

Oliver Kucyj Transducers and Signal Conditioning

by Oliver Kucyj

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Abstract

Throughout this report, different methods of filtering and conditioning signals are investigated. Two different signal conditioning circuits are created to condition a signal from a transducer. The signal conditioning circuit will filter, amplify and shift the level of the input signal.

One signal conditioning circuit has a Butterworth filter response and the other has a Chebyshev filter response. The experiments found that although the response time of the Butterworth filter was slightly better, the Chebyshev had much improved attenuation, making it ideal for use with a temperature sensor, where rapid response times are not critical.



2 Introduction

The purpose of this report is to design a circuit to filter and condition a voltage signal from a type E thermocouple. This is an industrial grade thermocouple made of a Chromel-Constantan junction. They have a temperature range of -200°C up to 750°C [1] and accuracy to 0.5% [2]. This means that as the temperature approaches 100°C the accuracy will begin to drop. An example of one can be purchased from Farnell [3].

The circuit must produce an output a voltage between 0V and 5V for a temperature reading of -50°C to 100°C .

2.1 Overvoltage protection

Overvoltage protection is designed to protect all components in the event of a fault. A Zener diode clipping circuit can be used. This involves using two opposing Zener diodes in series, connected to ground, shown in figure 1.

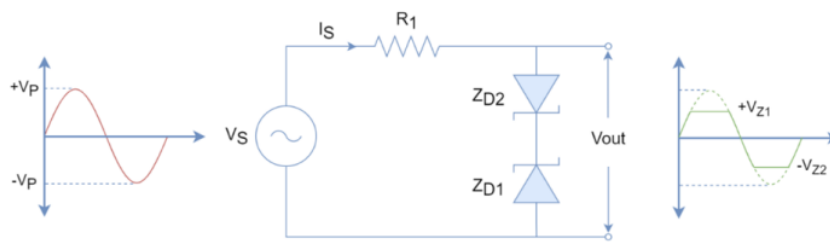


Figure 1 – Bidirectional Zener diode clipping circuit [4]

Zener diodes have a 0.7V forward voltage and will conduct in the reverse bias once the Zener voltage has been reached. Any input voltage over this is clamped to ground, maintaining a constant voltage value equal to the Zener voltage + the forward voltage. Using two opposing Zener diodes allows both positive and negative voltages to be clamped to a maximum value. With just one Zener diode, the negative voltage would be clamped to 0.7V.

2.2 Active and passive filters

The two filter types are active and passive filters. Passive usually consist of RLC circuits, whilst active LPFs usually consist of RC circuits and op-amps.

Although active filters are more complex and expensive, they have many advantages. They do not require inductors. Inductors are very large in size compared with op-amps and bring additional complications due to the equivalent series resistance (ESR) [5]. The high input impedance and low output impedance characteristics of op-amps means that no buffers are required. Active filters are well suited to signals with low voltage levels due to the high gain available.

2.3.1 Sallen & Key active filter

This report will look at the Sallen and Key filter, also referred to as a Voltage Control Voltage Source (VCVS) filter. A second order VCVS filter is shown in figure 2.

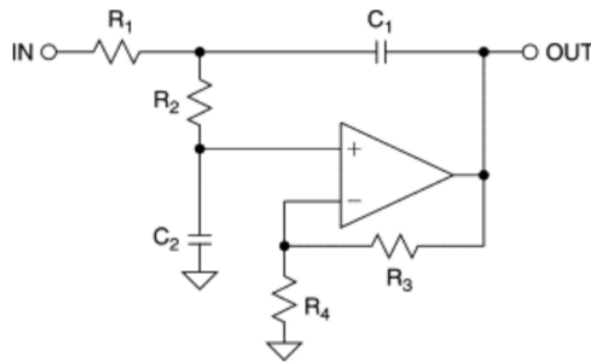


Figure 2 – 2nd order VCVS filter [6]

This filter uses two RC networks and a single op-amp. The filter order can be increased infinitely by cascading 2nd order filters.

In the filter, the RC networks are connected to the non-inverting input of the op-amp. The capacitor from the first RC network is bootstrapped to the output of the op-amp to create positive feedback. Higher frequency components are fed back through this capacitor and then grounded. Lower frequencies are amplified to the output [7].

A complication with the VCVS filter is the reliance on accurate component values. It is important that components with low tolerances are used.

2.3.2 Filter response types

There are three common filter response types associated with VCVS filters. The Butterworth, Chebyshev and the Bessel responses. The response is determined by the components chosen in the design stage.

Butterworth filters have a flat passband response. The passband is the frequency range lower than frequency cut-off. It has a moderate frequency roll off beyond the frequency cut-off. They are often used in audio applications for the flat passband, providing equal, predictable gain throughout a range of frequencies.

The Bessel filter has very good time response and linear phase shift characteristics. The passband flatness and the roll-off rate are two negatives of this filter response.

The Chebyshev filter has a ripple in the passband and a steep frequency roll-off beyond this. The size of the ripple is proportional to the steepness of the slope. The time and phase response characteristics of a Chebyshev filter are relatively poor. They do not perform well with pulsed signals. They are closer to a practical filter than the Butterworth response, since in reality even a Butterworth response has a small ripple in the passband [9].

It is clear from this that there are advantages and disadvantages to each filter response type. The application requirements must be considered when choosing the filter response to provide maximum performance with minimum complexity.

2.4 Amplification

Amplification is done using a simple non-inverting amplifier, shown in figure 3. The gain of the op-amp is set using R_F and R_2 . The op-amp current rule states that the inputs draw no current [10]. Based on this, all current must flow through both R_2 and R_F . This information can be used to generate the formula in equation 1.

$$V_{out} = V_{in} + i_1 \times R_F$$

$$V_{out} = V_{in} \times \left(1 + \frac{R_F}{R_2}\right)$$

Equation 1 – Non-inverting amplifier gain

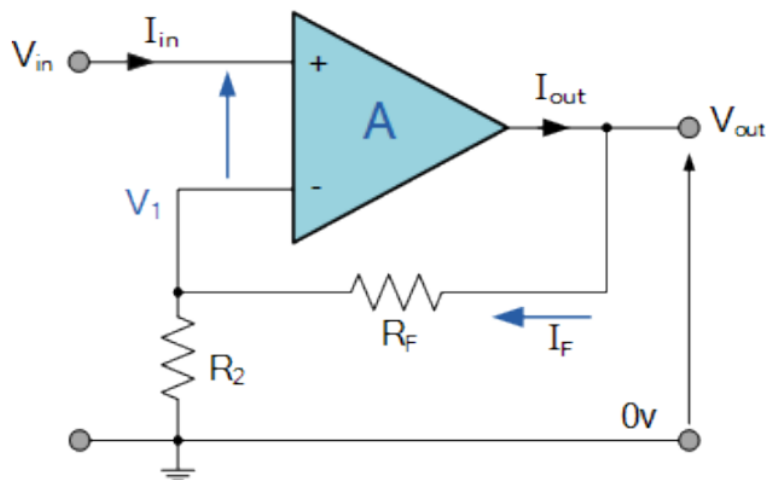


Figure 3 – Non-inverting op-amp [11]

2.5 Level shifting

After filtering and amplification is complete, the voltage range will be 5V. The issue is that this voltage will be at the wrong level. For example, the signal range may be -2.5V up to +2.5V. The required signal range is 0V to 5V.

To solve this, level shifting is required. This could be done using a summing amplifier, however, this would invert the voltage. The most optimal solution is a unity gain differential amplifier, shown in figure 4.

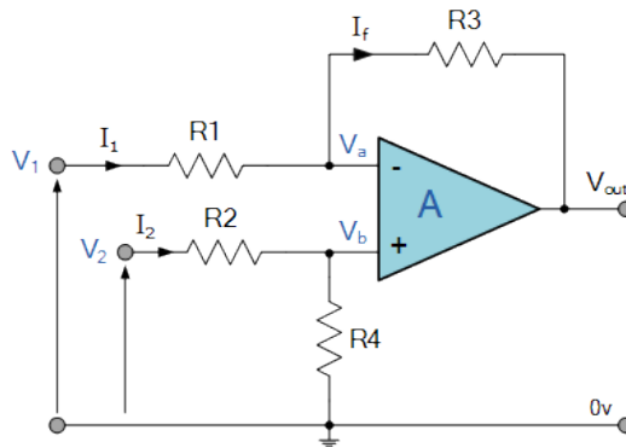


Figure 4 – Differential amplifier [11]

This configuration will output the difference between the two inputs. To ensure unity gain, all four resistors must be of equal value. When this is the case, equation 2 applies.

$$V_{out} = V_2 - V_1$$

Equation 2 – Unity gain differential amplifier

The operation can be explained using the basic op-amp voltage rule. When used with negative feedback, the output will always be the difference between the two inputs multiplied by the gain.

There is another option. Unity gain instrumentation amplifiers are available which internally contain 3 op-amps. Two of the op-amps are configured as buffers and the 3rd is connected as a differential amplifier. These are available as configured packages to ensure high precision and accuracy.

3 Designing the circuit

This section will discuss two separate designs to complete a comparison of the Butterworth and the Chebyshev filter responses. These responses were chosen because the response characteristics are both well suited to the specification.

The Butterworth is a simpler design than the Chebyshev filter, however the flat passband associated with it is not important for a DC signal. Thanks to the faster roll-off, the Chebyshev filter should attenuate more noise. This report will look to verify that this is correct.

Component tolerances can have a large effect on the circuits used so it is important that the real values are as close to the specified values as possible. 0.1% E96 resistors will be chosen throughout.

The final circuit designs can be viewed in Appendix A & B.

3.1 Overvoltage protection

It is vital that overvoltage protection is placed at the start of the circuit. The op-amp being used can accept an input voltage of $\pm 15V$ [13].

A suitable and readily available Zener diode rating is 5.1V. Two of these will be used in a bidirectional clipping circuit to ensure the voltage does not exceed $\pm 5.8V$. The circuit design is shown in figure 5.

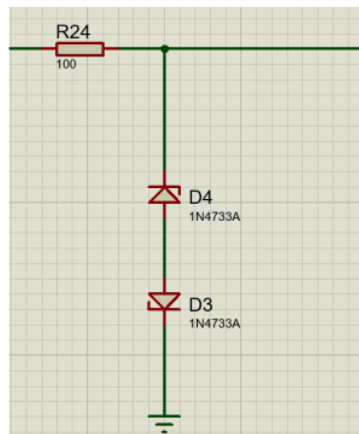


Figure 5 – Overvoltage protection circuit in proteus

3.2 Designing the VCVS filters

3.2.1 Deciding the filter order

The VCVS filter will be used for both response types. The values of the capacitors and resistors determine the response of the filter.

To determine the filter order, an acceptable level of unfiltered noise must be chosen. This determines how much the output can vary from its expected value due to noise. Some research on currently available products has shown that many devices used to monitor temperatures from thermocouples advertise very high accuracies [14]. To achieve this, the absolute maximum acceptable noise level is 0.05°C .

The maximum acceptable noise can then be used to calculate the minimum attenuation. Equations 3 & 4 demonstrate this.

$$\text{Acceptable noise} = 0.05^{\circ}\text{C}$$

$$\text{Transducer sensitivity} = 68\mu\text{V}$$

$$\text{Acceptable voltage variation} = \text{maximum noise} \times \text{sensitivity}$$

$$\text{Acceptable voltage variation} = 0.05 \times 68 \times 10^{-6} = 3.4\mu\text{V}$$

Equation 3 – Calculating the acceptable voltage variation due to noise

$$\text{Minimum Attenuation} = 20 \times \log_{10} \frac{\text{Voltage variation}}{V_{Pk} - Pk \text{ of noise}}$$
$$20 \times \log_{10} \frac{3.4 \times 10^{-6}}{120 \times 10^{-3}} = -90.95dB$$

Equation 4 – Calculating the minimum attenuation

The minimum attenuation is used to determine the order of the filter. Using the rule that there is a 20dB roll-off per decade per order, a minimum of a 5th order filter is required. Three 2nd order VCVS filters will be cascaded to create a 6th order filter.

3.2.2 Calculating the capacitor and resistor values

The frequency cut-off point must be decided to calculate the resistor and capacitor values of the filter. A lower frequency cut-off will have higher attenuation, however the filter time response will be longer. To decide this value, trial and error was used to find a balance between the filter response time and the attenuation.

Originally the frequency cut-off was 5Hz, however this was eventually increased to 8Hz to improve the frequency response time for the final version of the circuit.



Butterworth filter

All RC networks for the Butterworth response are equal. The first component to be calculated is the capacitor. There are relatively few capacitor values readily available so it is logical to calculate this first.

Equation 5 shows how to calculate the capacitor value. X_C is estimated to be 15kΩ.

$$C = \frac{1}{2 \times \pi \times F_c \times X_c}$$

$$C = \frac{1}{2 \times \pi \times 8 \times 15000} = 1.33\mu F$$

$$C = 1.5\mu F$$

Equation 5 – calculating capacitance

This capacitance can be used to calculate the resistor value. There is no inductance in the filter, so $X_c = R$. Equation 6 shows this.

$$R = \frac{1}{2 \times \pi \times F_c \times C}$$

$$R = \frac{1}{2 \times \pi \times 8 \times 1.5 \times 10^{-6}} = 13262\Omega$$

$$R = 13k\Omega$$

Equation 6 – Calculating the resistance

The gain resistors can now be calculated. The gain will differ for each op-amp. There are design tables available which specify the gain for each stage of a VCVS filter. They consider the total number of poles and the required filter response type.  In this design, a table in the Art of Electronics is used [15, p. 408]. Equations 7-9 show the calculations.

$$K = 1 + \frac{R2}{R1} = 1.068$$

$$0.068 = \frac{R2}{10000}$$

$$R2 = 0.068 \times 10000 = 680\Omega$$

$$R2 = 680 \, \Omega$$

Equation 7 – Calculating the gain of the stage 1 filter

$$K = 1 + \frac{R2}{R1} = 1.586$$

$$0.586 = \frac{R2}{10000}$$



$$R2 = 0.586 \times 10000 = 5680 \, \Omega$$

$$R2 = 5.6k\Omega$$

Equation 8 – Calculating the gain of the stage 2 filter

$$K = 1 + \frac{R2}{R1} = 2.483$$

$$1.483 = \frac{R2}{10000}$$

$$R2 = 1.483 \times 10000 = 14830$$

$$R2 = 15k\Omega$$

Equation 9 – Calculating the gain of the stage 3 filter

Chebyshev filter design

To calculate the RC network values for a Chebyshev response, a normalizing scale factor, C_N must be applied to each resistor. The value of the normalizing factor is given in the design table mentioned previously.

Equations 10-12 show the calculations. The capacitor values are the same as the Butterworth filter, $1.5\mu F$.

$$R = \frac{1}{2 \times \pi \times C_n \times F_c \times C}$$

$$C_N = 0.316$$

$$R = \frac{1}{2 \times \pi \times 0.316 \times 8 \times 1.5 \times 10^{-6}} = 41,971\Omega$$

$$R = 43k\Omega$$

Equation 10 – Calculating resistance of the stage 1 RC network

$$C_N = 0.730$$

$$R = \frac{1}{2 \times \pi \times 0.730 \times 8 \times 1.5 \times 10^{-6}} = 18,168\Omega$$

$$R = 18k\Omega$$

Equation 11 – Calculating resistance of the stage 2 RC network

$$C_N = 0.983$$

$$R = \frac{1}{2 \times \pi \times 0.983 \times 8 \times 1.5 \times 10^{-6}} = 13,492\Omega$$

$$R = 13k\Omega$$

Equation 12 – Calculating resistance of the stage 3 RC network

Next, the gain is calculated. The method is the same as the Butterworth filter. Equations 13-15 demonstrate this.

$$K = 1 + \frac{R2}{R1} = 1.891$$

$$0.891 = \frac{R2}{10000}$$

$$R2 = 0.891 \times 10000 = 8910\Omega$$

$$R2 = 8.7k\Omega$$

Equation 13 – Calculating the gain of the stage 1 filter

$$K = 1 + \frac{R2}{R1} = 2.648$$

$$1.648 = \frac{R2}{10000}$$

$$R2 = 1.648 \times 10000 = 16480\Omega$$

$$R2 = 16.5k\Omega$$

Equation 14 – Calculating the gain of the stage 2 filter

$$K = 1 + \frac{R2}{R1} = 2.904$$

$$1.904 = \frac{R2}{10000}$$

$$R2 = 1.904 \times 10000 = 19040\Omega$$

$$R2 = 19.1k\Omega$$

Equation 15 – Calculating the gain of the stage 3 filter

Figures 6 & 7 show the Proteus circuits for the Butterworth and Chebyshev responses.

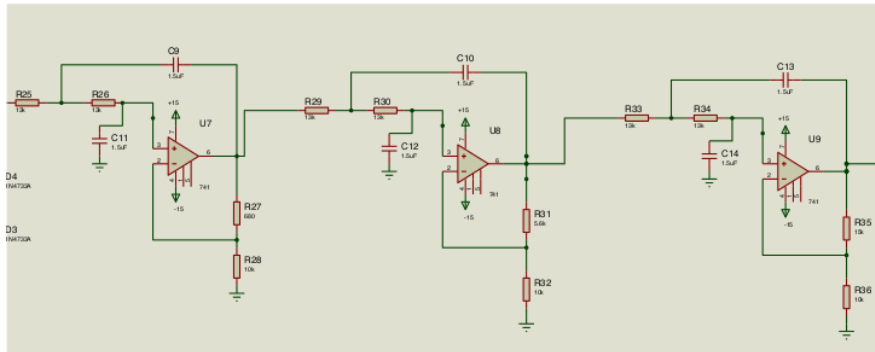


Figure 6 – 6th order Butterworth filter with 8Hz F_c

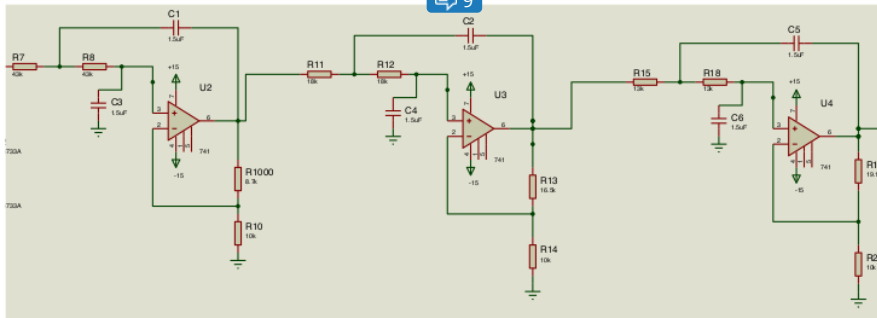


Figure 7 – 6th order Chebyshev filter with 8Hz F_c

3.3 Amplification

To amplify the signal the required gain must be calculated. To do this, the total required amplification between the input and the output must be calculated. Equation 16 shows this.

$$\text{Amplification, } K = \frac{\text{Output Range}}{\text{input Sensitivity} \times \text{temperature range}}$$

$$K = \frac{5}{68 \times 10^{-6} \times 150} = 490.196$$

$$\text{Gain, dB} = 20 \times \log_{10} 490.196 = 53.807 \text{ dB}$$

Equation 16 – Calculating total circuit gain

The VCVS filter provides amplification. The non-inverting amplifier must amplify the gain by the remaining amplification. The remaining amplification is found by simulating the filter in proteus. A frequency analysis graph can be used to measure the exact filter gain.

Figure 8 shows the frequency response of both filters. The gain of each circuit can be measured by highlighting the filter signal at the start of the response. This gain is used to calculate the remaining gain. Equations 17 & 18 show this.

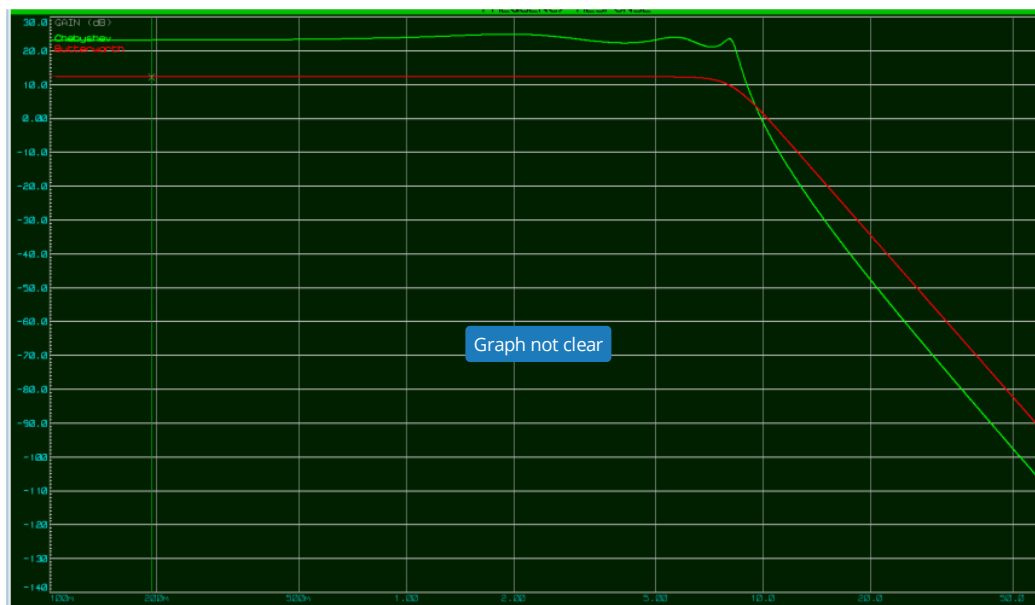


Figure 8 – Chebyshev (red) and Butterworth (Green) frequency response

$$\text{Remaining gain, dB} = \text{Total gain} - \text{Filter gain}$$

$$\text{Butterworth filter gain} = 12.4$$

$$\text{Remaining gain} = 53.807 - 12.4 = 41.407$$

$$\text{Remaining amplification} = 10^{\frac{\text{Remaining gain}}{20}}$$

$$\text{Remaining amplification} = 10^{\frac{41.407}{20}} = 117.58$$

Equation 17 – Required amplification for Butterworth filter

$$\text{Chebyshev filter gain} = 23.2$$

$$\text{Remaining gain} = 53.807 - 23.2 = 30.607$$

$$\text{Remaining amplification} = 10^{\frac{30.607}{20}} = 33.91$$

Equation 18 – Required amplification for Chebyshev filter

These values are then used to calculate the amplifier gain resistors. Equations 19 and 20 show this.

$$K = 1 + \frac{R2}{R1} = 117.58$$

$$116.58 = \frac{R2}{100}$$

$$R2 = 116.58 \times 100 = 11658\Omega$$

$$R2 = 11.7k\Omega$$

Equation 19 – Amplifier resistor values for the Butterworth circuit

$$K = 1 + \frac{R2}{R1} = 33.91$$

$$32.91 = \frac{R2}{100}$$

$$R2 = 32.91 \times 100 = 3291\Omega$$

$$R2 = 3.3k\Omega$$

Equation 20 – Amplifier resistor values for the Chebyshev circuit

These are the resistor values which will be used for the amplifiers. Figures 9 & 10 show the Amplifier circuits for the Butterworth and Chebyshev filters.

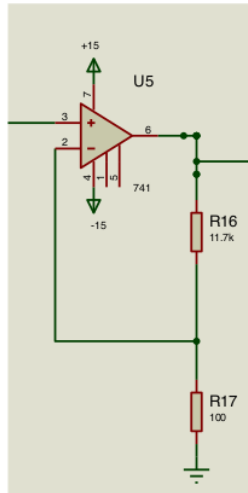


Figure 9 – Non-inverting amplifier for Butterworth filter, $K = 33.91$

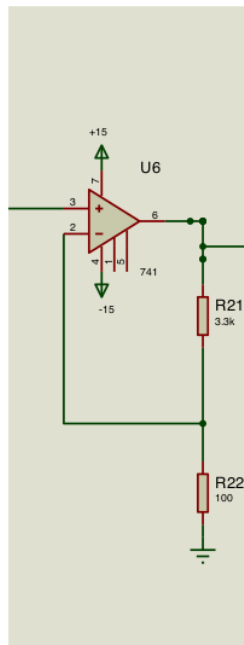


Figure 10 – Non-inverting amplifier for Chebyshev filter, $K = 117.58$

To verify that the amplification is correct, a frequency response graph can be plotted after the amplification stage, shown in figure 11. It verifies that the total circuit gain is 53.8dB on both filter responses.

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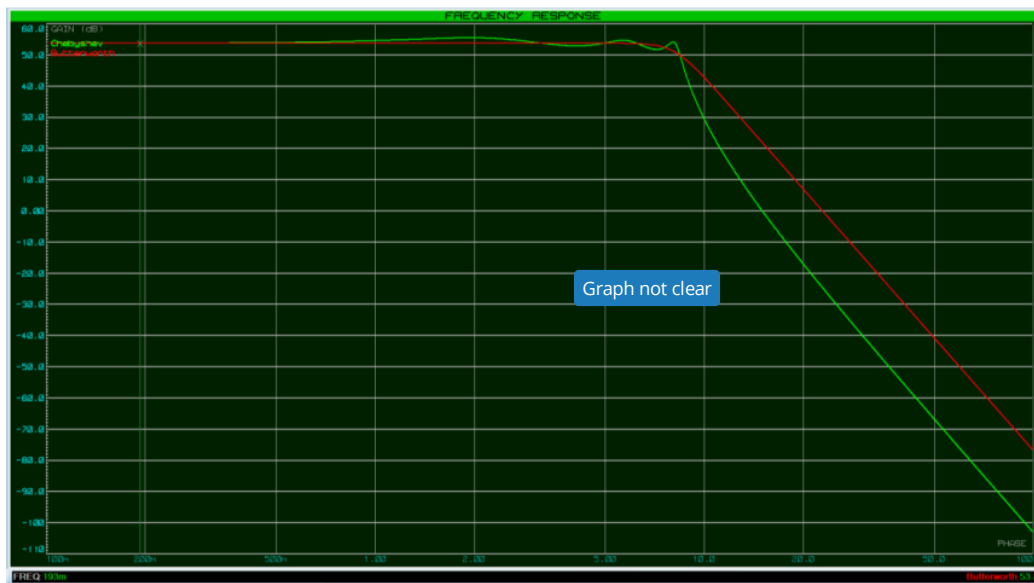


Figure 11 – Gain of the filter and amplifier – both circuits are exactly 53.8dB at DC

3.4 Level shifting

The level shifting is complete with a differential amplifier. All resistor values are equal to provide unity gain. Figure 12 shows this.

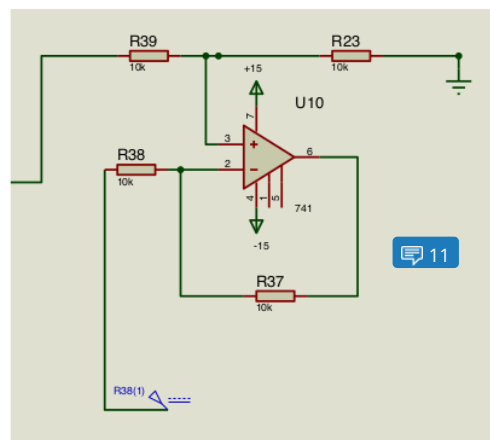


Figure 12 – Differential amplifier for level shifting

To shift the voltage level correctly, the correct voltage must be applied to the non-inverting input. The level shifting required will differ based on the filter parameters.

The simplest method of finding the required voltage is to simulate the circuit with an input signal equal to -50°C (-3.4mV). The output to this must be 0V after level shifting. The non-inverting input of the differential amplifier should be 0V. The level shifting required will be equal to the output voltage measured.

Figure 13 shows the Butterworth filter output under these conditions. The measured output was -2.16V. When the non-inverting input on the differential amplifier was set to -2.16V, the new output was 0V. Figure 14 demonstrates this. Figures 15 & 16 demonstrate this for the Chebyshev filter. The non-inverting input voltage for the Chebyshev filter was -4.1V.

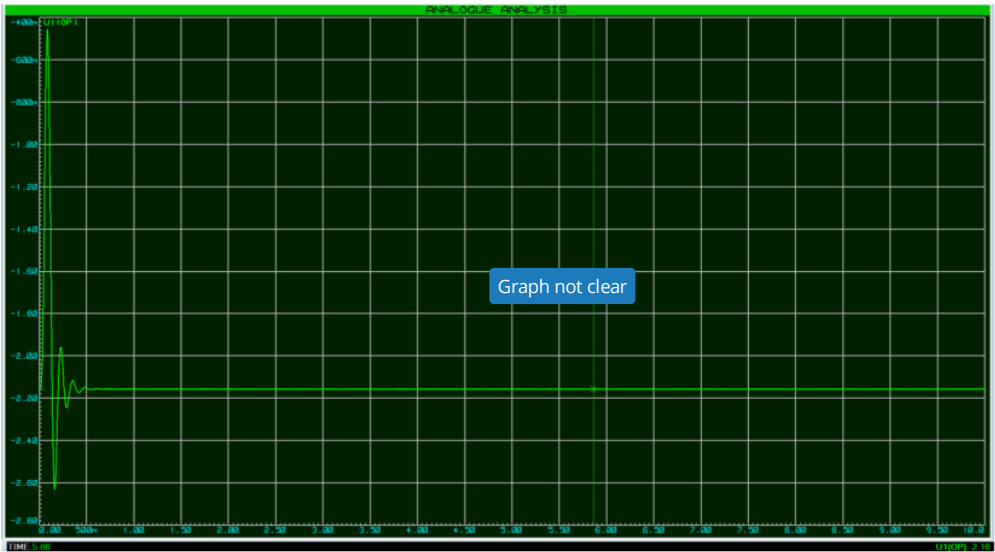


Figure 13 – Butterworth circuit output with a -3.4mV input without level shifting.

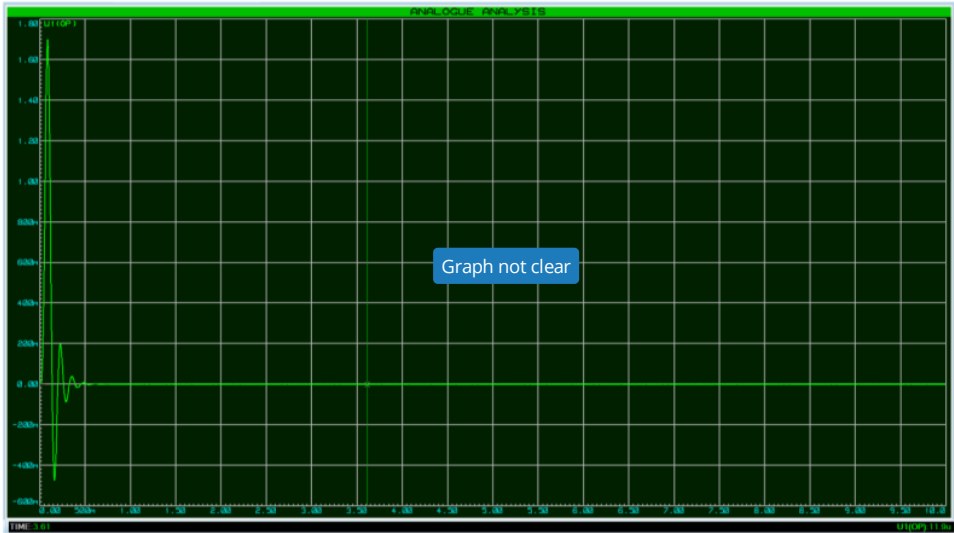


Figure 14 – Butterworth circuit output with a -3.4mV input with -2.16V level shifting



Figure 15 - Chebyshev circuit output with a -3.4mV input with no level shifting

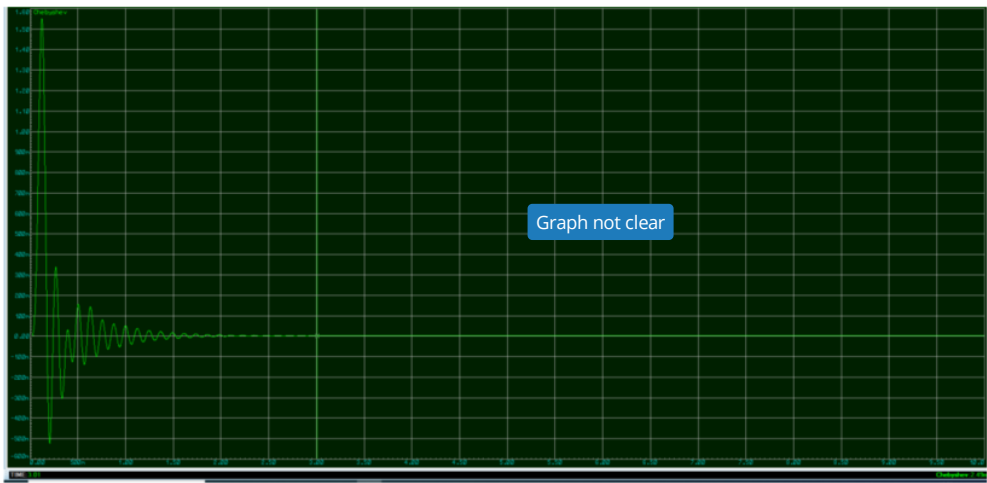


Figure 16 - Chebyshev circuit output with a -3.4mV input with- 4.1V level shifting

3.5 Bill of materials

Table 1 contains a Bill of Materials (BoM) for both filter designs. Although the resistor values differ, the cost remains the same.

Component	Component description	Farnell order number	Cost per unit	Quantity
Op-amp UA741CDT	741 op-amp	2563139	£0.77	5
Zener diode 1N5231B	5.1V Zener diode	2145973	£0.09	2
Assorted resistors +/- 0.1% E96 series	Metal film chip resistors	-	£0.28	20
1.5 μ F capacitor +/- 5%	SMD multilayer Ceramic capacitor	2905779	£0.74	6
Thermocouple type E 5TC-TT-E-36-36	Pack of 5 Type E thermocouples 1m	3794835	£75.97	1
Total Cost		£90.04		

Table 1 – BoM for both circuits

4 Results

This section contains graphs from the proteus simulations carried out on the final circuits, as well as some graphs created in excel using data collected from the simulations.

All proteus simulations were carried out with a 50Hz, 120mVpk-pk voltage applied to the DC signal.

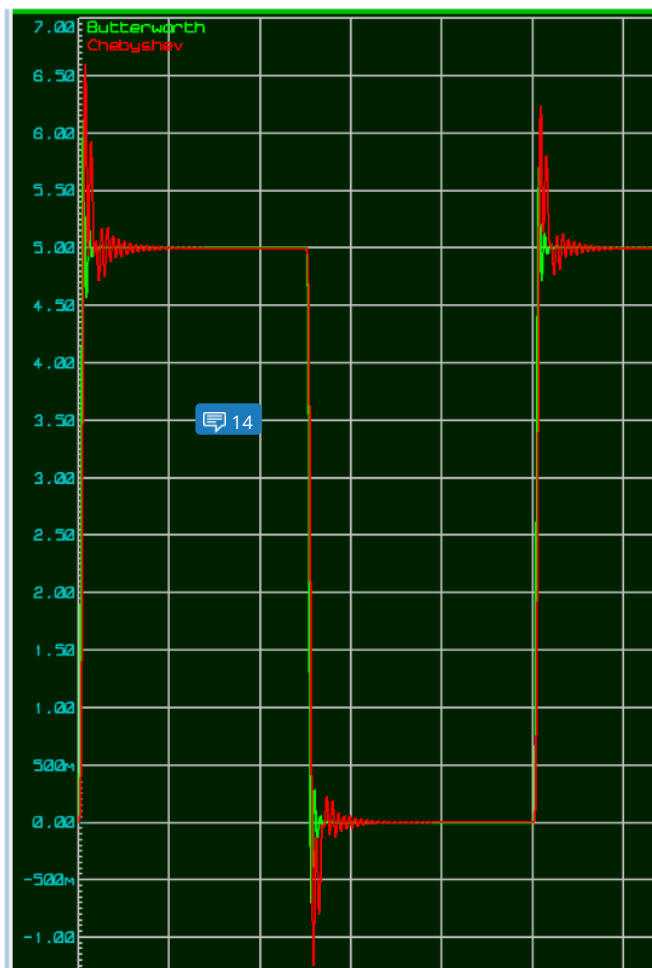


Figure 17 – Circuit outputs with a -3.4mV to 6.8mV pulsed input

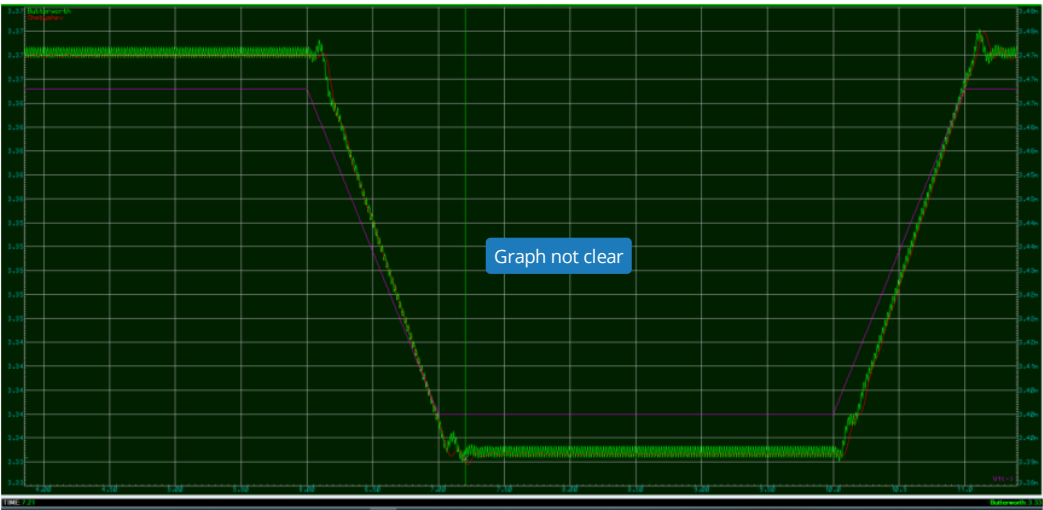


Figure 18 – Butterworth (Green) and Chebyshev (Red) outputs with a 3.4mV to 3.468mV pulsed input (Purple). The input represents a 1°C temperature change

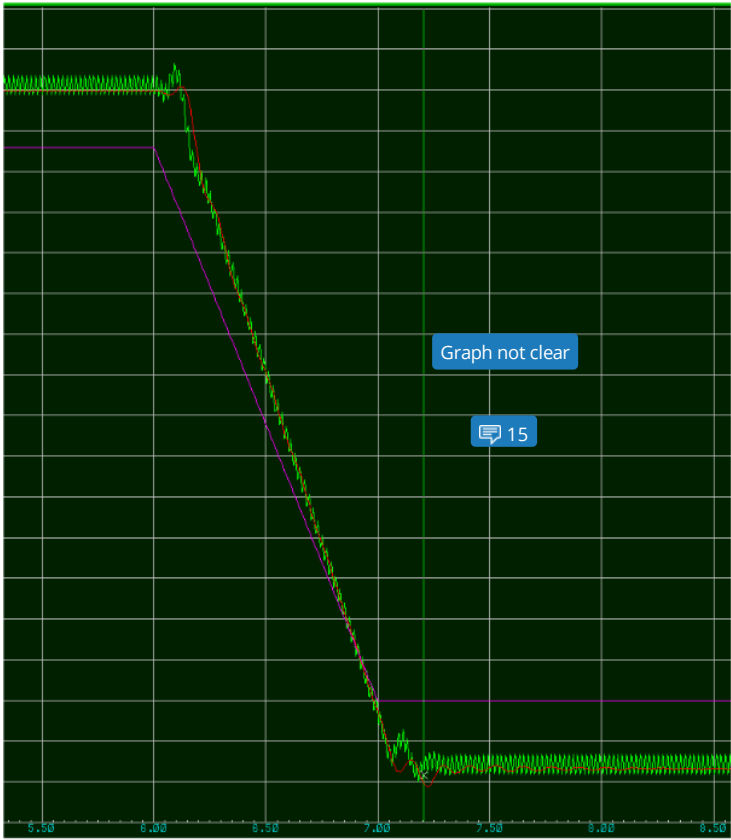


Figure 19 – Zoomed in version of figure 18

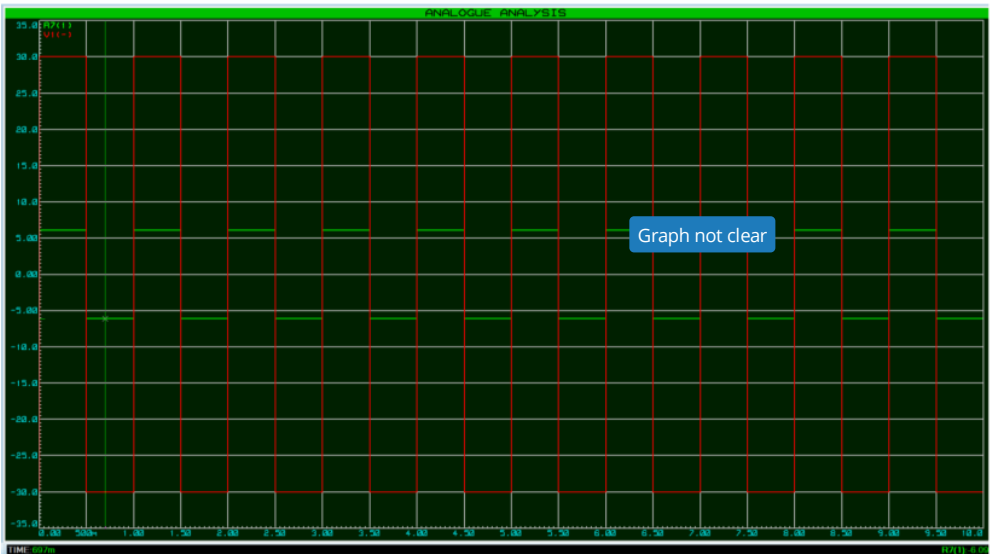


Figure 20 – A 30V voltage surge applied to the input in positive and negative polarity. The output from the overvoltage protection circuit is then measured.

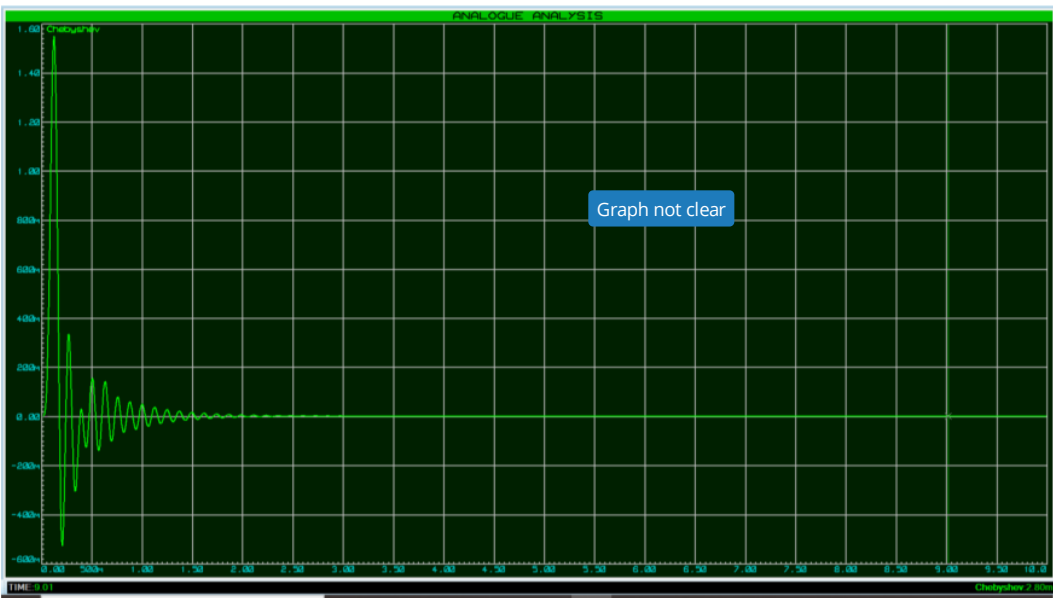


Figure 21 – Chebyshev response to a -3.4mV input with exact resistor values selected

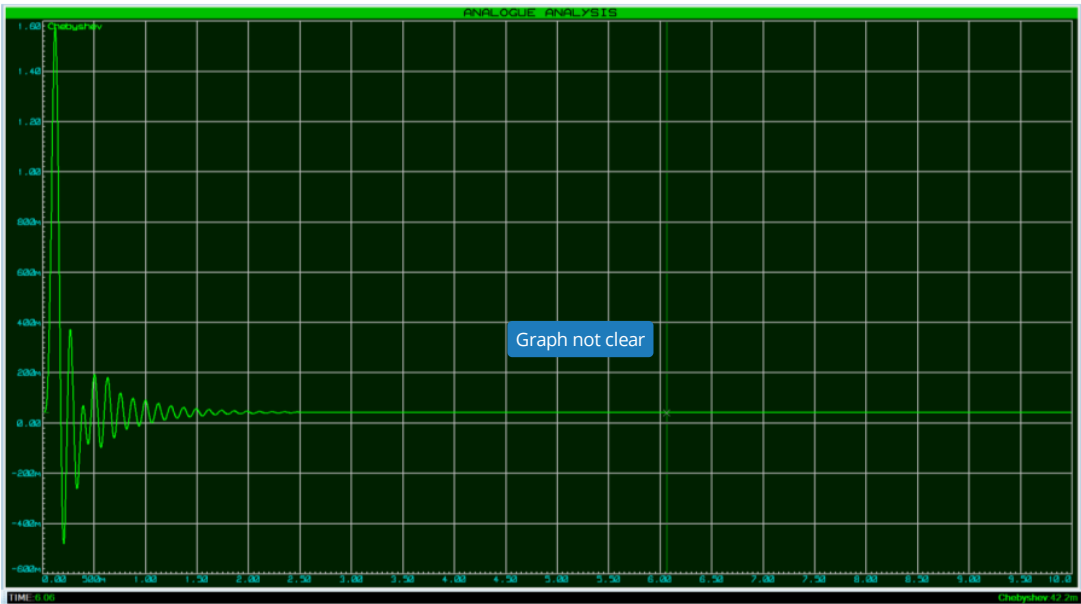
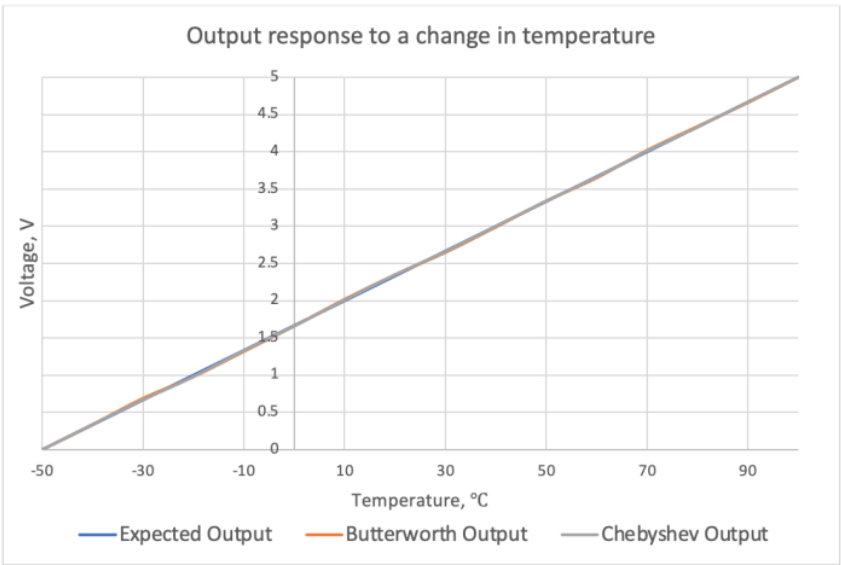


Figure 22 – Chebyshev response to a -3.4mV input with a single gain resistor on the non-inverting amplifier increased by 1%.



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Figure 23 – Relationship between output voltage and the full-scale temperature on both circuits

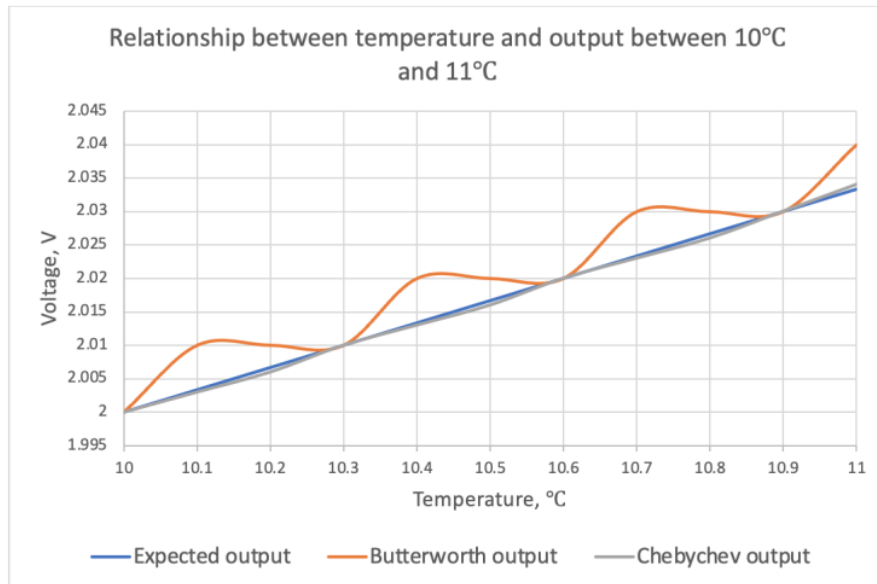


Figure 24 – Relationship between output voltage and the temperature from 10 °C to 11 °C on both circuits

5 Discussion of results

5.1 Circuit Accuracy

The results from circuit simulations prove that both circuit designs are able to accurately filter out the 50Hz mains interference and condition the circuit to the required voltage range.

Analysing figure 17, it is clear that the output voltage switches between 0V and 5V. This is the expected filter performance with a -3.4mV and +6.8mV DC input signal, replicating a -50°C to +100°C temperature change. This demonstrates that both filter response types have enough attenuation at 50Hz to filter signal to a relatively accurate level.

Figures 18 & 19 show a temperature change on a smaller scale present a better representation of the output accuracy. A pulsed input of 3.4mV and 3.468mV replicates a temperature change of 1°C. The pulse is set to have a rise and fall time of one second to greater replicate a realistic temperature fluctuation. It shows that the Chebyshev response is a much smoother line with a miniscule amount of ripple, providing a greater degree of accuracy than the Butterworth. This proves that changing the response type to Chebyshev allows greater accuracy to be achieved.

These findings are backed up by the graphs in figures 23 and 24. Figure 23 was generated by logging the output of both circuits at 10°C intervals and plotting them against the expected output voltage. All three lines appear to be very close together, indicating that the accuracy is very high. Figure 24 takes a closer look at the signal. The output of both circuits was logged at 0.1°C intervals between 10°C and 11°C. This reveals that there is still a small level of noise present on the Butterworth filters output. This suggests that the attenuation of the filter is too low.

The attenuation of each circuit at 50Hz was measured during the design stage. The Butterworth filter has 82.5db and the Chebyshev has 97.5dB attenuation. The calculated

minimum attenuation to attenuate 0.05°C of noise was 90.95dB. The simulation findings prove that these calculations were an accurate method of deciding the minimum attenuation, since the Butterworth filter does not achieve 0.1°C accuracy.

This 0.1°C accuracy does not consider the inaccuracies potentially present in the thermocouple being used.

5.2 Overvoltage protection

Figure 18 proves that the overvoltage protection works. The +/-30V input is limited to +/- 5.9V. This will provide adequate protection for the circuit components.

5.3 Frequency response time

The frequency response time of both circuits is relatively fast. This is due to the fact a relatively higher frequency cut-off value was chosen and justifies that decision. Figure 19 shows that both filters respond to a small change in the input within 0.2S. It is difficult to measure the exact time due to the undershoot and overshoot of the signal which causes a longer settle time.

The Butterworth filter does not experience a long settle time. The temperature can be accurately monitored within 0.4S of the temperature change. The Chebyshev filter takes roughly 1 second to completely settle. Whilst this is considerably worse than the Butterworth response, the Chebyshev ripple is smaller than the Butterworth ripple after 0.4S, meaning an accurate reading could be taken after 0.4S. The Chebyshev ripple continues to reduce beyond this point though, whilst the Butterworth ripple remains.

The reduced time response characteristics of the Chebyshev filter was expected and discussed in section 2.3.1. The response is worse with a pulsed input as figure 17 shows, however the slow changing input used in figure 19 is a realistic temperature change. The

time delay does not pose any complications. An extremely accurate reading could be taken every second. This does prove that all filter responses will have its own unique application.

5.4 Component tolerances

One of the downsides of the circuits used for this design is the sensitivity to component tolerances. To prove this, figures 21 and 22 show the output signal with a -3.4mV input applied. Figure 22 has 20 one resistor on the non-inverting amplifier increased by 1% to create the circuit shown in figure 25. This increased the output voltage by 40mV, which is an error of over 1°C. This verifies the reason for using high precision components.

22 Op-amps suffer from tolerance issues too. Op-amps can have a small internal voltage between the two inputs. This small voltage can offset the output. To resolve this, the offset null pin on the 741 op-amp is used. This can be connected to ground through a variable resistor. Each op-amp would need to be calibrated using this variable resistor to ensure that when the two inputs are equal, the output is 0V.

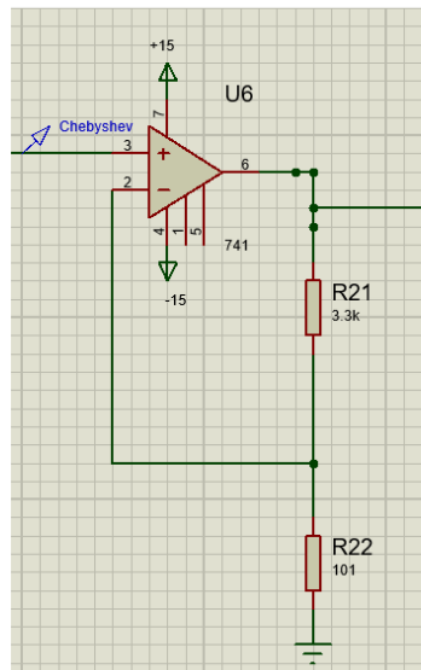


Figure 25 – Non-inverting amplifier with modified resistor

6 Conclusion

The findings of this report conclude that a 6th order VCVS filter used with a non-inverting amplifier and a differential amplifier is able to effectively attenuate 50Hz noise from a considerably smaller DC signal. The two filter responses analysed successfully filtered out the noise.  23 however the Chebyshev filter provided higher attenuation and hence, higher accuracy. This confirmed what was discussed in section 2. Despite the slightly worse signal response time of the Chebyshev filter, it is a superior alternative to the Butterworth filter for this application.

It was also found that the margins for a filter such as this are extremely fine. Small variances in components due to tolerances can completely distort the output, hence why high precision resistors were required.

7 References

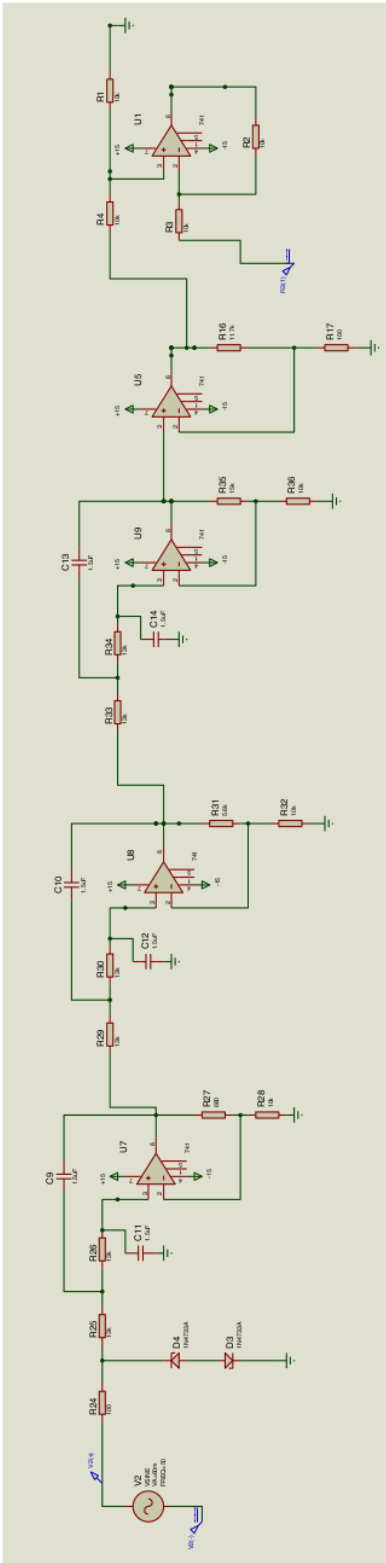
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Ref Qual

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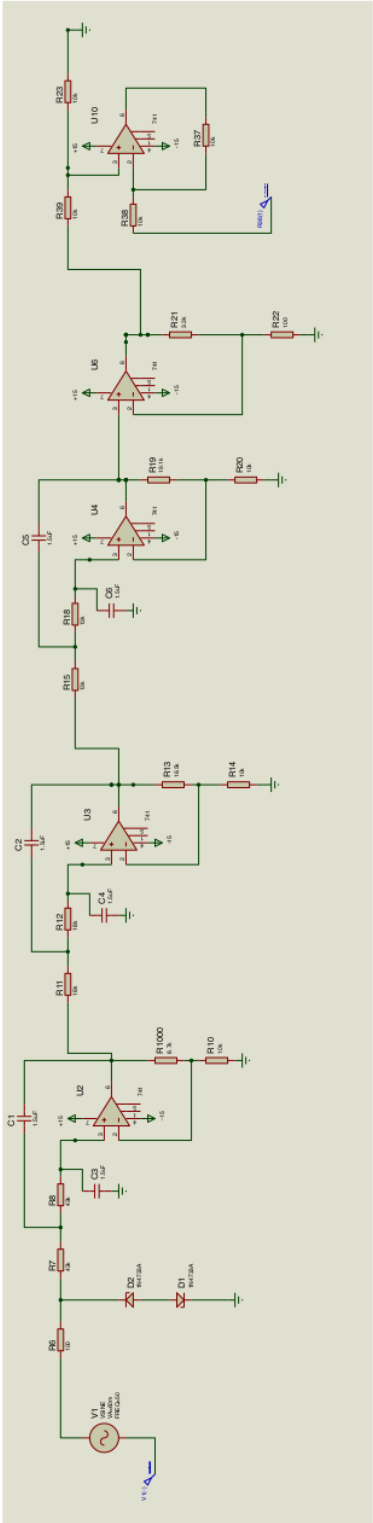
Appendix A

Appendix A shows the Butterworth filter circuit design



Appendix B

Appendix B contains the Chebyshev filter design circuit



Oliver Kucyj Transducers and Signal Conditioning

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

71 /100

PAGE 1

PAGE 2

PAGE 3



Comment 1

Good abstract, but you should quantify statements like these with actual figures from your results.

PAGE 4

PAGE 5



Comment 2

This is only true for certain configurations, as the input impedance can be significantly different for inverting and non-inverting amplifiers. e.g. Z_{in} of inverting amplifier is approximately equal to input resistor as inverting input of op-amp is a virtual earth. Z_{in} of non-inverting amplifier is governed by the non-inverting input of the op-amp and is usually in the Megaohm range. Therefore an inverting amplifier *can* cause loading effects of a source if low value resistors are used.

PAGE 6



Comment 3

Good point, but robust design practices can ensure intended operation by taking account of these tolerances. e.g. capacitors generally have a wider tolerance than resistors therefore if a lower value capacitor is used with a higher value resistor the cutoff frequency is maintained but the effects of the capacitor's tolerance are minimised. A balance has to be

struck between trading capacitor tolerance for higher resistances as large resistor values can induce thermal (Johnson-Nyquist) noise into circuits.



Comment 4

Good example

PAGE 7

PAGE 8



Comment 5

They are configured as a pair of linked non-inverting amplifiers which can be changed to unity gain buffers by removing the gain resistor linking the two halves.

PAGE 9

PAGE 10

PAGE 11



Comment 6

What effect did this have on the circuit's ability to attenuate the 50 Hz interference?

PAGE 12



Comment 7

Why not reproduce the table here and cite it?

PAGE 13



Comment 8

These calculations are quite repetitive. Do you think they may have been presented better if the equations were given once with variables instead of numbers, along with a table of calculated values?

PAGE 14

PAGE 15

PAGE 16



Comment 9

These two images look identical as the component values are too small and too blurred to read



Graph not clear

Graph is not clear.

Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.



Comment 10

at what frequency?



Graph not clear

Graph is not clear.

Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.



Comment 11

output of circuit is not clearly marked.



Comment 12

This is a somewhat tautological statement



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Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.



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Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.



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Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.



Comment 13

Are figures 13 - 16 really needed? could they be replaced by a couple of short statements:

"The filters' output high and low level voltages were measured from the simulations and are shown in table 2. These voltages will be used to determine the level shifting circuit parameters."



Comment 14

There seems to be quite a lot of overshoot and ringing on this. Why? Is this just down to the rise and fall times of the input signal coupled with the response of the filter?



Graph not clear

Graph is not clear.

Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.



Graph not clear

Graph is not clear.

Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.



Comment 15

axis removed. - makes this graph very difficult to read

PAGE 27

QM

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Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.

QM

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Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.

PAGE 28

QM

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Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.

PAGE 29

PAGE 30

PAGE 31



Comment 16

This sentence seems confused. I think you mean:

"The minimum attenuation required to attenuate the noise present on the input to an equivalent temperature variation of 0.05 degC was 90.95 dB."



Comment 17

What does the input of 5.9V produce as an output?



Comment 18

You could measure the time difference between the 50% point of the input to the 50% of the output, this way you are avoiding the overshoot and settling issue.



Comment 19

Did you measure it? What were the values? How much smaller?

PAGE 32

PAGE 33



Comment 20

Which one?



Comment 21

This could be minimised by spreading the gain over several amplifier sections. e.g. also applying gain in the difference amplifier stage could help with this without increasing component count.



Comment 22

This is caused by an imbalance of impedances seen on the input terminals of the amplifier. There are ways of minimising this effect.

PAGE 34



Comment 23

Would a 4th order Chebyshev performed as well as a 6th order Butterworth? Could you have achieved the same performance with fewer components?

PAGE 35



Ref Qual

You should try to use more high quality reference sources, such as textbooks from reputable academic publishers and articles from peer reviewed journals.

PAGE 36



Ref Qual

You should try to use more high quality reference sources, such as textbooks from reputable academic publishers and articles from peer reviewed journals.

PAGE 37

PAGE 38

OLIVER KUCYJ

71.10

ENGAGEMENT WITH LITERATURE

including reading, referencing, academic conventions and academic honesty



A comprehensive range of research informed literature embedded in the work. Excellent selection of relevant and credible sources. High-level referencing skills, consistently applied

3.5

KNOWLEDGE & UNDERSTANDING

Knowledge of the basic underlying concepts and principles of a subject.



Excellent knowledge and understanding of the main concepts and key theories. Clear awareness of challenges to established views and the limitations of the knowledge base.

22.5

COGNITIVE & INTELLECTUAL

Evaluate underlying concepts and principles of a subject and interpret qualitative and quantitative data in order to develop lines of argument and make sound judgements.



Thoroughly logical work, supported by evaluated evidence. High quality analysis, developed independently. Ability to investigate contradictory

21.6

information and identify reasons for contradictions. Strong, persuasive, conclusions, justifiable recommendations.

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



A very good application of a range of methods, materials, tools and/or techniques. Very good consideration of the context of the application, with perceptive use of examples, where relevant. Evidence of some innovation and creativity.

20.4

TRANSFERABLE SKILLS

Communicate the results of their study/work accurately and reliably, and with structured and coherent arguments; the qualities needed for employment requiring the exercise of some personal responsibility within a structured and managed environment.



2908 words after removal of: cover page, tables, headings, captions, equations, reference lists, appendices, headers and footers. This is 16% over the limit. You NEED TO BE MORE CONCISE. Take care when inserting images - make sure they are clear. Can communicate well, confidently and consistently in a suitable format. Work is coherent and fluent and is well structured and organised.

3.1