160k(1n)1} = 961\Omega$$

Stage 2

$$R3 = \frac{1}{\pi f_c C a_1} = \frac{1}{\pi 160k(1n)1.4142} = 1.4k\Omega$$

$$R4 = \frac{a_1}{4\pi f_c C b_1} = \frac{1.4142}{4\pi 160k(1n)1} = 703\Omega$$

Stage 3

$$R5 = \frac{1}{\pi f_c C a_1} = \frac{1}{\pi 160k(1n)0.5176} = 3.85k\Omega$$

$$R6 = \frac{a_1}{4\pi f_c C b_1} = \frac{0.5176}{4\pi 160k(1n)1} = 257\Omega$$

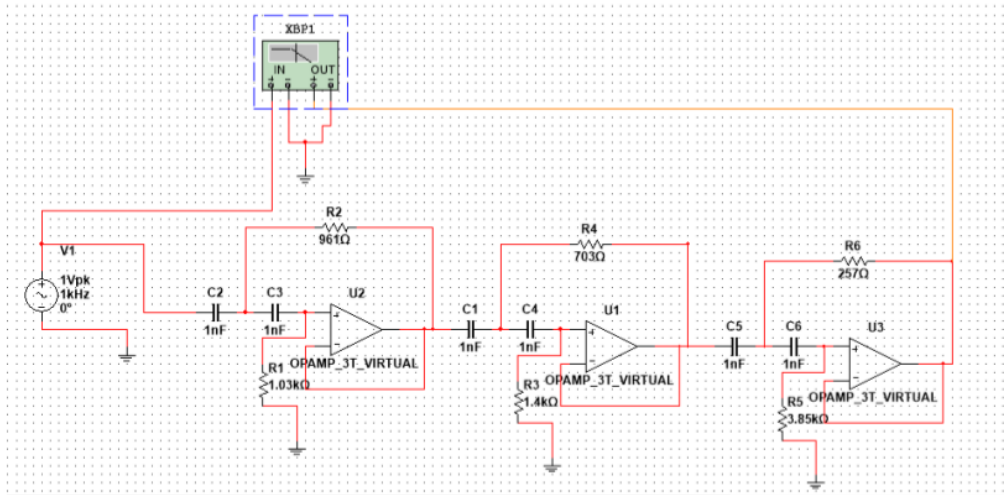


Figure 26: 6th order Butterworth high pass filter

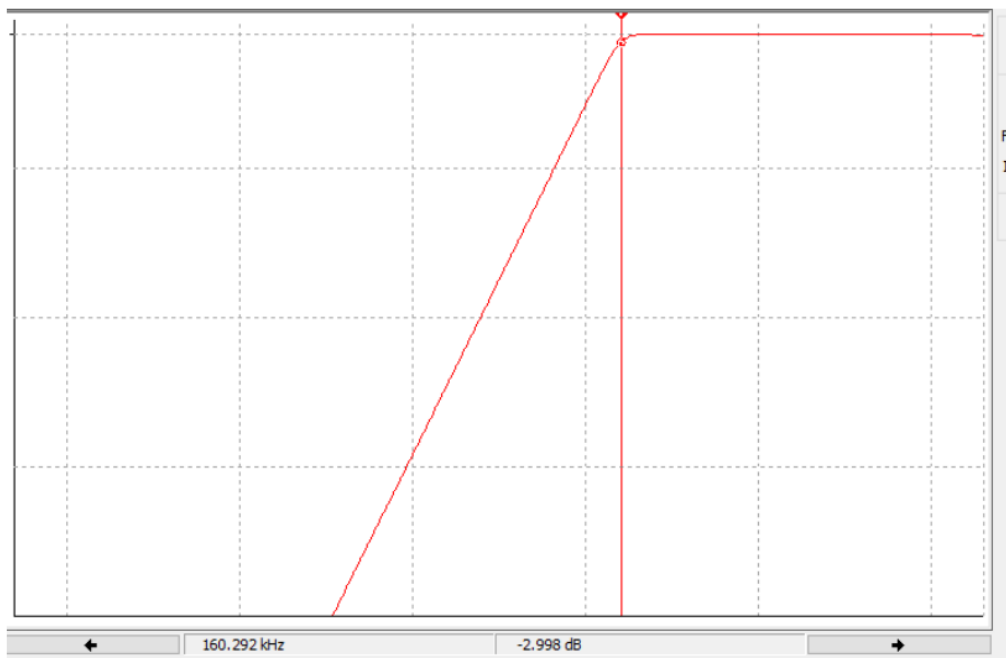


Figure 27: 6th order Butterworth cut off frequency

Figure 27 shows the cut off occurring at -3dB at 160KHz

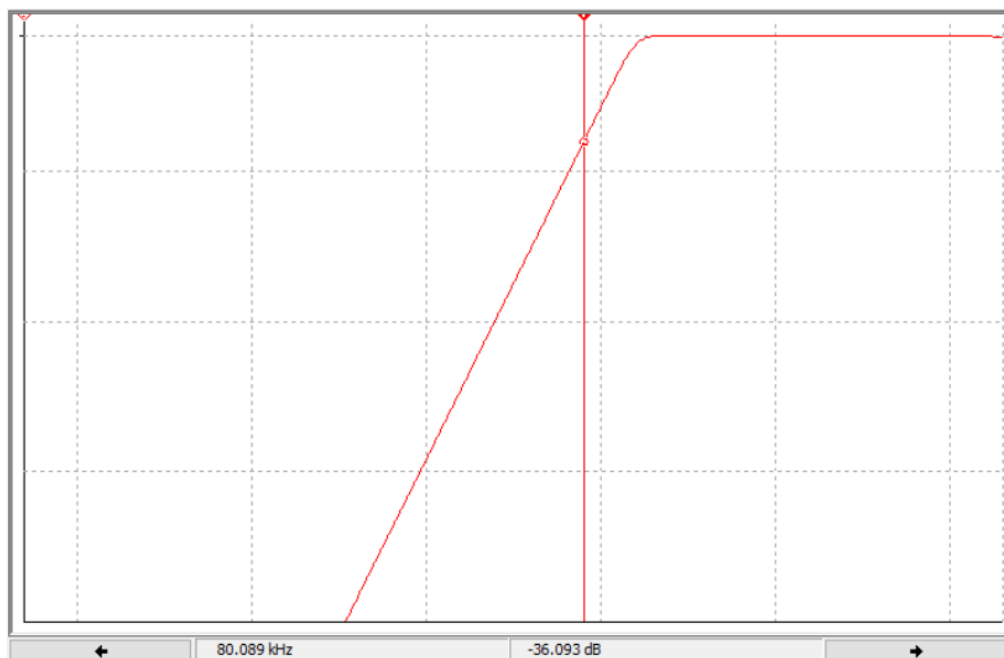


Figure 28: 6th order Butterworth roll off gradient

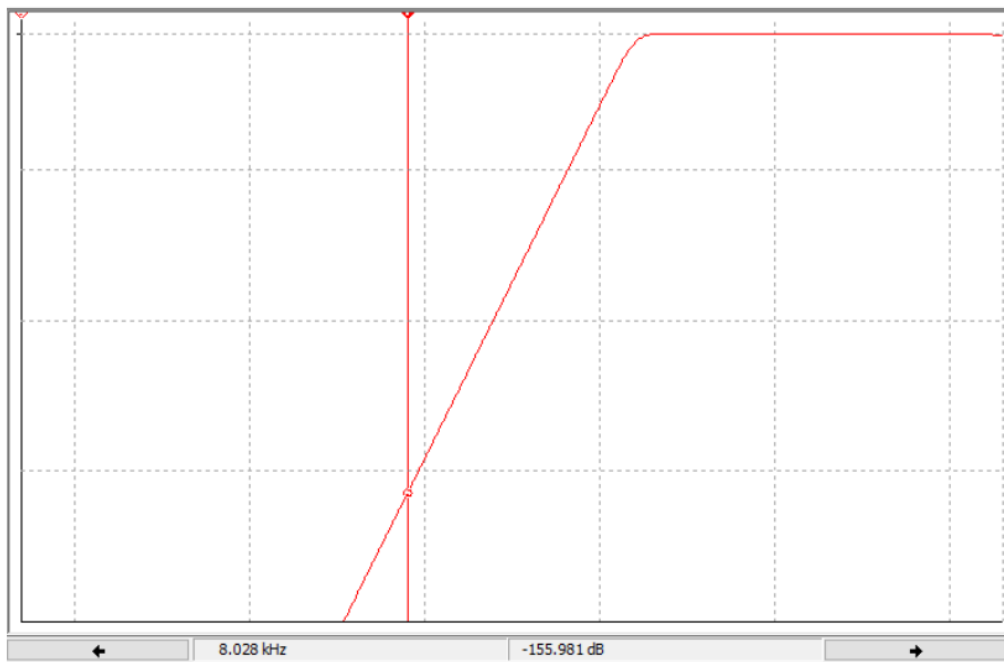


Figure 29: 6th order Butterworth roll off gradient

Figures 28 & 29 show that there is meant to a calculated 120db/decade roll off. $-156.98 - (-36.09) = 120.89\text{dB/decade}$, between 80KHz and 8KHz

9th order Butterworth

Stage 1

$$R1 = \frac{1}{2\pi f_c C a_1} = \frac{1}{2\pi 160k(1n)1} = 995k\Omega$$

Stage 2

$$R2 = \frac{1}{\pi f_c C a_1} = \frac{1}{\pi 160k(1n)1.8794} = 1.00k\Omega$$

$$R3 = \frac{a_1}{4\pi f_c C b_1} = \frac{1.8794}{4\pi 160k(1n)1} = 935\Omega$$

Stage 3

$$R4 = \frac{1}{\pi f_c C a_1} = \frac{1}{\pi 160k(1n)1.5321} = 1.3k\Omega$$

$$R5 = \frac{a_1}{4\pi f_c C b_1} = \frac{1.5321}{4\pi 160k(1n)1} = 762\Omega$$

Stage 4

$$R6 = \frac{1}{\pi f_c C a_1} = \frac{1}{\pi 160k(1n)1} = 2.00k\Omega$$

$$R7 = \frac{a_1}{4\pi f_c C b_1} = \frac{1}{4\pi 160k(1n)1} = 497\Omega$$

Stage 5

$$R8 = \frac{1}{\pi f_c C a_1} = \frac{1}{\pi 160k(1n)0.3473} = 5.7k\Omega$$

$$R9 = \frac{a_1}{4\pi f_c C b_1} = \frac{0.3473}{4\pi 160k(1n)1} = 173\Omega$$

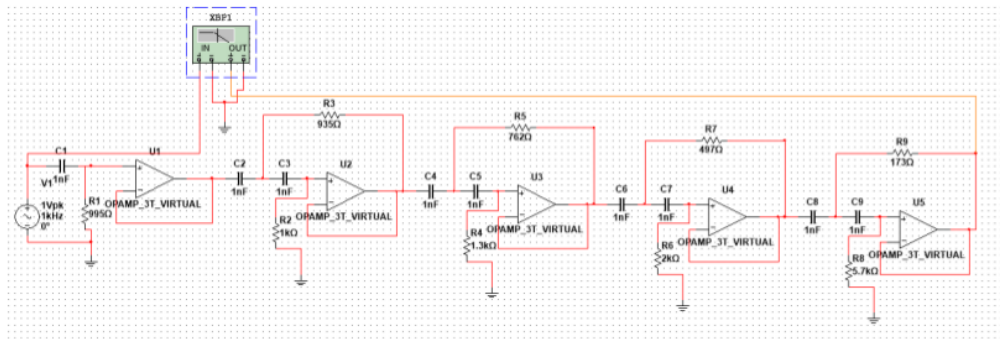


Figure 30: 9th order Butterworth high pass filter

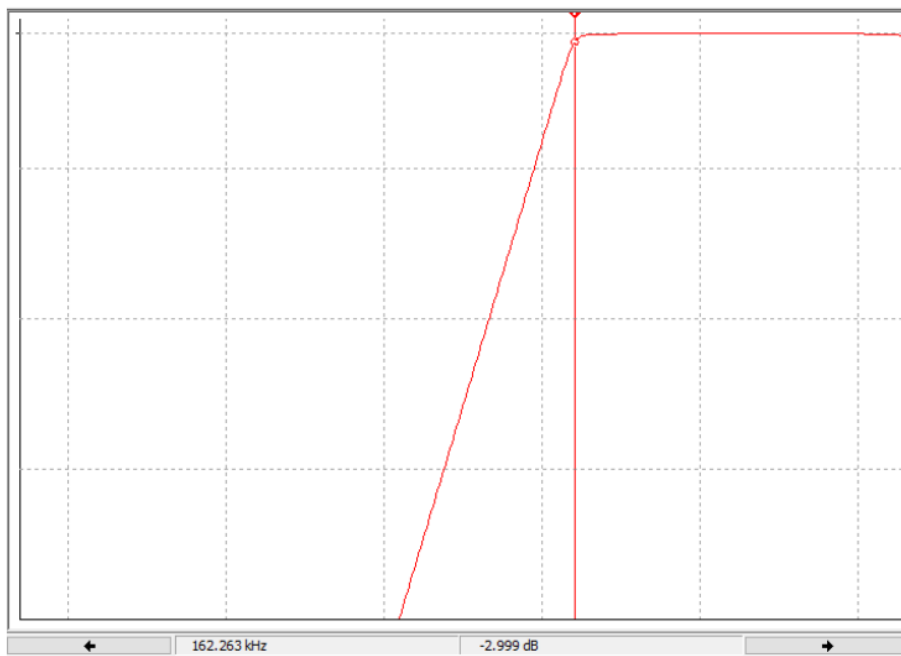


Figure 31: 9th order Butterworth cut off frequency

Figure 31 shows a cut off at -3dB at 160KHz

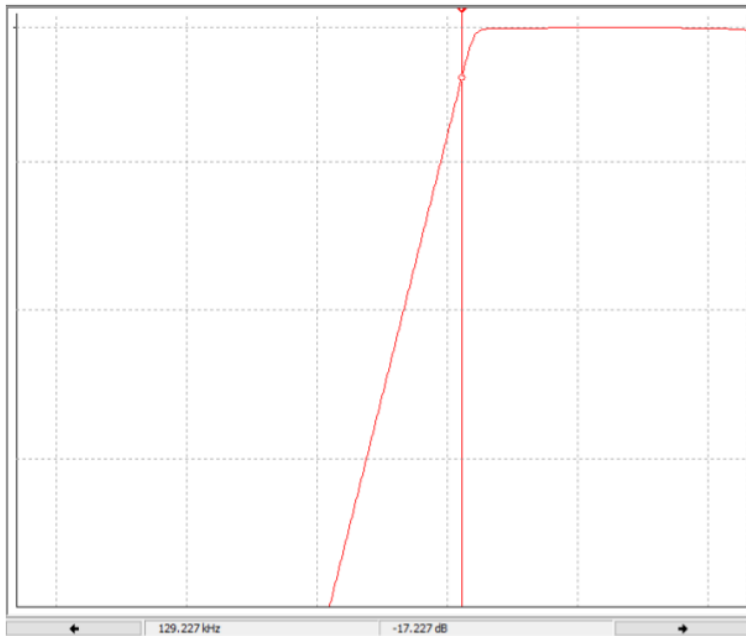


Figure 32: 9th order Butterworth roll off gradient

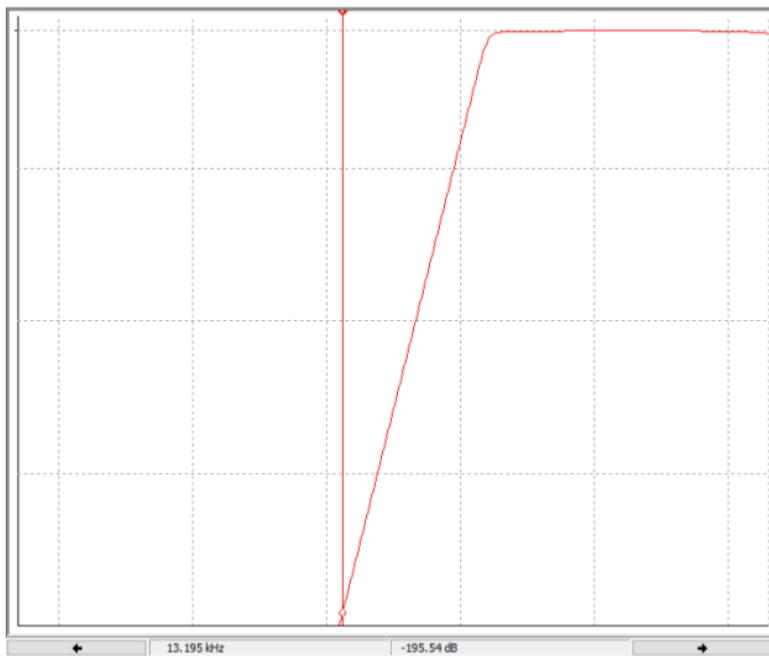


Figure 33: 9th order Butterworth roll off gradient

Figures 32 & 33 show that there is $-195.54\text{dB} - (-17.27) = 178.27\text{dB/decade}$ roll off, between 130KHz and 13KHz. Which is close to the expected roll off 180dB/decade for a 9th order Butterworth high pass filter.

Testing and improving the design

Throughout this assignment expected and simulated results have been gathered. For the 5th order low pass filters, of the 3 types it was expected that the cut off frequency would occur at -3dB at the given frequency chosen, 160KHz in this case. Which all of them did and can be seen in the figure below. Also, for these 5th order filters the roll off gradient should be the same, 100dB/decade. This is because a 1st order filter has a roll off 20dB/decade. As you increase the number of orders by 1 you double the 1st order. Meaning for a 5th order filter $20\text{dB/decade} \times 5 = 100\text{dB/decade}$ roll off occurs. Which is what was achieved for all the 3 types of filters.

As for the 3rd, 6th and 9th order high pass Butterworth filters produced this have the same cut off frequency at -3dB at 160KHz however they have a change in roll off gradient due to the same reason as before. Meaning the 3rd order produced $20\text{dB/decade} \times 3 = 60\text{dB/decade}$ roll off, 6th order $20\text{dB/decade} \times 6 = 120\text{dB/decade}$ roll off and finally 9th order $20\text{dB/decade} \times 9 = 180\text{dB/decade}$ roll off. Which is what was seen.

5th order low pass filters			
		Cut off frequency at -3dB (Hz)	Roll off gradient
Bessel	Expected	160K	100dB/decade
	Achieved	160.175K	100dB/decade
Butterworth	Expected	160K	100dB/decade
	Achieved	159.883K	100dB/decade
Chebyshev	Expected	160K	100dB/decade
	Achieved	159.234K	100dB/decade

Figure 34: comparison between expected and achieved

For the 3rd, 6th and 9th order Butterworth high pass filters results were as follows

Butterworth high pass filter			
Order		Cut off frequency at -3dB	Roll off gradient
3rd	Expected	160KHz	60dB/decade
	Achieved	160.655KHz	59.7dB/decade
6th	Expected	160KHZ	120dB /decade
	Achieved	160.292KHz	120.89dB/decade
9th	Expected	160KHZ	180dB/decde
	Achieved	162.263KHz	178.27dB/decade

Figure 35: Butterworth high pass filters

As seen in figures 34 & 35 the expected and achieved results are near spot on. Meaning the calculations are correct and the testing using the bode plotter was accurate.

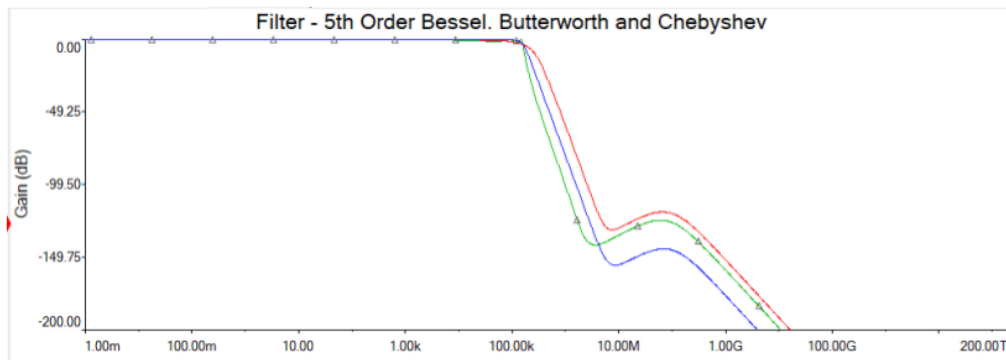


Figure 36: Combined graphs for the 5th order filters

Figure 36 shows the 5th order low pass filters combined. Chebyshev, green, Butterworth, blue and Bessel, red. It is evident to see that Chebyshev has the sharpest roll off gradient with Bessel being the least aggressive. From this graph is not obvious that Chebyshev has a ripple in the pass band as the clarity is off. However, all filters have behaved as expected.

The Butterworth 3rd, 6th and 9th order high pass filters also exhibited values and graphs of what was expected, see figure 37 below.



Figure 37: 3rd, 6th and 9th Butterworth HP filters

From figure 37, 9th order, green, has the steepest roll off at 180dB/decade, 6th order, blue, 120db/decade roll off and 3rd order, red, 60dB/decade roll off.

Conclusion

Throughout this assignment a wealth of knowledge has been gained in the theory and practicality of design and testing of active filters with specific reference to 5th order low pass Bessel, Butterworth and Chebyshev filters. Along with 3rd, 6th and 9th order Butterworth high pass filters.

In depth research into all 3 types of filters, different orders and high and low pass bands. Application of filters, properties, characteristics were also investigated. Discovering what they are used for and how they are useful to each application. Many are used in audio application where noise reduction in the pass band is critical, so the selection of the correct filter is vital, Butterworth in this circumstance as it has a maximally flat response. While a clear-cut roll off gradient may be critical so a Chebyshev will be used.

Complex calculations to design the correct circuit to perform as required for each filter was carried out. The layout of each filter was also critical. Making sure that the resistor and capacitors were orientated correctly to produce either a low or high pass filter with the use of the correct noninverting Op Amp.

Once all filters had been produced, testing to clarify that the simulated values matched the expected calculated, were carried out. For the 5th order 3 types of low pass filters, cut off frequencies were expected to happen at -3dB at the chosen frequency, 160KHz which is what was found. The roll off for all 5th order filters was 100dB/decade as explained before.

As for the 3rd, 6th and 9th order high pass filters the roll off per decade increased as the order increased, as explained before. The cut off frequencies were all simulated and compared to the calculated stated, which proved that the circuits were designed correctly, with the correct values of resistors and capacitors used throughout.

Taking the entire assignment into consideration, all sections were completed and expectations against calculations and simulations, were made. Thus, I feel this assignment can be deemed a success.

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FINAL GRADE

GENERAL COMMENTS

Instructor

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GRADING FORM: CSG-RUBIC

MICHAEL MORGAN

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RESEARCH-INFORMED LITERATURE



There was evidence of further reading and research and some in text referencing. Your references were mainly appropriate to the task, however there was a heavy reliance on information gained from the course notes.

4/10

KNOWLEDGE AND UNDERSTANDING



The knowledge and understanding of the subject demonstrated by this assignment was reasonably detailed and mainly accurate. There were very few gaps in your knowledge of the basic concepts and your understanding of the higher level concepts was demonstrated to a limited degree - you could have explained in more detail how the circuit evolved. Further work – Your explanations need to be more detailed and written with a greater emphasis on critical evaluation rather than description.

20/30

ANALYSIS



Your explanation of the design process was good and the conclusions showed that you can interpret quantitative and qualitative data, although this was often descriptive. You could have evaluated the results and specified whether they concurred with theory suggesting reasons for any discrepancies. You have however demonstrated good analytical skills and your approach to the task was logical. Arguments made in the conclusions were mostly valid and demonstrated a good understanding of the topic. Further work – in your conclusion, you should relate the results to the original specification and to accepted theory.

12/20

PRACTICAL APPLICATION AND DEP.



Your application of practical skills for this task was generally very good. You used the resources

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appropriately when designing the circuit and you used appropriate options for testing and evaluating the circuit performance. You managed to design an effective circuit that functioned within the specification and achieved this by only asking for assistance when appropriate thus demonstrating some advanced problem solving skills. Your results were comprehensive and allowed for a detailed conclusion to be attempted.

SKILLS FOR PROFESSIONAL PRAC.



In this assignment you have demonstrated skills in working individually and also collaboratively. Your written report was written in a professional and confident style, however you still need to be more efficient with your word count. The report was very well presented, with excellent diagrams in appropriate places, good sentence/paragraph structure and clear calculations.

7/10