

Transducers final

by Nicholas Tim Jones

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Transducers & Signal Conditioning (ACDA5006).

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Abstract.

A temperature monitoring circuit is to be simulated using Proteus simulation, the sensor's output is in the microvolt range, the final output needs to range from 0 to 5 Volts, the circuit has mains hum of 50 Hz applied to it. Suitable filtering has been included in the design to eliminate the interference from the mains hum, also amplification is used to get the desired output of 0 to 5 Volts, voltage level shifting is required as the temperature sensor specifications states that it is capable of measuring from -80°C but the asked for value is from -20°C where this needs to be at 0 Volts. Voltage readings by use of oscilloscope and voltage probes have been used to for testing and building the circuit, frequency response graph is included to show the effectiveness of each of the low pass filter stages. Response time and rise time of the circuit has been determined. The application for this circuit has not been stated so the commonly known and easy to use 741 op amp has been used throughout the design.



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1 Introduction.

Design a circuit that can monitor temperature and have an output voltage range from 0V to 5V. The circuit will need some filtering as there will be contamination from mains supply at 50Hz, once the circuit is built a response time will need to be determined.

1.1 Specification.

The following specifications have been given.

- The temperature sensor produces $120\mu\text{V} / ^\circ\text{C}$ where $0\text{V} = -80^\circ\text{C}$.
- Mains hum will be 1.2V pk-pk at 50Hz.
- The output voltage at -20°C should = 0V.
- The output voltage at 100°C should = 5V.

2 Design.

The circuit can be split into multiple blocks, each block will have its own purpose at minimum it needs to include the following.

- Temperature sensor.
- Over voltage protection.
- Filtering.
- Gain.
- Level shifting.

2.1 Temperature sensor.

The final temperature range that needs to be measured is from -20°C to 100°C , the specification given for the sensor is at $0\text{V} = -80^\circ\text{C}$ and it produces $120\mu\text{V}/^\circ\text{C}$, the following sums will determine what the minimum and maximum output voltage from the sensor are for the range -20°C to 100°C .

Maximum voltage:

For -80 to 100 there is 180 steps.

$$180 * 120\mu\text{V} = 21.6 * 10^{-3}\text{V}$$

At 100°C the output would be 21.6 mV.

Minimum voltage:

For -80 to -20 there is 60 steps.

$$60 * 120\mu\text{V} = 7.2 * 10^{-3}\text{V}$$

At -20°C the output voltage would be 7.2 mV.

Minimum = 7.2 mV.

Maximum = 21.6 mV.

To simulate the maximum and minimum then a DC power source with a switch is used.

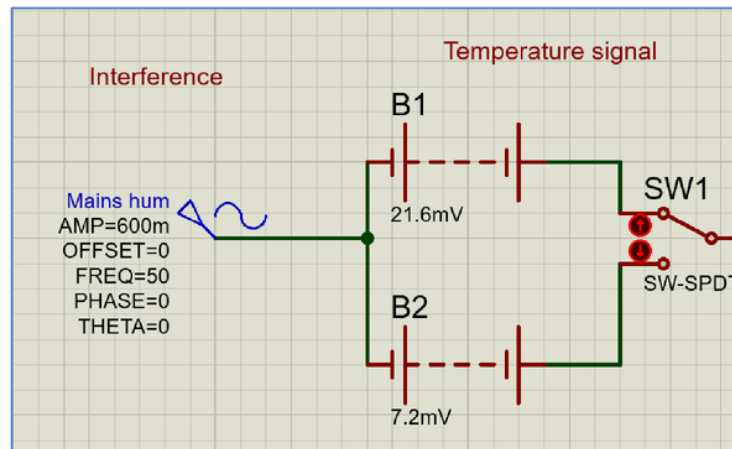


Figure 1 Temperature signal with mains hum simulated

Two batteries have been used B1 is set to 21.6 mV and B2 is set to 7.2 mV, the switch can be operated to allow either maximum or minimum voltage through, to simulate mains interference then a sine wave generator has been added to the negative side of the batteries this interference has been set to 1.2 V pk-pk at 50 Hz.

2.2 Over voltage protection.

As the circuit is simulated to be near mains 240V supply, then suitable over voltage protection will be needed to ensure no damage occurs to the circuit if there was an induced high voltage spike or direct coupling to the mains.

Overvoltage protection has been created using two **zenier** diodes and a resistor [1, p. 37], these diodes will create a path to ground if their breakdown voltages have been met thus stopping this extra voltage reaching other components within the circuit the resistor is used to limit current through the diodes if they conduct to ground [1, p. 36].

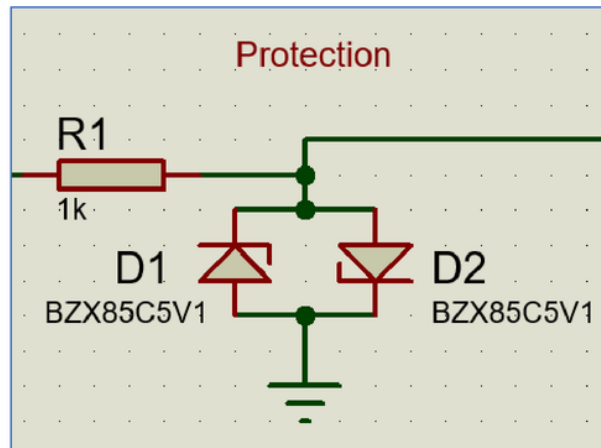


Figure 2 Over voltage protection.

Figure 2 shows the overvoltage protection block used, as the circuit has an induced sine wave applied to it two diodes have been used here instead of just one.

2.3 Unity gain buffer.

As the output voltage from the temperature sensor is small then a unity gain buffer has been used, it is a noninverting voltage follower that has a high input impedance and low output impedance with a gain of one [1, p. 227] this helps to reduce attenuation caused by the first filter.

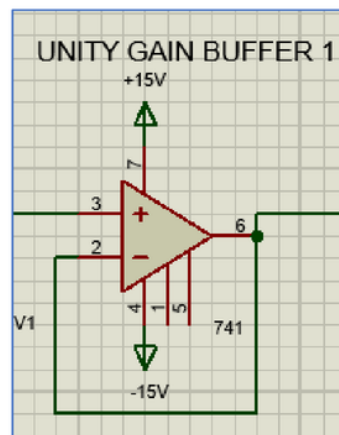


Figure 3 Unity gain buffer 1

Putting a voltage probe on the output of this Unity gain buffer and setting the temperature signal to maximum 21.6 mV shows that there is a small gain of approximately 1 mV.

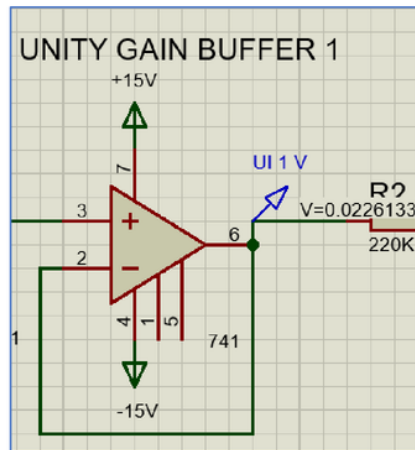


Figure 4 Unity gain buffer voltage output.

Figure 4 shows the output from the buffer is 0.0226 V.

2.4 Filtering.

Interference from mains supply will be at 50Hz, so suitable low pass filtering will be needed to eliminate this.

As the temperature is a slow responding sensor then a cut off frequency of 10Hz will be used. The filters will be active filters created out of 741 series op amps and passive using Resistor and Capacitors.

2.4.1 Low pass filter design.

Consulting the book called "The art of Electronics" there are 3 main types of active filter response characteristics, these are, Butterworth, Bessel, and Chebyshev, each has their own advantages and disadvantages,

A Butterworth filter has a flatter response within the passband when compared to a Chebyshev which allows more ripple inside the passband, the trade-off is the steepness of the roll off where the Butterworth's roll off is a gentler slope and the Chebyshev is more steeper [1, p. 401]. The Bessel filter response is more useful when time delay and phase is needed to be accurate within a circuit [1, p. 403].

When Cascading multiple filters then designing a Butterworth filter is easier than a Chebyshev or Bessel the reason is the latter two have differing Resistor and Capacitor products and must be scaled by a normalising factor [1, p. 408].

Based on the above then a Butterworth filter will be implemented into the circuit and after some experimentation it was deemed that a 7 pole filter would be needed.

2.4.1.1 Cut off frequency calculation.

Too reduce loading on components then the input impedance to the filter should be relatively high, consulting with E24 range of Resistor values then a value of 220 K Ω will be used, to determine the Capacitor value the following formula will be used where F_c is the desired cut off frequency.

$$C = \frac{1}{2\pi R f_c} \text{ [1, p. 408]}$$

$$C = \frac{1}{2\pi * 220000 * 10}$$

$$C = 7.2343 * 10^{-8}$$

$$C = 72 \text{ nF}$$

Looking at "RS Components online" the nearest value capacitor would be 68 nF, substituting this into the above formula gives a cut off frequency off 10.64 Hz, this is ample for what is needed.

Using a 68 nF capacitor the calculated reactance at 10.64 Hz is:

$$x_c = \frac{1}{2\pi f C} \text{ [1, p. 42]}$$

$$x_c = \frac{1}{2\pi * 10.64 * 68 * 10^{-9}}$$

$$x_c = 219973.108 \Omega$$

$$\text{Capacitor reactance} = 219.973 \text{ K}\Omega$$

2.4.1.2 Filter gain calculations.

The art of Electronics has a section on designing different filters, it states that Butterworth filter uses the same value resistors and capacitors [1, p. 408], Also there is a table that shows the different gain of each stage that should be used depending on how many poles are needed [1, p. 408], after some experimentation there will be 3 active filters and 1 passive filter equating to 7 poles in total.

For a six pole Butterworth filter then the gain (K) of filter one would be 1.068, filter two K would be 1.586 and filter three K would be 2.483 [1, p. 408].

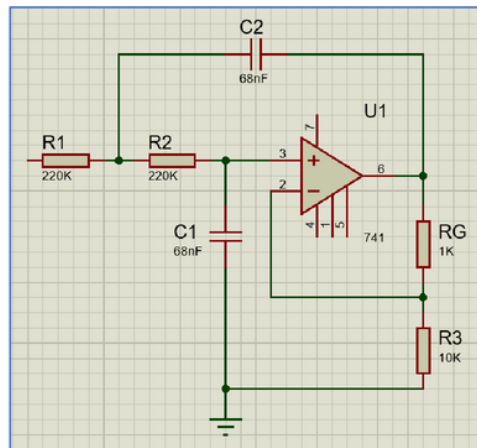


Figure 5 Active filter circuit.

Figure 5 shows the schematic used for an active low pass filter, here $R1 = R2$, $C1 = C2$, a random value of $10K\Omega$ has been picked for $R3$ and R_G is determined by the value of K for each filter where $R_G = (K-1) * R3$ [1, p. 407]

1. Filter 1, $K = 1.068$

$$R_G = (1.068 - 1) * R3.$$

$$R_G = 0.068 * 10 * 10^3$$

$$R_G = 680 \Omega$$

E24 resistor range has a 680Ω value resistor.

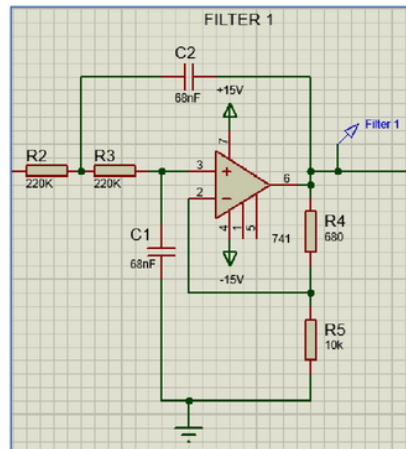


Figure 6 Filter 1.

Figure 6 shows the first second order filter this is set to have a gain of 1.068. Figure 7 shows the output of this filter is -0.0205 V there is a small attenuation into the negative volts this enforces the need to have the unity gain buffer before it.

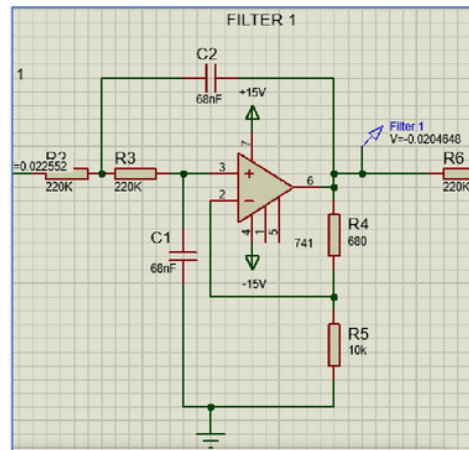


Figure 7 Filter 1 output

2. Filter 2, $K = 1.586$

$$R_G = (1.586 - 1) * 10 * 10^3$$

$$R_G = 5.860 \text{ K}\Omega$$

E24 resistor range has $5.6 \text{ K}\Omega + 240 \Omega + 20 \Omega$

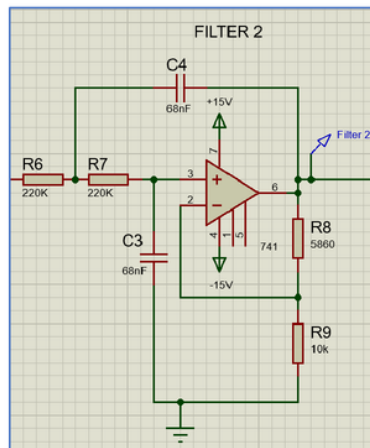


Figure 8 Filter 2.

Figure 8 shows the second active filter used. Figure 9 shows the gain of approximately 3 has been added instead of the calculated 1.586, more research would be needed to establish why, this has pushed the voltage down to -0.061 V.  3

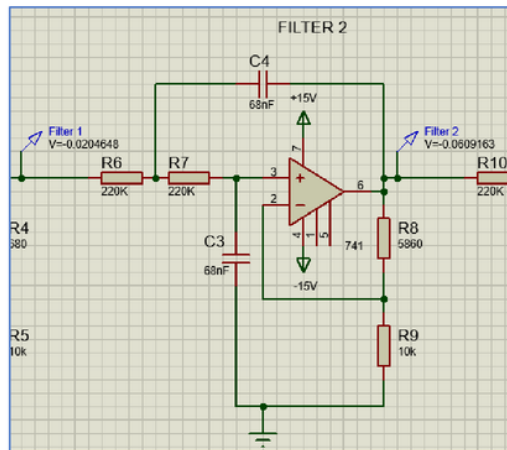


Figure 9 Filter 2 output

3. Filter 3, $K = 2.483$

$$R_G = (2.483 - 1) * 10 * 10^3$$

$$R_G = 14.830 \text{ K}\Omega$$

E24 resistor range has $13 \text{ K}\Omega + 1.8 \text{ K}\Omega + 30 \Omega$

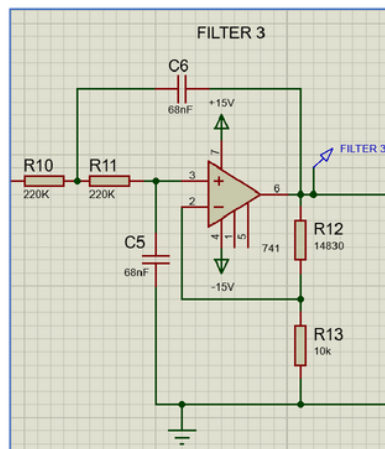


Figure 10 Filter 3.

Figure 10 shows the third active filter used. Figure 11 shows the output has been amplified by approximately 3 pushing the voltage down to -0.226 V .

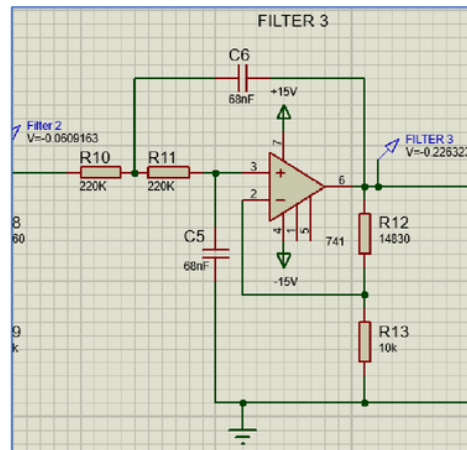


Figure 11 Filter 3 output.

For simulation purpose only one gain resistor has been used per filter, consulting the E24 Resistor range some of the filters would either need multiple series resistors or use potentiometer instead.

To get the desired 7 pole filter then a simple passive low pass filter has been used after the three active filters.

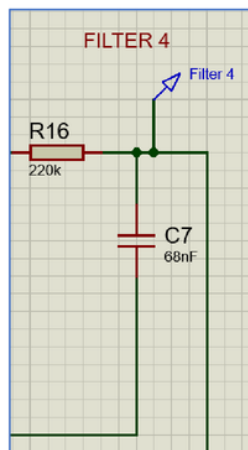


Figure 12 Filter 4.

Figure 12 is the passive low pass filter, putting this in minimised the AC ripple to a tolerable level.

With the temperature sensor set to 21.6 mV the voltage after filter four is -0.241 V.

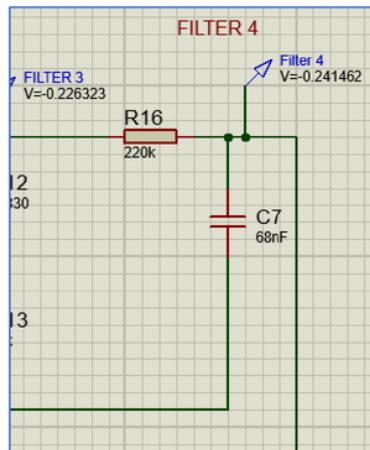


Figure 13 Filter 4 output.

Figure 13 shows the output voltage after filter four this is then passed to the second unity gain buffer.

2.5 Unity gain buffer 2.

A second unity gain buffer has been used after the filters as the level shifting block was causing too much attenuation to the voltage.

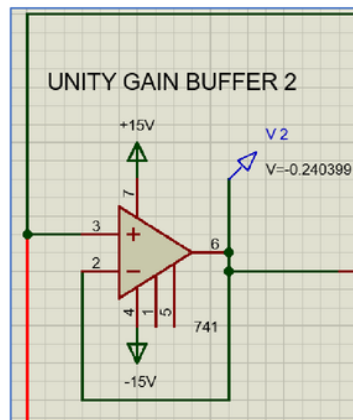


Figure 14 Unity gain buffer 2.

Figure 14 shows an output voltage which is equal to (give or take a mV) the input from filter four.

2.6 Voltage level shifting.

Setting the temperature sensor to 7.6 mV the output from the second unity gain buffer shows -0.296 V, this level now needs to be shifted up to 0 V.

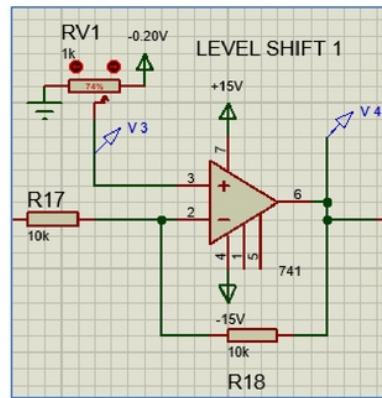


Figure 15 Level shifting.

Too fine tune the voltage level a 1 K Ω potentiometer has been used.

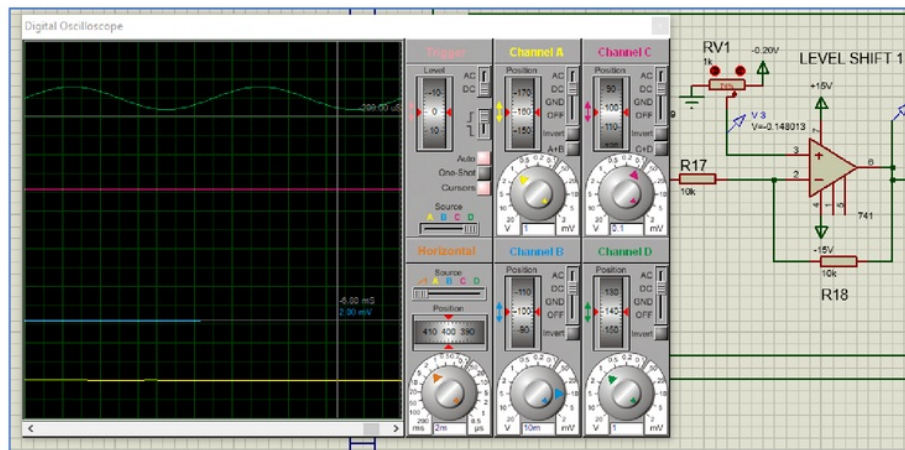


Figure 16 Scope after level shift.

Fine tuning of the potentiometer as seen on the blue trace of the oscilloscope in Figure 16 gives an output of 2 mV, in a live application this offset can be eliminated by using the offset null pins of the op amp but for simulation purpose this is close enough to 0 V to be acceptable.

2.7 Gain.

The temperature sensor outputs microvolts, and the circuit so far has had very little gain added to it, this block sets the gain needed within the circuit to amplify the signal to a level, in this case the maximum would be 5 V.

With the temperature sensor at 21.6 mV the scope shows a voltage of -53 mV coming into the gain amplifier, to calculate the gain simply divide 5 V by 53 mV, this gives a gain of

just over 94 is needed, for an inverting amplifier then the ratio of the feedback resistor and the input resistor is used.

$$\text{Gain} = -R_f / R_i$$

$$-R_f = \text{Gain} * R_i$$

$$-R_f = 94 * 10 * 10^3$$

$$-R_f = 940000 \Omega$$

The feedback resistor needs to be near 940 K Ω sticking with the E24 resistor range and wanting to make this variable then a 820 K Ω resistor with a 220 K Ω potentiometer has been used.

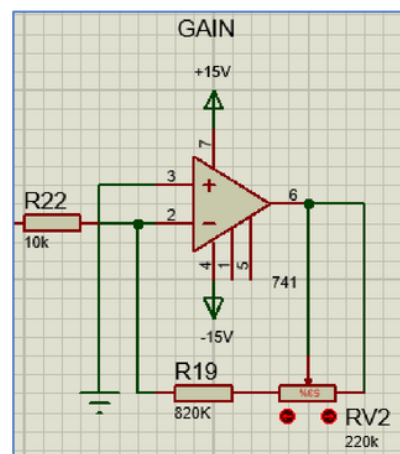


Figure 17 Gain.

Figure 17 shows the gain block used, it has been designed to include a variable resistor in series with the negative feedback thus enabling fine tuning of the gain to get the appropriate voltage levels.

Figure 18 shows the yellow trace on the oscilloscope is connected to the output of the gain stage, with the temperature set to 21.6 mV the output is 5 V.

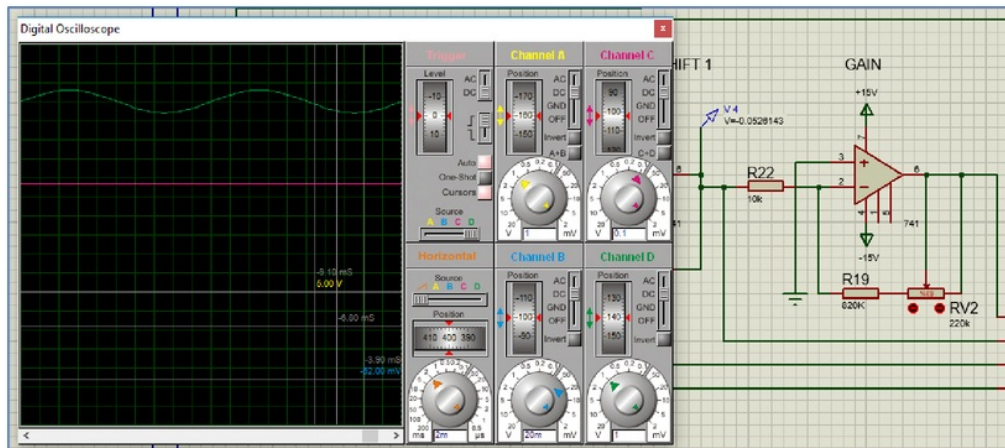


Figure 18 Gain output 5 V.

With the temperature sensor set to 7.2 mV as seen in Figure 19 the oscilloscope shows 0 V with slight fluctuation to 50 mV.

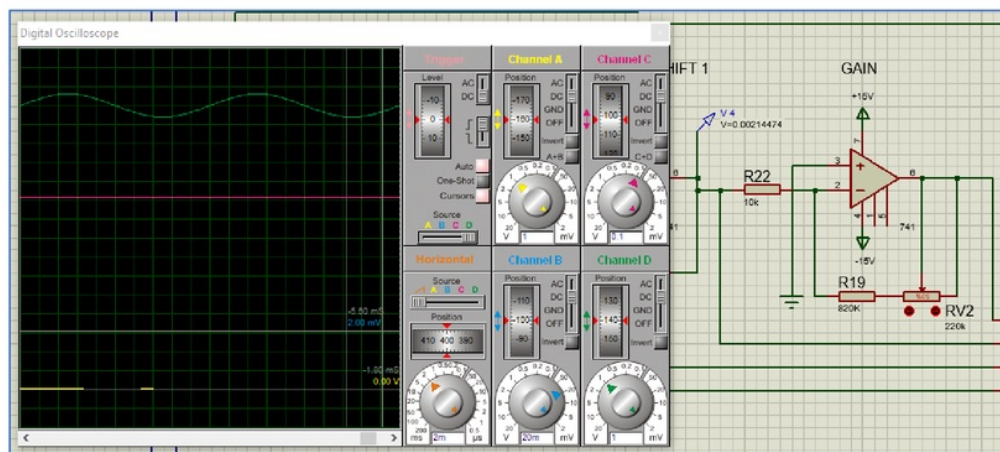


Figure 19 Gain output 0 V.

3 Completed circuit.

The complete circuit used is shown below.

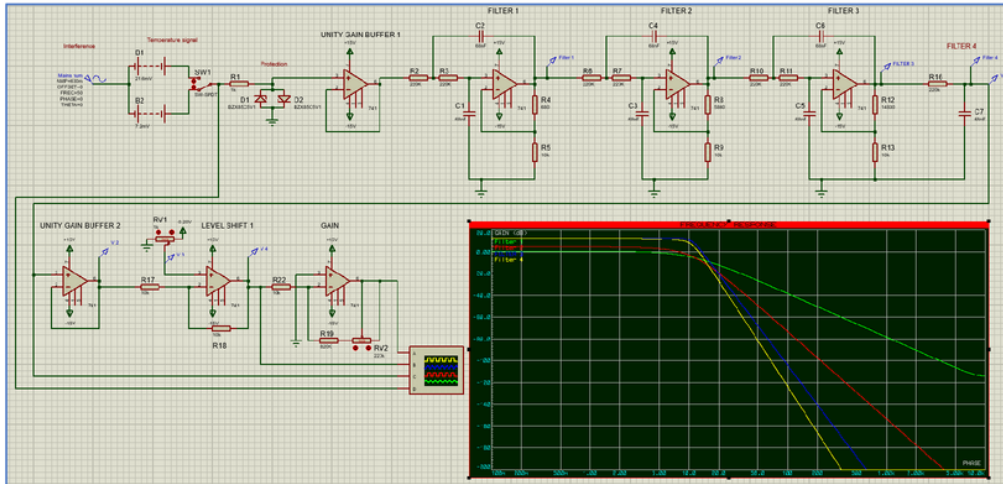


Figure 20 Completed circuit.

4 Further testing.

4.1 Oscilloscope on the filters.

Placing the 4 channel oscilloscope after each filter it can be seen that the 50 Hz noise gets attenuated through each stage, Figure 21 shows the yellow trace on the output of filter 1 has attenuated the noise from 1.2 V pk-pk down to 30 mV pk-pk, the blue trace is on the output of filter 2 which shows a significant drop where pk-pk is approximately 4 mV, the red trace shows further filtering after filter 3 and the fourth filter as seen on the green trace shows no ripple at all.

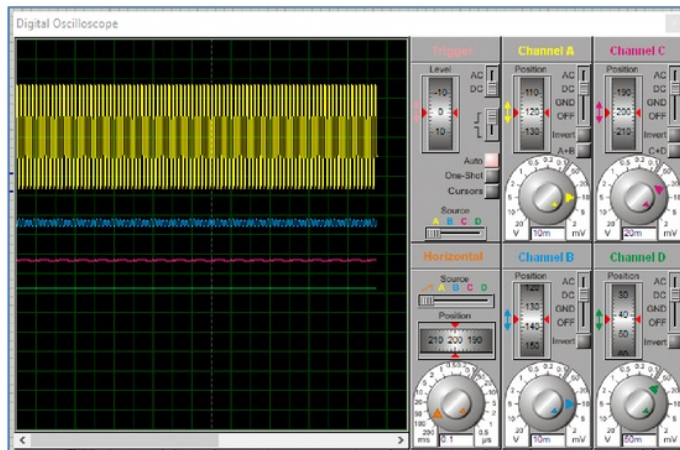


Figure 21 Scope on all filters.

4.2 Frequency response graph.

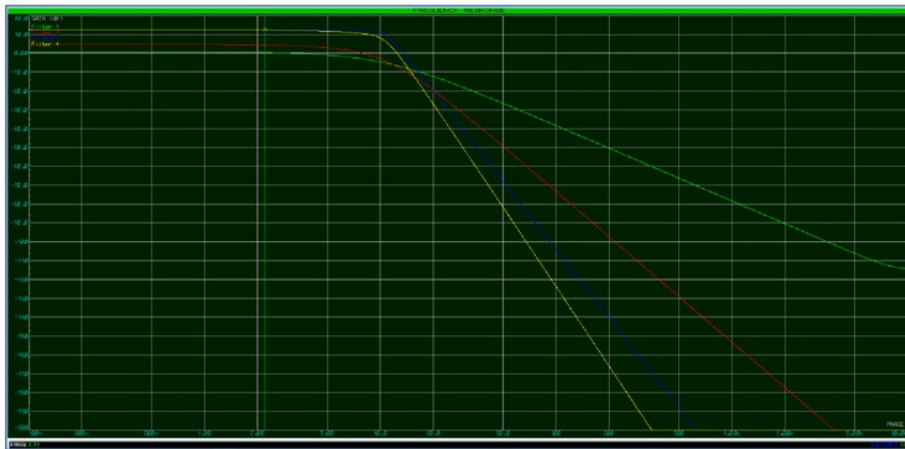


Figure 22 Frequency response graph 1.

Figure 22 shows a zoomed out shot of the frequency response graph.

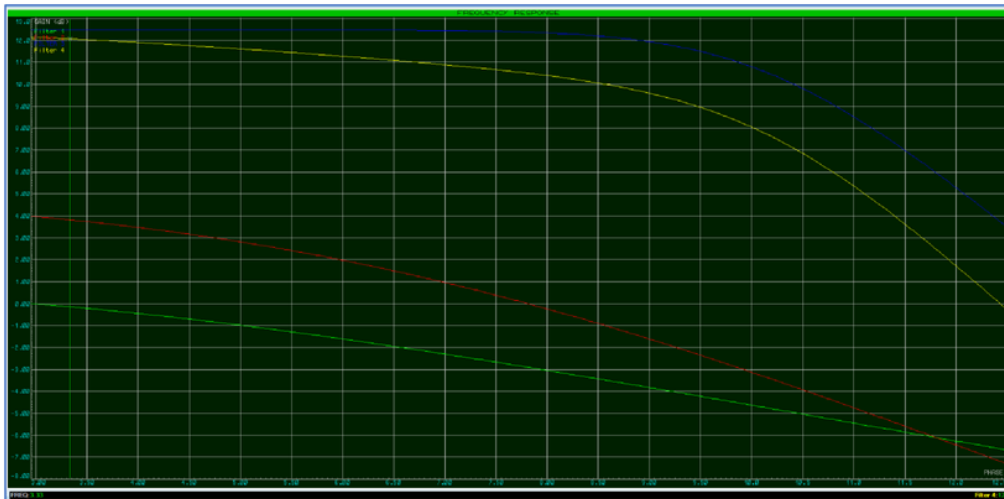


Figure 23 Frequency response graph 2

Shown in Figure 23, zoomed in on filter 4 (yellow) shows a gain of 12.1 dB the desired -3 dB cut off would then be 9.1 dB

Moving the cursor over to 9.1 dB the frequency shows 9.39 Hz this is within the tolerance that is expected. Figure 24 shows this.

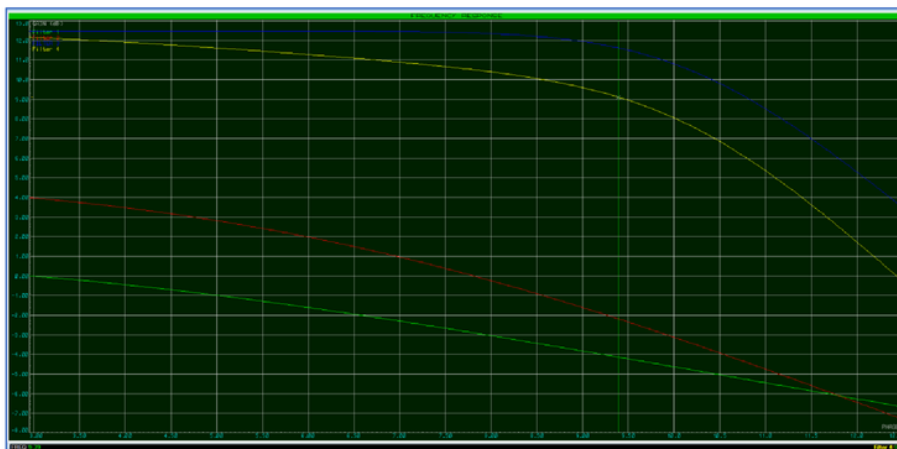


Figure 24 Frequency response -3 dB

Just for reference shown in Figure 25, at 50 Hz there is an attenuation of at least -81 dB

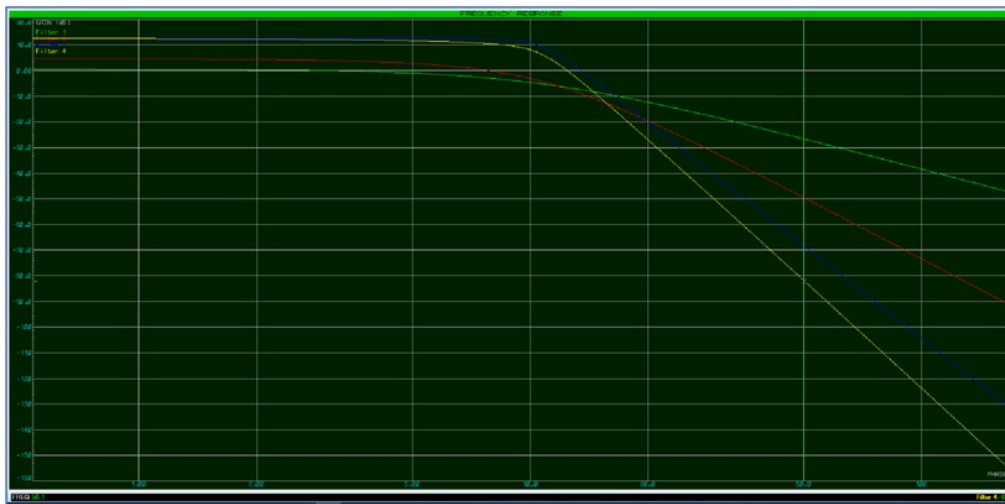


Figure 25 Frequency response 50 Hz.

4.3 Response time.

Response time is the time it takes for the output voltage to go from 0 to 50% of its range [1, p. 400], in this circuit 2.5 V is at 50%.

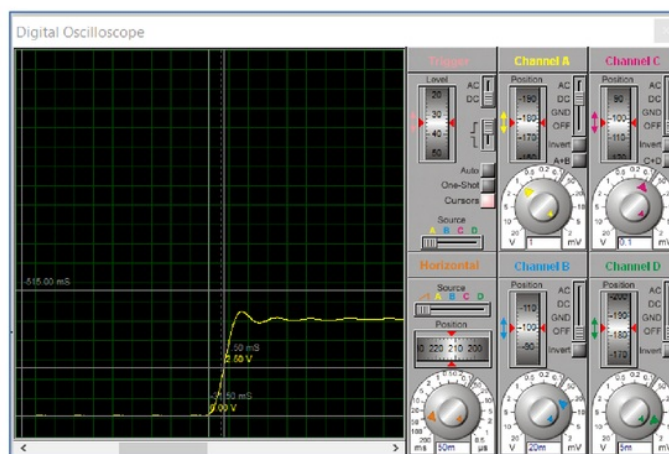


Figure 26 Response time 1.

The yellow trace Figure 26 shows the output going from 0 V to 5 V. Cursors have been placed at 0 V and 2.5 V.

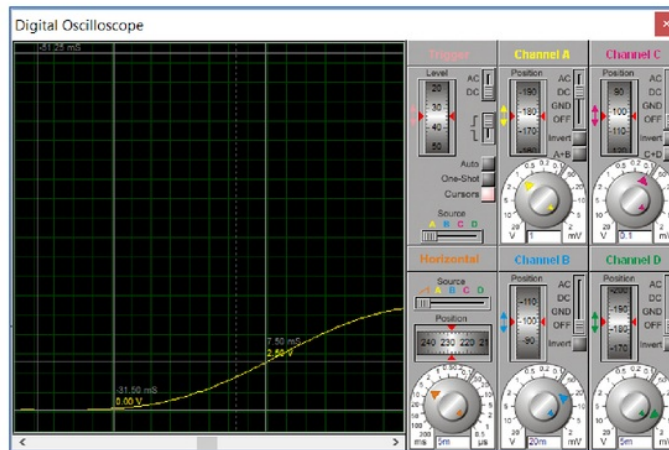


Figure 27 Response time 2

Figure 27 shows the oscilloscope has zoomed in on the cursors, the cursor at 0 V shows a time of -31.5 mS and at 2.5 V 7.5 mS adding these two values gives 39 therefore the response time of this circuit is 39 mS.

4.4 Rise time.

Rise time is calculated by measuring the time it takes for the output voltage to go from 10% to 90% of its range [1, p. 400] in this case 10% is at 0.5 V and 90% is at 4.5 V.

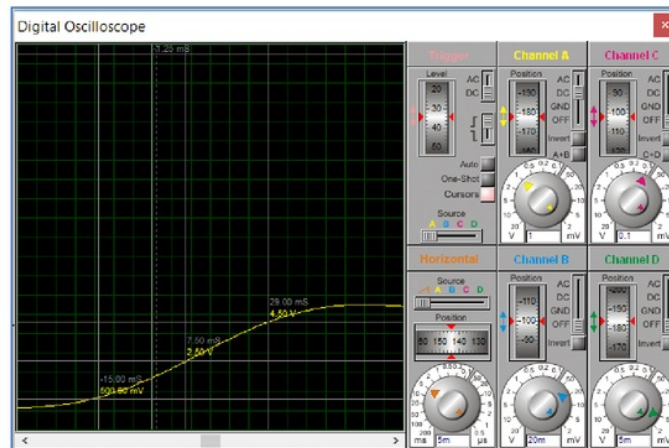


Figure 28 Rise time 1.

Looking at Figure 28 rise time is 15 mS + 29 mS = 44 mS.

5 Conclusion & discussion.

Completing this task has been a bit of a challenge, where initially each block to the circuit was created individually, but when they were all stitched together the circuit didn't

behave as expected, after some research and more experimentation more components needed to be added such as the unity gain buffers, this then added to the knowledge that input and output impedance within the circuit is critical when working with such low voltages.

As the application of the circuit is unknown then standard 741 op amps have been used, where as if the circuit was to be used in a critical environment then specialist instrumentation amplifiers would be used. Reading the data sheet for a LM741 op amp it does recommend that decoupling capacitors are used on the power pins to improve stability [2], these have been omitted from the simulation, future work would be to include them and then retest the circuit to see if they do make a difference in a simulated environment.

The measured response time of 39 mS may seem a bit slow in terms of electronics, this is due to the amount of stages the signal must go through before the final output, as a temperature sensor is a slow changing component then this response time would be adequate. Even though 7 pole filtering has been used, looking at the oscilloscope when testing each filter stage a 6 pole filter would probably of been fine, future work on filter design would be to test the circuit with the other filter response characteristics such as Chebyshev with a possibility of limiting the amount of components used.

6 References.

- [1] P. Horowitz, *The art of electronics*, Third edition. New York, NY: Cambridge University Press, 2015.
- [2] 'lm741.pdf'. [Online]. Available: <http://www.ti.com/lit/ds/symlink/lm741.pdf>. [Accessed: 16-Jan-2019].

Transducers final

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

79/100

Instructor

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Comment 1

Nice abstract. A brief statement of your results would have made this complete.

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Comment 2

Zener

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Comment 3

Your output voltage offset is most likely caused by the imbalance of currents on the input terminals of your op-amps. To reduce the effect of this you should aim to have the same (or similar) impedances connected to each of the inputs. Increasing the values of the gain control resistors (but maintaining the ratio) would have helped this.

In practice this could be eliminated by balancing the impedances and using the offset null pins

of the amplifier - unfortunately Proteus does not model these pins so you are unable to simulate it.

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Comment 4

approximately equal to...?

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NICHOLAS TIM JONES

78.95

ENGAGEMENT WITH LITERATURE

including reading, referencing, academic conventions and academic honesty



While the references you have used are from fairly reputable sources and you have listed and cited them correctly in your text, more reference sources were expected.

2.5

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 limitations of the knowledge base. The problems you encountered with the voltage offset is probably due to imbalances in the impedances seen at the input terminals of the op-amps.

23.4

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.



Exceptional work. Very high quality analysis, developed independently. Ability to investigate contradictory information and identify reasons for contradictions. Highly persuasive conclusions

27.3

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. 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 well, confidently and consistently in a suitable format. Work is coherent and fluent and is well structured and organised. A slight improvement to your writing style, i.e. use of third person passive voice with more formal language would have made your report even better.

3.25