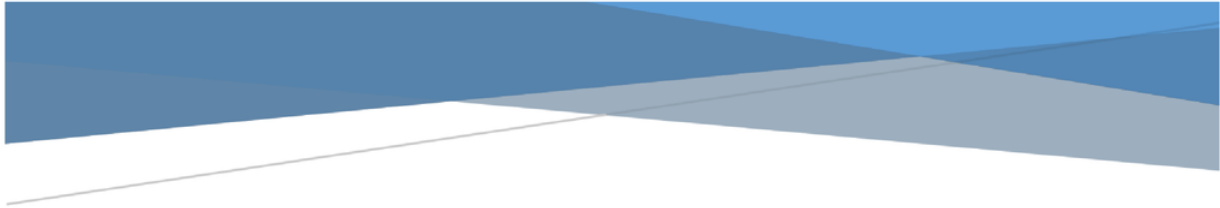


PSDE5006 Assignment 1

by Daniel Ince

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ACTIVE FILTER DESIGN

Assignment 1 - PSDE5006

Daniel Ince

07/01/2018

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1. Active Filter Research

Filters are electronic circuits that alter a signal as such to remove a portion of the frequency and only allow a specific frequency band range through. This can be done passively – either without active components, or actively. As stated in *A Basic Introduction to Filters*; “A filter is an electrical network that alters the amplitude and/or phase characteristics of a signal with respect to frequency.” (Lacanette, 1991, p. 1) The frequency range itself is not changed through addition of new frequencies but instead filter out unwanted portions of the signal.

A filter’s performance concerning frequencies can be explained in the form of a transfer function and is described as, *the ratio of the Laplace transforms of its output and input signals*. Similar to gain, the magnitude of this function tells us how the circuit will affect sine waves at different frequencies. (Lacanette, 1991)

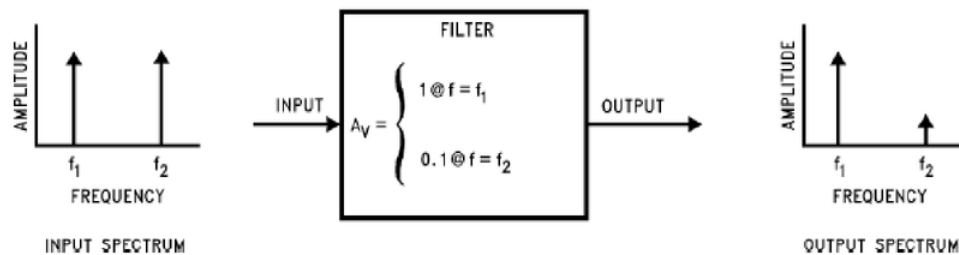


Figure 1

Figure 1 shows a diagram taken from *A Basic Introduction to Filters*, it shows how two different input frequencies are modified by the filter to produce a desired output. The f_2 frequency is suppressed as the filter characteristics suggest very little gain within that frequency range. For f_1 , the gain is 1 and so the output signal amplitude within that frequency range is identical to the input.

Filters are classed by order, with higher order filters being able to cut off at a sharper angle and the separation between wanted and unwanted frequency ranges more distinct. Typically, higher order systems have more resistor/capacitor/inductor banks in series as the order increases down the line.

There are several different types of filter designs; three of the most common are Bessel, Butterworth and Tchebycheff, for all of these, a -3dB cut off frequency is specified. They can have different classes, such as:

- Low pass – Allows lower frequencies to pass while attenuating those higher.
- High pass – Opposite of a low pass, allowing higher frequencies.
- Band pass – Allows a narrow frequency band through, while rejecting those either side of the band.
- Notch – Attenuates a narrow band of frequencies but allows those either side, opposite of a band pass.
- Phase shift – Does not reject any frequencies, but instead shifts the phase of the signal.

Butterworth

The most common of all these is the Butterworth design as it has a predictable ‘maximally-flat’ response with no ripples.

With the Butterworth low pass filter design, after the -3dB point, the drop off is 20dB per decade.

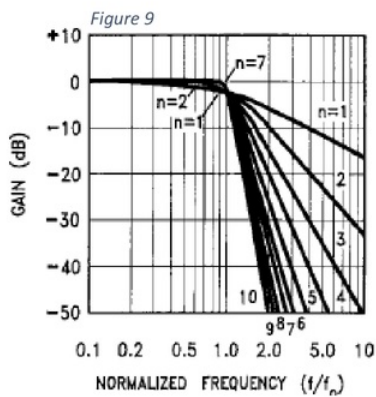
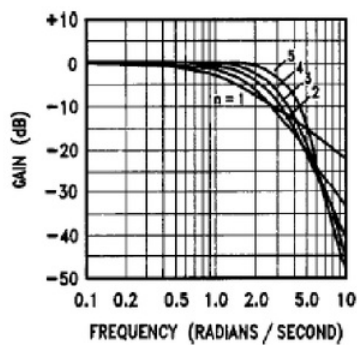


Figure 2 shows the drop off curves for a Butterworth low pass filter. The drop off occurs at the -3dB point and sharply declines the greater the order (n).

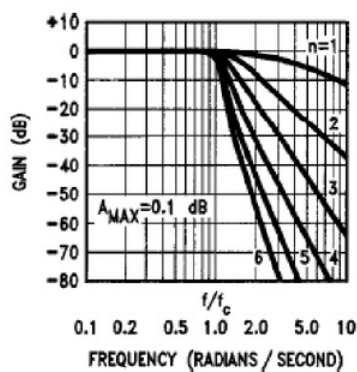
There are no ripples associated with this design and the roll off is relatively flat and predictable, the reason why this is the most popular type of filter.

Bessel



As explained in *Bessel RF Filter Basics*, Bessel filters are different from Butterworth filters most notably by the roll off rate being a lot smoother and not a sharp cut off. This also means that there is a longer time between cut off and there is no overshoot. (Poole, Radio-electronics)

Tschebycheff



Tschebycheff filter design offers a much sharper roll off at higher orders whereas at lower orders it is much more gradual. When designing a Tschebycheff filter, the coefficients become increasingly extreme with each order. This swings the resistor values very low and very high making it a tougher filter to design than the others. The trade-off for this steep roll off is that there is increased ripple or differences in response .

The design of these filters is in keeping with the Sallen-key topology; a benefit of these active filter circuit designs is that they can be combined to produce higher order filters. They also have gain, whereas a passive filter design does not.

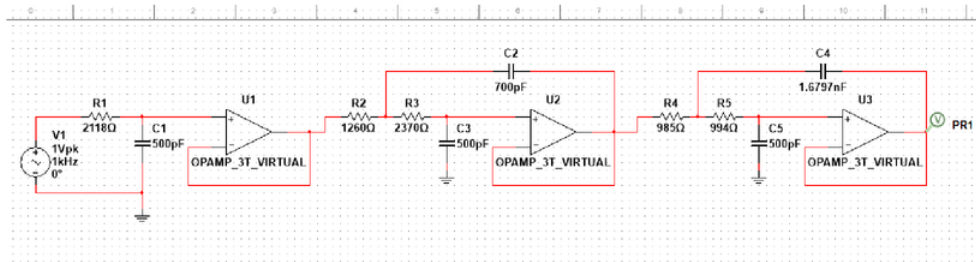


Figure 10

Shown above in figure 10 is a 5th order Bessel low pass filter of Sallen-Key design combining a first order and two second order circuits. Coefficients taken from each design's table are used for calculating the resistor and some capacitor values.

Filter applications

Frequency modulation radios use band pass filters to select the frequency range of the desired radio station. The adjustment dial is a variable capacitor, which varies the band that the filter is allowing to pass, rejecting all others. As explained on electronicshub. *"Due to its maximum flat pass band nature it is used as anti-aliasing filter in data converter applications."* (Electronicshub, 2015)

Anti-aliasing involves using a band pass filter to process a signal leaving only a desired bandwidth. *"An ideal anti-alias filter passes all the appropriate input frequencies (below f_1) and cuts off all the undesired frequencies (above f_1)."* (National Instruments, 2000) This explains why the Butterworth filter provides the most effective cut off at the f_1 and f_2 frequencies due to the flat roll off.

2. Filter Design and Testing

Bessel Low Pass Filter 5th Order

Figure 11 shows the 5th order low pass filter of Bessel type designed on multisim software.

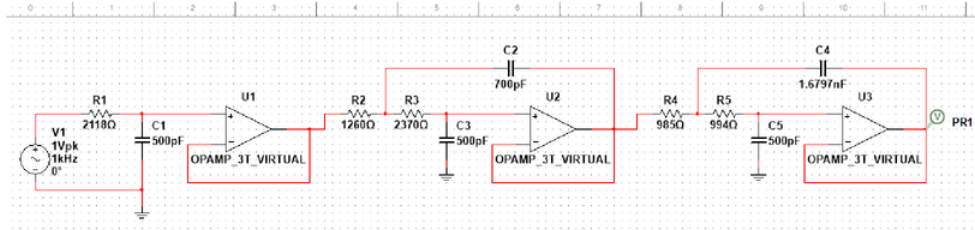


Figure 11

The following calculations determined component values for the filter.

1st stage:

$$R_1 = \frac{a_1}{2\pi f_c C_1} \quad R_1 = \frac{0.6656}{2\pi \times 100k \times 500pF} = 2118\Omega$$

2nd stage:

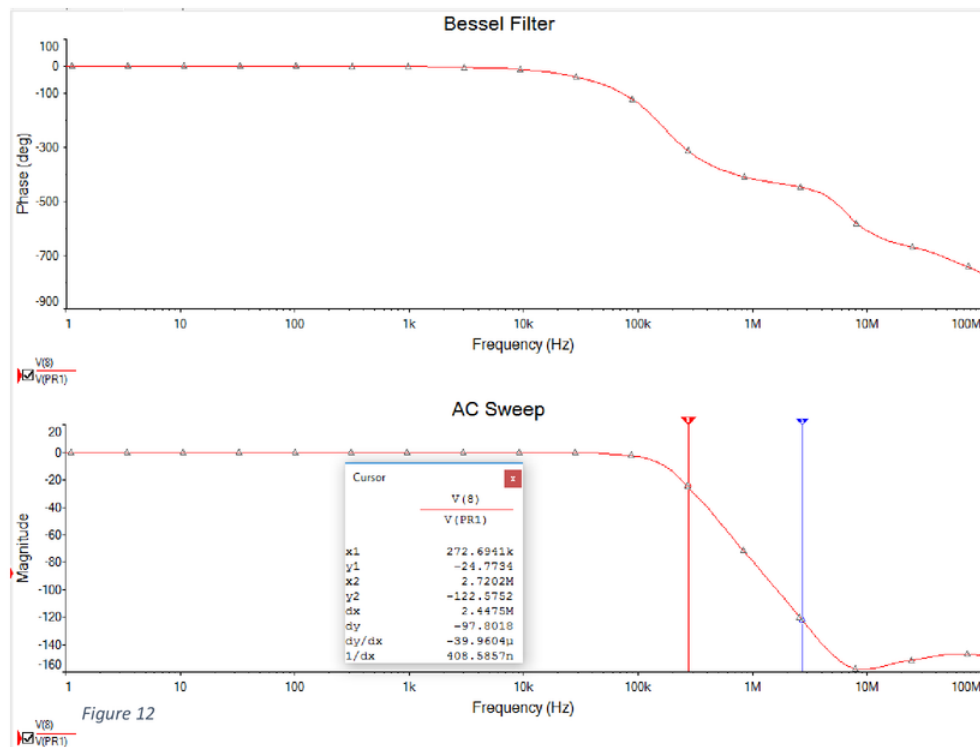
$$R_{1,2} = \frac{a_1 C_2 \pm \sqrt{a_1^2 C_2^2 - 4b_1 C_1 C_2}}{2\pi f_c C_1 C_2} \quad R_{1,2} = \frac{(1.1402)(700pF) \pm \sqrt{(1.1402^2)(700pF^2) - 4(0.4128)(500pF)(700pF)}}{2\pi \times 100k \times (500pF)(700pF)}$$

$$R_1 = 1.26k\Omega \quad R_2 = 2.37k\Omega$$

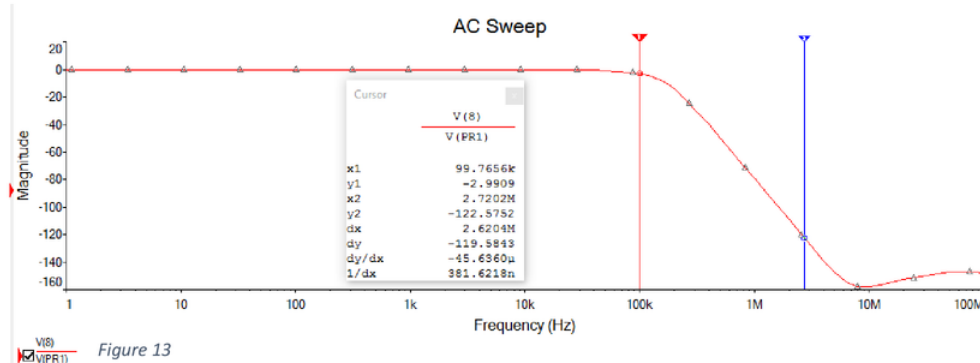
3rd stage:

$$R_{1,2} = \frac{a_1 C_2 \pm \sqrt{a_1^2 C_2^2 - 4b_1 C_1 C_2}}{2\pi f_c C_1 C_2} \quad R_{1,2} = \frac{(0.6216)(1679.7pF) \pm \sqrt{(0.6216^2)(1679.7pF^2) - 4(0.3245)(500pF)(1679.7pF)}}{2\pi \times 100k \times (500pF)(1679.7pF)}$$

$$R_1 = 985\Omega \quad R_2 = 994\Omega$$



The above test shown in figure 12 was performed as a decade test – It can be seen that dy drops 97.8 in magnitude between 272kHz and 2.72MHz. This test is successful because the 5th order filter designed should be $5 \times 20 = 100\text{dB}$ difference for the decade test in theory.



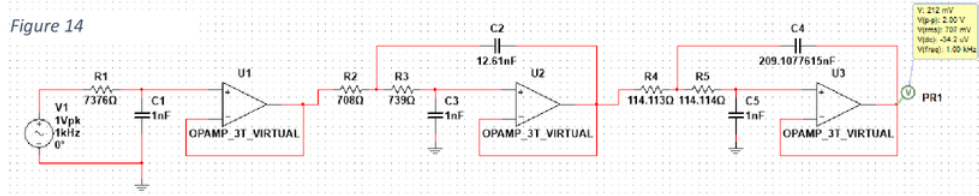
This next test in figure 13 is to check that the frequency is 100kHz at the -3dB limit, it is shown to be this when running a transient sweep, proving that calculations are correct. As it can be seen at roughly -3Db the frequency is 99.76kHz.

The bode plot for the Bessel filter ties in with the theory as the initial roll off is smooth before it declines at a relatively linear rate sticking to the 100dB drop in magnitude per frequency decade. The drop can be seen to mimic the diagram for 5th order Bessel in the theory.

Tscheyescheff -3dB Low Pass Filter 5th Order

Below in figure 14 shows the Tscheyescheff -3dB low pass filter designed on multisim as a three stage 5th order filter.

Figure 14



The following calculations determined component values for the filter.

1st stage:

$$R_1 = \frac{a_1}{2\pi f_c C_1} \quad R_1 = \frac{4.6345}{2\pi \times 100k \times 1000pF} = 7376\Omega$$

2nd stage:

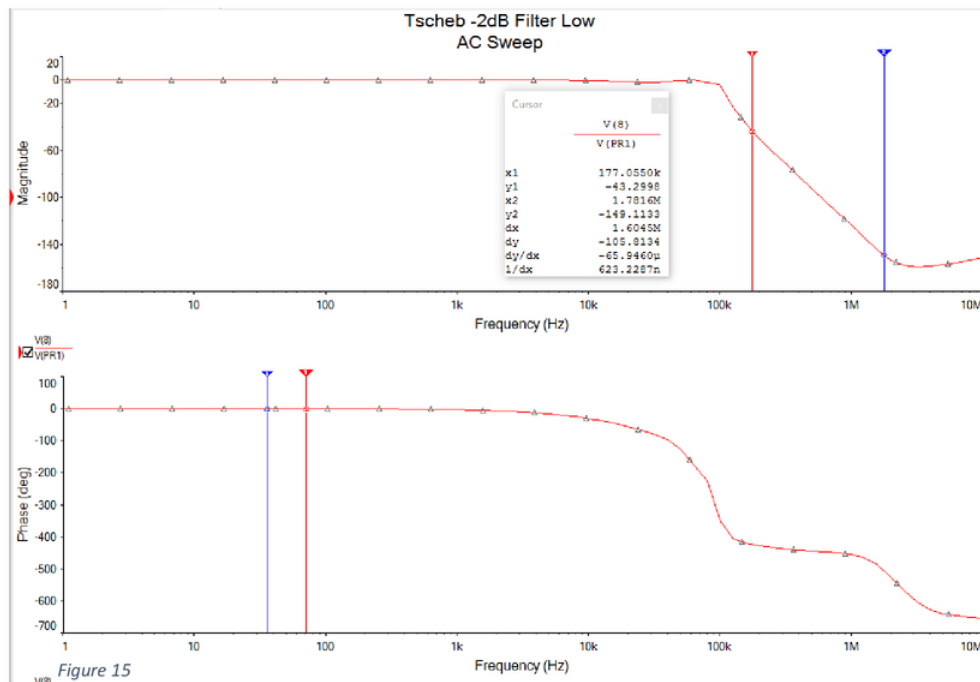
$$R_{1,2} = \frac{a_1 C_2 \pm \sqrt{a_1^2 C_2^2 - 4b_1 C_1 C_2}}{2\pi f_c C_1 C_2} \quad R_{1,2} = \frac{(0.909)(12.61nF) \pm \sqrt{(0.909^2)(12.61nF^2) - 4(2.6036)(1nF)(12.61nF)}}{2\pi \times 100k \times (1nF)(12.61nF)}$$

$$R_1 = 708\Omega \quad R_2 = 739\Omega$$

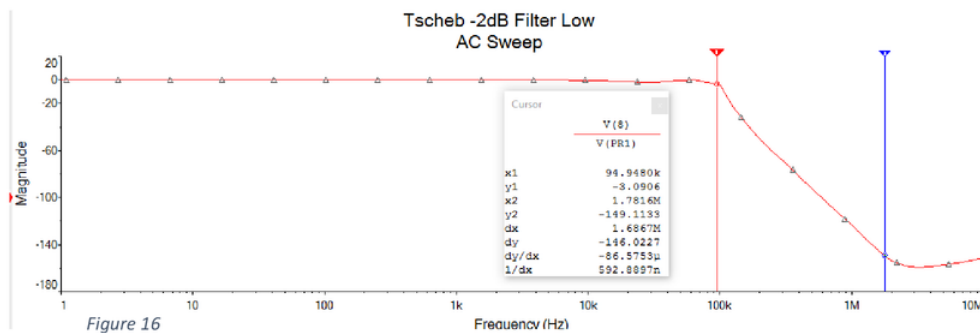
3rd stage:

$$R_{1,2} = \frac{a_1 C_2 \pm \sqrt{a_1^2 C_2^2 - 4b_1 C_1 C_2}}{2\pi f_c C_1 C_2} \quad R_{1,2} = \frac{(0.1434)(209.107nF) \pm \sqrt{(0.1434^2)(209.107nF^2) - 4(1.0750)(1nF)(209.107nF)}}{2\pi \times 100k \times (1nF)(209.107nF)}$$

$$R_1 = 114.113\Omega \quad R_2 = 114.114\Omega$$



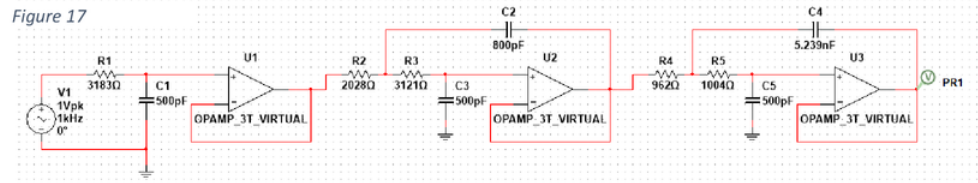
Above in figure 15 shows the AC sweep for the Tschebyscheff -2dB low pass filter. The test performed is the decade test to ensure that the decibel drop is adequate for the 5th order filter. As can be seen it is around 100dB with the step change from 177kHz to 177MHz.



The above figure 16 shows the frequency being checked at the -3dB point, as shown it is about 95kHz at -3dB which is close to the target 100kHz to which the filter is designed. The resulting roll off is not as flat as the Butterworth filter and explains why this type of filter is not used in anti-aliasing applications.

Butterworth Low Pass Filter 5th Order

Figure 17 below shows the 5th order Butterworth low pass filter configuration on Multisim.



The following calculations determined component values for the filter.

1st stage:

$$R_1 = \frac{a_1}{2\pi f_c C_1} \quad R_1 = \frac{1.0}{2\pi \times 100k \times 500pF} = 3183\Omega$$

2nd stage:

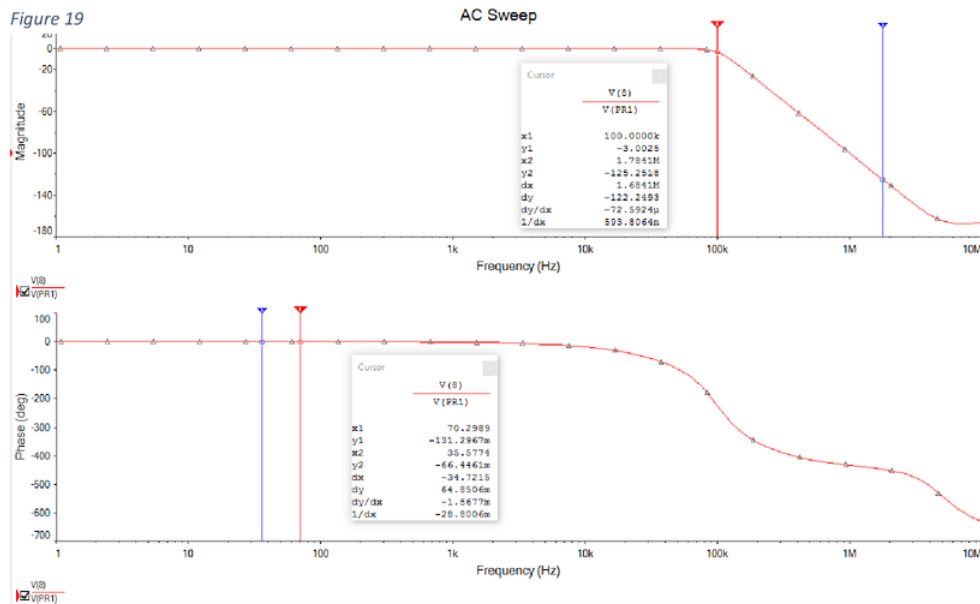
$$R_{1,2} = \frac{a_1 C_2 \pm \sqrt{a_1^2 C_2^2 - 4b_1 C_1 C_2}}{2\pi f_c C_1 C_2} \quad R_{1,2} = \frac{(1.618)(800pF) \pm \sqrt{(1.618^2)(800pF^2) - 4(1)(500pF)(800pF)}}{2\pi \times 100k \times (500pF)(800pF)}$$

$$R_1 = 2028.5\Omega \quad R_2 = 3121.6\Omega$$

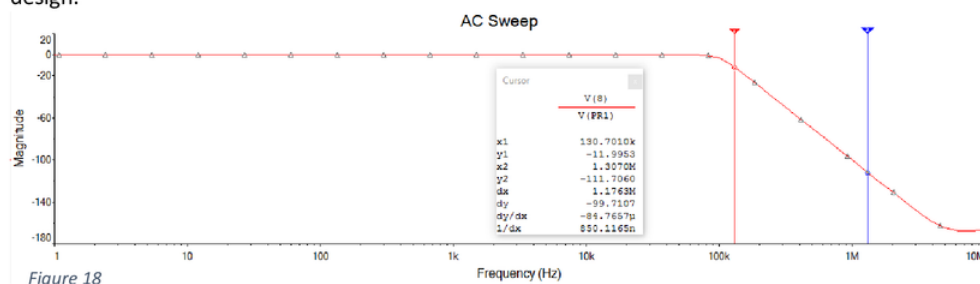
3rd stage:

$$R_{1,2} = \frac{a_1 C_2 \pm \sqrt{a_1^2 C_2^2 - 4b_1 C_1 C_2}}{2\pi f_c C_1 C_2} \quad R_{1,2} = \frac{(0.618)(5.239nF) \pm \sqrt{(0.618^2)(5.239nF^2) - 4(1)(500pF)(5.239nF)}}{2\pi \times 100k \times (500pF)(5.239nF)}$$

$$R_1 = 962\Omega \quad R_2 = 1004\Omega$$



Above in figure 18 is the screenshot for the AC sweep of the Butterworth low pass filter. The frequency check is being performed and it can be seen that it is 100kHz at -3dB which ties into the design.



The above figure 19 shows the decade test being performed, with the drop of 100dB when the frequency is reduced tenfold. The results shown are expected of a 5th order filter. The flat curve of the Butterworth roll off ties into the theory and is exactly why this filter design proves so popular.

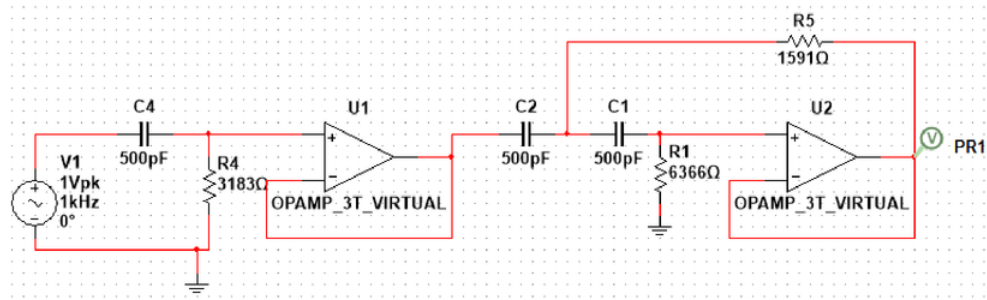
Butterworth High Pass 3rd Order

Figure 20

The above figure 20 shows the circuit configuration on Multisim for the Butterworth high pass 3rd order filter.

The following calculations were performed to achieve the component values.

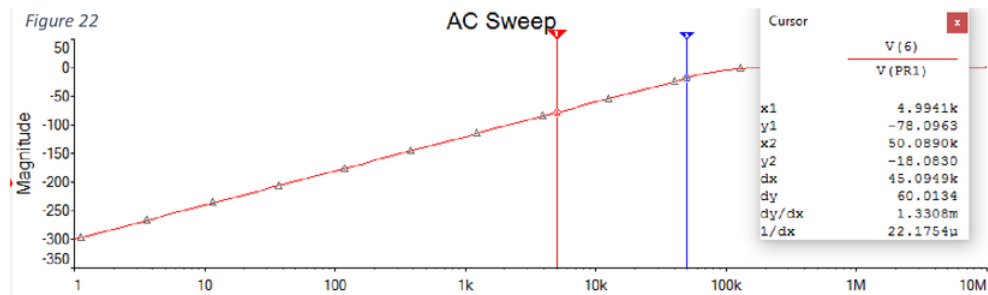
1st stage:

$$R_1 = \frac{1}{2\pi f_c a_1 C_1} \quad R_1 = \frac{1}{2\pi \times 100k \times 1.0 \times 500pF} = 3183\Omega$$

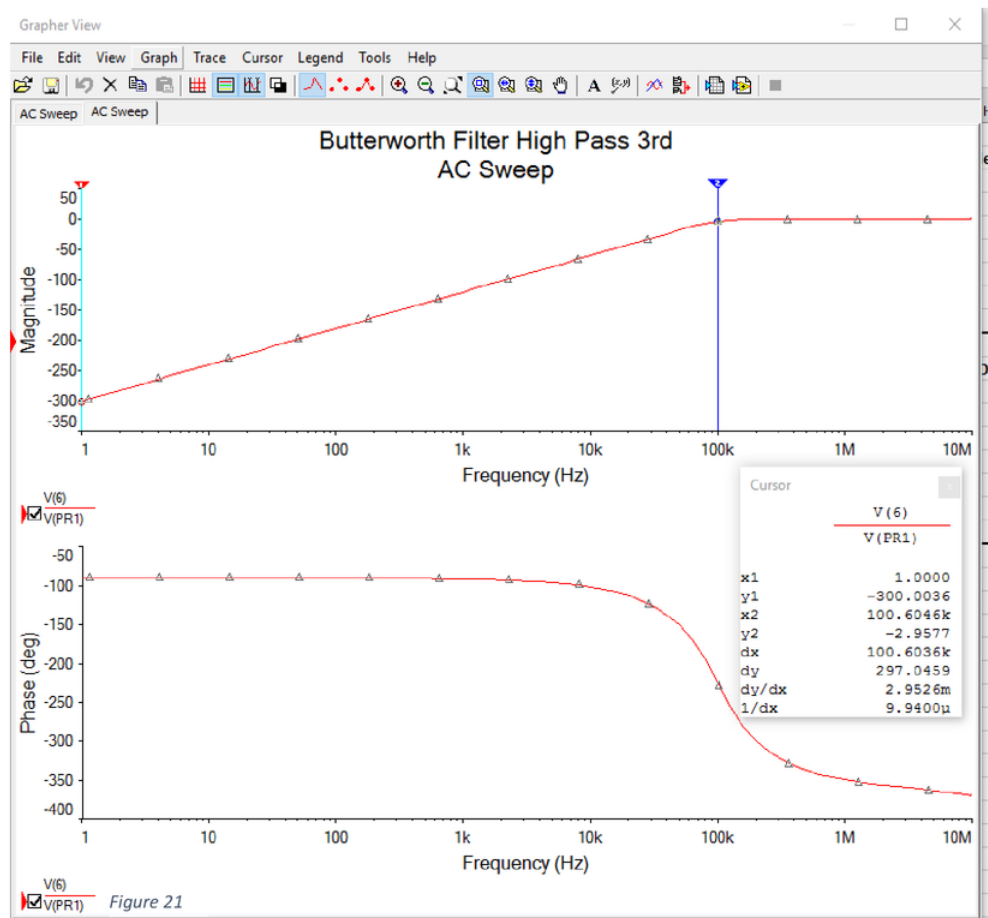
2nd stage:

$$R_1 = \frac{1}{\pi f_c a_1 C_1} \quad R_1 = \frac{1}{\pi \times 100k \times 1 \times 500pF} = 6366\Omega$$

$$R_2 = \frac{a_1}{4\pi f_c b_1 C_1} \quad R_2 = \frac{1}{4\pi \times 100k \times 1.0 \times 500pF} = 1591\Omega$$



Above in figure 21 shows the -3dB frequency test carried out on Multisim, it can be seen that it is 100kHz at this point. This characteristic ties into the theory for high pass filters as it is allowing the higher frequency band to pass through unhindered.



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The above figure 22 shows the decade test for the 3rd order high pass Butterworth filter. It can be observed that there is a difference of 60dB in magnitude from 50kHz down to 5kHz. This ties in with the 20dB per order rule.

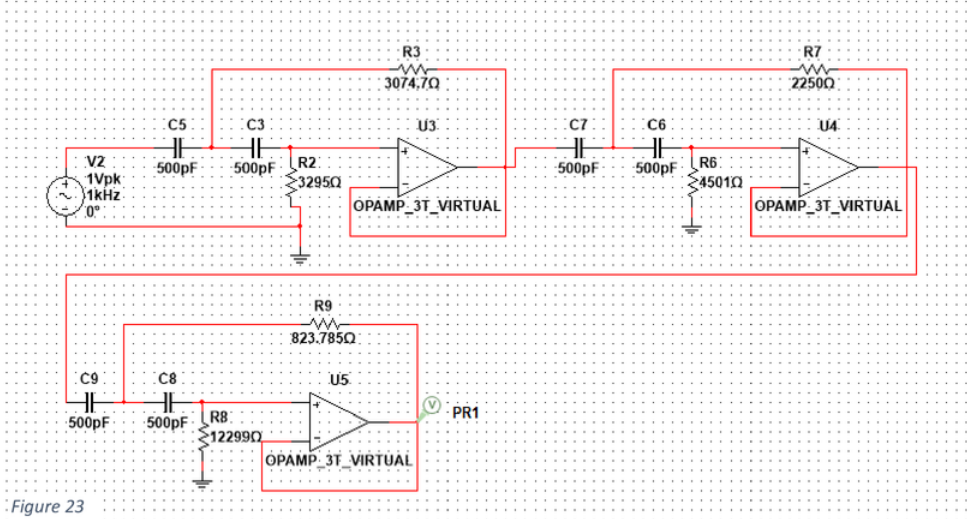
Butterworth High Pass 6th Order

Figure 23

Figure 23 shows the circuit configuration for the Butterworth high pass 6th order filter on Multisim. Each stage is a second order stage as the first stage does not need to be a first order.

The calculations to achieve the circuit values are as follows.

1st stage:

$$R_1 = \frac{1}{\pi f_c a_1 C_1} \quad R_1 = \frac{1}{\pi \times 100k \times 1.9319 \times 500pF} = 3295\Omega$$

$$R_2 = \frac{1}{4\pi f_c a_1 C_1} \quad R_2 = \frac{1.9319}{4\pi \times 100k \times 1 \times 500pF} = 3074.7\Omega$$

2nd stage:

$$R_1 = \frac{1}{\pi f_c a_1 C_1} \quad R_1 = \frac{1}{\pi \times 100k \times 1.4142 \times 500pF} = 4501.6\Omega$$

$$R_2 = \frac{a_1}{4\pi f_c b_1 C_1} \quad R_2 = \frac{1.4142}{4\pi \times 100k \times 1.0 \times 500pF} = 2250\Omega$$

3rd stage:

$$R_1 = \frac{1}{\pi f_c a_1 C_1} \quad R_1 = \frac{1}{\pi \times 100k \times 1.4142 \times 500pF} = 12299.45\Omega$$

$$R_2 = \frac{a_1}{4\pi f_c b_1 C_1} \quad R_2 = \frac{1.4142}{4\pi \times 100k \times 1.0 \times 500pF} = 823.785\Omega$$

Figure 24 below shows the decade test carried out at 5k and 50kHz, a difference of 120dB in magnitude can be observed, with 6 times 20dB equalling 120dB as seen in 'dy'.

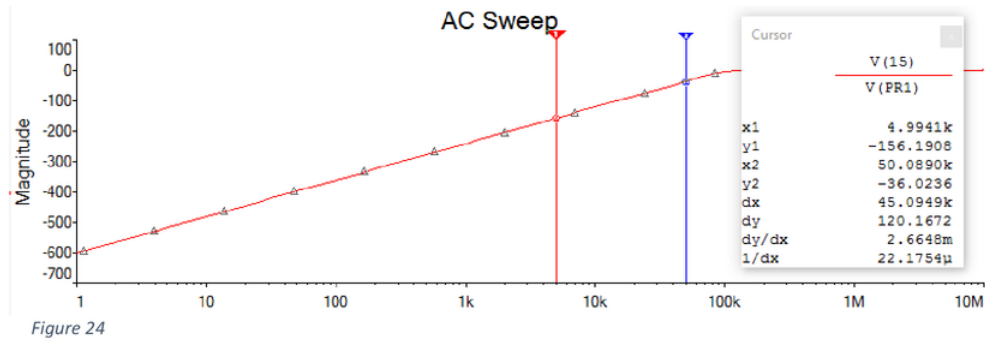
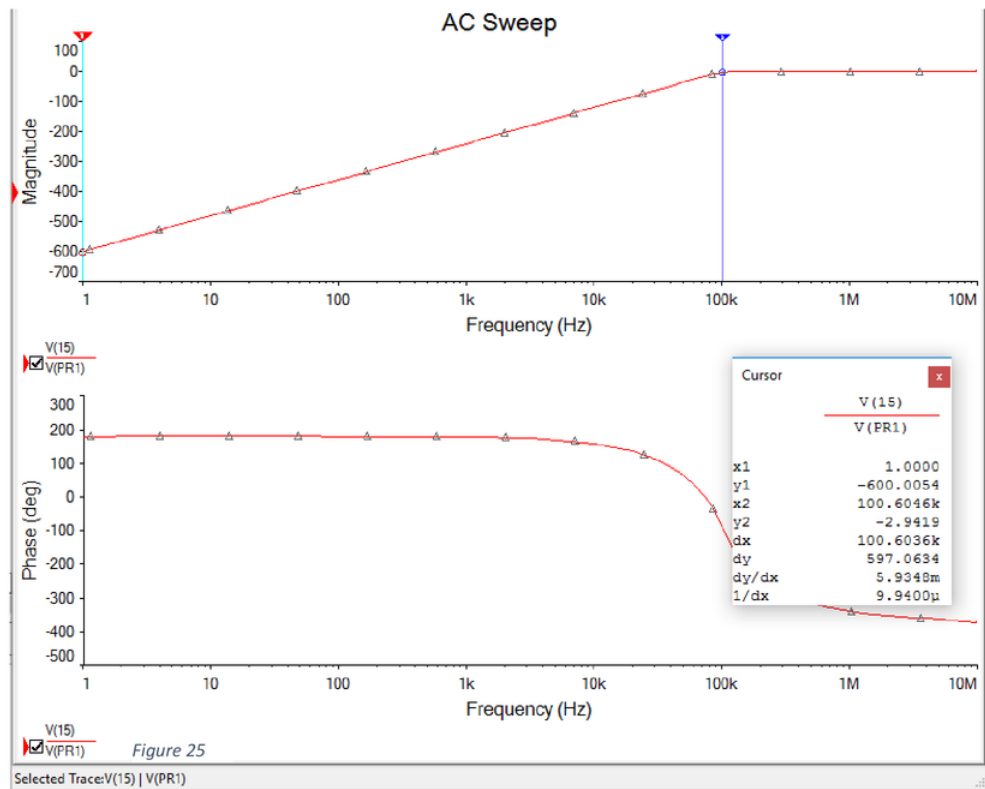
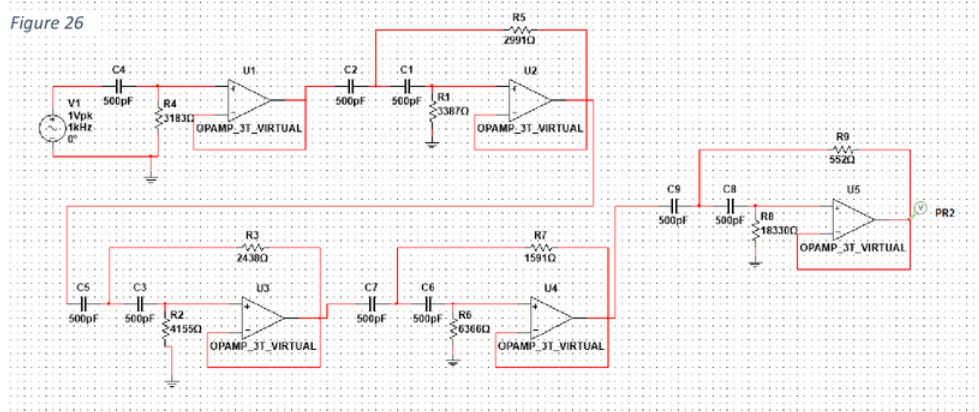


Figure 25 below shows the -3dB limit 100kHz frequency test which is successful as shown by 'x2'.

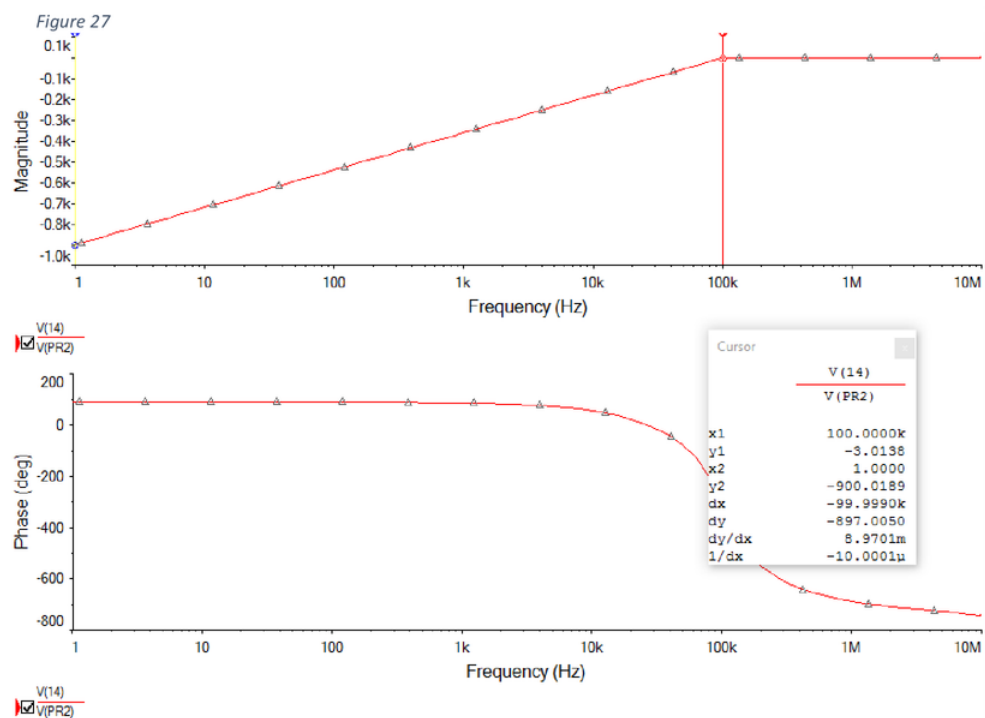


Butterworth High Pass 9th Order

Figure 26

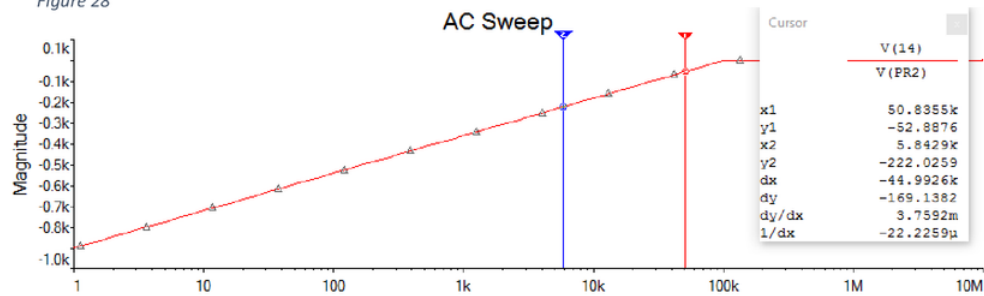


The above figure 26 shows the circuit design on multisim for the 9th order filter.



The 100kHz frequency test is performed and is shown to be within tolerance in figure 27 at -3dB.

Figure 28



In figure 28, roughly 170dB difference is seen when performing the decade test, this is true for a 9th order filter as $9 \times 20\text{dB} = 180\text{dB}$. The reason for the slightly off result on the decade test, 170dB versus 180dB, is most likely due to the final resistor values on the last (5th) stage. The target of the resistor values being between 1k and 10k Ohms is missed slightly. However, for the other component values chosen, they are the best possible values without altering the value for C1 across the entire filter.

In order to calculate the values for the 9th order filter, values for 'a' and 'b' were taken from the appropriate Butterworth table for this order.

1st stage:

$$R_1 = \frac{1}{2\pi f_c a_1 C_1} \quad R_1 = \frac{1}{2\pi \times 100k \times 1.0 \times 500pF} = 3183\Omega$$

2nd stage:

$$R_1 = \frac{1}{\pi f_c a_1 C_1} \quad R_1 = \frac{1}{\pi \times 100k \times 1.8794 \times 500pF} = 3387\Omega$$

$$R_2 = \frac{a_1}{4\pi f_c b_1 C_1} \quad R_2 = \frac{1.8794}{4\pi \times 100k \times 1.0 \times 500pF} = 2991\Omega$$

3rd stage:

$$R_1 = \frac{1}{\pi f_c a_1 C_1} \quad R_1 = \frac{1}{\pi \times 100k \times 1.5321 \times 500pF} = 4155\Omega$$

$$R_2 = \frac{a_1}{4\pi f_c b_1 C_1} \quad R_2 = \frac{1.5321}{4\pi \times 100k \times 1.0 \times 500pF} = 2438.4\Omega$$

4th stage:

$$R_1 = \frac{1}{\pi f_c a_1 C_1} \quad R_1 = \frac{1}{\pi \times 100k \times 1.0 \times 500pF} = 6366.19\Omega$$

$$R_2 = \frac{a_1}{4\pi f_c b_1 C_1} \quad R_2 = \frac{1.0}{4\pi \times 100k \times 1.0 \times 500pF} = 1591.55\Omega$$

5th stage:

$$R_1 = \frac{1}{\pi f_c a_1 C_1} \quad R_1 = \frac{1}{\pi \times 100k \times 0.3473 \times 500pF} = 18330.5\Omega$$

$$R_2 = \frac{a_1}{4\pi f_c b_1 C_1} \quad R_2 = \frac{0.3473}{4\pi \times 100k \times 1.0 \times 500pF} = 552\Omega$$

3. Conclusions

It is evident with increasing the Butterworth high pass filter order, that the values for the resistors become more extreme with each stage. At these higher stages, the smallest adjustment to component values throws the resulting calculations out massively. Tuning a circuit to achieve a high order filter will be much more difficult using the Tschebycheff design, as oppose to Butterworth or Bessel.

When evaluating the test results as the order increases, the magnitude of the filter moves in accordance. For example, the 3rd order high pass Butterworth filter has a magnitude which changes from -300 to 0dB across 0 to 100kHz. The 6th order magnitude is -600 to 0db across the same frequency range, and for the 9th order it is -900 to 0. This means that if the scale of these graphs was to be set to the same, the roll off would be getting steeper across the same frequency range as the order increases. A higher rate of roll off is desirable as it suppresses the unwanted frequency range to a higher extent than those filters of a lower order.

Out of all three filter designs, the Butterworth presents the flattest roll off curve, with the Bessel curve being almost as flat but with a smoother roll off, the Tschebycheff roll off features more ripple at the beginning, but steeply rolls off at a non-linear rate. The results of the test prove this and tie into the theory. All filters still maintain the 20db/Decade per order when analysing the attenuation curves.

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Available at: <http://www.radio-electronics.com/info/rf-technology-design/rf-filters/bessel-rf-filter-basics.php>

[Accessed 03 December 2017].

Figure 1:

https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=16&ved=0ahUKEwjmxDOZy_vXAhUpw4MKHT3FCQwQFgjATAP&url=https%3A%2F%2Fwww.researchgate.net%2Ffile.PostFileLoader.html%3Fid%3D586375025b495280e9556fc1%26assetKey%3DAS%253A444183577141250%25401482913025496&usg=AOvVaw1ElPErFBoFegUSdFpPc4kX 2

Figure 2:

https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=16&ved=0ahUKEwjmxDOZy_vXAhUpw4MKHT3FCQwQFgjATAP&url=https%3A%2F%2Fwww.researchgate.net%2Ffile.PostFileLoader.html%3Fid%3D586375025b495280e9556fc1%26assetKey%3DAS%253A444183577141250%25401482913025496&usg=AOvVaw1ElPErFBoFegUSdFpPc4kX 3

PSDE5006 Assignment 1

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

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DANIEL INCE**75****RESEARCH-INFORMED LITERATURE**

There was evidence of extensive further reading and research from credible and reliable sources. Your interpretation and understanding of the additional research was very good and demonstrated a deep underlying appreciation of the subject. Your references were appropriate to the task and your reference list was of an appropriate length for this assignment.

8**KNOWLEDGE AND UNDERSTANDING**

The knowledge and understanding of the subject demonstrated by this assignment was generally good. There were very few gaps in your knowledge of the basic principles and your understanding of the higher level concepts was demonstrated. You could have explained in more detail how the circuit evolved and the design process for how the overall system evolved.

24**ANALYSIS**

Your explanation of the experiment was good, however the conclusions lacked some detail. You could have evaluated the results in more detail and

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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. Further work – in your conclusion, you should relate the results to the original specification and to accepted theory.

PRACTICAL APPLICATION AND DEP.



Your application of practical skills for this task was generally very good. You used the resources available in MultiSim 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. Your results were comprehensive and allowed for a good conclusion to be attempted.

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SKILLS FOR PROFESSIONAL PRAC.



In this assignment you have demonstrated skills in working individually and also collaboratively. Your written report was of an appropriate length, you could however be more efficient with your word count. The report was well presented, with good diagrams in appropriate places, good sentence/paragraph structure and clear calculations.

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