

Signal Conditioning Design - Jayden Fox

by Jayden Fox

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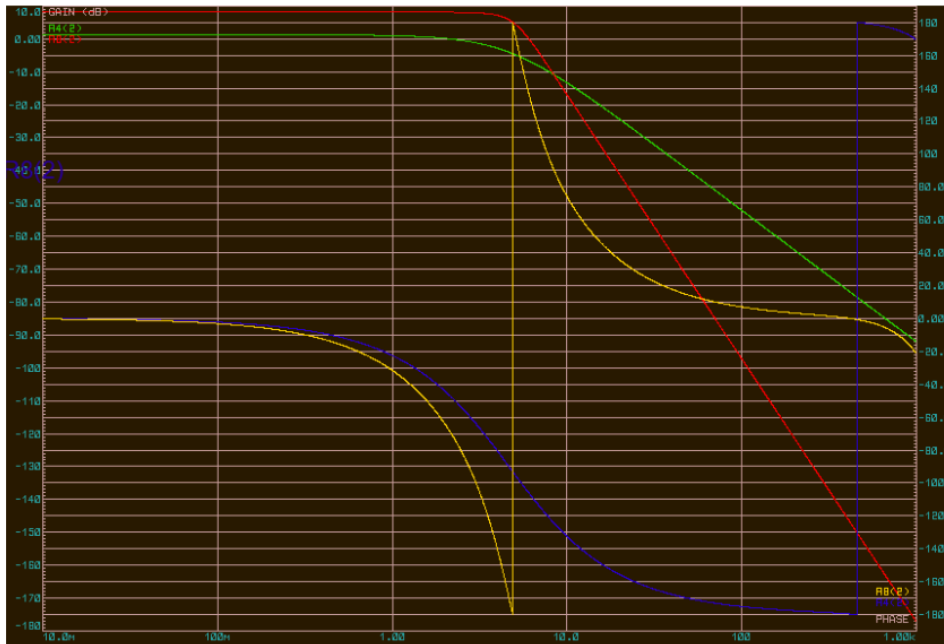
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Transducers and Signal Conditioning – ACDA5006

Signal Conditioning Design



Jayden Fox – 2316329

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Abstract

This report focuses on the design and simulation of a signal conditioning circuit for a temperature sensor output, which is contaminated with a 120mVpk-pk 50Hz mains interference. The circuit needed to achieve a clean output signal ranging from 0V at -50°C to 5V at 100°C, aligning with the temperature sensor's output of 68μV/°C.

The circuit contained key stages of the signal conditioning process to solve this issue: over voltage protection, a 4th order Sallen-Key low pass filter, amplification and level shifting. The over voltage protection section utilised Zener diodes to protect the circuit from high voltages. The filter was set up to give a Butterworth frequency response to attenuate the interference with a roll-off rate of 80db/decade, where component values were carefully chosen to achieve this whilst also conforming to the E24 series. A non-inverting amplifier was used to amplify the output of the filter and level shifting was required to move the output into the correct 0V to 5V range.

The results confirm that the circuit created met the requirements of removing the interference, having a clean output signal and achieving the Butterworth frequency response. The results were gained from simulating in Proteus, which allowed the creation of frequency response graphs to show the achieved Butterworth response and analogue analysis graphs to calculate the time delay of the circuit. The time delay was calculated to be 93ms, which was acceptable for the temperature sensor application.



This report documents the process of creating the circuit such as researching the available technologies to solve the issue, explaining why the chosen technologies were used, the calculation of component values along with the design and testing of the circuit. The results were then discussed to validate the circuit's design, as well as showing the solution of the problem with a clean and reliable final output.



Introduction

In this assignment, a signal conditioning circuit is required to filter out a temperature sensor output which has been contaminated by a 120mV peak to peak 50Hz mains interference. The task is to design a circuit that will reject the interference, whilst still producing an output signal of 0V at a temperature of -50°C and 5V at a temperature of 100°C. As the temperature sensor produces 68μV/°C, a type E thermocouple is the most appropriate to use as they are the best suited to the required low temperature output.

The circuit will utilise a 4th order Sallen-Key filter in a low pass configuration as this will reduce the noise and errors that the interference has created on the signal. The Sallen and Key filter is an active filter design based around a non-inverting amplifier, resistors and capacitors [2]. A 4th order Sallen-Key filter can be created by cascading two 2nd order Sallen-Key filters, meaning 2 non-inverting amplifiers, 6 resistors and 4 capacitors are required to build the filter.

The circuit will require over voltage protection, which utilises Zener diodes to prevent damage to the circuitry. Over voltage protection is important as there could be issues with the components, like transducers, which could lead to unexpected high voltages. An additional amplifier is also needed to amplify the Sallen-Key filter's small output to the correct range.

Additionally, there may be an issue where the voltage signal from the temperature sensor will not be in the correct range. A level shifting amplifier can be used to correct this and this is where an adjustable DC voltage is added to the signal to move it into the correct range.

This report will focus on the design of a 4th order Sallen-Key filter, which will reject the unwanted interference, and give a detailed insight on the technologies used to do so. The signal conditioning circuit will then be simulated in Proteus to prove that the interference has been removed and the correct frequency response has been received. The results will then be discussed to see whether the circuit has worked as expected.

Background of information

Signal conditioning is defined as the process of preparing signals from sensors in order to make them easier to use, as sensors are commonly affected by noise and other unwanted interference. Through signal conditioning, an interference can be removed from a raw output to make the signal more reliable for the next stage of processing. Signal conditioning is achieved in this report through Zener diodes as over voltage protection, a Sallen-Key type filter and a non-inverting amplifier to amplify the filter output. However, there are different technologies available which can also do the same job.

Over voltage protection alternative

Instead of using Zener diodes for overvoltage protection, regular diodes can be used. This diode setup is called diode limiter and limits the output swing [3]. By having 2 diodes connected in inverse parallel, both the positive and negative half cycles of the input would be clipped. The clipping point would occur at +0.7V for diode 1 and -0.7V for diode 2.

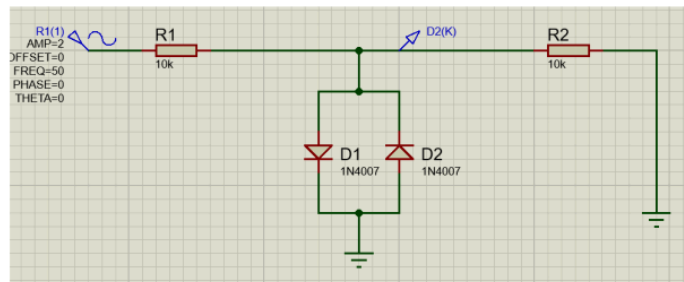


Figure 1: Alternative OVP setup with diodes

Filter alternative

An alternative signal conditioning filter to the Sallen-Key type is a multiple feedback filter. Although a multiple feedback filter shows less overall sensitivity to component variations and has a better high-frequency performance, these benefits were shown to be unneeded in the scenario. Additionally, the required calculations were shown to be more complex to complete on a multiple feedback filter [4].

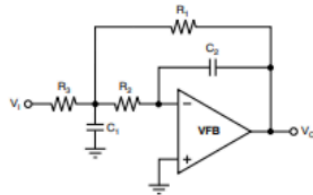


Figure 2: Example of a 2nd order filter based on multiple feedback topology [5]

Gain alternative

An inverting op amp could be used here but it would require further inversion from later circuitry to give a required positive output. The gain could be calculated using $-\frac{R2}{R1}$, which would give a negative output. Non-inverting amplifiers were preferred as they were less complex.

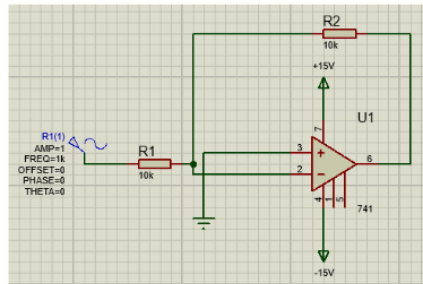


Figure 3: Non-inverting amplifier

Method

There are three types of classic filter responses associated with a Sallen-Key filter, which are Bessel, Butterworth and Chebyshev responses. A Bessel response gives a smooth roll off with no ripples and no time delay but has a very slow roll off speed. Additionally, the Chebyshev filter type has a faster roll off speed but gives ripples in the pass band. A Butterworth filter type was chosen here as it has the smoothest curve with no ripples. Despite its slow roll off speed, a Butterworth response was preferred as it has a better pulse response compared to a Chebyshev response and a better rate of attenuation compared to the Bessel response [6].

Higher order filters are more complex and expensive to design; however, they have steeper roll-off rates so they can provide a better attenuation of unwanted frequencies. This creates a trade-off between whether circuit complexity or better attenuation is preferred, and this is why a 4th order filter was selected. They are still relatively simple to build compared to even higher order filters and still give the attenuation qualities that are shown to be weaker in lower order filters.

With a 4th order Sallen-Key filter, the desired roll-off rate is 80db/decade. A cut-off frequency of 5Hz was chosen to achieve a good attenuation at 50Hz, as 5Hz to 50Hz is a decade. 5Hz was also the point at which the filter response was at -3dB.

When deciding on the gain of the filter, the values of the gain needed to be 1.152 and 2.235 respectively. As a 4th order filter is used, the first stage of the filter needs a gain of 1.152 and the second stage of the filter needs a gain of 2.235 to achieve the desired Butterworth filter response [7].

Cn	Gain (K)
1	1.152
1	2.235

Table 1: Table showing values needed to achieve a Butterworth response on a 4th order Sallen-Key filter [7].

By using the equation $R = \frac{1}{2\pi \cdot F \cdot C \cdot Cn \cdot C}$, the filter resistance was calculated at 6772.55Ω.

According to the E24 series, a 6.8kΩ resistor is the closest possible this will need to be used.

For the first stage of the filter, the gain of 1.152 was achieved by using a 10kΩ resistor (R1) and a 1.52kΩ resistor (R2). The value of the second resistor was calculated using the formula $R2 = R1 \cdot (K-1)$. The second stage of the filter needed a gain of 2.235 and this was achieved by using a 10kΩ resistor along with a 12.35kΩ resistor, which again was calculated using the $R2 = R1 \cdot (K-1)$ formula.

The temperature sensor produces 68μV/°C with 0V = 0°C, as stated in the brief. This means that at -50°C, the voltage will be -3.4mV (68μV*50) and therefore at 100°C, the voltage will be 6.8mV (68μV*100).

Temperature (°C)	Voltage (mV)	Filter output Missing Units	Required final output (V)
-50	-3.4	-0.00705	0
0	0	0	
100	6.8	0.0193	5

Table 2: Table showing the temperature range, with the voltages at each interval

- Temperature range = 150°C
- Voltage range = 10.2mV
- Filter output range = 26.35mV
- Needed final output range = 5V

As a final output of 0-5V is needed, an amplifier is needed to increase the output. By taking the range of the required filter output and dividing it by the actual filter output, it was seen a gain of 189.75 was needed. A 150kΩ resistor was used and although the second resistor was calculated to be 794.688Ω (using the equation $R1 = \frac{R2}{k-1}$), an 820Ω resistor was used as this was the closest possible value in accordance with the E24 series.

Design

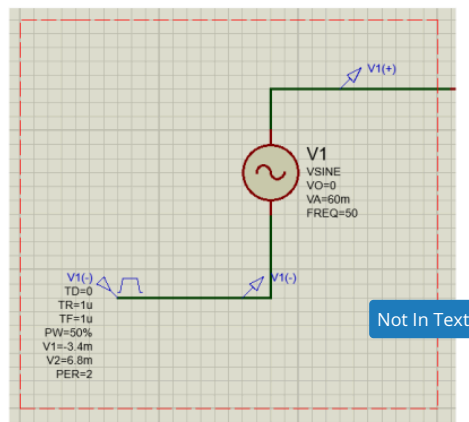
To reject the noise and errors the interference has caused, a 4th order Sallen-Key filter will be used. As seen in figure 2, the temperature sensor output will pass through the over voltage protection setup b7 reaching the filter. The filter output will then be amplified and the level shifting setup will be used to ensure the final output voltage is in the correct range. The resistor values chosen all conformed to the E24 series, which are more cost effective as they are standard values and wouldn't require the additional use of a potentiometer to get the other resistor values [8].



Figure 4: Circuit block diagram

Not In Text

Input



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Figure 5: Input stage of circuit

A signal generator was used to simulate the maximum and minimum voltage from the thermocouple and the sine voltage source was used to replicate the noise that would be caused.

Components used:

- Signal generator – low voltage at -3.4mV, high voltage at 6.8mV
- Sine voltage source – 60mV, 50Hz

Over voltage protection

As previously explained, over voltage protection is needed to protect the circuit and Zener diodes were used to clamp any dangerous voltages. Diodes were 3.1V reverse biased and 0.7V forward biased, giving a total of 3.8V.

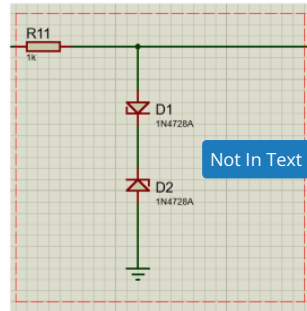


Figure 5: OVP section of circuit

Components used:

- Resistor – 1k Ω
- 2 x Zener diode (1N4728A)

Filtering

The filter used in the circuit is made up of two 2nd order filters. A second order filter is characterised by two sets of RC networks with equal resistor and capacitor values. To create the 4th order filter, the output of a 2nd order filter can flow into a following 2nd order filter. The output of the 4th order filter is considered as the output of the final 2nd order filter. There is a voltage probe on the output of the first filter (R4(2)) and on the output of the second filter (R8(2)) so the values can be used in simulations. The values of the components were decided in accordance with the **VCVS lowpass filters table found in the Art of Electronics textbook [7]**.

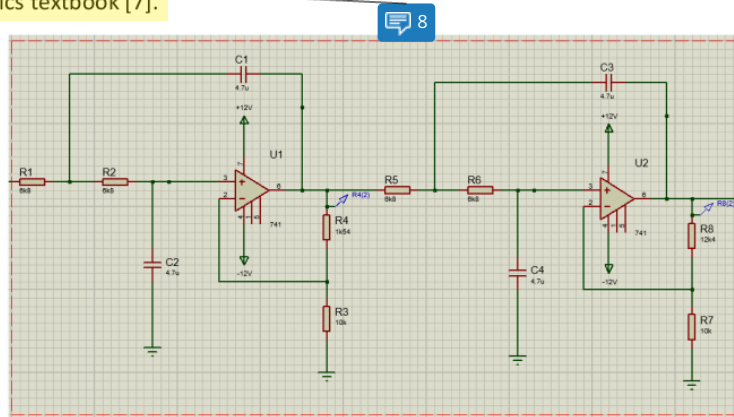


Figure 6: 4th order Sallen-Key filter

Components used:

- 4 x 6.8k Ω resistor
- 4 x 4.7 μ F capacitor
- 2 x LM741 amplifier
- 2 x 10k Ω resistor
- 1 x 12.4k Ω resistor
- 1 x 1.54k Ω resistor

Amplification

This is needed to amplify the filter output to the correct range of 5V. In the case of this part of the circuit, the range is currently approximately -1.12V to 3.88V. This needs to be changed to fit the range given in the assignment brief. The voltage probe (R9(2)) allows the amplified output to be visualised as it can then be used on results graphs.

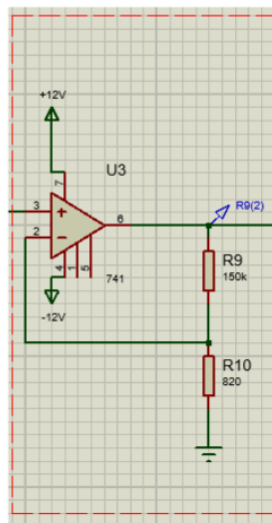


Figure 7: Post filter amplifier

Components used:

- 1 x LM741 amplifier
- 1 x 150k Ω resistor
- 1 x 820 Ω resistor

Level shifting/offset

A level shifting amplifier has been used to shift the range of the voltage signal. The offset of -1.12V is placed at the top of the amplifier and after this, the output voltage signal range is now 0V to 5V.

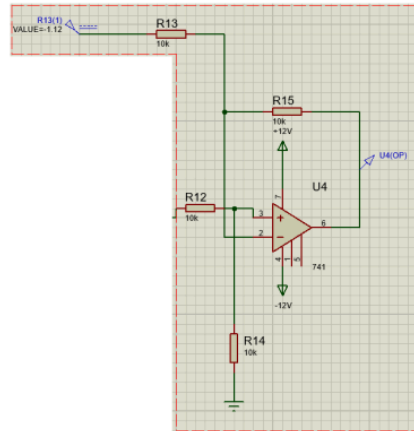


Figure 8: Level shifting

Components used:

- 1 x LM741 amplifier
- 4 x 10kΩ resistor
- DC Generator set at -1.12V

Whole circuit

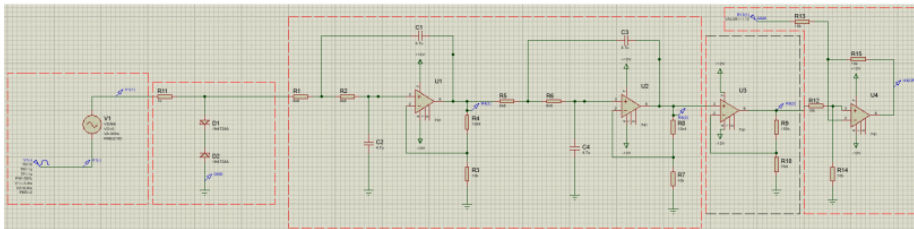


Figure 9: Whole circuit diagram

Results

A graph of the input voltage (green line), the amplified filter output (blue line) and the final circuit output (red line) was created to calculate the time delay and to visualise the need for level shifting. For the input voltage, the time response was shown to be 2 seconds and for the final output, the time response was 2.093 seconds. The time delay was shown to be 93ms.

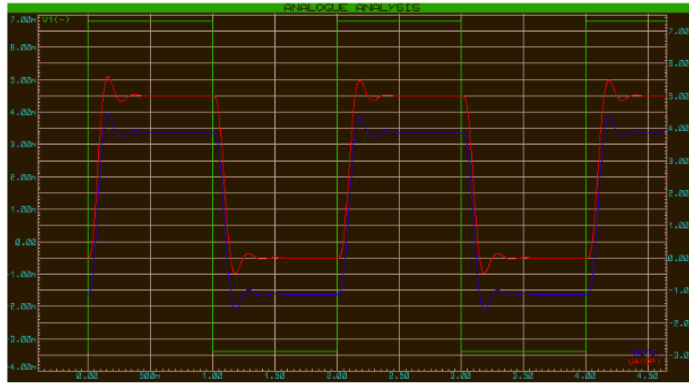


Figure 11: Graph showing time domain results.

Frequency response graph to show Butterworth curve

The green line on the frequency response graph is the attenuation of the first stage of the amplifier and the red line is the attenuation after the second stage. This graph was created using voltage probes on the first and second stages of the filter output to show the gain against the phase response. It can be seen that the desired smooth Butterworth response and roll off rate has been achieved. At 50Hz, the gain of the filter output had been attenuated by 80dB. The yellow line on the graph is the phase response and the green line was included to show the need of the 2nd filter to get the correct attenuation.

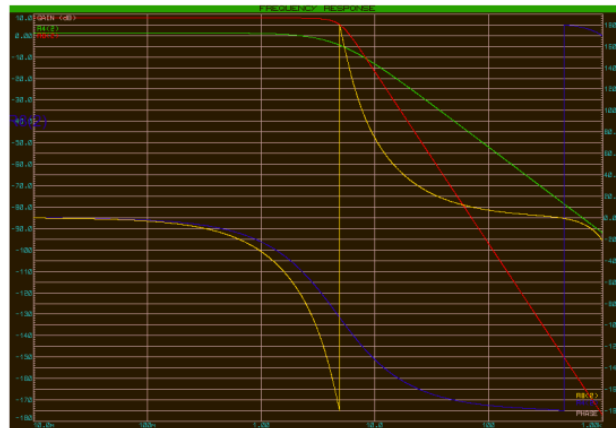


Figure 12: Graph showing the frequency responses at different stages of the circuit.

After testing the over voltage protection, it can be seen that the input voltage of 12V is being clamped when it reaches 3.8V.

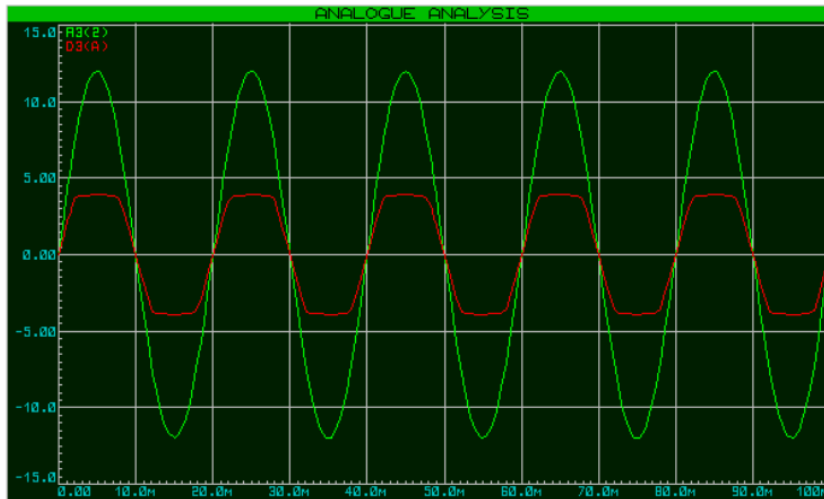


Figure 13: Graph showing over voltage protection results.

Discussion

A thermocouple was used over other temperature measuring options as thermocouples are typically inexpensive, self-powered, highly accurate and more durable. As a temperature sensor output of $68\mu\text{V}/^\circ\text{C}$ was needed, a type E thermocouple was perfect for this due to it being able to produce this output and being able to handle the required temperature range of -50°C to 100°C . The only disadvantage of using a thermocouple in this application is that they only produce millivolts as output and will always need that further amplification to continue with processing.

When calculating the time delay, the order of the filter related to the size of the time delay. It was seen that the lower of the order of the filter, the smaller the time delay was. Additionally, if the values of the filtering components were larger, the time delay would also be larger. The time delay was shown to be 93ms and this was acceptable for a temperature sensor as temperature changes in most systems tend to change relatively slowly. A 93ms delay is very unlikely to cause a significant impact in this temperature-based scenario. Additionally, this graph shows the input voltage (green line) to be at a range of -3.4mV to 6.8mV , creating a square wave cycle which takes 2 seconds to complete.

From the analogue graph of the voltage protection test, it can be seen that the input voltage is clipped at 3.8V. The Zener diode setup was preferred over a diode limiter setup as they can allow the over voltage to be set higher as they have different forward voltages. This can be seen in many manufacturer's datasheets where there are a variety of options for setting voltages [9].

The frequency response graph showed that we achieved a Butterworth response and the expected roll-off rate of 80db. It starts out flat at zero frequency then starts to curve at the cut off frequency of 5Hz (and -3dB) point on the X-axis. The gain and level shifting stages produced a linear output ranging from 0V to 5V, meaning that the component values selected were all correct and the signal was filtered properly. Regarding the level shifting, the need of the shift can be shown when comparing the blue and red lines on the graph. The blue line is the filter output before level shifting and this is shown to be ranging between approximately around -1V and 4V. Then, after the level shifting, the final filter output (red line) can be seen ranging from 0V to 5V. The frequency response graph also contained a yellow line, showing the phase response. The phase response is the relationship between the phase of the input and the output signal passing through the filter [10].

This shows that the temperature sensor output, that was contaminated with a 120mV peak to peak 50Hz mains interference, was successfully conditioned to give a signal output of 0V for a temperature of -50°C and 5V for 100°C . This will ensure a clean and reliable output signal that can give precise measurements ready for the next stages of processing.

Conclusion

- Created a functioning 4th order Sallen-Key filter

A 4th order filter was chosen compared to lower and higher order options as it gave a good balance between complexity, cost and attenuation results. The Sallen-Key filter type minimises the number of components needed and still offer the benefits of non-inverting gain, low output impedance, small spread of component values and the easy adjustability of gain [7].

- Decided on appropriate component values in accordance with E24 series.

The needed gain for the filter was correctly calculated using a variety of component values to ensure the expected results were obtained.

- Used signal conditioning processes to remove the noise interference on the signal.

This was done through the use of a signal generator and sine voltage source to simulate the minimum/maximum voltages and the noise interference respectively. This input was then fed into an over voltage protection setup with Zener diodes to protect the circuit from unexpected high voltages. The filtering setup followed the over voltage protection and gave a small output, which needed a non-inverting amplifier to increase it to an appropriate voltage range. The initial range was slightly out so level shifting was required where a DC voltage generator allowed the output voltages to be moved to the correct range.

- Carried out simulations to get results that prove the success of the circuit and show the conditioned output signal.

The circuit was built and simulated in Proteus where the graphing features were used to create analogue and frequency response graphs. The results of the simulations showed that the circuit functioned as it was set up to.

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Appendix

Total component list:

Component	Value	Quantity
Signal Generator	-3.4mV to 6.8mV	1
VSINE	60m, 50Hz	1
Resistor	1kΩ	1
Resistor	6.8kΩ	4
Resistor	1.54kΩ	1
Resistor	10kΩ	6
Resistor	12.4kΩ	1
Resistor	150kΩ	1
Resistor	820Ω	1
Capacitor	4.7μF	4
Zener diode 1N4728A	N/A	2
LM741 amplifier	N/A	3
DC Generator	-1.12V	1

Table of resistor values that conform to E24 series [8]:

E24	Nominal values of resistances							
1.0	0.01 Ω	0.1 Ω	1 Ω	10 Ω	100 Ω	1 kΩ	10 kΩ	100 kΩ
1.1	0.011 Ω	0.11 Ω	1.1 Ω	11 Ω	110 Ω	1.1 kΩ	11 kΩ	
1.2	0.012 Ω	0.12 Ω	1.2 Ω	12 Ω	120 Ω	1.2 kΩ	12 kΩ	
1.3	0.013 Ω	0.13 Ω	1.3 Ω	13 Ω	130 Ω	1.3 kΩ	13 kΩ	
1.5	0.015 Ω	0.15 Ω	1.5 Ω	15 Ω	150 Ω	1.5 kΩ	15 kΩ	
1.6	0.016 Ω	0.16 Ω	1.6 Ω	16 Ω	160 Ω	1.6 kΩ	16 kΩ	
1.8	0.018 Ω	0.18 Ω	1.8 Ω	18 Ω	180 Ω	1.8 kΩ	18 kΩ	
2.0	0.02 Ω	0.2 Ω	2.0 Ω	20 Ω	200 Ω	2.0 kΩ	20 kΩ	
2.2	0.022 Ω	0.22 Ω	2.2 Ω	22 Ω	220 Ω	2.2 kΩ	22 kΩ	
2.4	0.024 Ω	0.24 Ω	2.4 Ω	24 Ω	240 Ω	2.4 kΩ	24 kΩ	
2.7	0.027 Ω	0.27 Ω	2.7 Ω	27 Ω	270 Ω	2.7 kΩ	27 kΩ	
3.0	0.03 Ω	0.3 Ω	3.0 Ω	30 Ω	300 Ω	3.0 kΩ	30 kΩ	
3.3	0.033 Ω	0.33 Ω	3.3 Ω	33 Ω	330 Ω	3.3 kΩ	33 kΩ	
3.6	0.036 Ω	0.36 Ω	3.6 Ω	36 Ω	360 Ω	3.6 kΩ	36 kΩ	
3.9	0.039 Ω	0.39 Ω	3.9 Ω	39 Ω	390 Ω	3.9 kΩ	39 kΩ	
4.3	0.043 Ω	0.43 Ω	4.3 Ω	43 Ω	430 Ω	4.3 kΩ	43 kΩ	
4.7	0.047 Ω	0.47 Ω	4.7 Ω	47 Ω	470 Ω	4.7 kΩ	47 kΩ	
5.1	0.051 Ω	0.51 Ω	5.1 Ω	51 Ω	510 Ω	5.1 kΩ	51 kΩ	
5.6	0.056 Ω	0.56 Ω	5.6 Ω	56 Ω	560 Ω	5.6 kΩ	56 kΩ	
6.2	0.062 Ω	0.62 Ω	6.2 Ω	62 Ω	620 Ω	6.2 kΩ	62 kΩ	
6.8	0.068 Ω	0.68 Ω	6.8 Ω	68 Ω	680 Ω	6.8 kΩ	68 kΩ	
7.5	0.075 Ω	0.75 Ω	7.5 Ω	75 Ω	750 Ω	7.5 kΩ	75 kΩ	
8.2	0.082 Ω	0.82 Ω	8.2 Ω	82 Ω	820 Ω	8.2 kΩ	82 kΩ	
9.1	0.091 Ω	0.91 Ω	9.1 Ω	91 Ω	910 Ω	9.1 kΩ	91 kΩ	

Equations used:

$$R1 = \frac{R2}{k - 1}$$

$$R2 = R1 * (k - 1)$$

Signal Conditioning Design - Jayden Fox

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

76/100

PAGE 1

PAGE 2

PAGE 3



Comment 1

Excellent



Comment 2

Excellent abstract

PAGE 4



Comment 3

Excellent work identifying the correct sensor.



Comment 4

Shouldn't this be 8 resistors?

PAGE 5

PAGE 6



Comment 5

Missing the word "lower"

"...whether LOWER circuit complexity or better attenuation is preferred.."



Comment 6

What was the capacitor value?

QM

Missing Units

What units is this in?

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Make it clear for your reader and remove any ambiguity.



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Comment 9

This is too small to see the detail.

If you put the components closer together and made the image larger the detail would be clearer.

PAGE 12



Comment 10

Do you mean the transition point you were measuring to/from were at these times?

The response time is a property of the circuit.

PAGE 13

PAGE 14



Comment 11

excellent



Comment 12

shown in figure.....

Direct the reader where to look.

PAGE 15

PAGE 16



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.

GRADING FORM: SMU GENERIC_SMOSEY

JAYDEN FOX

76.25

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

3.75

KNOWLEDGE & UNDERSTANDING*Knowledge of the basic underlying concepts and principles of a subject.*

Highly detailed knowledge and understanding of the main theories/concepts, and a critical awareness of the ambiguities and limitations of knowledge.

24

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 or through effective collaboration. Ability to investigate contradictory information and identify reasons for contradictions. Strong, persuasive, conclusions, justifiable recommendations.
"

22.5

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



"An advanced application of a range of methods, materials, tools and/or techniques. The context of the application is well considered, with extensive use of relevant examples. Application and deployment extend beyond established conventions. Innovation and creativity evident throughout.
"

22.5

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.



Can communicate professionally and, confidently in a suitable format. Work is coherent, very fluent and is presented professionally.

3.5