

1809802

by Mason Morgan

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1) Introduction, aims and objectives

Throughout the course of this report, research will be carried out to compare and contrast the three different filters available, these being the Bessel, Tschebyscheff, Butterworth.

After providing information comparing and contrasting these three filters, examples will be provided for each. For each filter, an explanation will be given on how they are used in modern technology. In order to support each discussion and another explanation will be given on how filters are used in two specific control processes.

After the research has been completed a 5th order low pass filter using each of the filters will be designed showing calculations. Three high pass filters will be designed which will be over 3rd, 6th and 9th order. A test schedule will be made to show the operation of the 6 filters.

2) Research into filter design

2.1) Research into active filters

Active filters can be described as a type of analogue circuit implementing an electronic circuit using active components, typically an amplifier.

Active filter is used in filter circuits because when a load is applied to the circuit the cut off frequency will be modified; therefore, these problems can be solved to using the active filter.

The active filter not only selectively passes the gain of frequency, but it also provides the gain to the input signal. As the name suggests the active filters are designed using the active components like the OP-amp and the transistor.

The advantage of using an OP-amp filter circuit is that it has a high input impedance and a low output impedance, so because of these characteristics the circuit can be used as a buffer to isolate the load from the filter circuitry, furthermore this could then be used to isolate the load at different stages of the filter.

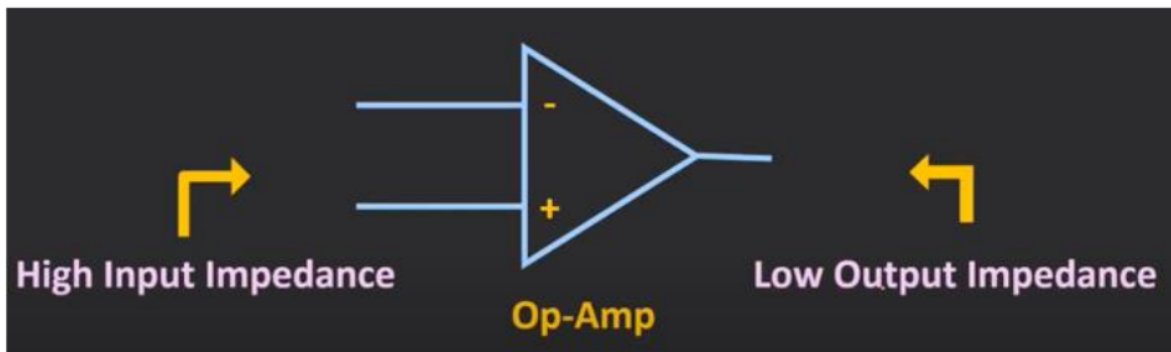


Figure 1: Op- amp explanation

2.2) Comparing and contrasting the three main types of filters

The following information provided into Butterworth, Chebyshev and Bessel filters are known as pole responses. As you progress through each filter in the order above the frequency cut-off is a lot sharper, however the time domain gets a lot.

2.2.1) Butterworth filter

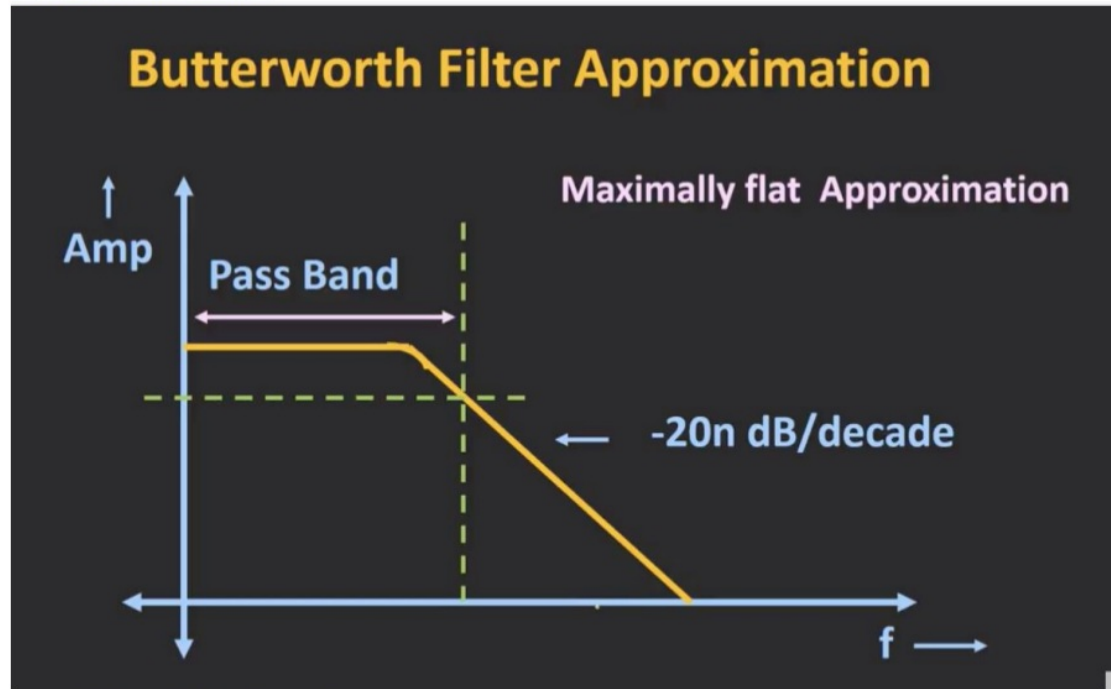


Figure 2: Butterworth Filter Approximation

(ELECTRONICS, 2017)

From figure ??? above you can see that the Pass band is very flat, this is known as the maximally flat approximation. In this approximation the roll off from Pass Band to Stop Band is at the rate of -20dB/decade .

If this Butterworth filter was being designed form a 2nd order, then it would have a roll off of -40dB/decade . Similarly, if the Butterworth filter was being designed off a 5th order it would have a roll off of -100dB/decade . So, in this Butterworth filter approximation you will not see any type of ripple in the Stop Band. This typical Butterworth filter can be used a lot in audio processing.

2.2.2) Chebyshev filter

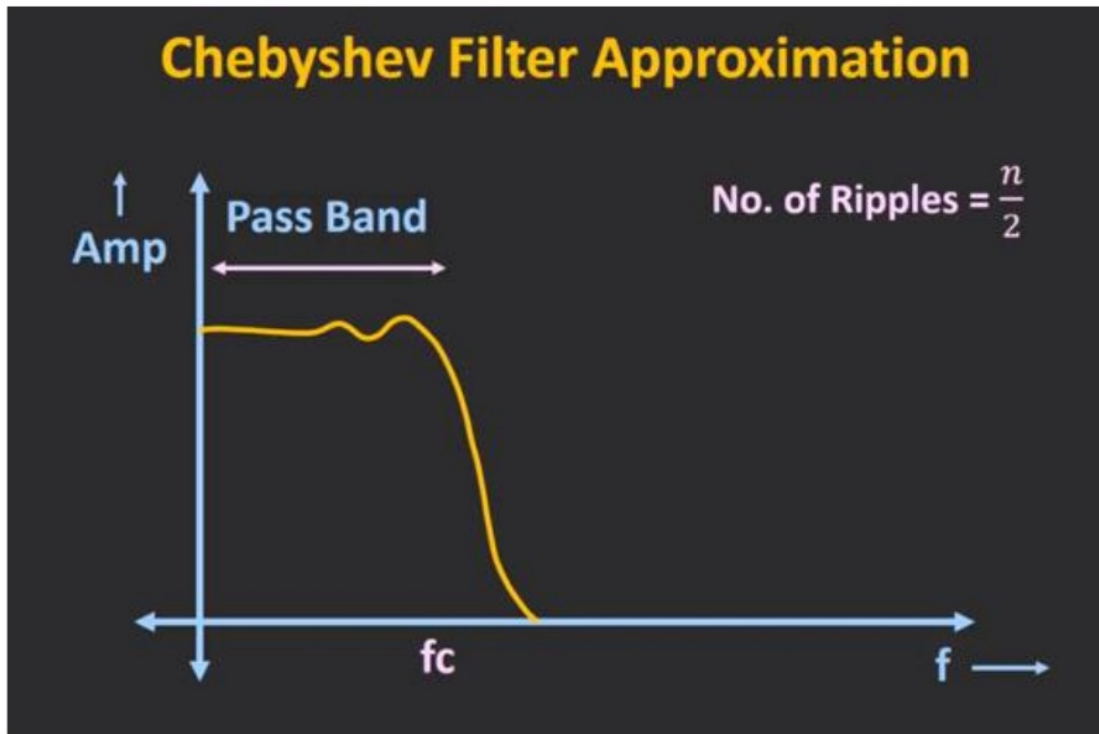


Figure 3: Chebyshev Filter Approximation

(ELECTRONICS, 2017)

As shown by Figure 3 the difference in this particular Chebyshev filter compared to the Butterworth filter in figure 2 shows ripples in the Pass Band while in the stop Band you will not see any ripples.

In this Chebyshev filter approximation, the roll off or transition from the Pass Band to Stop Band happens a lot faster meaning that the trend of the slope is a lot steeper rather than the gradual decline in the Butterworth filter.

When choosing what specific filter is best for you and your Pass Band and Stop Band are not priority and if you require a faster transition then in such cases the Chebyshev Filter is the best option to use. In the case of this Chebyshev filter the number of ripples in the pass band will be equal to:

$$\text{no. of ripples} = \frac{n}{2}$$

This is where n is equal to the order of the filter. So, as you can see by the 4th order filter the number of ripples in the pass band will each be equal to 2. Now, in the case of this Chebyshev design you also need to provide maximum amount of ripple which is acceptable by the filter design shown by Figure 3.

In most cases this ripple is in the range of 0.1dB/decade between 3Bd/decade.

2.2.3) Bessel filter

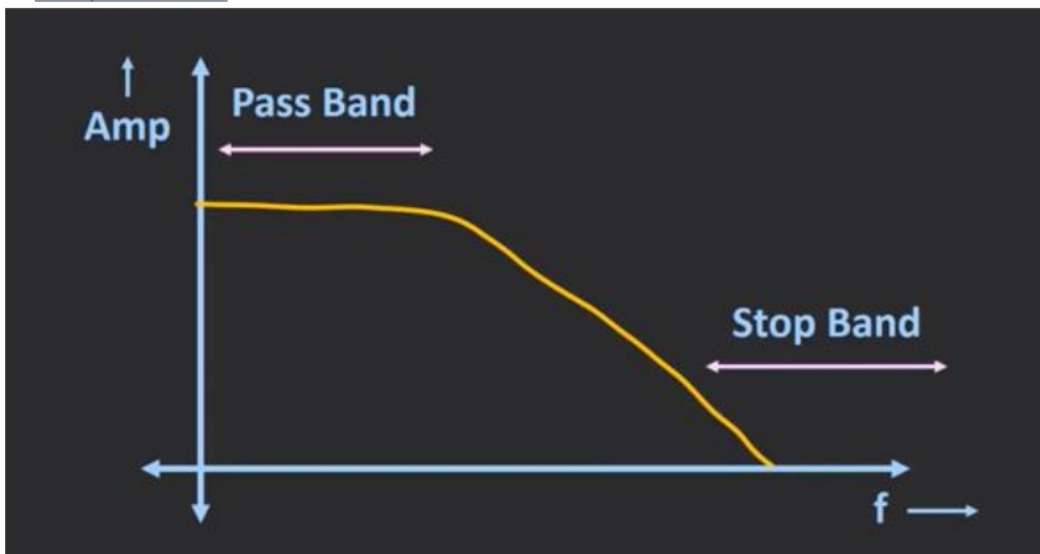


Figure 4: Bessel Filter Approximation

(ELECTRONICS, 2017)

The Bessel Filter Approximation shown by figure 4 provides the flat response in the Pass Band and does not have any type of ripple in the Stop Band, but the roll off from the Pass Band to the Stop Band will be the lowest amount out of all three Filter Approximations shown.

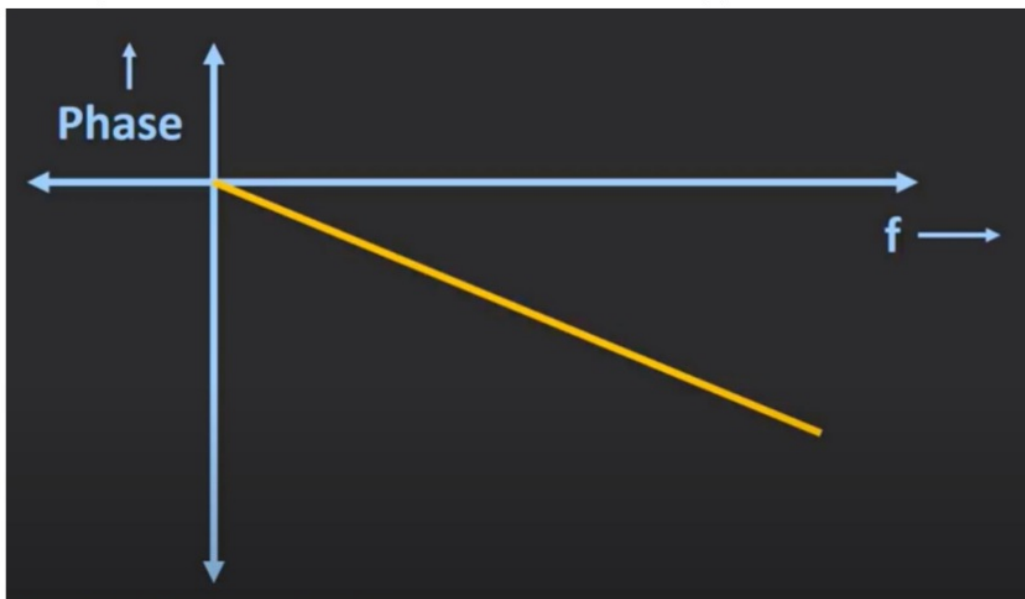


Figure 5: Bessel Filter frequency relationship

(ELECTRONICS, 2017)

In this Bessel Filter the frequency relationship is quite is quite linear so, it is very useful for when you're using an application which has a non-sinusoidal signal. If in the application has a square waveform then this filter will provide a linear phase shift to all the other frequency components, because of this in the time domain it will provide a constant amount of delay to the input signal and because of this, this filter has a very good step response.

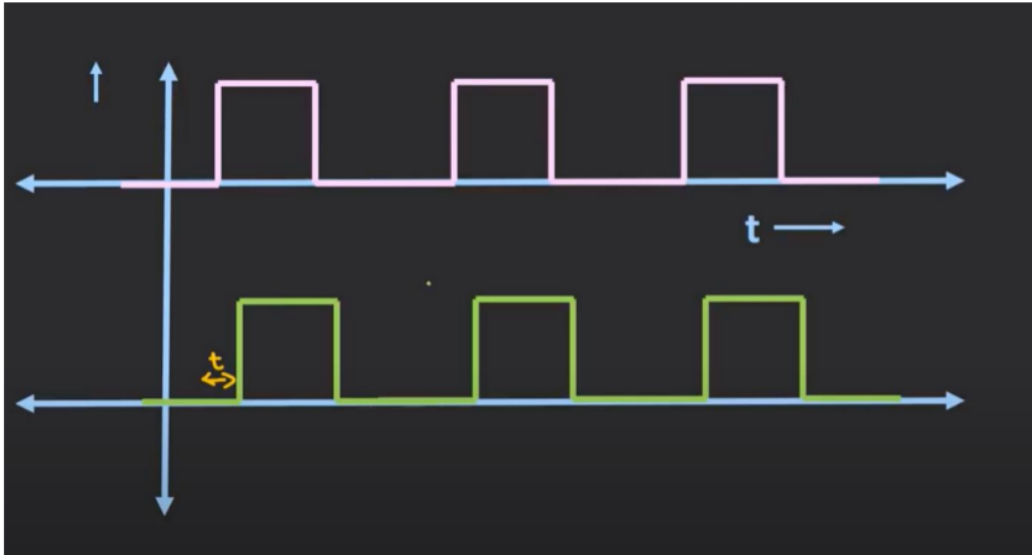


Figure 6: Applying a square wave to a Bessel filter

(ELECTRONICS, 2017)

If you are applying a square wave to this Bessel Filter, then this Bessel Filter will provide the particular amount of delay to the square wave.

You can also compare the roll-off parameters of all three filters, this can be shown below by figure 7

Type	f_c , dB	$2f_c$, dB
Butterworth	3	36
Chebyshev	3	63
Inverse Chebyshev	3	63
Elliptic	3	93
Bessel	3	14

Figure 7: Table of results for 3 main filters

(ELECTRONICS, 2017)

When considering the three main filters discussed about In terms of roll-off rate figure 7 shows that the Bessel filter is the slowest, whilst the Chebyshev being the fastest and the Bessel being in-between.

Type	Passband	Stopband	Roll-off	Step Response
Butterworth	Flat	Monotonic	Good	Good
Chebyshev	Rippled	Monotonic	Very Good	Poor
Inverse Chebyshev	Flat	Rippled	Very Good	Good
Elliptic	Rippled	Rippled	Best	Poor
Bessel	Flat	Monotonic	Poor	Best

Figure 8: Table of results showing waveform data

(ELECTRONICS, 2017)

Figure 8 above shows the data collected between all the three particular filters mentioned in previous pages.

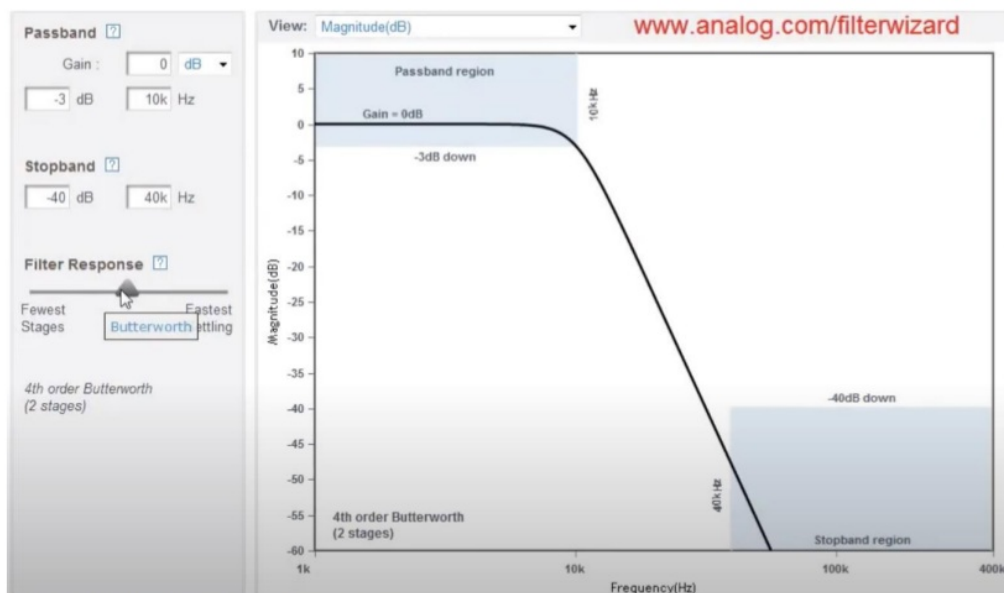


Figure 9: The Magnitude of a Butterworth Filter

(Analog Devices, 2014)

Figure 9 provides an example of a Butterworth filter Passband which is measuring the Magnitude in dBs. From the results you can see that this particular graph uses 2 stages to make a 4th order Butterworth wave from.

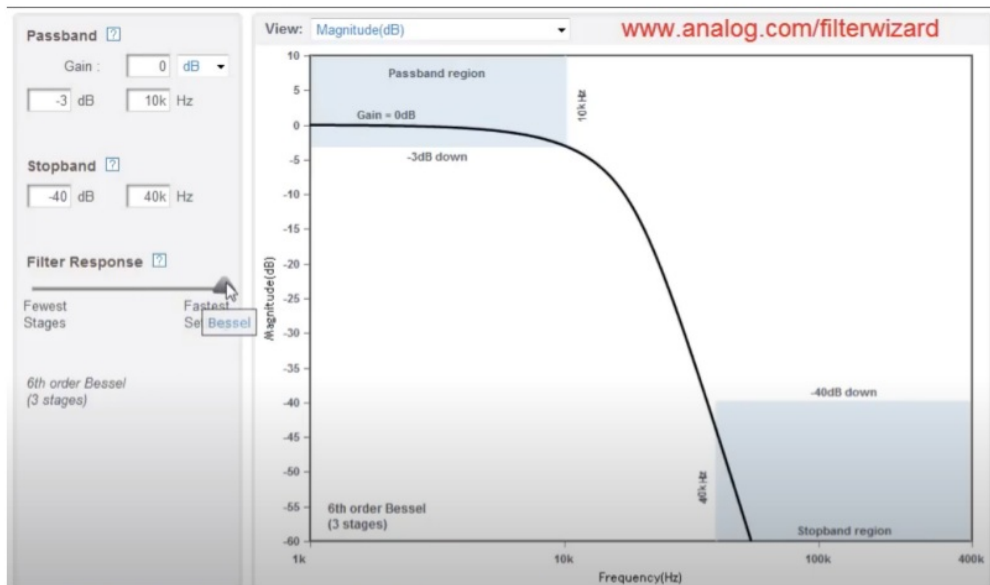


Figure 10: The Magnitude response for a Bessel Filter

(Analog Devices, 2014)

From Figure 10 you can now see a Bessel Filter which uses 3 stages to produce a 6th order Bessel.

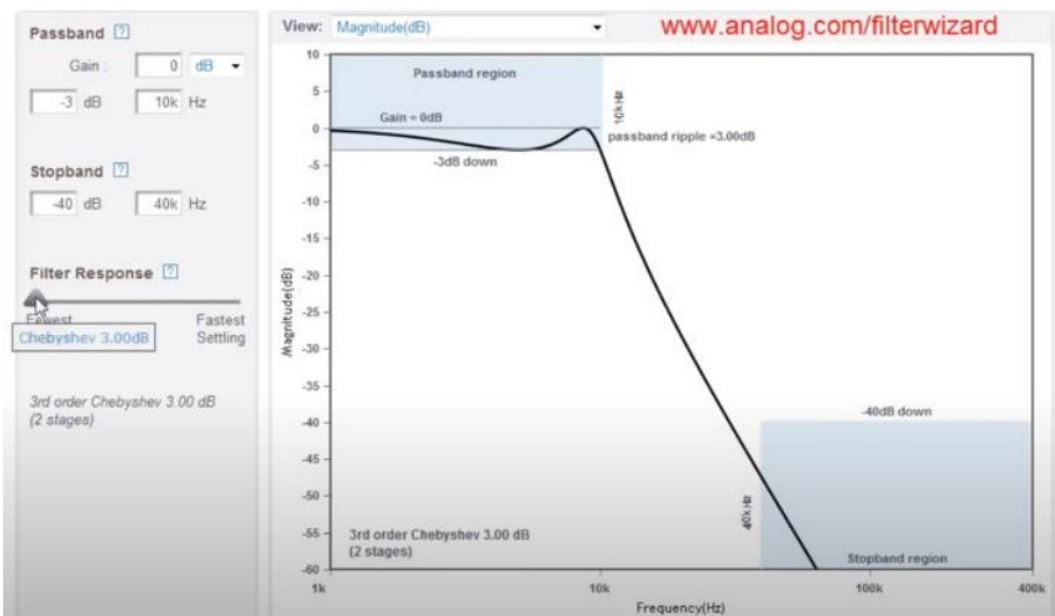


Figure 11: The magnitude response for a Chebyshev Filter

(Analog Devices, 2014)

Figure 11 shows a Chebyshev Filter which uses 2 stages to make a 3rd order waveform.

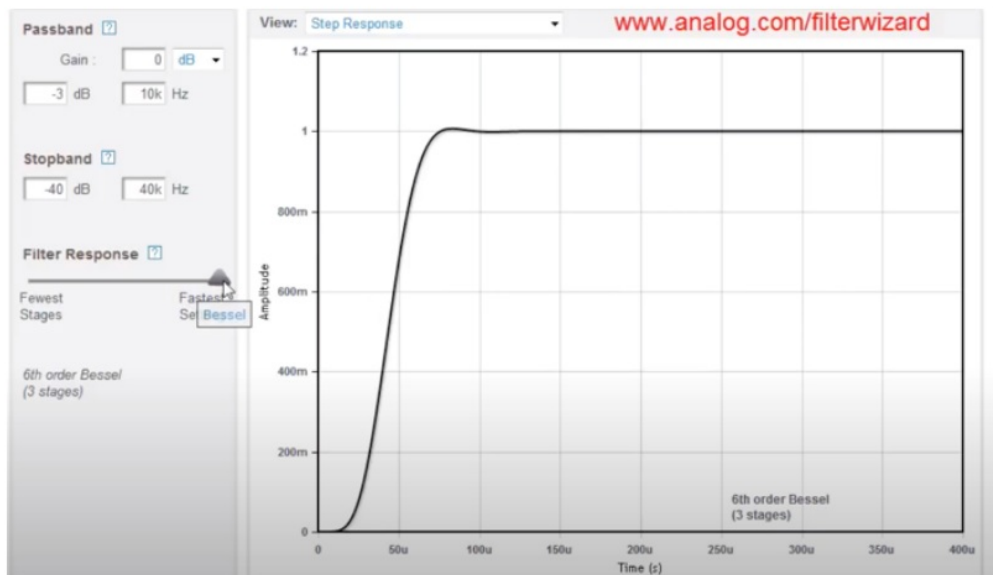


Figure 12: Step response for a Bessel Filter

(Analog Devices, 2014)

This time in figure 12 the step response has been calculated for a Bessel Filter which uses 3 stages to make a 6th order Bessel. This Bessel Filter has no spikes and is stabilises straight away.

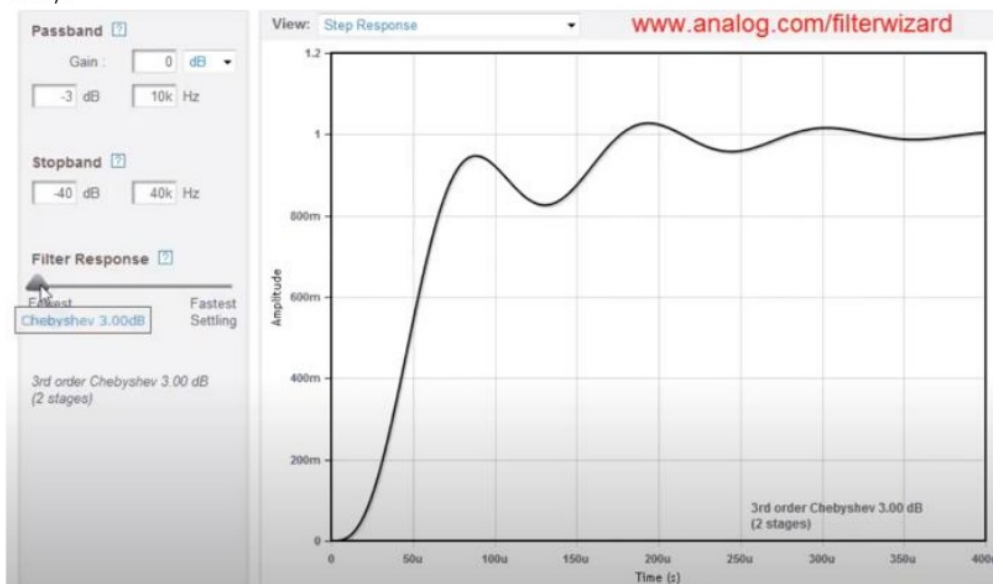


Figure 13: Step response for a Chebyshev Filter

(Analog Devices, 2014)

In figure 13 the step response for a Chebyshev filter has been calculated using 2 stages to make a 3rd order waveform. The Chebyshev Filter starts very unstable with a great deal of peaks recorded before the waveform stabilises.

Figure 14 below shows a Butterworth filter which uses 2 stages to construct a 4th order wave. The results show an instant spike where the wave peaks and then stabilises.

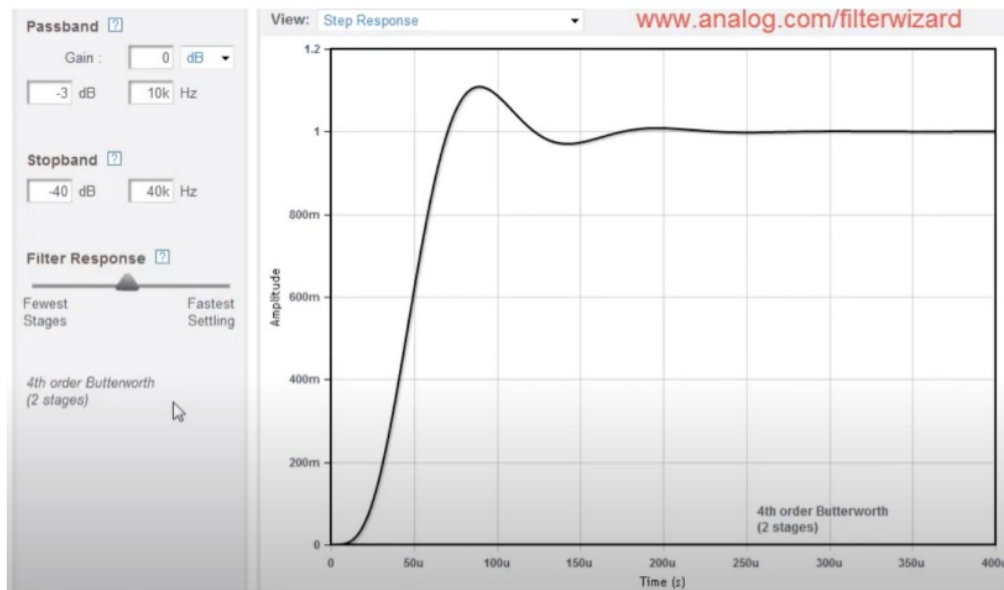


Figure 14: Step response for a Butterworth Filter

(Analog Devices, 2014)

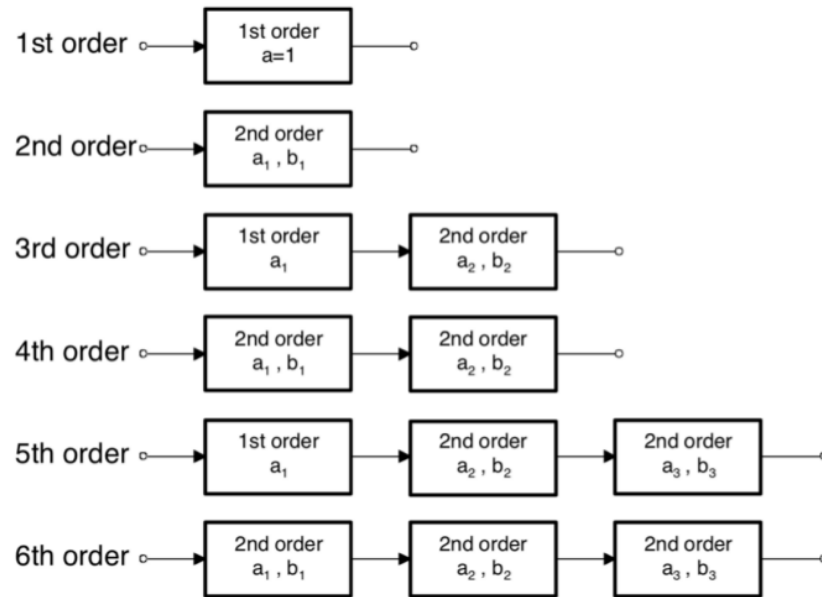


Figure 15: Making different orders

(COLEGSIRGAR, 2011)

Figure 15 shows how each order waveform is produced. In order to produce anything other than a 2nd order, they must start to be combined to reach higher orders.

2.3) Filters used in modern electronic systems

If using a DC power supply which might contain some high frequency noise. A filter can be implemented into this power supply to get a noise free supply. Equalizers used in the music industry use a lot of filters to deliver a much clearer sound. You can also find filters used vastly in radio communication processes.

Figure 16 shows an example of a high-pass active filter of the Sallen-key topology

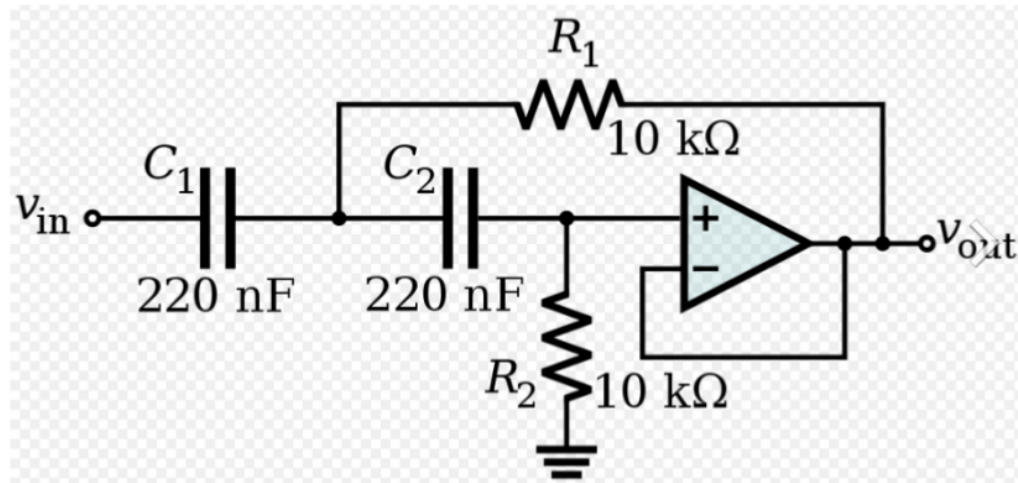


Figure 16: High pass active filter

(Murmman, 2010)

2.4) How are filters used in two specific control processes

You can often find the below filters being used most commonly in control systems, these being:

2.4.1) Noise Filter

These are commonly used to smooth out high-frequency noise from a process measurement signal which can be shown by figure 17.

The Noise filter are commonly applied to flow measurement signals. This is because these signals in particular have a tendency to produce a lot of noise from the components.

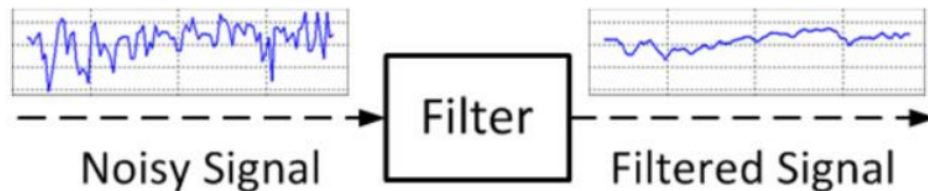


Figure 17: Noise Filter

(wikipedia, 2012)

Lots of level measurements can also have a large noise component, this could include liquid gas separation or boiling water which both will affect the level. The controller can become very sensitive to noise because they require a much higher controller gain, therefore filters with long time constants will be required which produce a value of 10 – 20 seconds.

2.4.2) Anti-Aliasing Filter

These particular filters are used on analog input signals. The reason why this is, it removes high frequency components from the signals before they are sampled by the digital control system. Furthermore, the Anti- Aliasing Filter can be used before a signal sampler to restrict the bandwidth of a signal.

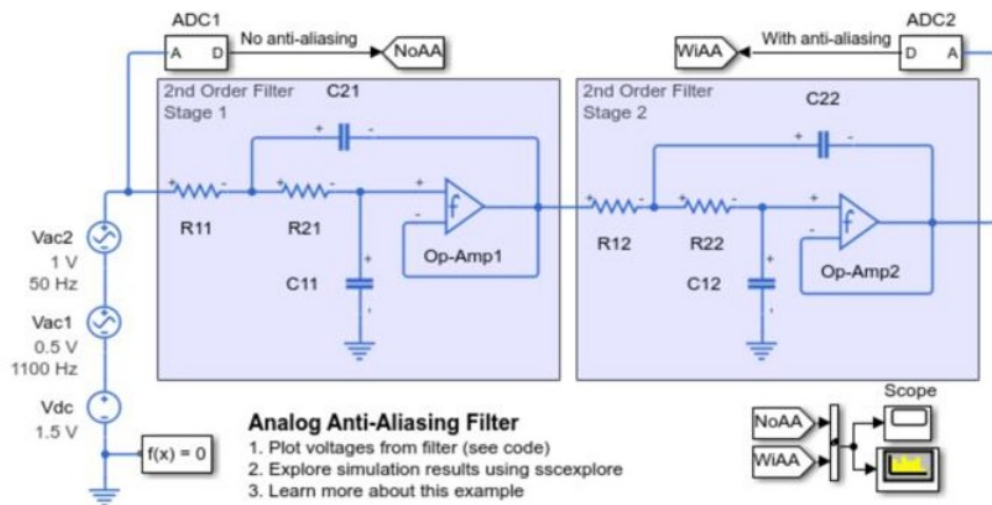


Figure 18: Anti-Aliasing Filter

(Anon., 2012)

Figure 18 above shows an example of an analog implementation of an anti-aliasing filter which can be used with an AC to DC converter.

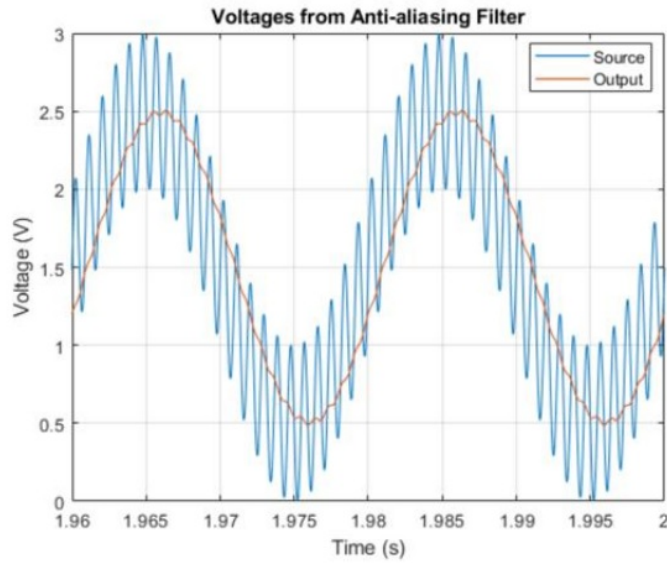


Figure 19: Graph displaying input and output filter signals

(Anon., 2014)

Figure 19 displays both the input and output values in the form of a scope. From the results it displays the drastic improvement on the output wave compared to the input signal.

3) Design method, choices and calculations (500)

3.1) Designing three 5th order low pass filters

3.1.1) Using a Bessel filter

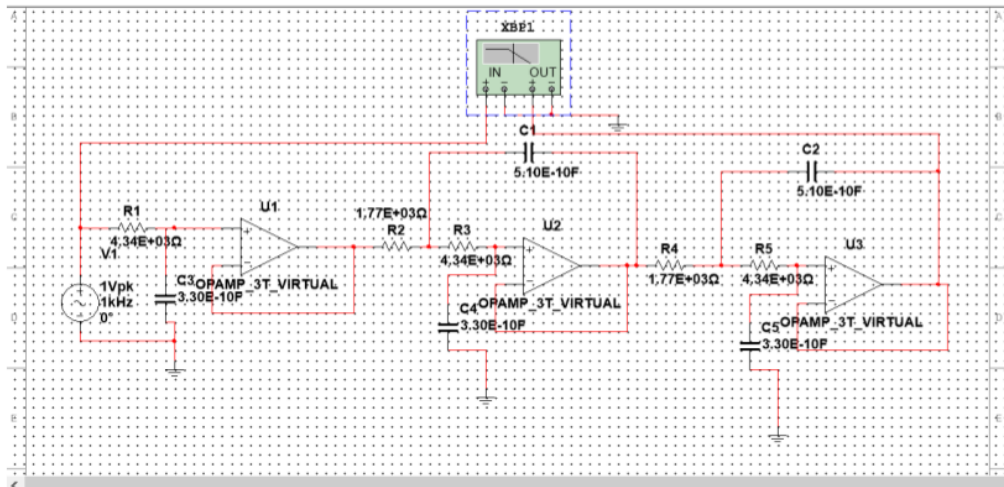


Figure 20: 5th Order Bessel filter

Figure 20 shows the circuitry and working components with values for a 5th order Bessel Filter.

3.1.2) Using a Tschebyscheff filter

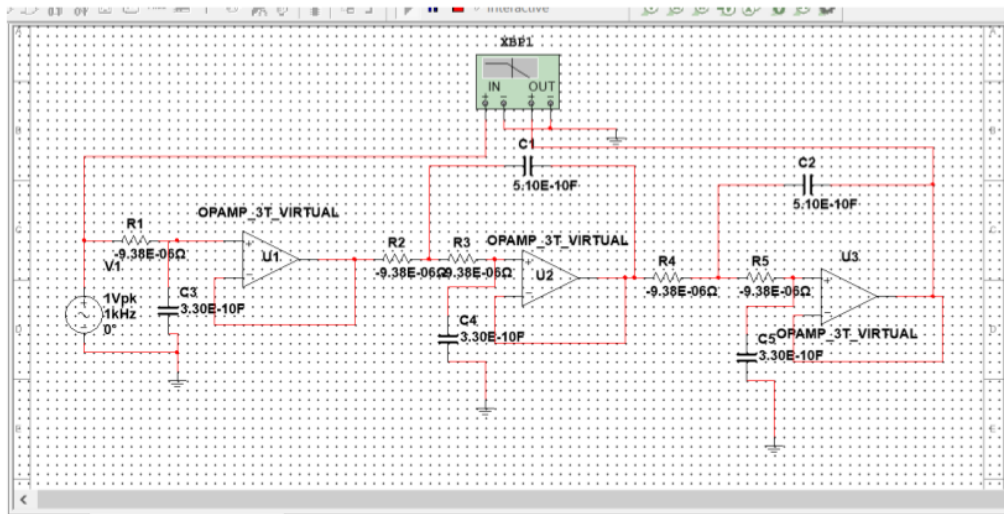


Figure 21: 5th Order Tschebyscheff Filter

Figure 21 shows a 5th Order Chebyshev Filter with the capacitor and resistor values.

3.1.3) Using a Butterworth filter

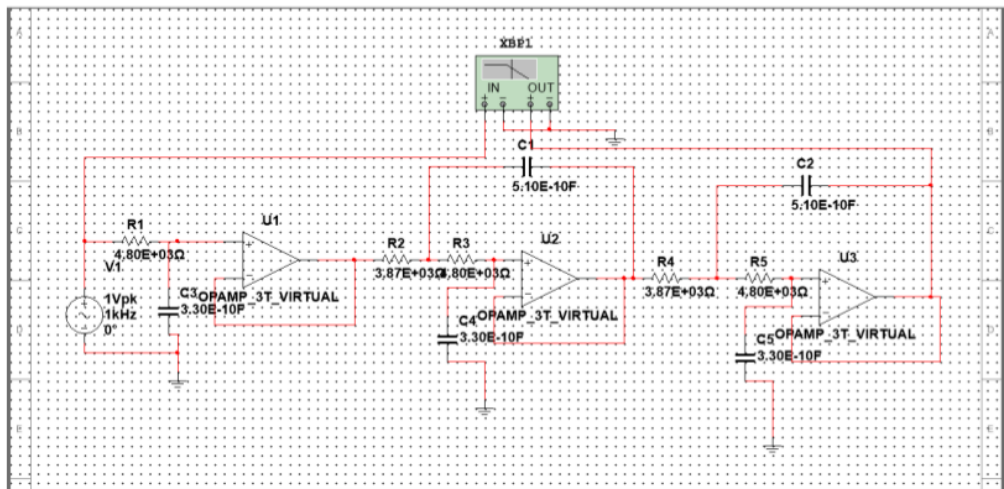


Figure 22: 5th Order Butterworth Filter

Figure 22 shows a 5th Order Butterworth Filter which gives the working component values for both the resistors and the capacitors.

3.2) Justify any arbitrary design decisions you make and show all calculations

3.2.1) Butterworth filter workings

Table 16–5. Butterworth Coefficients

n	i	a_i	b_i	$k_i = \frac{f_{Ci}}{f_C}$	Q_i
1	1	1.0000	0.0000	1.000	—
2	1	1.4142	1.0000	1.000	0.71
3	1	1.0000	0.0000	1.000	—
	2	1.0000	1.0000	1.272	1.00
4	1	1.8478	1.0000	0.719	0.54
	2	0.7654	1.0000	1.390	1.31
5	1	1.0000	0.0000	1.000	—
	2	1.6180	1.0000	0.859	0.62
	3	0.6180	1.0000	1.448	1.62

Figure 23: Butterworth Coefficients

The values highlighted in figure 23 show the Butterworth coefficients of values a_i and b_i . From these values, new resistor and capacitor values can be determined and inputted into the Butterworth circuit.

	A	B	C	D	E	F	G	H	I	J
1	Frequency =	90000								
2	a1 =	1.618						a1c2=	8.2518E-10	
3	b1 =	1			R1 =	3.87E+03		4b1c1c2	6.73E-19	
4								4pifcc1c2=	1.90E-13	
5	C1 =	3.30E-10			R2 =	4.80E+03				
6										
7	C2 =	5.10E-10								
8										

Figure 24: Butterworth Filter component calculations for R1, R2, C1, C2

From figure 24 it can be seen that the a and b values have been extracted from figure 23 and placed in this excel sheet to make further workings.

To determine the R1 value and R2 value the following workings must be made:

$$R1 = (I2 - (\text{SQRT}((I2 * I2) - I3))) / I4$$

In order to determine the values for I2, I3 and I4 the following mathematical equations must be implemented, these being:

$$I2 = B2 * B7$$

$$I3 = 4 * B3 * B5 * B7$$

$$I4 = 4 * \text{PI}() * B1 * B5 * B7$$

From the finished equations, these can be used to calculate the resistor values.

From the graph a value of 150.94 has been recorded which is then against a value of -25.68 dB

3.2.2) Bessel filter workings

Table 16–4. Bessel Coefficients

n	i	a _i	b _i	k _i = f _{ci} / f _c	Q _i
1	1	1.0000	0.0000	1.000	—
2	1	1.3617	0.6180	1.000	0.58
3	1	0.7560	0.0000	1.323	—
	2	0.9996	0.4772	1.414	0.69
4	1	1.3397	0.4889	0.978	0.52
	2	0.7743	0.3890	1.797	0.81
5	1	0.6656	0.0000	1.502	—
	2	1.1402	0.4128	1.184	0.56
	3	0.6216	0.3245	2.138	0.92

Figure 25: Bessel Coefficients table

The values for the bessel coefficient have been extracted and used from this table. The values that have been extracted from the 5th order are the a_i value being 1.1402 and the b_i values being 0.4128.

	A	B	C	D	E	F	G	H	I
1	Frequency	90000							
2	a1 =	1.1402						a1c2=	5.82E-10
3	b1 =	0.4128			R1 =	1.77E+03		4b1c1c2	2.78E-19
4								4pifcc1c2=	1.90E-13
5	C1 =	3.30E-10			R2 =	4.34E+03			
6									
7	C2 =	5.10E-10							
8									

Figure 26: Bessel Filter component calculations for R1, R2, C1, C2

Figure 28 presents the workings for the Bessel filter. From these workings a value for the R1, R2, C1, and C2 can be found.

In order to work out the R1 and R2 values the following equation must be made:

$$R1 = (I2 - (\text{SQRT}((I2 * I2) - I3))) / I4$$

$$R2 = (I2 + (\text{SQRT}((I2 * I2) - I3))) / I4$$

In order to complete this equation you must first calculate the a1c2 value, the 4b1c1c2 value and the 4pifcc1c2. To do this the following equations must be used:

$$A1c2 = B2 * B7$$

$$4b1c1c2 = 4 * B3 * B5 * B7$$

$$4pifcc1c2 = 4 * PI() * B1 * B5 * B7$$

Once the results were found from these equations which can be seen in figure 28, they were used in the resistor equations above to produce a final value.

3.2.3) Chebyshev filter workings

Table 16–9. Tschhebyscheff Coefficients for 3-dB Passband Ripple

n	i	a _i	b _i	k _i = f _{ci} / f _c	Q _i
1	1	1.0000	0.0000	1.000	—
2	1	1.0650	1.9305	1.000	1.30
3	1	3.3496	0.0000	0.299	—
	2	0.3559	1.1923	1.396	3.07
4	1	2.1853	5.5339	0.557	1.08
	2	0.1964	1.2009	1.410	5.58
5	1	5.6334	0.0000	0.178	—
	2	0.7620	2.6530	0.917	2.14
	3	0.1172	1.0686	1.500	8.82

Figure 27: Coefficient values for a Chebyshev filter at -3dB

Figure 31 shows the coefficient values for ai and bi.

	A	B	C	D	E	F	G	H	I	J
1	Frequency	90000								
2	a1 =	0.762						a1c2=	3.89E-10	
3	b1 =	2.653			R1 =	-9.38E-06		4b1c1c2	1.79E-18	
4								4pifcc1c2=	1.90E-13	
5	C1 =	3.30E-10			R2 =	-9.38E-06				
6										
7	C2 =	5.10E-10								
8										

Figure 28: Chebyshev Filter component calculations for R1, R2, C1, C2

The above excel spreadsheet displays the final values for the resistors and capacitors that have been used in the circuit.

In order to reach a resistor value, the values for $a1c2$, $ab1c1c2$, and $4pifcc1c2$ must be calculated. These are as follows:

$$A1c2 = B2 * B7$$

$$4b1c1c2 = 4 * B3 * B5 * B7$$

$$4pifcc1c2 = 4 * \pi() * B1 * B5 * B7$$

From these workings the final resistor values can be calculated, these being:

$$R1 = (I2 - (\text{SQRT}((I2 * I2) - I3))) / I4$$

$$R2 = (I2 + (\text{SQRT}((I2 * I2) - I3))) / I4$$

3.3) Designing a 3rd order Butterworth filter

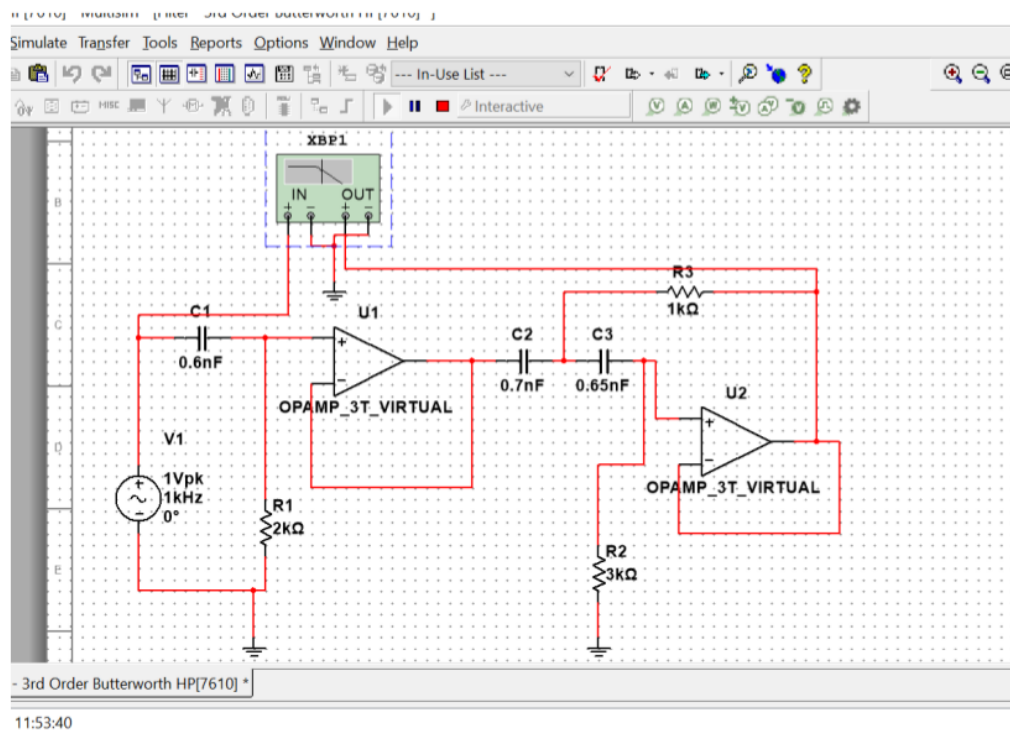


Figure 29: 3rd Order Butterworth filter

Figure 29 shows the circuitry and testing equipment for a 3rd Order Butterworth Filter. Each capacitor and resistor value had to be varied many times to determine a final value of 150kHz.

3.4) Designing a 6th order Butterworth filter

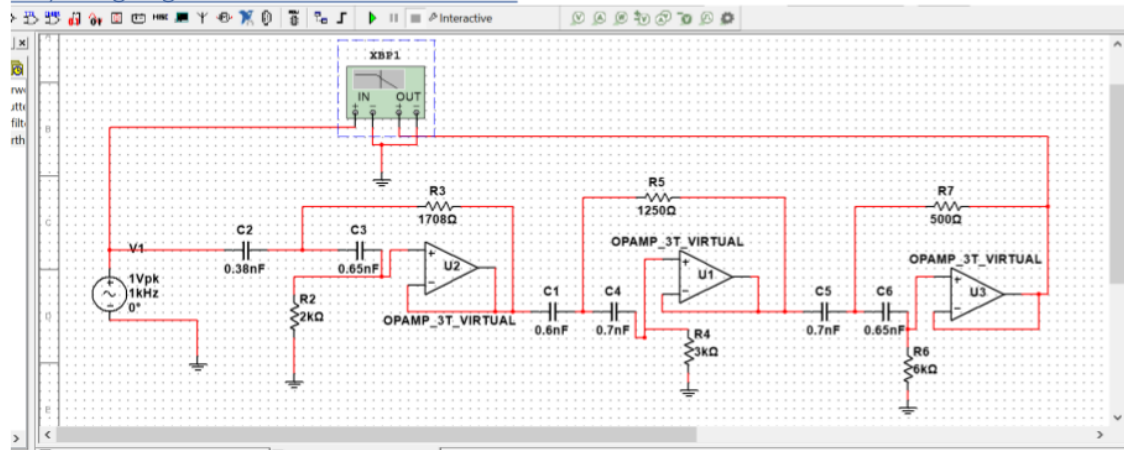


Figure 30: 6th Order Butterworth Filter

Figure 30 above displays a 6th order Butterworth filter. Figure 15 shows how different orders are calculated. For 6th order Butterworth circuit 3 2nd order filters must be used. The resistor values and capacitor values have been adjusted to meet a final magnitude reading of 150kHz.

3.5) Designing a 9th order Butterworth filter

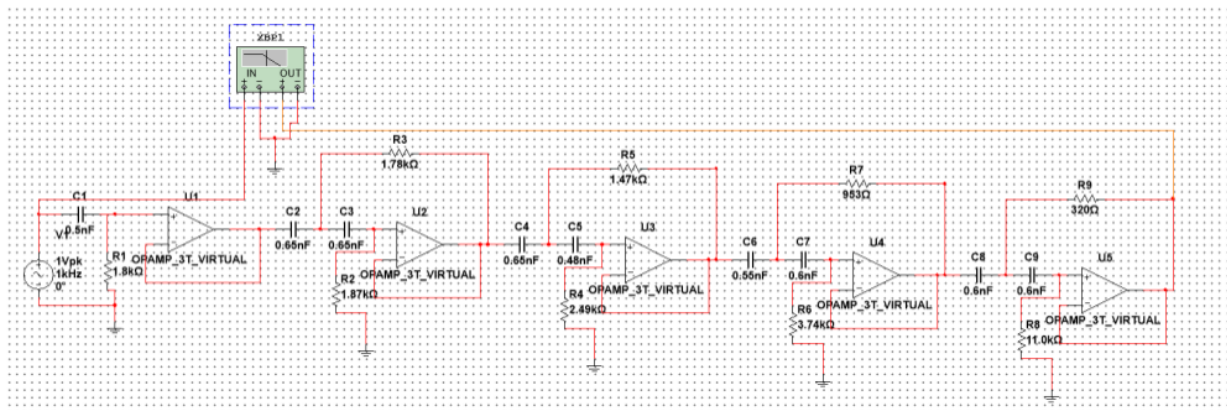


Figure 31: 9th Order Butterworth Filter

Figure 31 shows a 9th Order Butterworth Filter. This filter combines five 2nd order filters in order to make a 9th order circuit. The capacitor values and resistor values have been adjusted to present a final calculated magnitude value of 150kHz.

4) Testing and improving the design

4.1) Graph displaying the results

Below you can see 3 different filters with 6 different graphs. 3 graphs have been displayed showing the magnitude and phase of a Butterworth filter, a Bessel filter, and a Chebyshev Filter. The next three graphs show the readings for all three filters but set up at 5th order circuits.

4.1.1) 5th Order Butterworth filter graph results

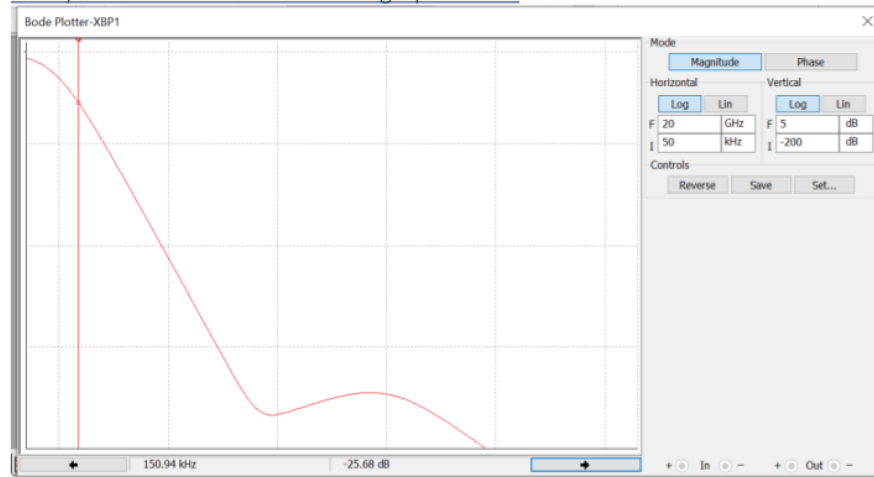


Figure 32: Magnitude for a Butterworth filter

Figure 25 presents a graph result showing a magnitude reading. A value of 150 kHz has been given to attempt to meet and scale on the graph.

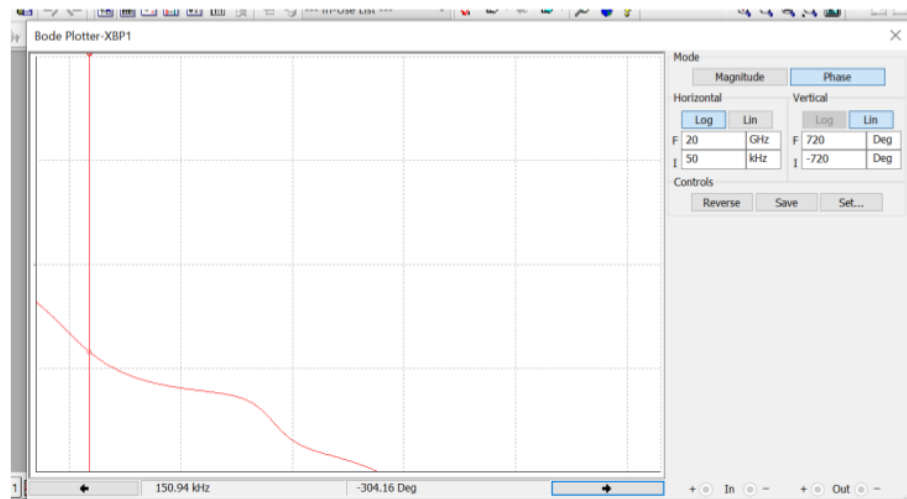


Figure 33: Phase graph for a Butterworth filter

Figure 26 shows a phase graph for a Butterworth filter. Again a 150.94 kHz has been met which is against a reading of -304.16 degrees.

4.1.2) 5th Order Bessel filter graph results

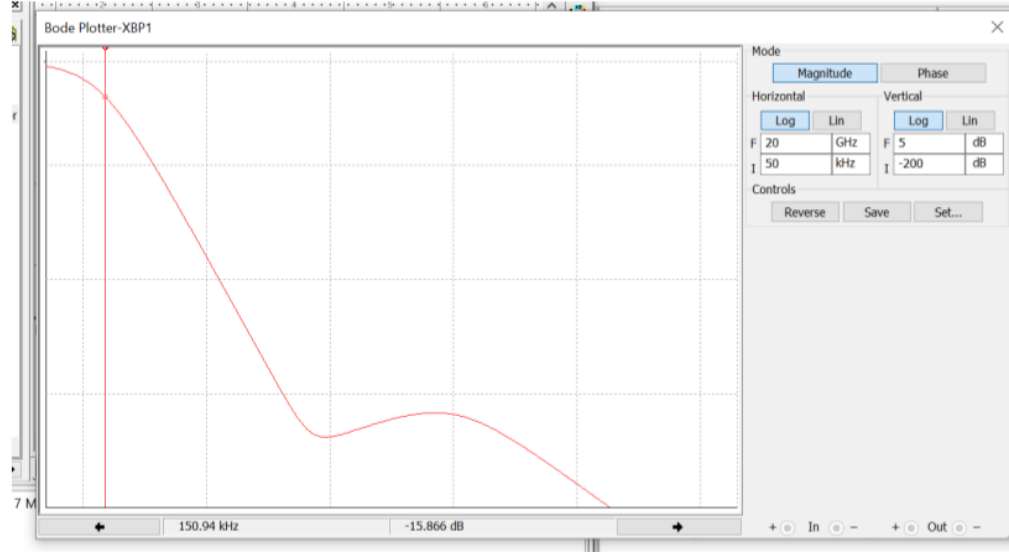


Figure 34: Magnitude graph for a Bessel filter

Figure 29 shows a graph for a magnitude reading from the Bessel filter. The value of 150 kHz has been plotted and a matching results of -15.866 dB has been recorded.

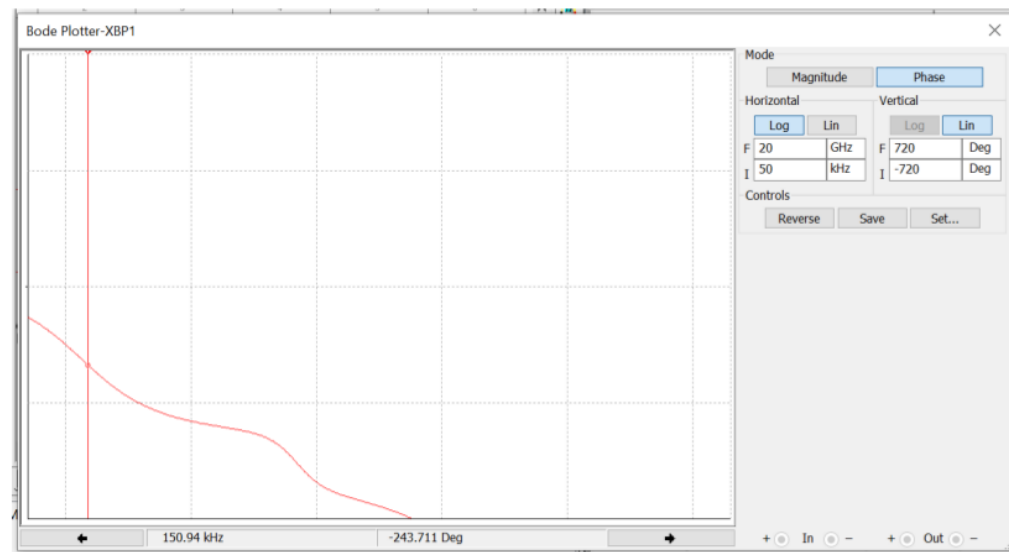
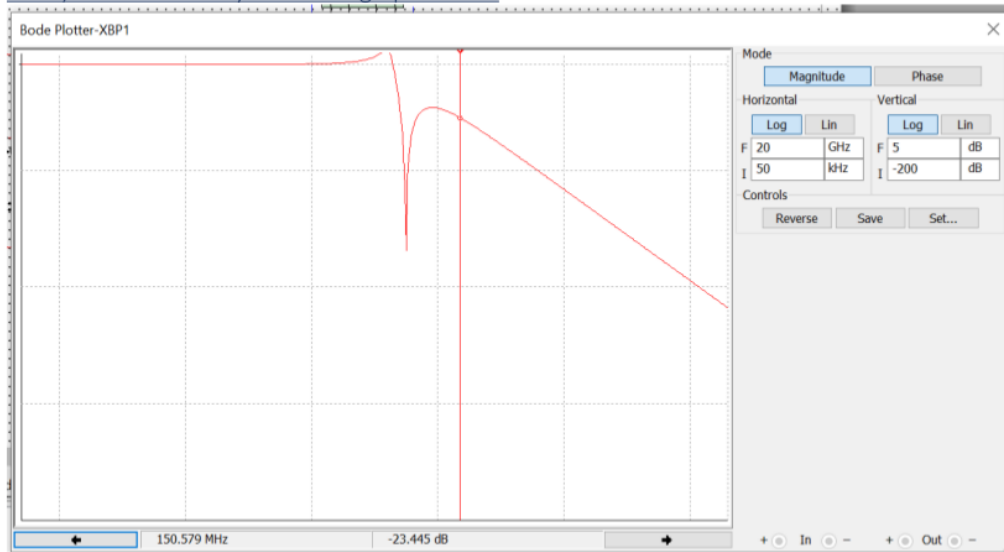


Figure 35: Phase graph for a Bessel filter

Figure 30 shows a Bessel filter recording the phase. A value of 150.94 kHz has been plotted against a value of -243.711 degrees.

4.1.3) 5th Order Chebyshev filter graph results



A graph can then be determined from the testing equipment in the circuit. A magnitude showing values of 150.579MHz and -23.445 dB can be plotted.

4.1.4) 3rd order Butterworth filter graph results

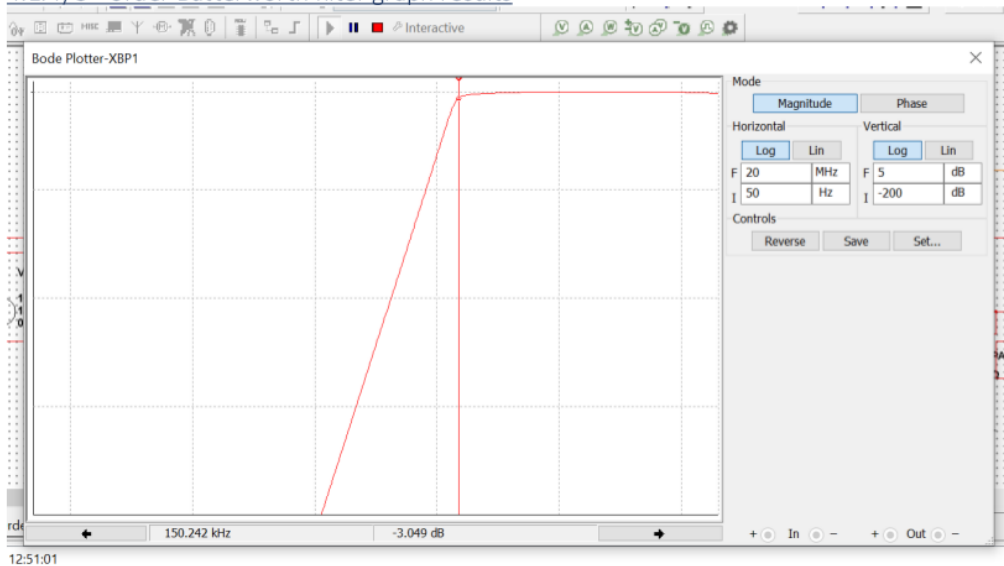


Figure 36: 3rd Order Butterworth graph

Figure 36 displays the reading for a 3rd order Butterworth filter. Using such test equipment a magnitude waveform and a phase waveform were formed from the working circuitry in the 3rd order circuit. A value of 150kHz had to be met therefore the capacitor and resistor values were adjusted accordingly.

A final value of 150.242kHz was recorded at a -3.049 dB reading. The line that calculated these results was found just before the peak of this waveform.

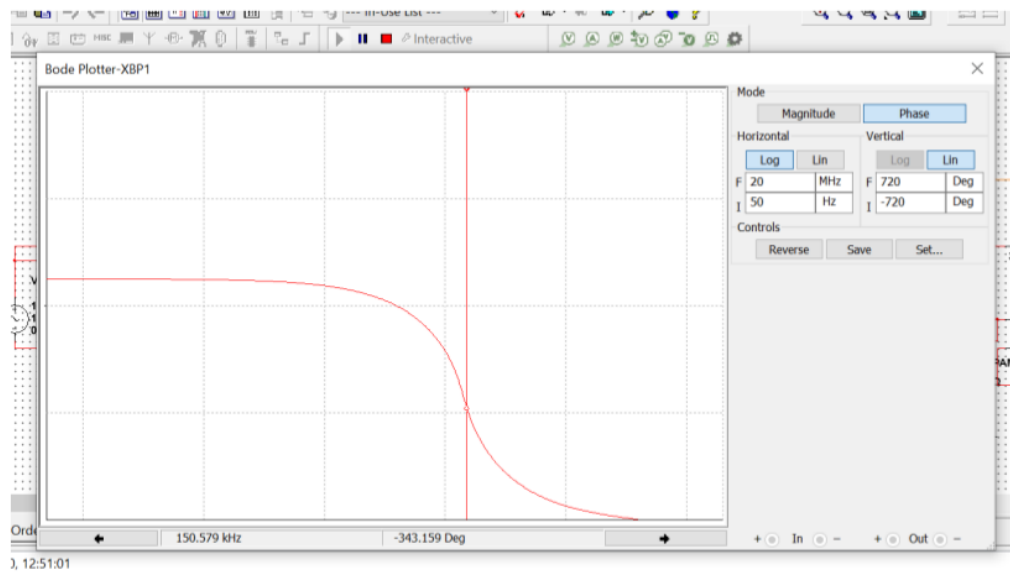


Figure 37: Waveform showing the phase for a 3rd order Butterworth Filter

Figure 37 shows the waveform for a 3rd order Butterworth Filter. This waveform presents a phase result, these being 150.579kHz and -343.159 Deg. These results have been plotted directly in the centre of the waveform.

4.1.5) 6th order Butterworth filter graph results

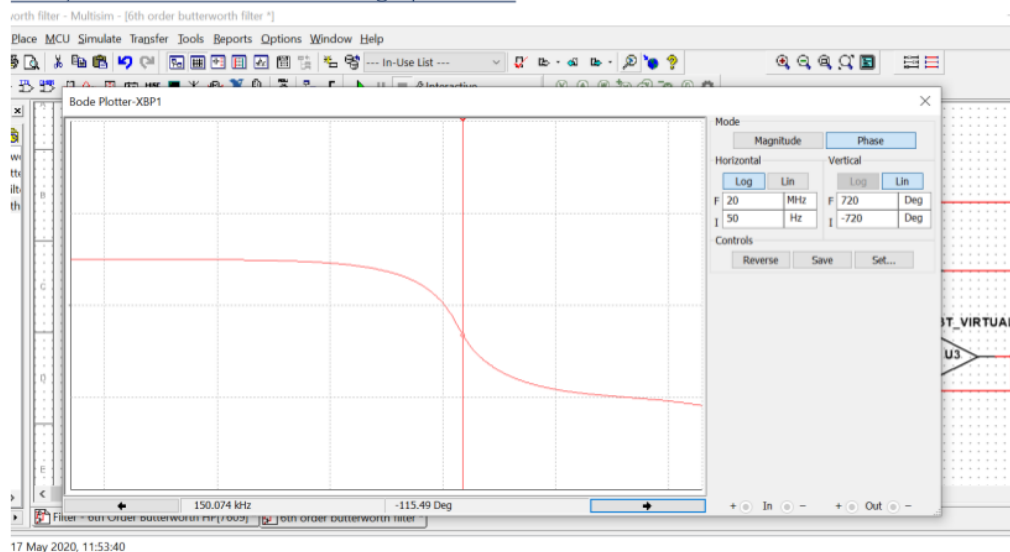


Figure 38: Magnitude for a 6th order Butterworth filter

A value for the phase have been plotted above in figure 38. These plotted results show both the frequency and the angle. These being 150.074kHz and -115.49 Deg.

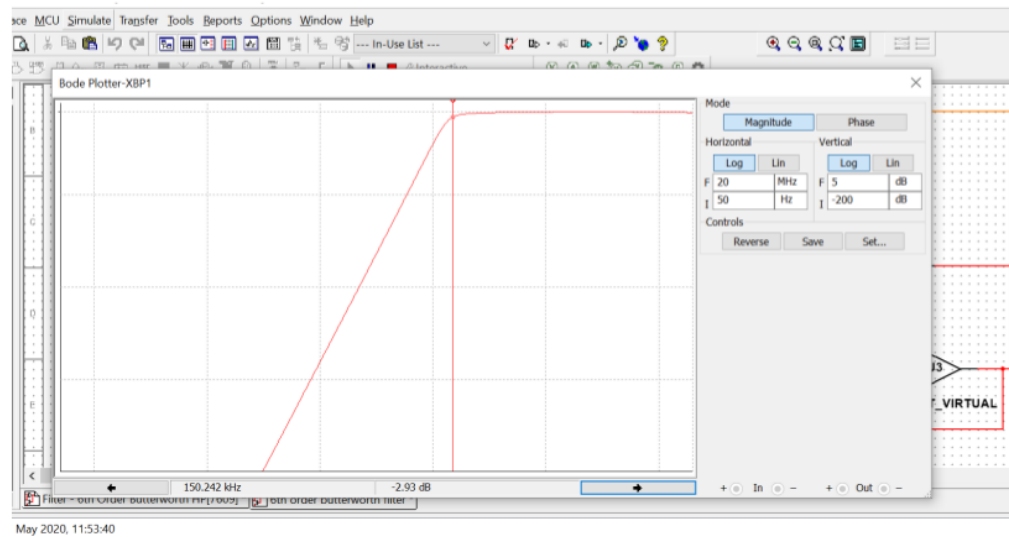


Figure 39: Magnitude for a 6th order Butterworth Filter

Figure 39 above shows the plotted results for a 6th order Butterworth filter displaying a magnitude waveform. The values that have been plotted in this waveform are 150.242kHz and -2.93dB.

4.1.6) 9th Order Butterworth filter graph results

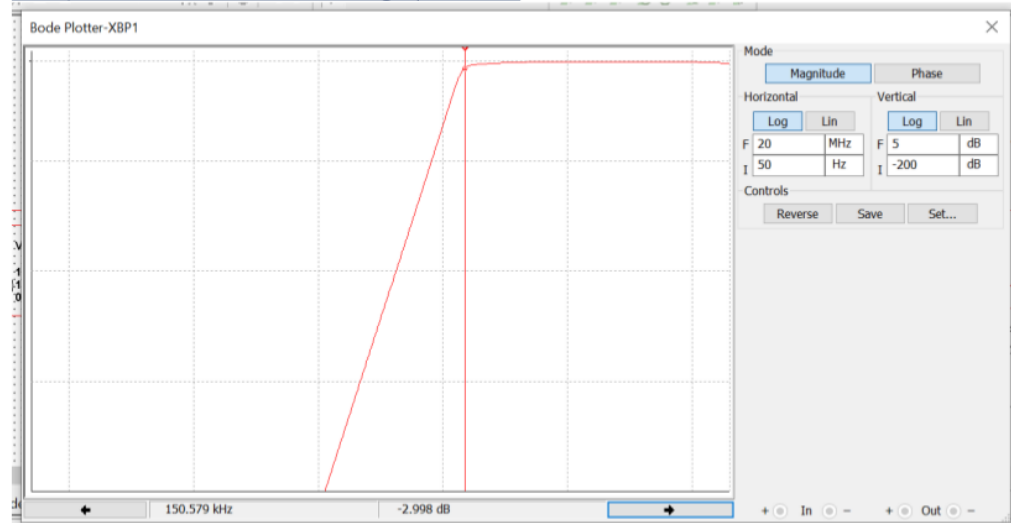


Figure 40: Magnitude for a 9th Order Filter

Figure 40 shows the waveform of the magnitude reading. A line has been plotted against the waveform to determine different values for both the frequency and the dB's. These values can be seen above as 150.579kHz and -2.998dB.

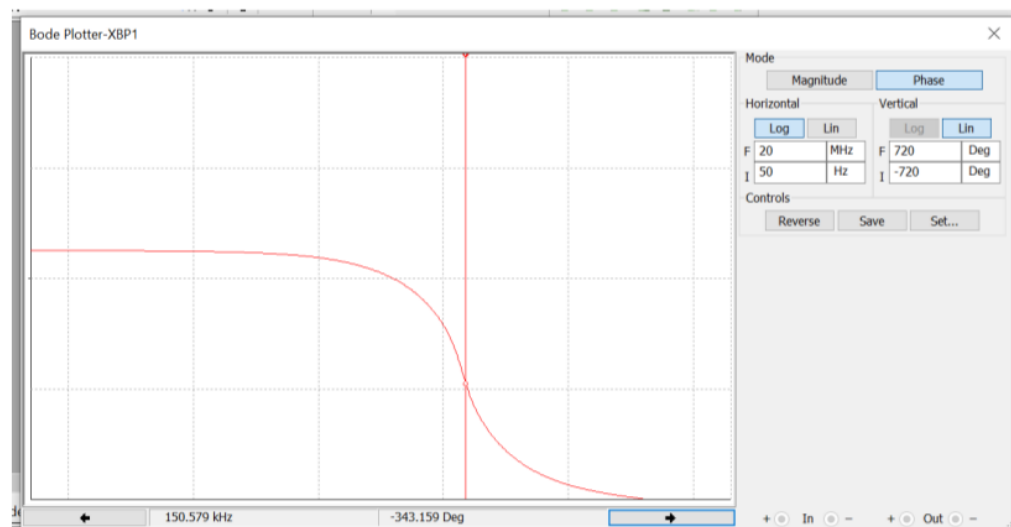


Figure 41: Phase waveform for a 9th Order Butterworth filter

Figure 41 shows the phase mode waveform. This waveform displays a plotted line through the centre of the waveform. A value of 150.579kHz and -343.159 Deg can be found where the line meets the waveform.

5) Conclusions (400)

To conclude, from this report I have carried out heavy research into active filters. I firstly gained a better knowledge and understanding of what a active filter was, what an active filter was made up of and how to construct an active filter with working circuitry.

I later expanded my research into the three different types of filters, these being the Butterworth filter, the Bessel filter and the Chebyshev filter. From watching videos and extracting research from the web. I later began to gain a better understanding of how each filter differs. After I had a better understanding of the circuitry of each I then found different test equipment that could be used to extract a graph from the data in the circuit. Through this research I was able to understand in what areas different actions happen. For example in a Butterworth filter graph there is a very flat band pass with no rippling. In the Bessel Filter again there is a flat pass band but the roll off from the Pass Band to the Stop Band will be the lowest amount out of all three Filter Approximations shown.

Research was later gathered from sources explaining about different ordered circuits and combining different orders to make bigger orders.

I later carried out some research into Filters used in specific control processes, like the noise and anti-aliasing filters used in modern day electronics.

I then carried out the task of designing three 5th order low pass filters using the Bessel, Butterworth and Chebyshev. I used the 5th order template to base my capacitor and resistor values around so that I could later link in the test equipment to gain a waveform for the magnitude and the phase. In order to plot my capacitor and resistor reading I had to use the filter calculation template. From here I was able to extract information from the coefficients table and use to determine final values for all three filters. Once the capacitor and resistor values were added I could then derive a graph in which I plotted a line which produced a frequency of 150kHz or as close to.

I later constructed the working circuitry for a 3rd, 6th, and 9th order Butterworth Filter. Through trial and error I varied all of my capacitor and resistor values until I reached by target value of 150kHz which produced a gain of -3dB.

After this all 6 filter circuits had been constructed a graph value was taken for both the Magnitude and the phase of the waveform. From these plots I was able to record the values for the frequency and the gain.

6) Reference list and bibliography

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7) Annexe for diagrams, data sheets, results tables etc

16.9 Filter Coefficient Tables

The following tables contain the coefficients for the three filter types, Bessel, Butterworth and Tschhebyscheff. The Tschhebyscheff tables (Table 16–9) are split into categories for the following passband ripples: 0.5 dB, 1 dB, 2 dB, and 3 dB.

The table headers consist of the following quantities:

n	is the filter order
i	is the number of the partial filter.
a_i, b_i	are the filter coefficients.
k_i	is the ratio of the corner frequency of a partial filter, f_{Ci} , to the corner frequency of the overall filter, f_C . This ratio is used to determine the unity-gain bandwidth of the op amp, as well as to simplify the test of a filter design by measuring f_{Ci} and comparing it to f_C .
Q_i	is the quality factor of the partial filter.
f_i / f_C	this ratio is used for test purposes of the allpass filters, where f_i is the frequency, at which the phase is 180° for a second-order filter, respectively 90° for a first-order all-pass.
T_{gr0}	is the normalized group delay of the overall all-pass filter.

n	i	a_i	b_i	$k_i = f_{Ci}/f_C$	Q_i
1	1	1.0000	0.0000	1.000	—
2	1	1.3617	0.6180	1.000	0.58
3	1	0.7560	0.0000	1.323	—
	2	0.9996	0.4772	1.414	0.69
4	1	1.3397	0.4889	0.978	0.52
	2	0.7743	0.3890	1.797	0.81
5	1	0.6656	0.0000	1.502	—
	2	1.1402	0.4128	1.184	0.56
	3	0.6216	0.3245	2.138	0.92
6	1	1.2217	0.3887	1.063	0.51
	2	0.9606	0.3505	1.431	0.61
	3	0.5131	0.2756	2.447	1.02
7	1	0.5937	0.0000	1.648	—
	2	1.0944	0.3395	1.207	0.53
	3	0.8304	0.3011	1.695	0.66
	4	0.4332	0.2381	2.731	1.13
8	1	1.1112	0.3162	1.164	0.51
	2	0.9754	0.2979	1.381	0.56
	3	0.7202	0.2621	1.963	0.71
	4	0.3728	0.2087	2.992	1.23
9	1	0.5386	0.0000	1.857	—
	2	1.0244	0.2834	1.277	0.52
	3	0.8710	0.2636	1.574	0.59
	4	0.6320	0.2311	2.226	0.76
	5	0.3257	0.1854	3.237	1.32
10	1	1.0215	0.2650	1.264	0.50
	2	0.9393	0.2549	1.412	0.54
	3	0.7815	0.2351	1.780	0.62
	4	0.5604	0.2059	2.479	0.81
	5	0.2883	0.1665	3.466	1.42

[illegible]

Table 16–9. Tschhebyscheff Coefficients for 3-dB Passband Ripple

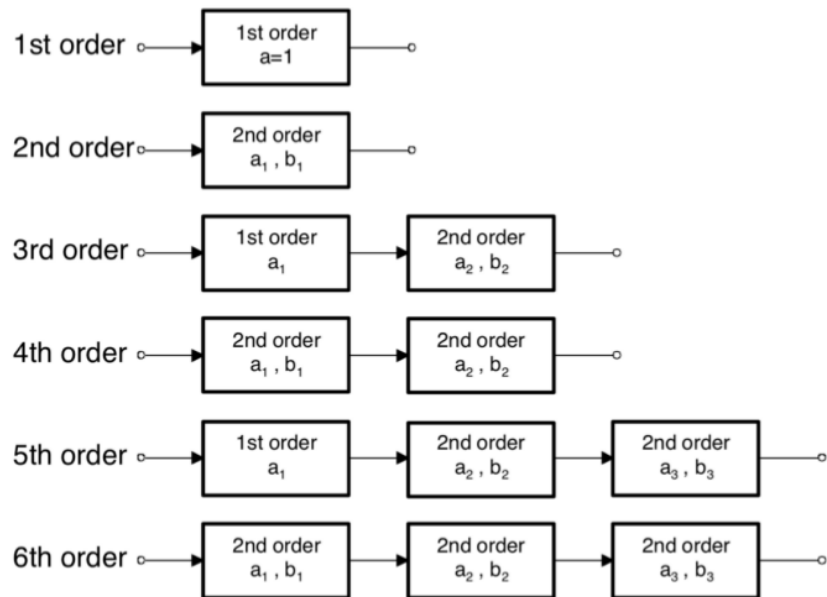
n	i	a_i	b_i	$k_i = f_{Ci} / f_C$	Q_i
1	1	1.0000	0.0000	1.000	—
2	1	1.0650	1.9305	1.000	1.30
3	1	3.3496	0.0000	0.299	—
	2	0.3559	1.1923	1.396	3.07
4	1	2.1853	5.5339	0.557	1.08
	2	0.1964	1.2009	1.410	5.58
5	1	5.6334	0.0000	0.178	—
	2	0.7620	2.6530	0.917	2.14
	3	0.1172	1.0686	1.500	8.82
6	1	3.2721	11.677 ₃	0.379	1.04
	2	0.4077	1.9873	1.086	3.46
	3	0.0815	1.0861	1.489	12.78
7	1	7.9064	0.0000	0.126	—
	2	1.1159	4.8963	0.670	1.98
	3	0.2515	1.5944	1.222	5.02
	4	0.0582	1.0348	1.527	17.46
8	1	4.3583	20.294 ₈	0.286	1.03
	2	0.5791	3.1808	0.855	3.08
	3	0.1765	1.4507	1.285	6.83
	4	0.0448	1.0478	1.517	22.87
9	1	10.175 ₉	0.0000	0.098	—
	2	1.4585	7.8971	0.526	1.93
	3	0.3561	2.3651	1.001	4.32
	4	0.1294	1.3165	1.351	8.87
	5	0.0348	1.0210	1.537	29.00
10	1	5.4449	31.378 ₈	0.230	1.03
	2	0.7414	4.7363	0.699	2.94
	3	0.2479	1.9952	1.094	5.70
	4	0.1008	1.2638	1.380	11.15
	5	0.0283	1.0304	1.530	35.85

[illegible]

Table 16–5. Butterworth Coefficients

n	i	a_i	b_i	$k_i = f_{Ci} / f_C$	Q_i
1	1	1.0000	0.0000	1.000	—
2	1	1.4142	1.0000	1.000	0.71
3	1	1.0000	0.0000	1.000	—
	2	1.0000	1.0000	1.272	1.00
4	1	1.8478	1.0000	0.719	0.54
	2	0.7654	1.0000	1.390	1.31
5	1	1.0000	0.0000	1.000	—
	2	1.6180	1.0000	0.859	0.62
	3	0.6180	1.0000	1.448	1.62
6	1	1.9319	1.0000	0.676	0.52
	2	1.4142	1.0000	1.000	0.71
	3	0.5176	1.0000	1.479	1.93
7	1	1.0000	0.0000	1.000	—
	2	1.8019	1.0000	0.745	0.55
	3	1.2470	1.0000	1.117	0.80
	4	0.4450	1.0000	1.499	2.25
8	1	1.9616	1.0000	0.661	0.51
	2	1.6629	1.0000	0.829	0.60
	3	1.1111	1.0000	1.206	0.90
	4	0.3902	1.0000	1.512	2.56
9	1	1.0000	0.0000	1.000	—
	2	1.8794	1.0000	0.703	0.53
	3	1.5321	1.0000	0.917	0.65
	4	1.0000	1.0000	1.272	1.00
	5	0.3473	1.0000	1.521	2.88
10	1	1.9754	1.0000	0.655	0.51
	2	1.7820	1.0000	0.756	0.56
	3	1.4142	1.0000	1.000	0.71
	4	0.9080	1.0000	1.322	1.10
	5	0.3129	1.0000	1.527	3.20

[illegible]



FINAL GRADE

GENERAL COMMENTS

Instructor

33/100

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RESEARCH-INFORMED LITERATURE



There was evidence of further reading and research with the inclusion of a reference list and appropriate in text referencing. Your interpretation and understanding of the additional research was good. Some of the sources were over-used and you should consider widening your range of sources for future assignments.

4/10

KNOWLEDGE AND UNDERSTANDING



The knowledge and understanding of the subject demonstrated by this assignment was generally superficial and lacked critical understanding. The report lacked a lot of the required detail and contained significant inaccuracies and too much irrelevant material. Additionally, your understanding of most of the basic principles as well as the higher level concepts was not shown. Further work - There were a few omissions and misunderstandings throughout the task, which could be read up on for future reference. Explanations need to be written in much more detail and written in a more logical and clearer way.

9/30

ANALYSIS



Your analysis of the task was mainly descriptive and superficial and lacked a lot of the required detail. Your conclusions were also mainly descriptive and there were several instances of flawed understanding. There was little evidence of critical analysis with most results accepted uncritically as

6/20

fact and without explaining the underlying principles. You did however demonstrate some basic analytical skills and your approach to the task was logical.

PRACTICAL APPLICATION AND DEP.



The application of your practical skills for this task was generally rudimentary; you used the resources appropriately when designing the circuit and you used appropriate options for testing and evaluating the circuit performance - albeit to a limited fashion. Testing generally lacked a lot of the required detail however and you should have included a comprehensive set of results for each stage.

12/30

SKILLS FOR PROFESSIONAL PRAC.



Your written report was reasonably well presented in terms of content and layout and was mostly structured in a coherent way, however you should endeavour to use the available word count more effectively in future. -5 for exceeding word count

2/10