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HNC yr2 electrical and electronic engineering

SGEE5000 – Electronics 2

Assignment 2
Active filter design

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Introduction

During the course of this assignment research will be conducted into three main types of active filters and how they are used in modern systems. Six filter circuits will then be designed, tested and evaluated in a report on the findings of the activities undergone. The aim of this assignment is to form a better understanding of active filters and how they are designed and built. Three 5th order filter circuits will be designed which will be of different types along with three circuits of the same type with different order values to form a better understanding of circuit design and how order value and filter type affect the results.

Research

Executive summary rather than aims and objectives.

A filter circuit takes an inputted frequency and only allows a selected part of the inputted frequencies bandwidth to pass to its output. These circuits are used to block unwanted frequencies or signals to improve the operation of the receiving device. E.g. a speaker. Because of this, filter circuits are said to be “frequency selective” (LinkedIn, 2020)

Filters can be placed into four categories: Low-pass, High-pass, Band-stop and Band-pass. A low-pass filter allows frequencies lower than its cut-off point to pass whereas a high-pass filter allows frequencies higher than its cut-off point to pass. A band-stop filter however, prevents all frequencies within a specific bandwidth from passing and a Band-pass filter only allows frequencies within a specified bandwidth to pass.

There are two main types of filter circuits: Passive and active.

Passive filters are created using RL, RC or RLC (Resistor/Inductor/Capacitor) circuits and Active filters are created using a combination of op-amps, resistors and capacitors.

In terms of performance. Butterworth, Bessel and Chebyshev are all pole response filters, but they all have different characteristics when shown on a filter response graph with magnitude as the Y-axis and frequency as the X-axis. If you plot the three against each other it can be seen that the Chebyshev has the sharpest frequency cut-off, the Bessel has the softest frequency cut-off and the Butterworth sits between the two (see figure 1). But as you go from Chebyshev to Butterworth to Bessel, the time domain gets steadily better and in practical terms this would mean less ringing.

However, when using similar values to those used in figure 1, the Bessel filter will have the best step response as it will be smooth and settle at its desired value quickly while the Chebyshev will have the worst step response and will take far longer to settle. (Analog devices, 2020)

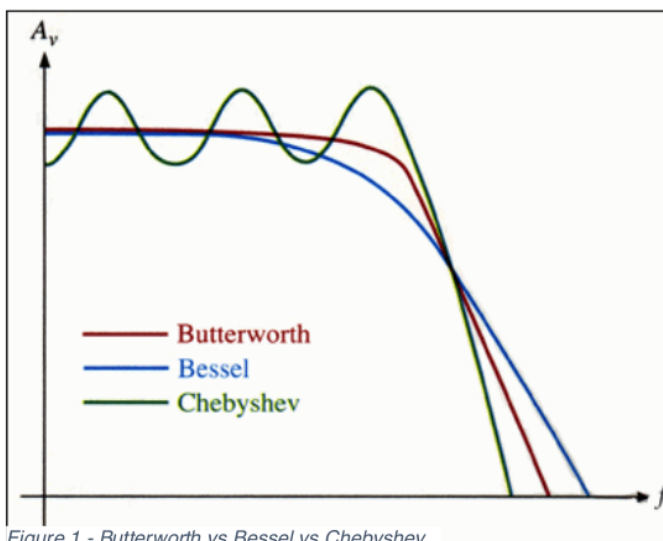


Figure 1 - Butterworth vs Bessel vs Chebyshev

Bessel filter:

The Bessel filter is more often used in audio-crossover devices like a cars speaker system because when compared to the Butterworth and Chebyshev filters it has a cut-off frequency curve which preserves the wavelength shape. Because it preserves the wavelengths shape when cut-off is reached it gives good phase characteristics and is great for preserving a good audio quality. For use in a speaker system low-pass Bessel filters are used for subwoofers as they primarily only use the lower frequencies. Other audio cross-over devices also using Bessel filter technology set for high-pass, will send the higher frequencies to better suited speakers.

Butterworth filter:

The Butterworth has arguably the most stable frequency response of the three in the sense that once the cut-off frequency is reached the roll-off drops at a steady and constant rate to negative infinity. If compared to a Chebyshev filter, the Chebyshev has a faster roll-off to negative infinity. Which means the Butterworth filter will require a higher order filter circuit to achieve the same roll-off as the Chebyshev filter. However, when looking at pass-band. Butterworth filters have a more linear phase response compared to Chebyshev filters. Also, the Butterworth filter is the only of the three with a monotonically changing magnitude function which means it alternates but never increases or decreases in overall value. The Butterworth filter is normally used for data conversion devices as it has a good max flat-pass band characteristic.

Chebyshev filter:

"The Chebyshev filter topology is used in many RF applications because of its fast transition from pass-band to stop-band using LC combinations" (electronics-notes, 2020) the Chebyshev frequency response has the steepest roll-off of the three filters giving the fastest pass-band to stop-band transition but is the only one with pass-band ripple (shown in figure 1) and can also be seen in stop-band. This ripple makes it unacceptable for many applications but because of the steep roll-off, it does however cut down on unwanted harmonics and provides better results. Meaning it can be used as a noise filter. However, the higher the order of the Chebyshev filter, the smaller the ripple becomes. From passband to stopband the Chebyshev is the sharpest and thus, most efficient. Followed by the Butterworth and lastly the Bessel.

Filters and modern electronic systems

One common example of filters used in modern electronic systems is their use in communication/ speaker systems. In these systems they are mainly used to reduce unwanted harmonics and help to produce a clearer signal or transmission at output for the equipment to use. In order to do this the filter is set up to only allow certain frequencies/ signals through and block off the rest. Filters in speaker systems where good audio quality is a high priority are usually low-pass filters. Meaning high frequency interference and corruption of the required signal is minimised. The Bessel filter would be ideal for quickly and efficiently reducing the unwanted high-frequency noise so the signal can be used by speakers perhaps in a sound system or in a telephone speaker.

"When it comes to acoustics and sound, the filter is used to stop the high frequency signals from transmitting sound to prevent echoes." (Muthukrishnan, 2020)

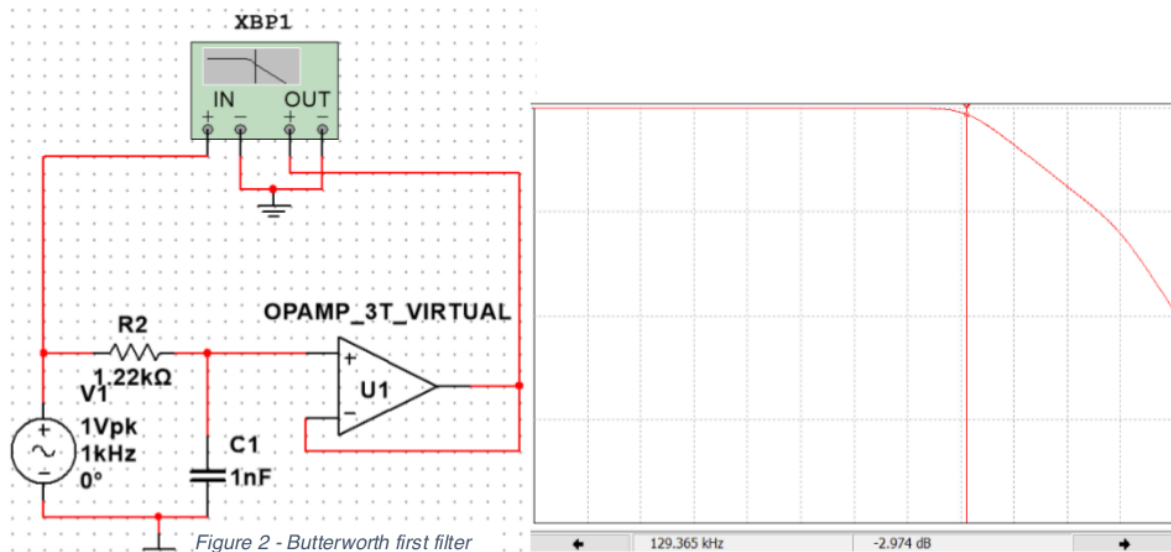
A second example of active filter use in modern electronic systems is the use of Butterworth filters in audio processing and data logging for use in things like biomedical

instruments which use specialised sensors to monitor a hospital patient for example. In this example, the Butterworth filter is used, since it has an exceptional flat-pass band characteristic when compared to the Chebyshev and Bessel filters. Meaning it is the most efficient at reducing unwanted frequencies outside its parameters. This makes it the most accurate since it reduces the unwanted frequencies the best out of the three, which allows it to output the best possible readings which is vital when a patient's life may be at risk.

Filter design

5th order Butterworth

First filter:



$$R_1 = \frac{a_1}{2\pi f_c c_1} = \frac{1}{2\pi \times 130 \times 10^3 \times 1 \times 10^{-9}} = 1.22K\Omega$$

Second filter:

With C1 set to 900pico-farads C2 must be greater than or equal to the value of C1.

$$C_2 = 900 \times 10^{-12} \times \frac{4b_2}{a_2^2} = 900 \times 10^{-12} \times \frac{4 \times 1}{1.618^2} = 1.38nF$$

Values for R1 (before) and R2 (after) the capacitor can be calculated by:

$$\frac{a_2 c_2 \pm \sqrt{a_2^2 c_2^2 - 4b_2 c_1 c_2}}{4\pi f_c c_1 c_2}$$

R1 using negative and R2 using positive

$$R_1 = \frac{1.618 \times 1.38 \times 10^{-9} - \sqrt{(1.618 \times 1.38 \times 10^{-9})^2 - 4 \times 1 \times 900 \times 10^{-12} \times 1.38 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 900 \times 10^{-12} \times 1.38 \times 10^{-9}} = 1.04k\Omega$$

$$R_2 = \frac{1.618 \times 1.38 \times 10^{-9} + \sqrt{(1.618 \times 1.38 \times 10^{-9})^2 - 4 \times 1 \times 900 \times 10^{-12} \times 1.38 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 900 \times 10^{-12} \times 1.38 \times 10^{-9}} = 1.17k\Omega$$

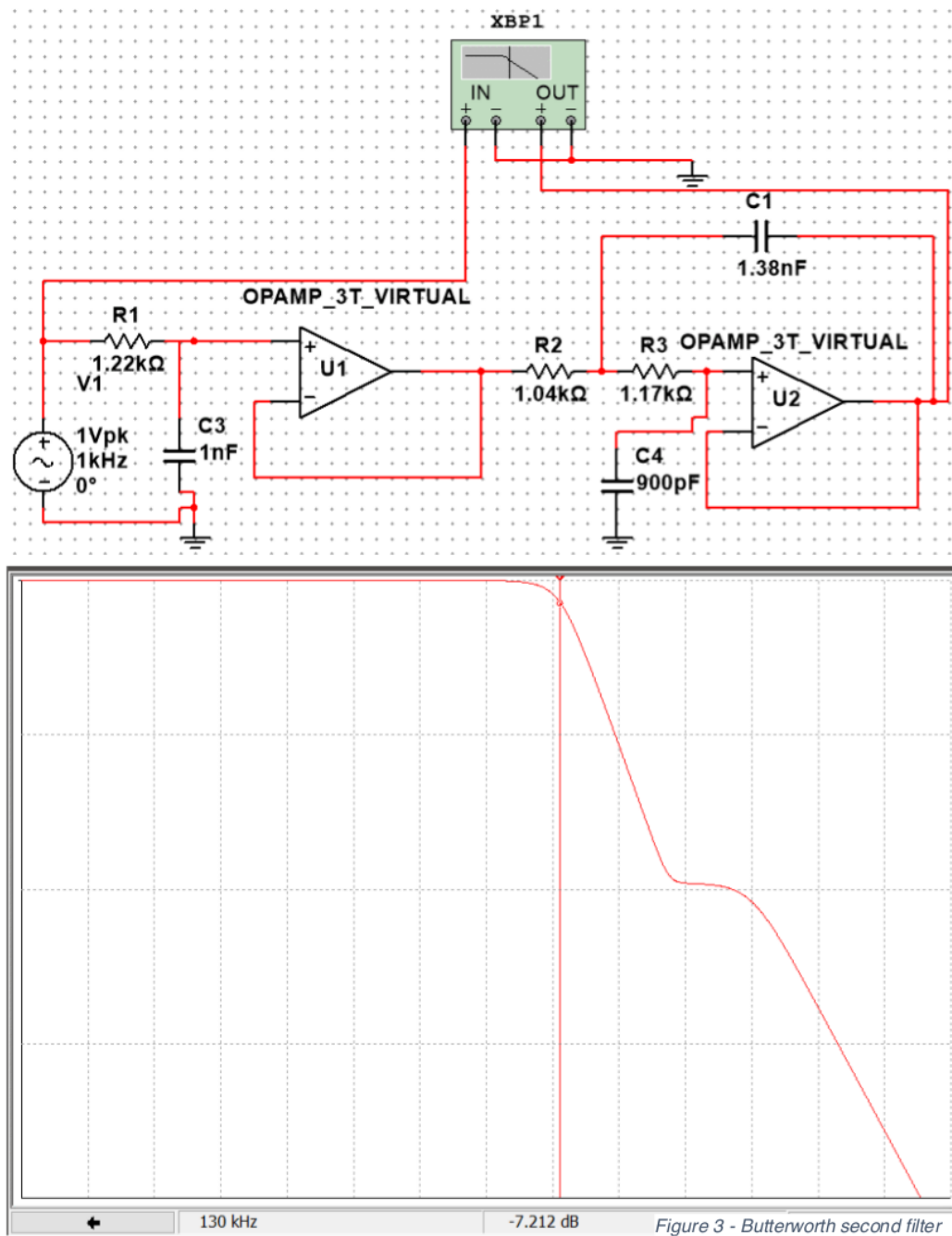


Figure 3 - Butterworth second filter

Third filter:

The previous process used in the second filter can be repeated for the third with the exception that a_2 and b_2 now become a_3 and b_3 and use their corresponding new values from the coefficient table.

Again, with C_1 set to 350pico-farads C_2 must be greater than or equal to the value of C_1 .

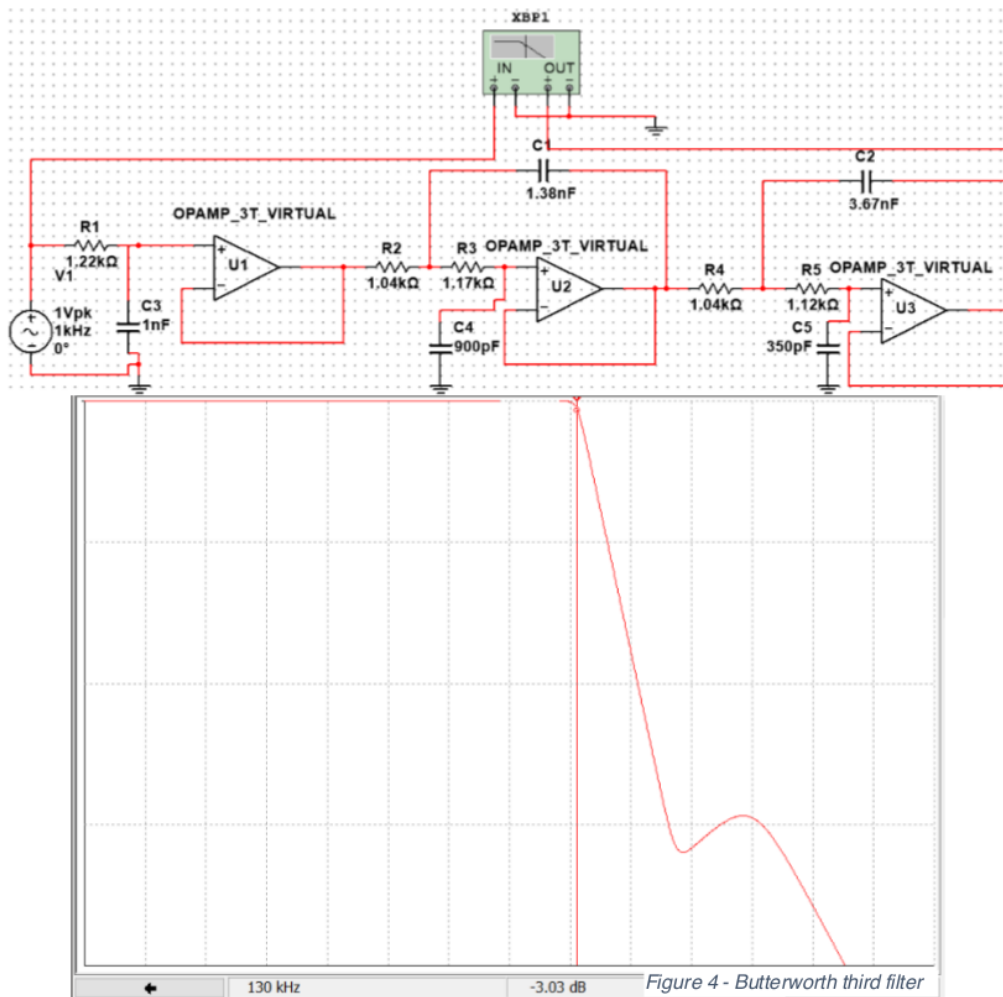
$$C_2 = 350 \times 10^{-12} \times \frac{4b_3}{a_3^2} = 350 \times 10^{-12} \times \frac{4 \times 1}{0.618^2} = 3.67nF$$

Values for R_1 (before) and R_2 (after) the capacitor can be calculated by:

$$\frac{a_3 c_2 \pm \sqrt{a_3^2 c_2^2 - 4b_3 c_1 c_2}}{4\pi f_c c_1 c_2}$$

R_1 using negative and R_2 using positive

$$R_1 = \frac{0.618 \times 3.67 \times 10^{-9} - \sqrt{(0.618 \times 3.67 \times 10^{-9})^2 - 4 \times 1 \times 350 \times 10^{-12} \times 3.67 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 350 \times 10^{-12} \times 3.67 \times 10^{-9}} = 1.04K\Omega$$



$$R_2 = \frac{0.618 \times 2.27 \times 10^{-9} + \sqrt{(0.618 \times 2.27 \times 10^{-9})^2 - 4 \times 1 \times 350 \times 10^{-12} \times 2.27 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 350 \times 10^{-12} \times 2.27 \times 10^{-9}}$$

$$= 1.12k\Omega$$

As shown in figure 4, the 5th order Butterworth filter is now complete with a 130Khz cut-off frequency. After which, the waveform decreases by 100Dbs per decade at roll-off.

Bessel filter

First filter

Using Bessel coefficients table:

$$R_1 = \frac{a_1}{2\pi f_c c_1} = \frac{0.6656}{2\pi \times 130 \times 10^3 \times 1 \times 10^{-9}} = 814.9\Omega$$

With a 1nF capacitor and a required cut off frequency of 130kHz, R1 can be calculated to be 814.9Ω

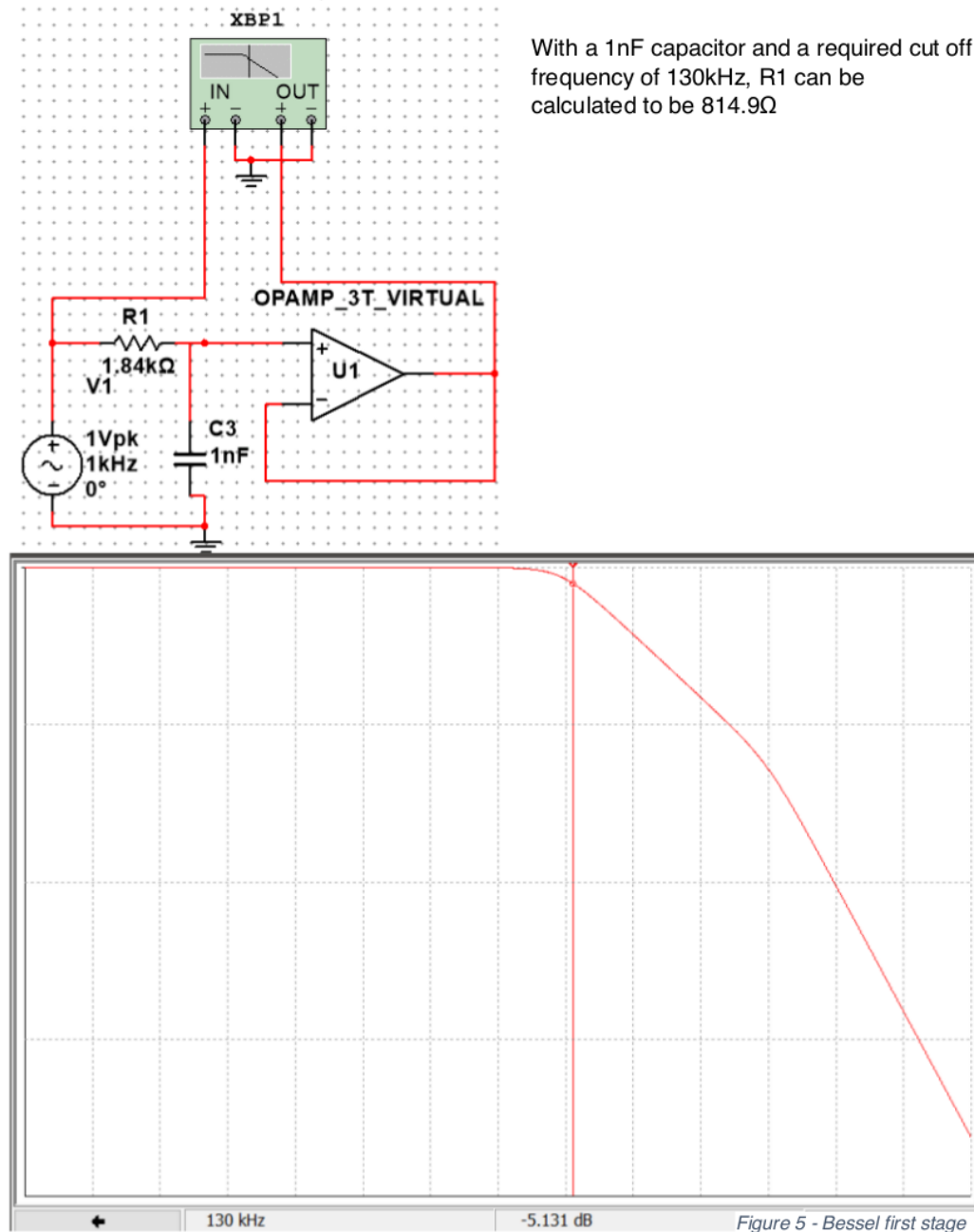


Figure 5 - Bessel first stage

Bessel Second filter

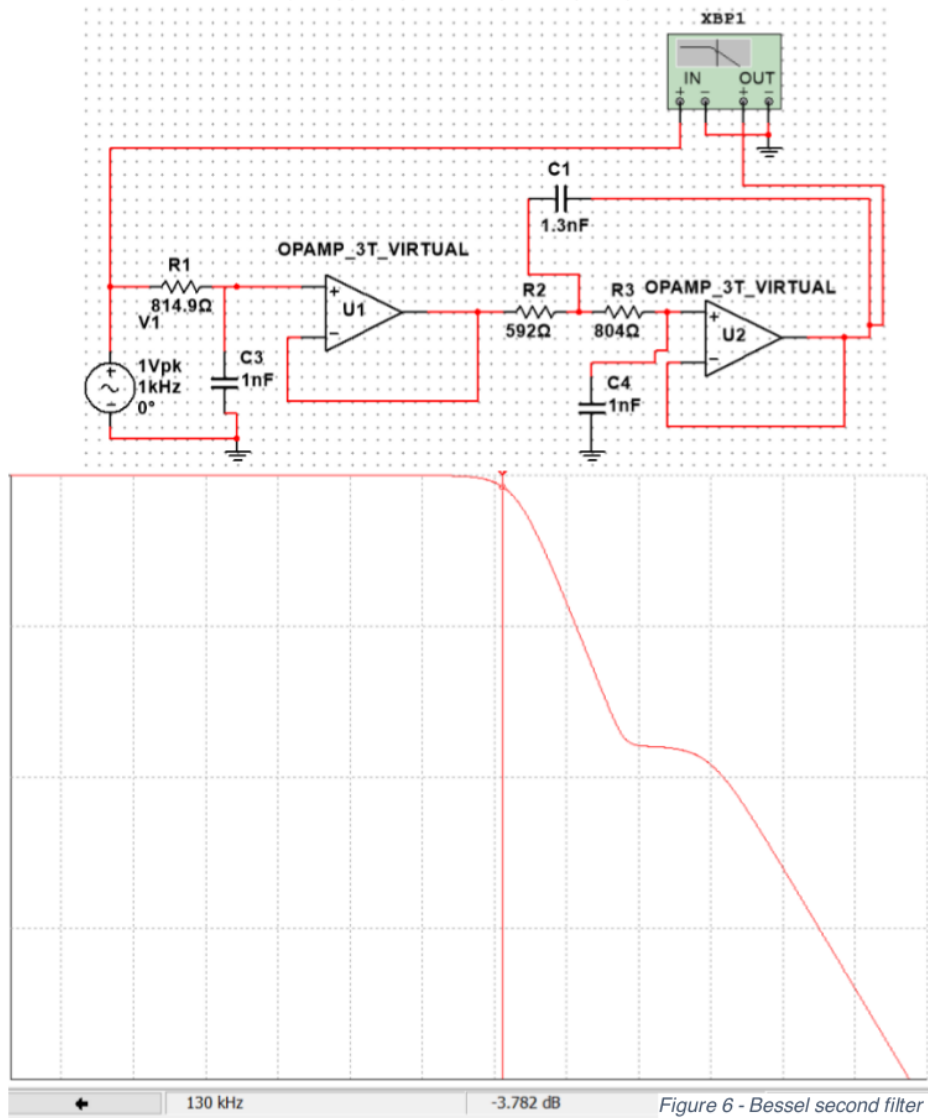
$$C2 = \frac{c_1 \times 4b_2}{a_2^2} = \frac{1 \times 10^{-9} \times 4 \times 0.4128}{1.1402^2} = 1.27nF$$

C2 as 1.27nF does not work. Increasing the value to 1.3nF gives no error.

$$\frac{a_2 c_2 \pm \sqrt{a_2^2 c_2^2 - 4b_2 c_1 c_2}}{4\pi f_c c_1 c_2}$$

$$R_1 = \frac{1.1402 \times 1.3 \times 10^{-9} - \sqrt{(1.1402 \times 1.3 \times 10^{-9})^2 - 4 \times 0.4128 \times 1 \times 10^{-9} \times 1.3 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1.3 \times 10^{-9}} = 592\Omega$$

$$R_2 = \frac{1.1402 \times 1.3 \times 10^{-9} + \sqrt{(1.1402 \times 1.3 \times 10^{-9})^2 - 4 \times 0.4128 \times 1 \times 10^{-9} \times 1.3 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1.3 \times 10^{-9}} = 804\Omega$$

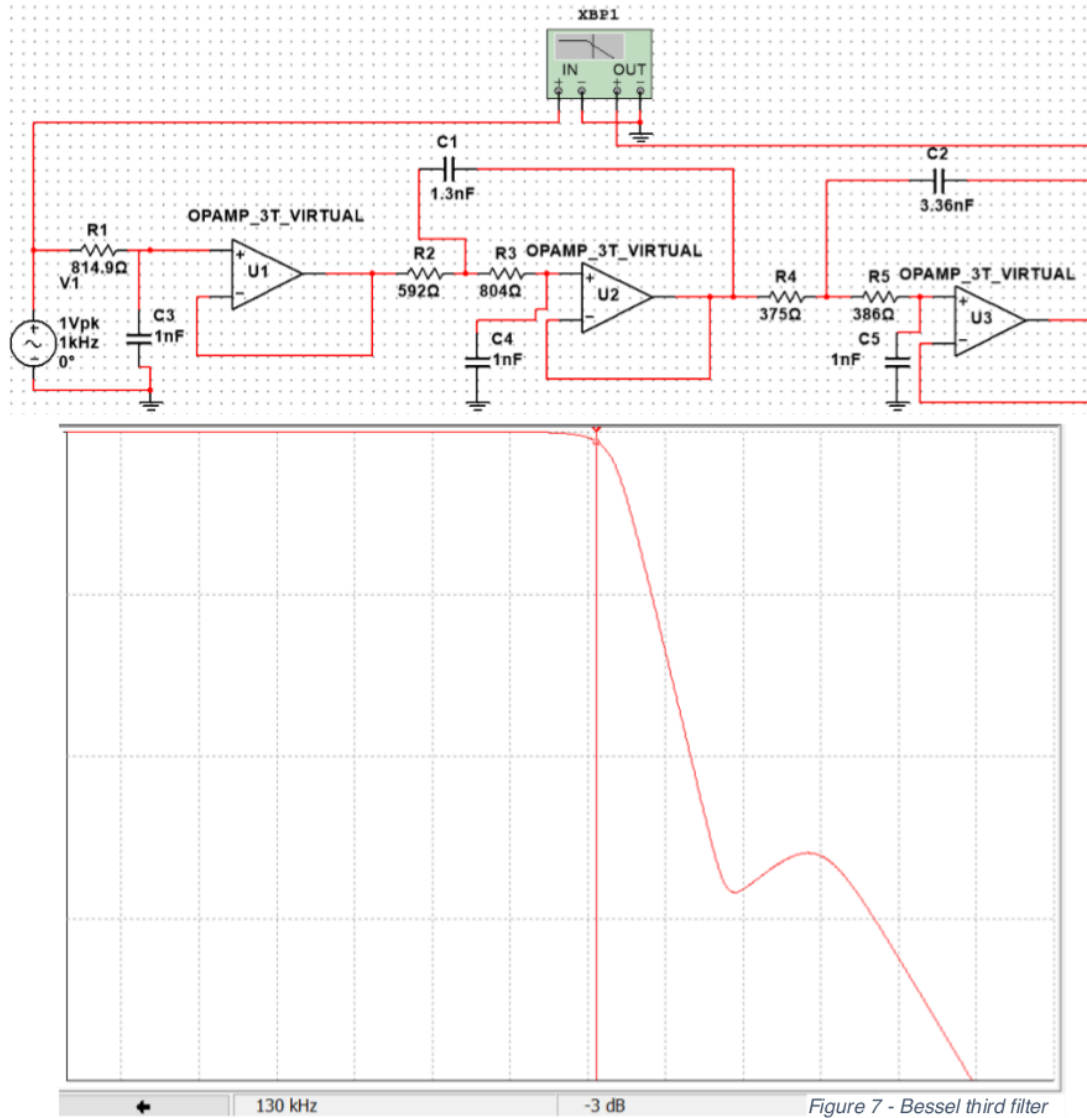


Third filter

$$C_2 = \frac{c_1 \times 4b_3}{a_3^2} = \frac{1 \times 10^{-9} \times 4 \times 0.3245}{0.6216^2} = 3.36nF$$

$$R_1 = \frac{0.6216 \times 3.36 \times 10^{-9} - \sqrt{(0.6216 \times 3.36 \times 10^{-9})^2 - 4 \times 0.3245 \times 1 \times 10^{-9} \times 3.36 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 3.36 \times 10^{-9}} = 375\Omega$$

$$R_2 = \frac{0.6216 \times 3.36 \times 10^{-9} + \sqrt{(0.6216 \times 3.36 \times 10^{-9})^2 - 4 \times 0.3245 \times 1 \times 10^{-9} \times 3.36 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 3.36 \times 10^{-9}} = 386\Omega$$



The finished Bessel circuit produces a cut off frequency of -3Db at 130Khz. However, the calculation for the second stage needed adjusting since the value calculated for C2 would not work. Therefore, the value was increased from 1.27nF to 1.3nF to get the desired output. The roll-off per decade was 100Dbs per decade. Same as the butterworth.

Tschebyescheff filter

First filter

$$R_1 = \frac{a_1}{2\pi f_c c_1} = \frac{5.6334}{2\pi \times 130 \times 10^3 \times 1 \times 10^{-9}} = 6.9k\Omega$$

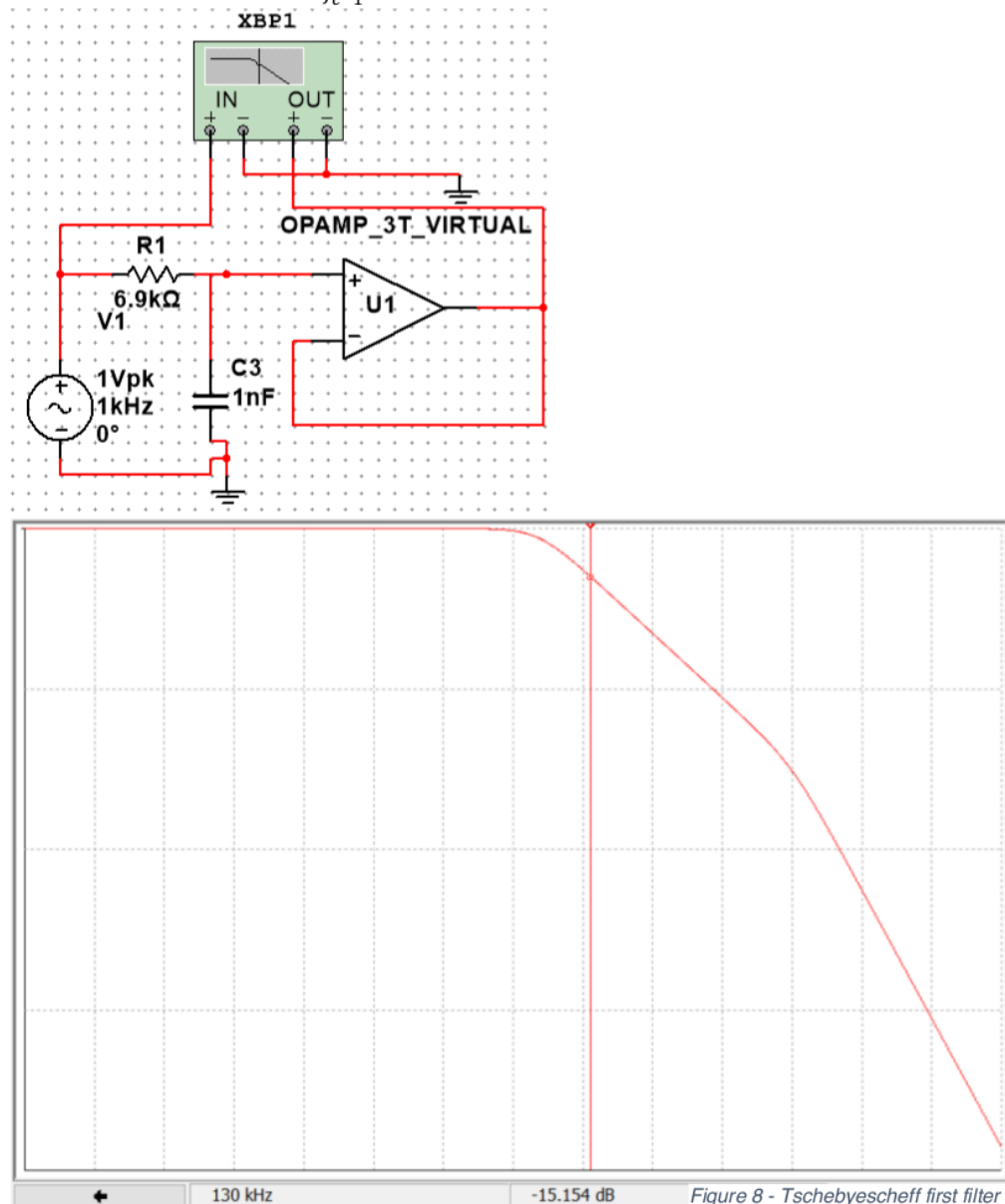


Figure 8 - Tschebyescheff first filter

Second filter

$$C2 = \frac{c_1 \times 4b_2}{a_2^2} = \frac{900 \times 10^{-12} \times 4 \times 2.6530}{0.7620^2} = 16.5 \text{ nF}$$

$$\frac{a_2 c_2 \pm \sqrt{a_2^2 c_2^2 - 4b_2 c_1 c_2}}{4\pi f_c c_1 c_2}$$

R_1

$$= \frac{0.7620 \times 16.5 \times 10^{-9} - \sqrt{(0.7620 \times 16.5 \times 10^{-9})^2 - 4 \times 2.6530 \times 900 \times 10^{-12} \times 16.5 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 900 \times 10^{-12} \times 16.5 \times 10^{-9}}$$

$$= 489 \Omega$$

R_2

$$= \frac{0.7620 \times 16.5 \times 10^{-9} + \sqrt{(0.7620 \times 16.5 \times 10^{-9})^2 - 4 \times 2.6530 \times 900 \times 10^{-12} \times 16.5 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 900 \times 10^{-12} \times 16.5 \times 10^{-9}}$$

$$= 547 \Omega$$

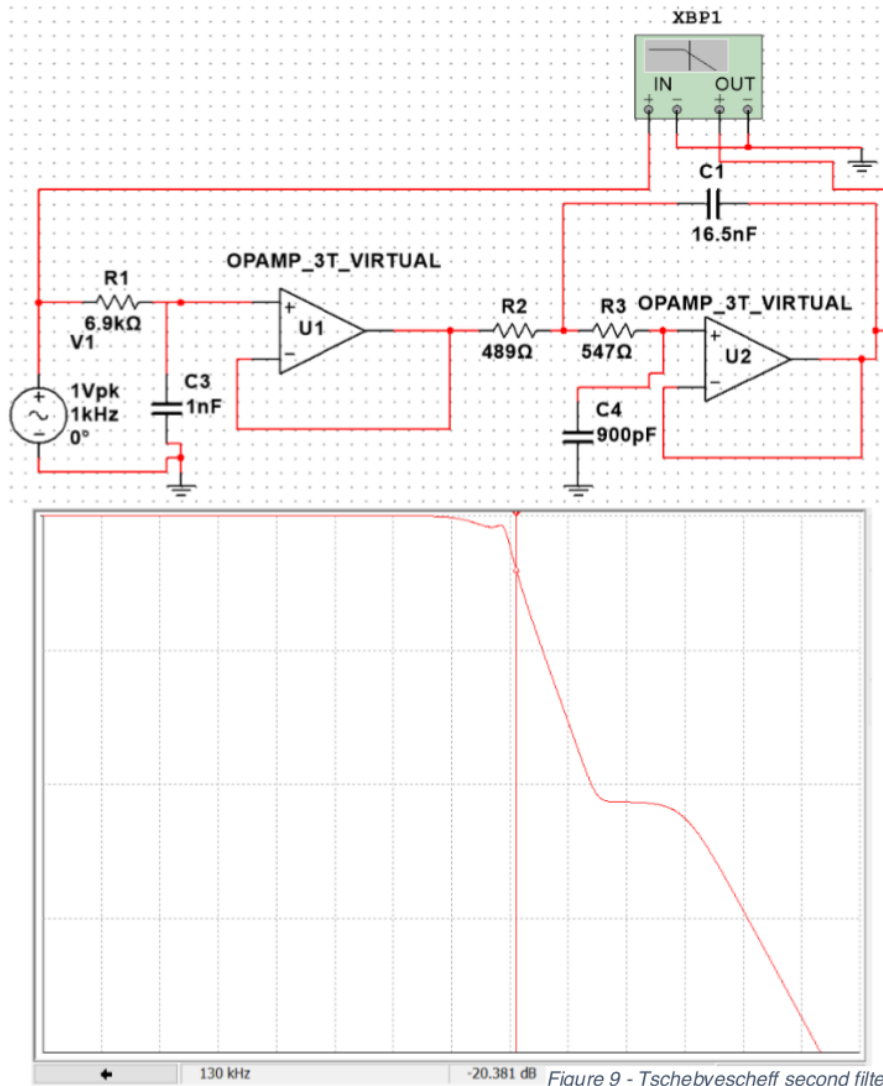
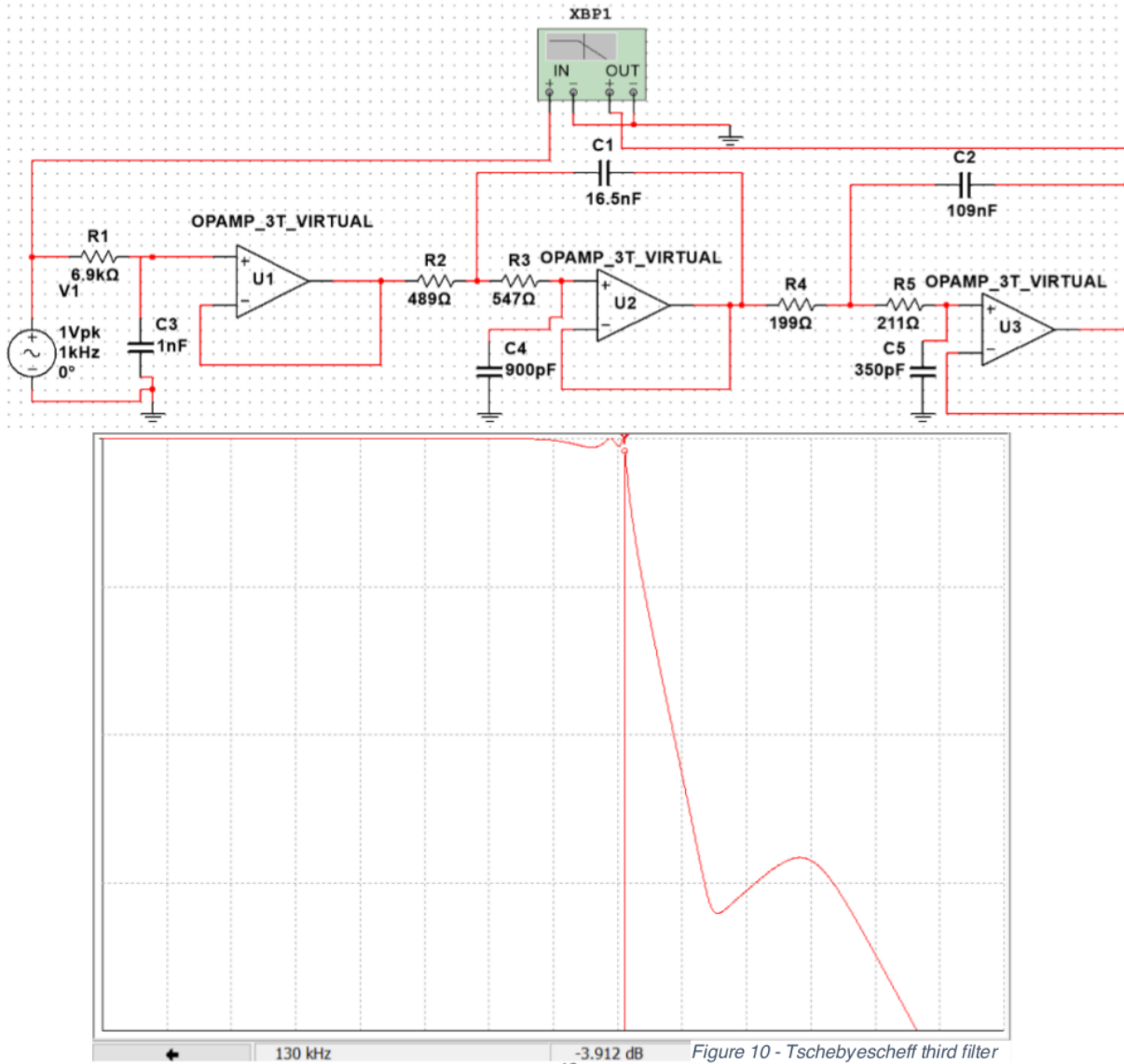


Figure 9 - Tschebyscheff second filter

Third filter



$$C2 = \frac{c_1 \times 4b_3}{a_3^2} = \frac{350 \times 10^{-12} \times 4 \times 1.0686}{0.1172^2} = 109nF$$

$$\frac{a_3 c_2 \pm \sqrt{a_3^2 c_2^2 - 4b_3 c_1 c_2}}{4\pi f_c c_1 c_2}$$

$$R_1 = \frac{0.1172 \times 109 \times 10^{-9} - \sqrt{(0.1172 \times 109 \times 10^{-9})^2 - 4 \times 1.0686 \times 350 \times 10^{-12} \times 109 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 350 \times 10^{-12} \times 109 \times 10^{-9}} = 199\Omega$$

$$R_2 = \frac{0.1172 \times 109 \times 10^{-9} + \sqrt{(0.1172 \times 109 \times 10^{-9})^2 - 4 \times 1.0686 \times 350 \times 10^{-12} \times 109 \times 10^{-9}}}{4\pi \times 130 \times 10^3 \times 350 \times 10^{-12} \times 109 \times 10^{-9}} = 211\Omega$$

Because of the ripple effect the cut-off frequency at 130Khz is 3.9db instead of three. Further fine tuning brings the value to 3.6db at 130Khz, however. Compared to the Bessel and the Butterworth filters, the Tscheyescheff filter had a slightly steeper roll-off of 110Dbs per decade.

Butterworth high pass filter design

Third order filter

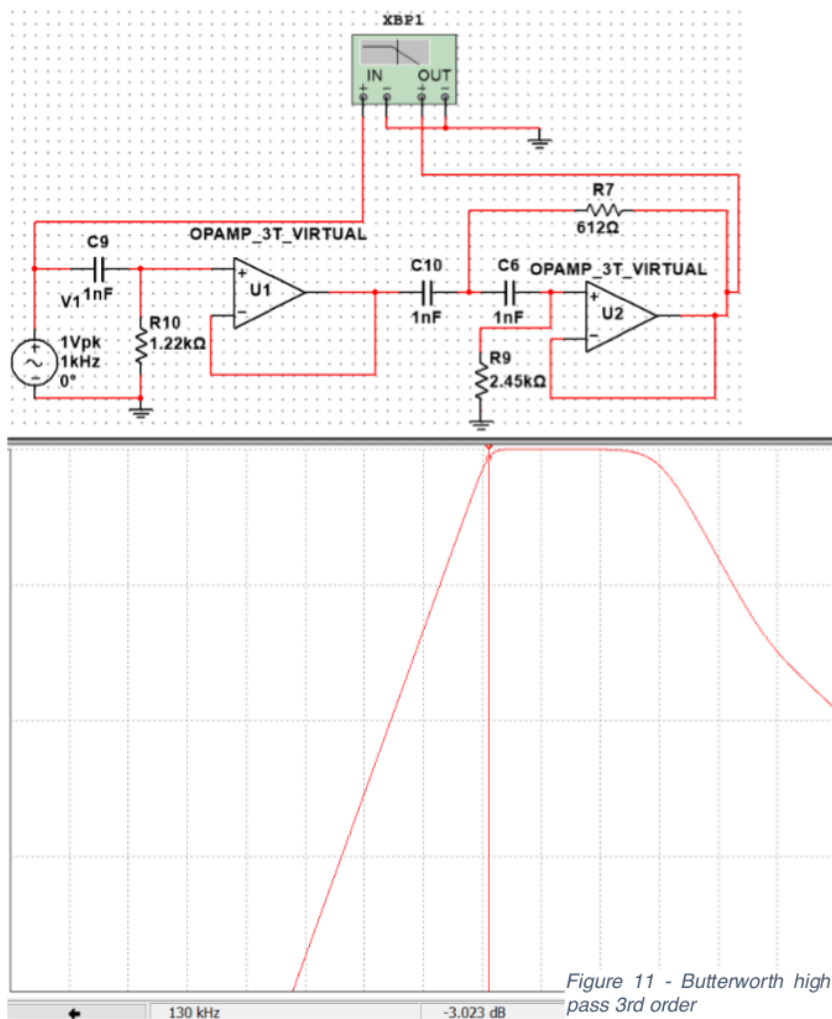
First filter

$$R_1 = \frac{1}{2\pi f_c a_1 c_1} = \frac{1}{2\pi \times 130 \times 10^3 \times 1 \times 1 \times 10^{-9}} = 1.22k\Omega$$

Second filter

$$R_1 = \frac{1}{\pi f_c c a_2} = \frac{1}{\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 2.45k\Omega$$

$$R_2 = \frac{a_2}{4\pi f_c c b_2} = \frac{1}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 612\Omega$$



Sixth order filter

First filter

$$R_1 = \frac{1}{\pi f_c c a_1} = \frac{1}{\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1.9319} = 1.28k\Omega$$

$$R_2 = \frac{a_1}{4\pi f_c c b_1} = \frac{1.9319}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 1.18K\Omega$$

Second filter

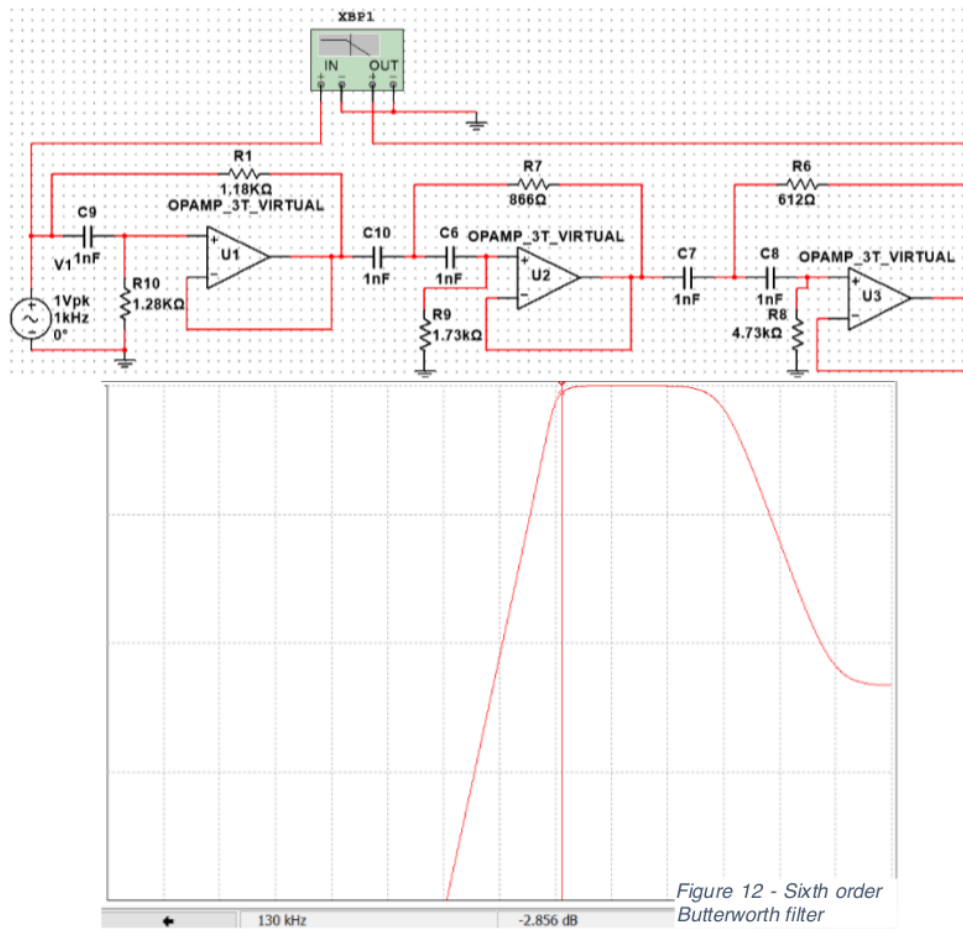
$$R_1 = \frac{1}{\pi f_c c a_2} = \frac{1}{\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1.4142} = 1.73k\Omega$$

$$R_2 = \frac{a_2}{4\pi f_c c b_2} = \frac{1.4142}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 866\Omega$$

Third stage

$$R_1 = \frac{1}{\pi f_c c a_3} = \frac{1}{\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 0.5176} = 4.73k\Omega$$

$$R_2 = \frac{a_3}{4\pi f_c c b_3} = \frac{0.5176}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 612\Omega$$



Ninth order filter

First filter

$$R_1 = \frac{1}{2\pi f_c a_1 c_1} = \frac{1}{2\pi \times 130 \times 10^3 \times 1 \times 1 \times 10^{-9}} = 1.22k\Omega$$

Second filter

$$R_1 = \frac{1}{\pi f_c c a_2} = \frac{1}{\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1.8794} = 1.3k\Omega$$

$$R_2 = \frac{a_2}{4\pi f_c c b_2} = \frac{1.8794}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 1.15k\Omega$$

Third filter

$$R_1 = \frac{1}{\pi f_c c a_3} = \frac{1}{\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1.5321} = 1.6k\Omega$$

$$R_2 = \frac{a_3}{4\pi f_c c b_3} = \frac{1.5321}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 937.9\Omega$$

Fourth filter

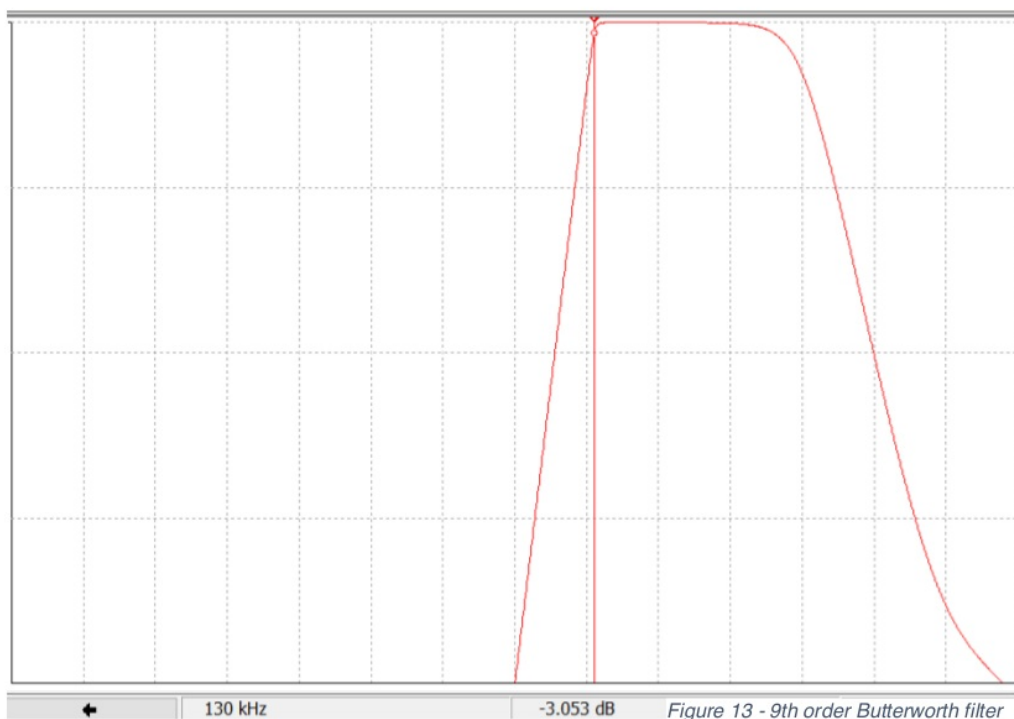
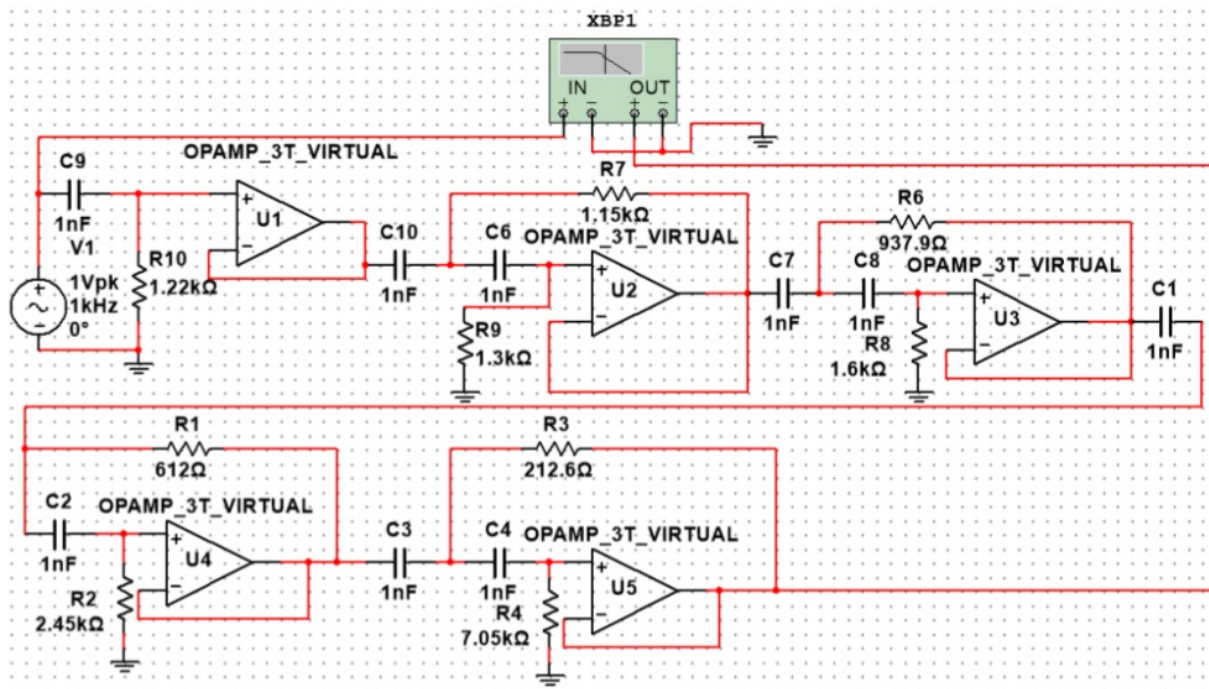
$$R_1 = \frac{1}{\pi f_c c a_4} = \frac{1}{\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 2.45k\Omega$$

$$R_2 = \frac{a_4}{4\pi f_c c b_4} = \frac{1}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 612\Omega$$

Fifth filter

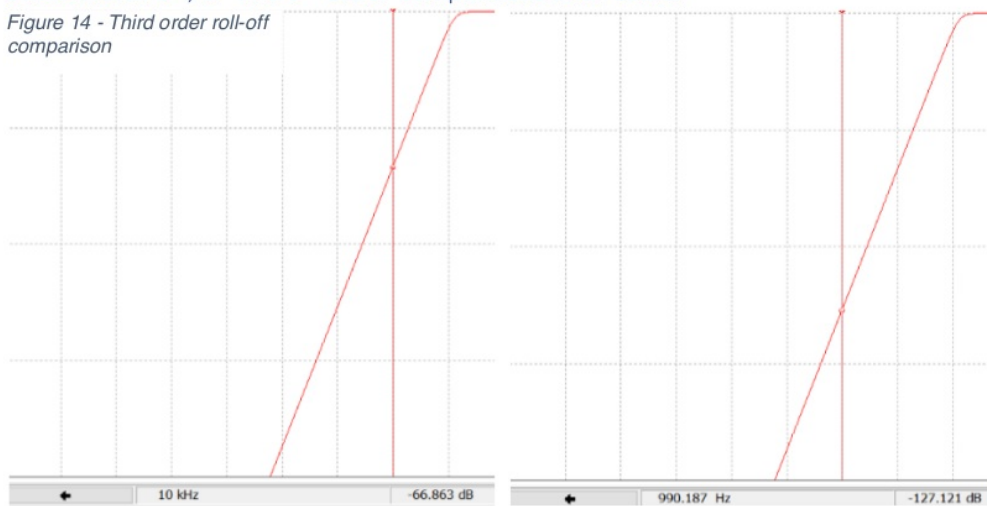
$$R_1 = \frac{1}{\pi f_c c a_5} = \frac{1}{\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 0.3473} = 7.05k\Omega$$

$$R_2 = \frac{a_5}{4\pi f_c c b_5} = \frac{0.3473}{4\pi \times 130 \times 10^3 \times 1 \times 10^{-9} \times 1} = 212.6\Omega$$



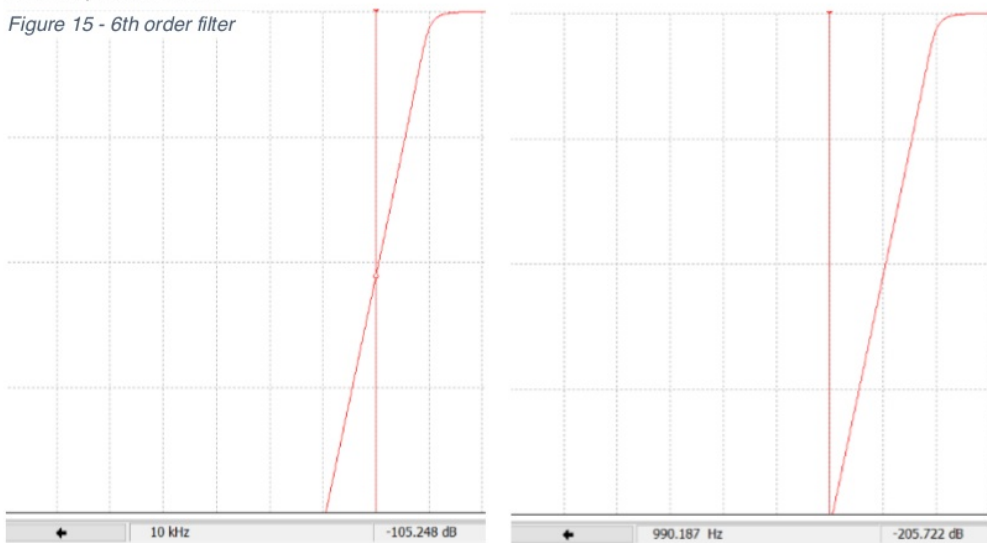
Butterworth 3rd, 6th and 9th order comparisons and results

Figure 14 - Third order roll-off comparison



As figure 14 shows, the roll-off for the finished third order Butterworth filter is roughly 60Dbs per decade.

Figure 15 - 6th order filter



Shown in figure 15 is the 6th order filter roll-off. Which is 100Dbs per decade.

Figure 16 - 9th order roll-off comparison

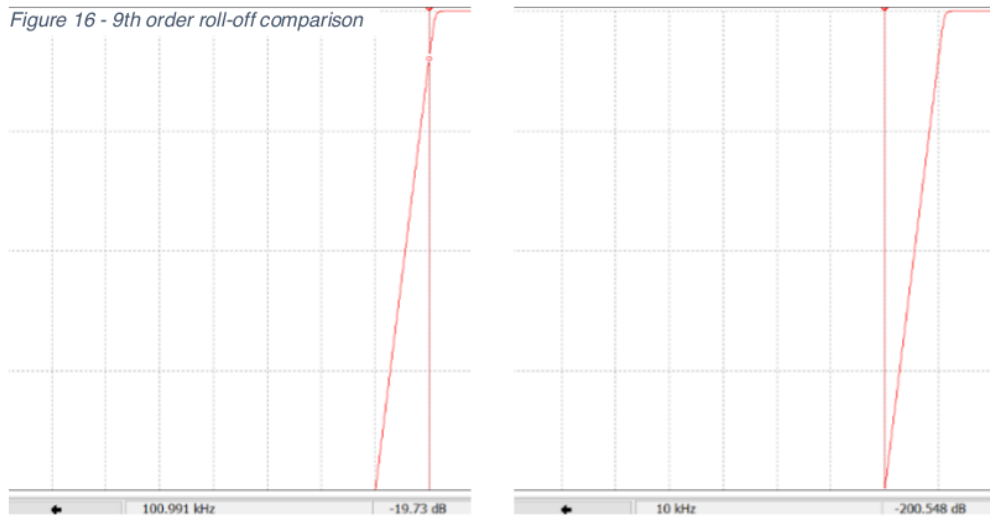


Figure 16 shows the roll-off for the 9th order filter once completed. Which is 180Dbs per decade.

From figures 14-16, we can deduce that the higher the order of the filter circuit. The steeper the roll-off will become.

Test summary comparing roll-off of each filter and conclusions

Table 1 – Roll-off comparison

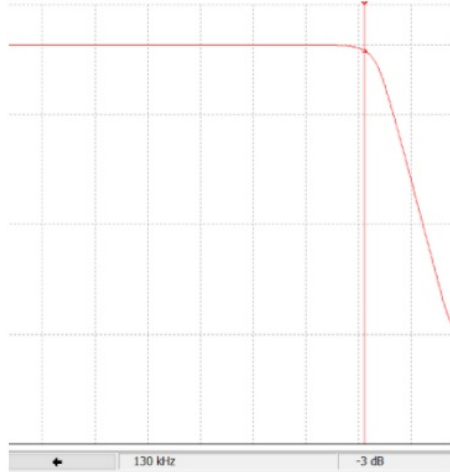
Filter	Roll-off per decade	Second peak (low pass) / Decline (high pass)
5 th order Butterworth	100	7Mhz second peak after roll-off
5 th order Bessel	100	7Mhz second peak after roll-off
5 th order Chebyshev	110	3.6Mhz second peak after roll-off
High pass 3rd order	60	10Mhz (beginning of decline)
High pass 6 th order	100	10Mhz (beginning of decline)
High pass 9 th order	180	10Mhz (beginning of decline)

From the table of roll-off results you can see that the roll off is directly proportional to the order of the filter. However, it is affected slightly by the type of filter used but the main deciding factor is the order number. This is proved through high and low pass filters since with low pass, different types all at 5th order were created and tested. Out of the three, only one had a different value for roll-off, which was only 10Dbs per decade in difference.

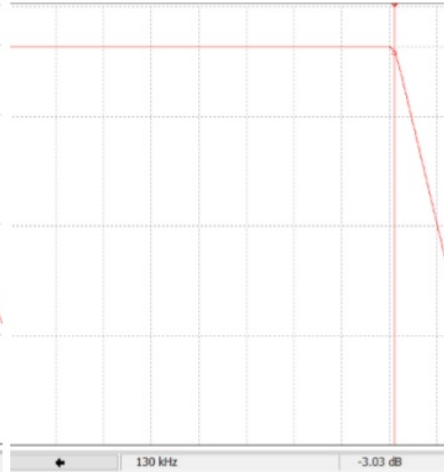
However, when constructing and testing high pass filters, the same type of filter was used (Butterworth) at different order values (3,6 and 9). This resulted in roll-off values that were spread out across a far larger range compared to the three 5th order filters. Proving that filter order has a direct impact upon the roll-off of a filter circuit.

Passband comparison

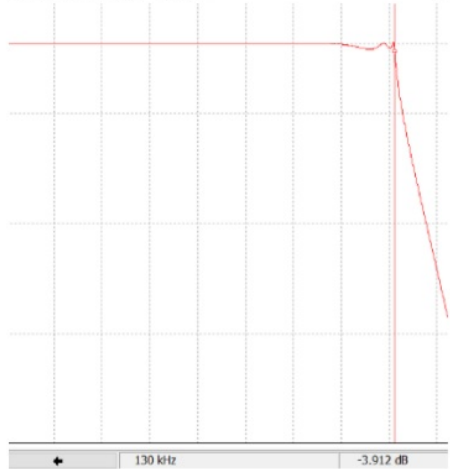
Bessel 5th order



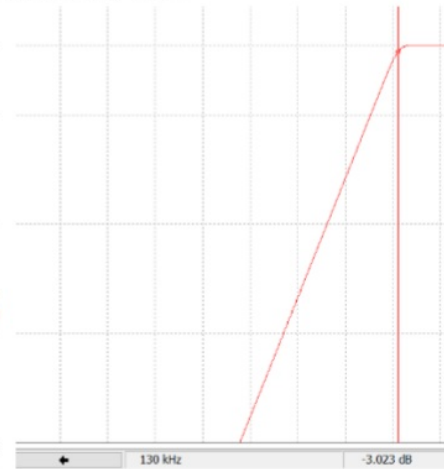
Butterworth 5th order



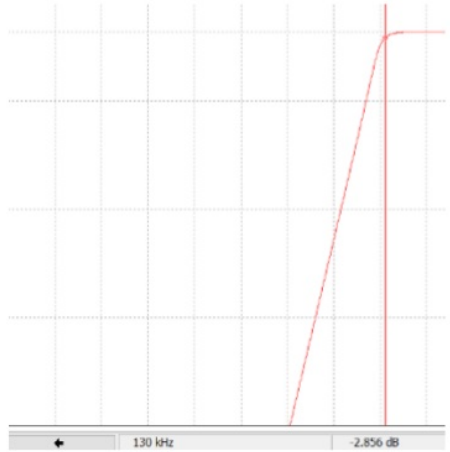
Chebyshev 5th order



Butterworth 3rd order



Butterworth 6th order



Butterworth 9th order

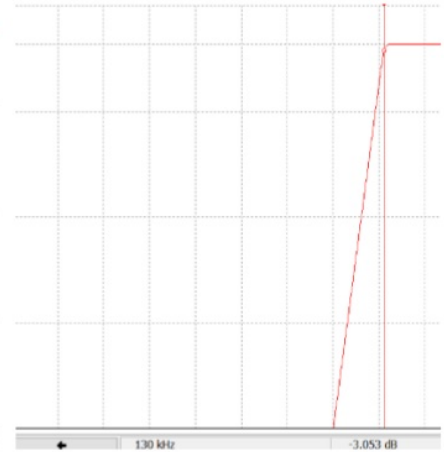


Figure 17 - Passband comparison

Figure 17 shows the waveform shape of each of the filters that have been created. The passband refers to the top, flat part of each waveform. From these graphs, you can see that passband ripple is different between the types of filter only. (Bessel, Butterworth and Chebyshev) The Bessel filter especially, preserves the wavelengths shape. A primary reason why it is used in sound systems. The Butterworth 5th order filter has the most abrupt change from passband to negative infinity. Meaning it is ideal for data conversion.

The Chebyshev filter, while having the steepest roll-off (reducing any unwanted noise) it unfortunately has passband ripple and is the only one to have this. This means it cannot be used for most applications and is limited to tasks such as filtering noise.

Possible improvements

In order to improve the current circuits, finer tuning could be done to reach exactly -3DBs at 130Khz and a higher order Chebyshev circuit could be created to reduce the passband ripple down further.

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Images

Figure1:

https://www.bing.com/images/search?view=detailV2&id=A8F848E0173CEC6701AC39EE7BF3EEBD3E1D437C&thid=OIP.ECG-1LAGBPmiOA4w5D89ugHaF7&mediaurl=http%3A%2F%2Fwww8.tfe.umu.se%2Fcourses%2Felektro%2Felmat1%2Fv36_01_da%2Fgr2%2FImage15.gif&exph=320&expw=400&q=bessel+vs+butterworth+vs+chebyshev&selectedIndex=5&ajaxhist=0&vt=0&eim=0

FINAL GRADE

GENERAL COMMENTS

Instructor

56/100

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Text Comment. Executive summary rather than aims and objectives.

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GRADING FORM: CSG-RUBIC

**RICHARD
HARRISON**

0

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. Your references were appropriate to the task and your reference list was of an appropriate length for this assignment. Some of the sources were not cited and you should consider widening your range of sources you actually use for future assignments.

5/10

KNOWLEDGE AND UNDERSTANDING



The knowledge and understanding of the subject demonstrated by this assignment was reasonably extensive. There were very few gaps in your knowledge of the basic principles and your understanding of the higher level concepts was demonstrated to a limited degree. You have demonstrated some critical understanding of the main concepts and expanded your knowledge beyond that contained in the course notes, however your explanations need to be more detailed and written with a greater emphasis on critical evaluation rather than description.

18/30

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.

11/20

PRACTICAL APPLICATION AND DEP.



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

16/30

appropriately when designing the circuit and you used appropriate options for testing and evaluating the circuit performance. You managed to design an efficient circuit that functioned within the specification and achieved this by only asking for assistance when appropriate. Some of the graphs looked inaccurate, but the numerical results were sound.

SKILLS FOR PROFESSIONAL PRAC.



In this assignment you have demonstrated skills in working individually and also collaboratively. Your written report was generally good and contained most of the required detail, it was also written in a coherent and logical way. The available word count was in the main effectively used.

6/10