

# TaSC\_REP\_by\_KM\_ID1804424\_2 020

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## **Transducers and Signal Conditioning – L5**

### **Designing appropriate signal conditioning circuit for transducer to feed the PIC input port**

Electronics Engineering Course @ UWTSD  
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## 1.0.0 Introduction:

As an Electronic Engineer my task is to produce a signal conditioning circuit which will effectively convert signal ranges from that of a temperature sensor transducer to a given required range. Additionally, due to Electromagnetic Interference (EMI) – also called Radio-Frequency Interference (RFI), the signal happens to be contaminated with noise that must be properly filtered, or attenuated to an acceptable range. Lastly, the circuitry must be protected from any unwanted voltage levels that could damage both itself and the output device.

### 1.0.1 Details:

The input signal specs are:

- Temperature sensor output: 120μV/°C  
with 0V = -80°C
- Noise contamination: 120mV(pk-pk) @ 50Hz

The output signal requirements are:

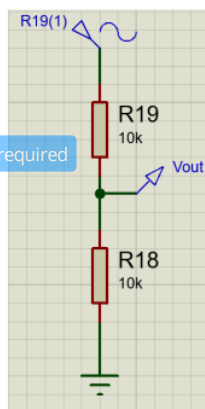
- Output range:  
0V = -20°C  
5V = 100°C

The final circuit must include sections for:

- Filtering circuit
- Level Shifting
- Gain
- Over voltage protection

### 1.1.0 Filtering circuits

Signal filtering works by combining Potential Divider with Capacitive Reactance.



#### 1.1.1 Potential Divider:

Potential Divider, given by equation:  $V_{out} = \frac{V_{in}R^2}{R^1 + R^2}$ , states the potential voltage difference between two electric components based on their resistivity. For example, if  $R_1$  and  $R_2$  are the same (Ratio 1:1), each  $R$  will then receive half of total  $V_{in}$ . Using  $R_1$  as a variable resistor allows modulation of  $V_{out}$  in real time.

Unlike  $DC$ , an  $AC$  signal source with such divider happens to be gently attenuated, this might be caused by constantly varying  $AC$  current.

Attenuation is measured in decibels ( $dB$ ),  $A(dB) = \frac{V_{out}}{V_{out(mid)}}$  with constant  $V_{in}$  at any frequency.



Through above equation I can easily calculate  $V_{out} = \frac{1V \cdot 10 \cdot 10^3}{10 \cdot 10^3 + 10 \cdot 10^3} = \frac{10 \cdot 10^3}{20 \cdot 10^3} V = \frac{1}{2} V = 0.5V$

However, the simulation below has shown that the output voltage is  $\approx 0.499V$  and signal is now at

-6.02dB Gain. On the side fact, cut-off frequency is usually given at -3dB Gain because of each having their own attenuation and therefore the design should consider its ability to stack itself per each RC Potential Divider.



### 1.1.2 Capacitive Reactance:

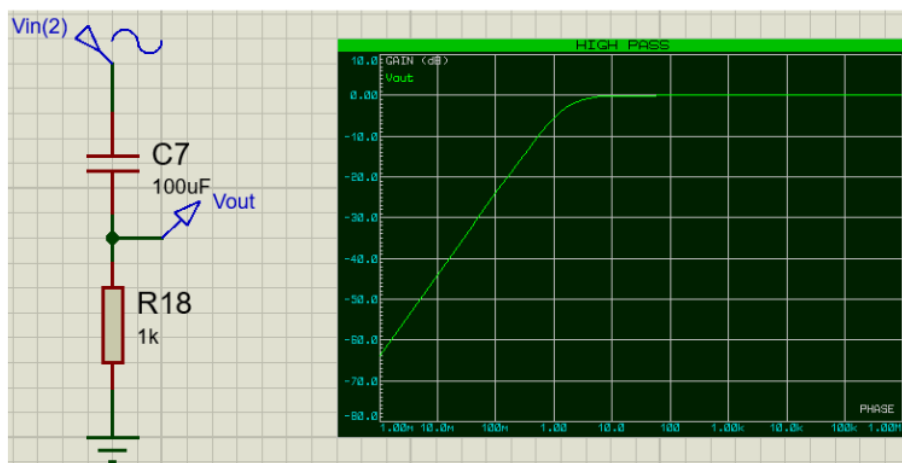
Capacitive Reactance, given by formula:  $X_c(\Omega) = \frac{1}{2\pi fC}$ , describes the effective resistance of a capacitor. That resistivity is based on frequency and is caused by the actual time capacitor requires to charge and discharge itself. In single capacitor circuit an Ohms Laws'  $I = \frac{V}{R}$ , requires R to be replaced with equation for impedance, and in RC circuits I is given by equation:  $I = \frac{V}{Z}$ , where Z is the total impedance of the circuit with formula:  $Z(\Omega) = \sqrt{R^2 + X_c^2}$ .

$$\text{And so } V_{out} = V_{in} \frac{X_c}{\sqrt{R^2 + X_c^2}} = V_{in} \frac{X_c}{Z}$$

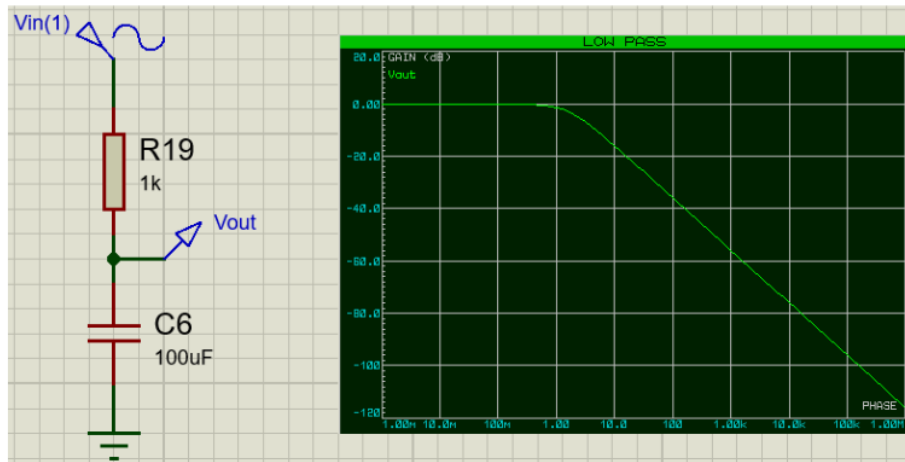
### 1.1.3 RC filter circuit:

A typical passive filter works by combining the Potential Divider with Reactance to utilize the impedance effect of the capacitor creating a formula of  $V_{out} = \frac{V_{in}R}{Z}$ , to create a variable divider which is meant to attenuate frequencies outside of chosen passband. Depending on the order of the components, the filter can be either high pass or low pass.

Example of a High Pass filter:



#### Example of a Low Pass filter:

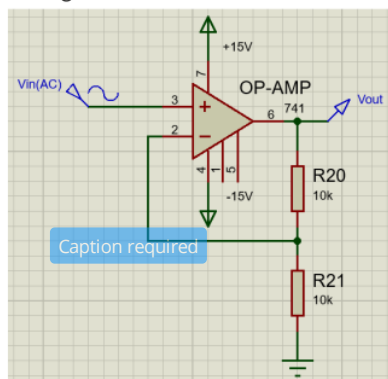


For the Cut-off frequency formula is:  $f_c = \frac{1}{2\pi RC}$ , and based on experiment above with Potential Divider – it should be placed at around -3.01dB because of the passive effect of a resistor.

Fun Fact: the Time Constant ( $\tau$ ) also plays a role in this circuit because it is effectively related to cut-off frequency as:  $\tau = RC = \frac{1}{2\pi f_c}$  or in:  $f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi \tau}$

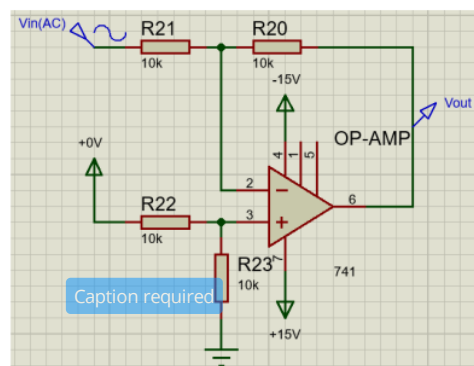
#### 1.1.4 Gain and Level Shifting – Op-Amps Configurations

With the use of 741 Op-Amp the signal will be properly amplified with the use of Non-Inverting configuration and then shifted using Difference configuration which works as subtractor for analogue currents.



The formula for **Gain** configuration is:

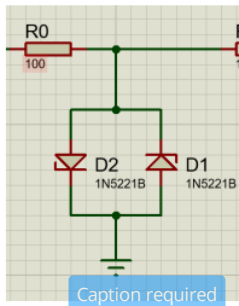
$$V_{out} = V_{in} \left( 1 + \frac{R_2}{R_1} \right)$$



The formula for **Level Shifting** configuration is:

$$V_{out} = \frac{R^2}{R^1} (V^2 - V^1)$$

### 1.1.5 Over Voltage Protection



Protection against excess voltage is done using two diodes which only conducts electricity in one direction and only if amplitude high enough to switch diode on. When that happens – the diode will short all the excess current to the ground.

## 2.0.0 Method

Entire circuit is going to be designed in Proteus supported by Excel spreadsheet for required calculations.

### 2.0.1 Design Stages:

- Decision-making for the  $f_c$ , and filling R and C
- Analyse frequency response graph
- Calculate requirements of noise attenuation
- Move single RC filter design to a Higher Order filter
- Analysis of cascading Passive filters limitations and ways of overcoming them
- Amplifying filtered signal output
- Shifting the output to a required range
- Applying voltage and current protection
- Approve final design

## 3.0.0 Design

### 3.0.1 The $f_c$ , C, and R calculations

Since task is dealing with the temperature sensor – the cut-off frequency for the Low Pass filter will be at 2Hz as it is very unlikely for a temperature to change twice within same second. The R however, it's best to keep relatively large in order to prevent any open loops in the circuit and so for this case scenario  $R = 10k\Omega$ .

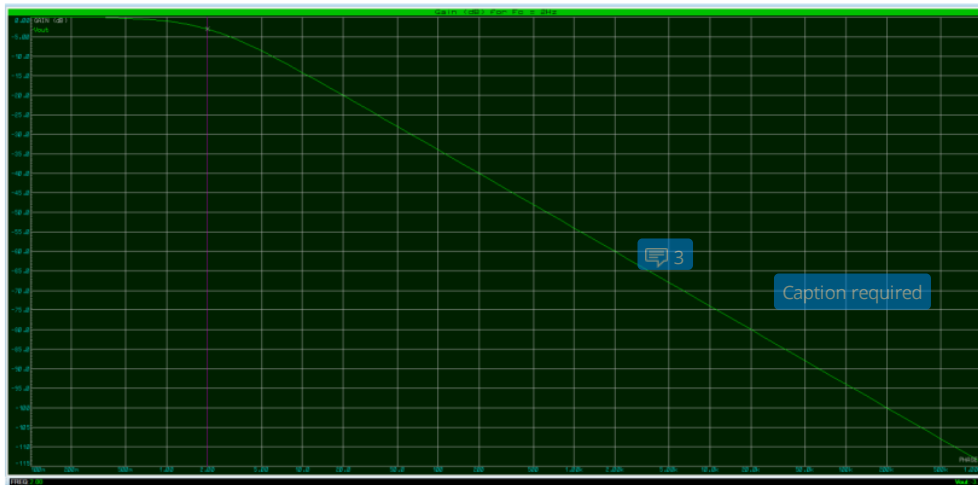
With the  $f_c$  and R determined, time to choose a suitable capacitor using rearranged version of:

$$f_c = \frac{1}{2\pi RC}, \text{ to } C = \frac{1}{2\pi f_c R}, \text{ Therefore } C = 7.95\mu\text{F} - \text{This gives a minimum capacitance required.}$$

Since resistors have more values and are more flexible to purchase and work, the capacitance should be at more findable value such as:  $C = 10\mu\text{F}$ . To get new R, the  $f_c$  formula must be rearranged again into:  $R = \frac{1}{2\pi f_c C}$ .

Since  $f_c = 2\text{Hz}$  and  $C = 10\mu\text{F}$  then the required is  $R \approx 7958\Omega$

Now when these values will be plotted into the Proteus in a single pole RC arrangement, the frequency response graph should show -3.01dB gain at frequency of 2Hz. With output  $V_{out} = V_{in} * 70.7\%$



Simulation has successful and the graph has returned the expected values. The proteus also returned that the current is out of phase by -45 at the  $f_c$ . After  $f_c$  point, the signal will slowly attenuate at a slope of  $-20\text{dB}/\text{Decade}$  or  $(-6\text{dB}/\text{Octave})$  "roll-off".

Decade means moving to a next power of 10 and Octave means moving to the next power of 2.

### 3.1.0 Is this level of attenuation suitable?

In order to decide if this level of noise attenuation is suitable, calculations for the minimal dB must be made.

#### 3.1.1 Output from temperature sensor:

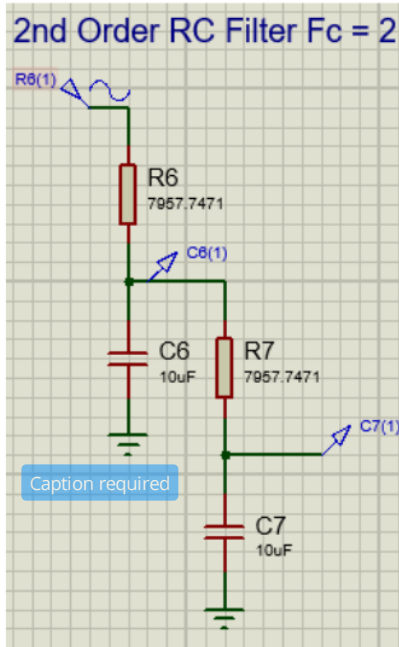
- Since minimal temperature in  $^{\circ}\text{C} = -20^{\circ}\text{C}$ , and maximal =  $100^{\circ}\text{C}$
- The required range of the temperatures will be from  $-20^{\circ}\text{C}$  to  $100^{\circ}\text{C}$
- Meaning:  $100^{\circ}\text{C} - (-20^{\circ}\text{C}) = 100^{\circ}\text{C} + 20^{\circ}\text{C} = 120^{\circ}\text{C}$
- Since sensor output is  $120\mu\text{V}/^{\circ}\text{C}$ , with  $0\text{V} = -80^{\circ}\text{C}$
- And minimal temperature is  $^{\circ}\text{C}_{min} = -80^{\circ}\text{C} - (-20^{\circ}\text{C}) = -80^{\circ}\text{C} + 20^{\circ}\text{C} = -60^{\circ}\text{C}$
- The minimal output of  $V_{min} = 120\mu\text{V} * 60^{\circ}\text{C} = 7.2\text{mV}$

#### 3.1.2 Noise contamination:

- Output noise should be much smaller than  $V_{min}$
- For e.g.  $\frac{1}{10}$  of signal output at  $-20^{\circ}\text{C}$
- Therefore noise  $7.2\text{mV} * 10^{-1} = 0.72\text{mV}$
- Resulted Attenuation:  $A(\text{dB}) = 20\text{LOG}\left(\frac{0.72\text{mV}}{7.2\text{mV}}\right) = -44.4\text{dB}$
- Output  $^{\circ}\text{C}$  will be contaminated with  $\frac{0.72\text{mV}}{0.12\text{mV}} = \pm 6^{\circ}\text{C}$  difference per  $^{\circ}\text{C}$
- This is not an acceptable noise range – trying 50% of actual output of a transducer per  $^{\circ}\text{C}$
- By reversing the above formula for  $0.5^{\circ}\text{C}$  noise of  $120\mu\text{V} * 0.5^{\circ}\text{C} = 60\mu\text{V}^{\text{pk-pk}}$

- Required attenuation of noise is  $A_{req}(dB) = 20 \log \left( \frac{60 \times 10^{-6}}{120 \times 10^{-3}} \right) = -66.02 \text{ dB}$
- Since  $A_{my}(dB) > A_{req}(dB)$

### 3.2.0 Next order filters



#### 3.2.1 Theory of $n^{th}$ -order Filter

Due to fact that the circuitry requires a steeper slope than that produced by a single RC network, the design must move to a next order filter. In theory, moving to next order is as simple as cascading two or more RC together.

For a number of RC stages, resulted in  $n^{th}$ -order filter circuit with a roll-off slope of:

$$A(dB) = n * -20 \text{ dB/Dec}$$

This means that as the order of the filter is increased, the roll-off slope becomes steeper and the actual stop band response approaches its ideal characteristics.

The downside for cascading RC filters is that with each next stage the output gain at the  $f_c$  will be attenuated by 3dB per  $n^{th}$  order as the roll-off slope increases.

For a passive low pass filter the gain at  $f_c$  is given by:

$$f_c = f_c * \left( \frac{1}{\sqrt{2}} \right)^n$$

[4 Citation Needed](#)

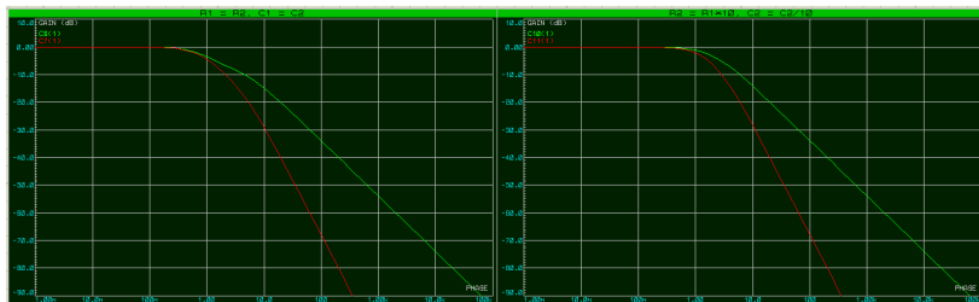
Theoretically for a 2<sup>nd</sup> order filter the  $f_c$  should be given by:  $f_c = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}}$

Where in the reality with the higher number of stages and with each increasing the roll-off slope the

actual  $f_c$  is given by:  $f_{(-3dB)} = f_c \sqrt{2^{\left(\frac{1}{n}\right)} - 1}$

#### 3.2.2 The limitations of Applications

However, in practice it is hard to cascade together passive filters to produce a larger filter because of a dynamic impedance of each network affecting its neighbour. Reducing the charging effect can be done by making each next stage networks impedance about 10x the previous stage. 2<sup>nd</sup> Order Filter:



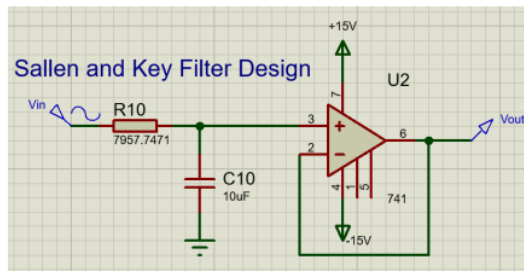
The response graph on the left represents the increase in the roll-off slope and the graph on the right shows the effect of increasing impedance of 2<sup>nd</sup> Order network  $R = 10R, C = \frac{C}{10}$

These show the roll-off slope has greatly decreased while maintaining almost equal  $f_c$  but worth noting that expected -6dB point ( $-3dB/Order$ ) has shifted to  $\approx 1.9Hz$ .

Working 2<sup>nd</sup> Order filter has a gain of  $\frac{-20dB/Decade}{Order} = -40dB/Decade$

But unfortunately,  $-40dB/Decade$ , still won't be enough to effectively attenuate the noise, but with each new order, the  $f_c$  will continue to shift and increase in difficulty to determine accurate results. To output gain at the  $f_c$  can be modulated, as well as the roll-off slope, if RC is combined with the *Op-Amp* to produce Voltage Controlled Voltage Source (VCVS) Amplifier – from *passive* to an *active* filter.

### 3.3.0 An Active Filters

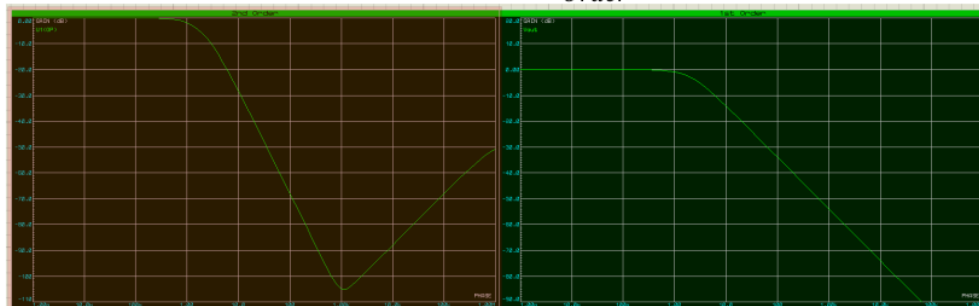


#### 3.3.1 Op-Amps benefits

By adding Op-Amp into the circuit, RC filter becomes an amplifier and thus attenuation becomes a gain which can be easily manipulated to provide just the right required amount. A typical *Op-Amp* can prevent external loading of the filter because of a high impedance at its input and low at the output, allowing it to be easily adjusted over a wide frequency range without altering the initial  $f_c$ .

#### 3.3.2 Moving to a Higher Order Filter

Since signal needs to be amplified, the network requires the Non-Inverting configuration without ( $R_1$  and  $R_2$ ). This is described as Sallen-Key Filter Design and the simulation has shown very good results with 1<sup>st</sup> Order configurations  $f_c$  at -3dB point and 2<sup>nd</sup> Order configuration  $f_c$  at -6dB which proves the 2<sup>nd</sup> Order Active RC filter with effective  $\frac{-20dB/Decade}{Order}$ .

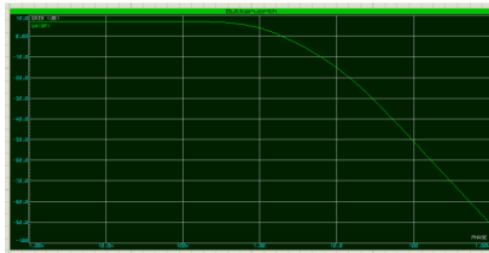
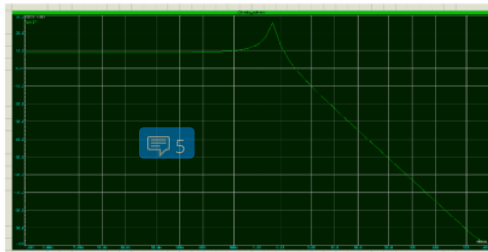


#### 3.3.3 Signal responses

When Sallen-key is cascaded in 2<sup>nd</sup> Order with Op-amp configured as Non-Inverting amplifier, the shape of the response can be modulated into various different responses, each possessing their own distinguished properties and applications. The three most commonly known as the:

- Chebyshev:

Has a very notable peak of a response at which the signal increases in gain instead of attenuated.

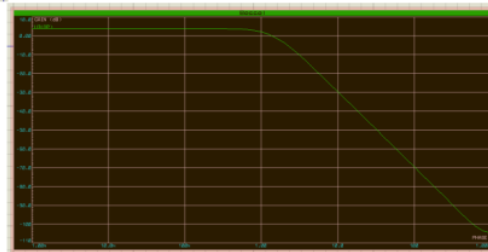


- Butterworth:

Very round type of a response with a very long roll-off slope and short cut-off slope.

- Bessel:

Very similar to regular response of a RC filter, a short roll-off and long cut-off slope.



## 4.0.0 Functioning Filter

### 4.0.1 The Configuration

Now with the acceptable solution for  $n^{th}$ , its time to produce a filter:

- Noise levels to be at -66dB minimum.
- 4<sup>th</sup> Order Active RC filter =  $4 * \frac{-20dB}{Dec/Ord} = \frac{-80dB}{Dec}$
- Sensor Output:  
 Min: 7.2mV  
 Max: 21.6mV
- Noise:  $120\mu V^{pk-pk} @ 50Hz$

Attenuation:

- Signal naturally attenuates per Order and so  $f_c = \frac{(-3dB)}{Order} = -12dB$
- Extra Op-amps  $K = \frac{1.5}{OpAmp}$

- 6 Resulted Output: Chebyshev response
- Increased gain by 0.5
- Resulted Output: Bessel(ish)

4<sup>th</sup> Order Filter Output:

- For  $V_{min} = 15.8mV$
- For  $V_{max} = 50.8mV$

#### 4.0.2 Required Gain

The Gain can be calculated by  $K(dB) = \frac{V_{req}}{(V_{max} - V_{min})} = \frac{5V}{(50.8mV - 15.8mV)} = \frac{5V}{0.035} \approx 142.86dB$

Gain for a Non-Inverting Amplifier is given by formula  $V_{out} = V_{in} \left[ 1 + \frac{R_2}{R_1} \right]$  and so it can be rearranged to  $\frac{V_{out}}{V_{in}} = \left[ 1 + \frac{R_2}{R_1} \right] \rightarrow A_V = 1 + \frac{R_2}{R_1} \rightarrow A_V - 1 = \frac{R_2}{R_1} \rightarrow R_2 = R_1(A_V - 1)$

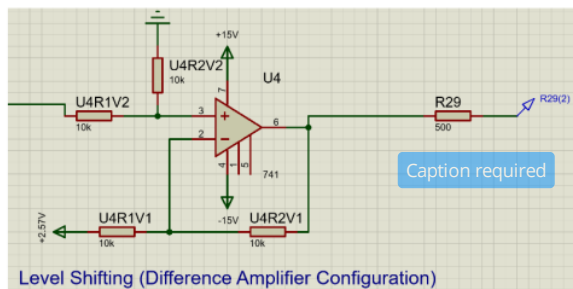
$$R_2 = 10 * 10^3 * (142.86 - 1) = 10 * 10^3 * 141.86 \approx 1418571\Omega$$

After running simulation, the output is:

- For  $V_{min} = 2.53V$
- For  $V_{max} = 7.52V$

This is a very good output to move down to a maximum of 5V. 

#### 4.0.3 Level Shifting



The signal has been properly amplified to create a range of 5V but there's an excess of around 2.57V that needs to be removed.

If  $R_1$  and  $R_2$  are equal then  $V_{out}$  is defined as:

$$V_{out} = \frac{R_2}{R_1} (V_2 - V_1)$$

In this scenario – since the resistor ratio equals to 1 the  $V_{out} = V_2 - V_1$  where  $V_2 =$

And so  $V_{out} = V_{in} - 2.52V$

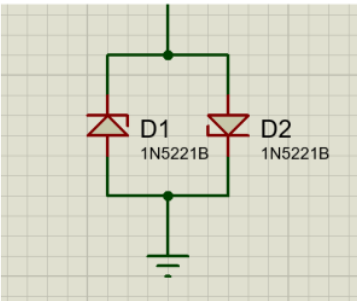
$$V_{out}^{max} = V_{in}^{max} - 2.52V = 7.52V - 2.52V = 5V$$

$$V_{out}^{min} = V_{in}^{min} - 2.52V = 2.53V - 2.52V = 0.01V \approx 10mV \rightarrow \text{leftover noise}$$
 

A simple equation can check If the remaining 10mV at the  $V_{min}$  is acceptable:

$$V_{out}/^{\circ}C = \frac{V_{max} - V_{min}}{^{\circ}C_{max} - (^{\circ}C_{min})} = \frac{4.99V}{120^{\circ}C} \approx 41.6mV/^{\circ}C \rightarrow \text{The 10mV is acceptable as it is about 4 times smaller than } V_{out}/^{\circ}C.$$
 

4.0.4 Over voltage protection

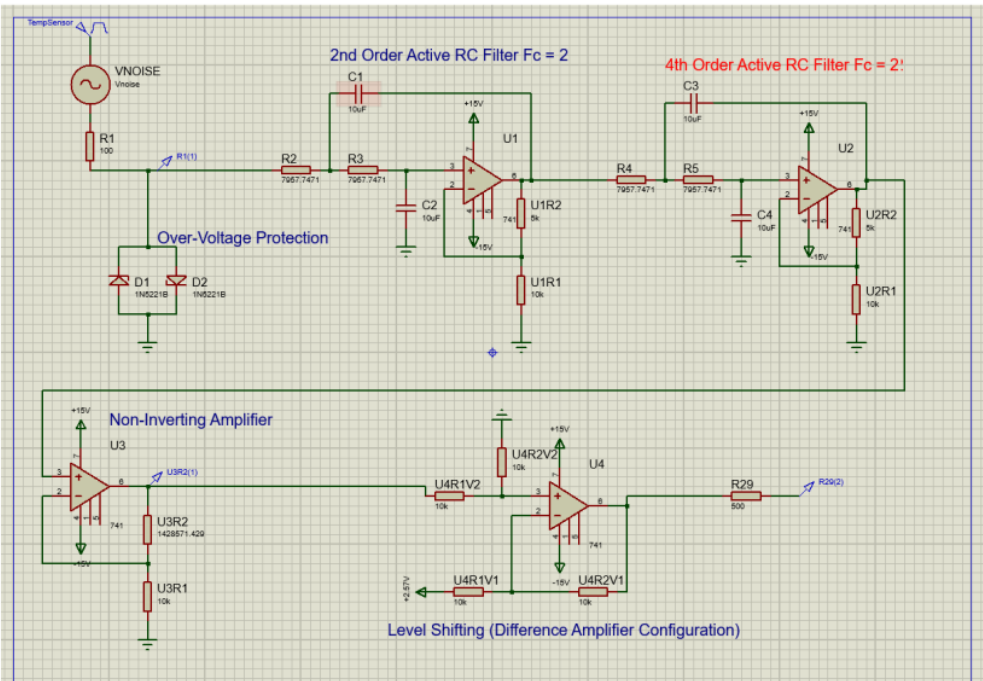


Over-voltage Protection is done by adding a pair of Zener diodes which conducts electrical current only when voltage is higher than minimum required to switch it on.

Any excess voltage would disrupt the performance of the circuit and possibly damaging it as well.

Not only voltage is risky but the current as well. Output required is ranging within 0 – 5V and so is the preferred inputs to a PIC, and so I would expect the current to never exceed 20mA.

5.0.0 Simulation



10

5.1.0 Components Values

5.1.1 Signal Input

| SIGNAL INPUT |                   |                |
|--------------|-------------------|----------------|
| Component ID | Component type    | Value          |
| TempSensor   | Square wave input | 7.2mV ↔ 21.6mV |
| VNOISE       | VSINE             | 120μF @ 50Hz   |
| RIN          | Resistor          | 100Ω           |
| D1&D2        | Zener Diodes      | 2.4V / 20mA    |

### 5.1.2 Signal Filter

| SIGNAL FILTER |                                                                                                         |                         |
|---------------|---------------------------------------------------------------------------------------------------------|-------------------------|
| Component ID  | Component type                                                                                          | Value                   |
| R1&R2&R3&R4   | Resistor                                                                                                | $7957.747\Omega$        |
| C1&C2&C3&C4   | Capacitor                                                                                               | $10\mu F$               |
| U1&U2         | Operational Amplifier  | $K(dB) = 0.5dB / OpAmp$ |
|               | U1R1&U2R1                                                                                               | $10k\Omega$             |
|               | U1R2&U2R2                                                                                               | $5k\Omega$              |

### 5.1.3 Signal Gain

| SIGNAL GAIN  |                       |                  |
|--------------|-----------------------|------------------|
| Component ID | Component type        | Value            |
| U3           | Operational Amplifier | $21.6mV / 7.2mV$ |
| R2           | Resistor              | $1418571\Omega$  |
| R1           | Resistor              | $10k\Omega$      |

### 5.1.4 Level Shifting

| LEVEL SHIFTING |                       |                       |
|----------------|-----------------------|-----------------------|
| Component ID   | Component type        | Value                 |
| U4             | Operational Amplifier | $K(dB) \approx 142dB$ |
| R1&R2&R3&R4    | Resistor              | $10k\Omega$           |
| $V_1$          | Power input           | $+2.52V$              |

## 6.0.0 Conclusion

Sallen and key Voltage-Controlled Voltage-Source circuit is an excellent introduction into designing methods behind a signal conditioning circuit because of its simplicity. It only requires a few components and it makes great use of their properties to achieve 3 different signal responses each having their own unique benefits.

Despite great attributes such as: small number of parts, output impedance, or low demand on slew rate, shown circuit is not without limitations. Same as in a simple RC circuit with  $n^{th}$  orders, the op-amps also have their own impedance that can affect remaining circuits performance. This can be most noted in the section 4.0.0 where after applying Gain there was about 0.01 difference to expected voltage.

To deal with this offset a designer must take into account the internal resistance of each individual op-amp configurations and voltage sources, such as transducers. A properly tweaked circuit will have high-impedance at input and low-impedance at output of each section of the circuit. High-impedance can be considered a point where electric current “collapse” into voltage which means that a low-impedance component can have its current flow right through it without taking a full note of it.

Interesting fact is that before op-amp integration, VCVS filters used inductors instead to achieve same results. The main problem with such analogue design is the “cook-book” approach, having a number of different values components with each section needing to take into account impedance of a previous sections must had been a difficult task and it shows how useful the high-impedance input of an op-amp actually is.

## 7.0.0 Appendix



### Proteus Filter Design:



Trans\_A1\_V01.pdsp  
rj



### MS Excel Spreadsheet:



TaSC\_Math\_by\_KM\_  
ID1804424.xlsx

FINAL GRADE

GENERAL COMMENTS

Instructor

51 / 100

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QM

### Caption required

You should always include a caption on figures, equations and tables to allow you to refer to them in your text.

e.g. An illustration of this can be seen in figure 2. The relationship of the variables is shown in equation 2. Table 1 shows the results of the first experiment where the control variable, temperature in degrees celsius is shown in the first column....



### Comment 1

Equation should be

$A(\text{dB}) = 20 \log(V_{\text{out}} / V_{\text{in}})$

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### Comment 2

What do you mean by "Open Loop"?

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### Comment 3

Axis labels are unclear. You should consider making the graph smaller before copying and pasting it.

QM

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#### Comment 4

You are stating equations without citing a source for them. You need to reference things like this.



#### Citation Needed

Cite Source:

Please use the link below to find links to information regarding specific citation styles:  
[http://www.plagiarism.org/plag\\_article\\_citation\\_styles.html](http://www.plagiarism.org/plag_article_citation_styles.html)

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#### Comment 5

Axis labels on all these graphs are too small to read. You should make the graph smaller before copying it so that the text is larger.



#### Comment 6

Which filter type did you intend to produce? Bessel or Chebyshev?

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#### Comment 7

Why?



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#### Comment 8

Do you think this could be to do with imbalances in the resistance seen by each input of the amplifiers? Could this be adjusted for in the level shifting circuit?



#### Comment 9

Good check



### Comment 10

Where are your results? You were supposed to include a time graph and a frequency response graph.



### Comment 11

120uF? do you mean 120uV?



### Comment 12

The gain set resistors in a Sallen-Key VCVS filter set the shape of the response in the frequency domain.

There are certain gain values which should be used for each amplifier in an nth order filter to give these responses. In the lectures, I went through the gain requirements for Bessel, Butterworth and Chebyshev responses. These have not been included.

Similarly, with the Chebyshev and Bessel responses, the cut-off frequency of the filter is varied at each stage to give the response shape in the frequency domain.



### Comment 13

Where are your references?



### Comment 14

I do not have access to these files. They do not persist when submitting to TurnItIn

GRADING FORM: SMU GENERIC\_SMOSEY

KRZYSZTOF SYLWESTER MATELA

# 50.70

## ENGAGEMENT WITH LITERATURE

*including reading, referencing, academic conventions and academic honesty*



Unfortunately, I cannot award you any marks for this section as you have not provided any references at all. You need to provide references for all sources you use when you write your reports.

## KNOWLEDGE & UNDERSTANDING

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



Knowledge is accurate with a good understanding of the field of study.

### 17.4

## 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.*



Evidence of some logical, analytical thinking and synthesis. Can analyse new and/or abstract data and situations without guidance. An emerging awareness of different stances and ability to use evidence to support the argument. Valid conclusions.

### 17.1

## PRACTICAL APPLICATION SKILLS

*Different approaches to solving problems in particular contexts.*



An adequate awareness and mostly appropriate application of well-established methods, materials, tools and techniques. Basic appreciation of the context of the application.

**14.1**

## 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 in a suitable format but with some room for improvement. Work lacks coherence in places and could be better structured.

**2.1**