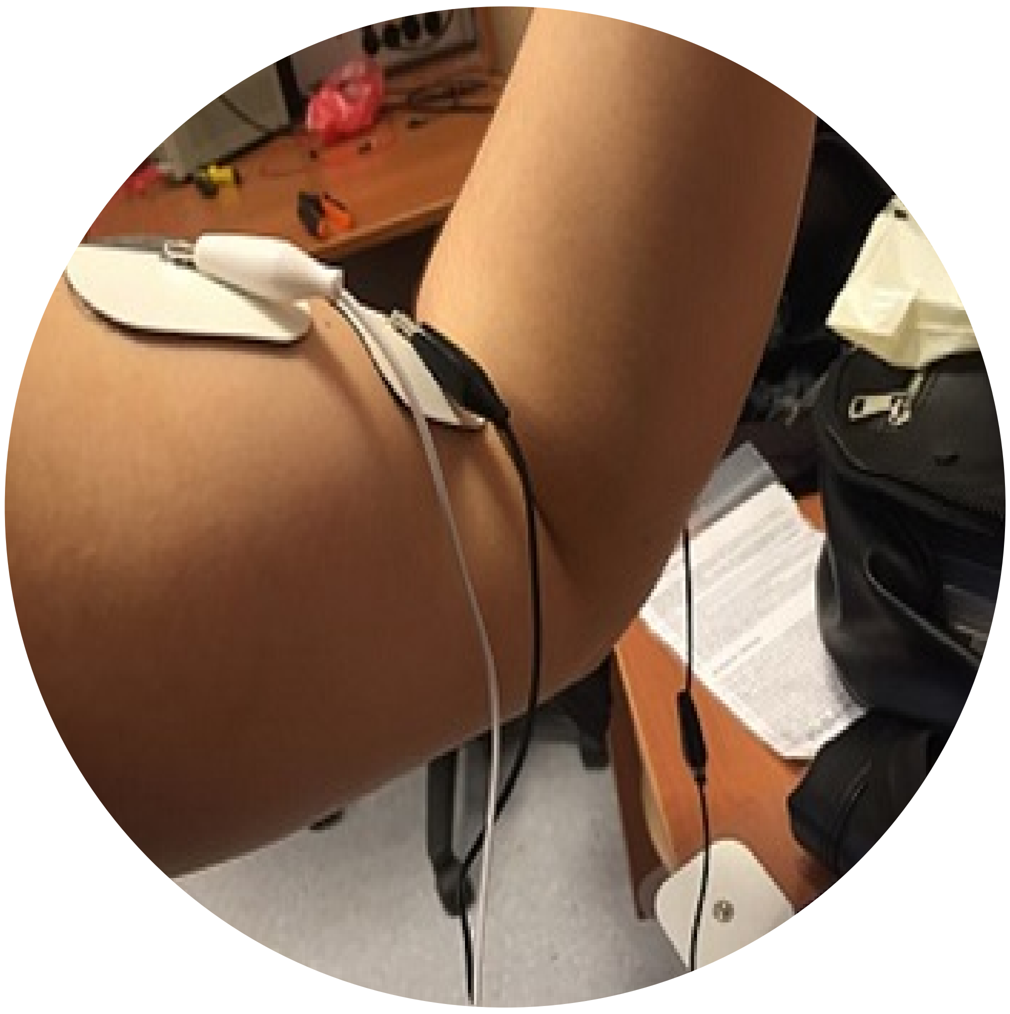


EMG Sensor Circuit

23.07.2019

Projects

1. PROBLEM DEFINITION

Our main objective for this project is designing and implementing a Surface Electromyogram (EMG) Conditioning Circuit and provide pc communication by using arduino. In order to understand what we are trying to build, we should first make an introduction,and then give some basics about EMG.

Surface electromyography (sEMG) is the non–invasive recording of electrical muscle activity that is used to diagnose neuromuscular disorders, among other applications. Muscle fibers are activated by motor neurons and the resulting electrical signals produced by the muscle fibers can be detected by electrodes placed on the surface of the skin. EMG can be used for many useful applications in biomechanics, rehabilitation medicine, neurology, gait analysis, exercise physiology, pain management, orthotics, incontinence control, prosthetic device control, even unvoiced speech recognition and man–machine interface.

Most sEMG signals have a frequency content ranging from 0 to 500 Hz, with dominant energy between 50 to 150 Hz. However, content at up to 2000 Hz may be useful. The amplitude of the signal may vary from less than 50 µV up to 30 mV

Besides motor unit (muscle cell group) and electrode characteristics, there are other factors that distort and add undesirable noise to the signal. A DC offset due to half–cell potentials within the tissues can be as high as 300 mV. Muscle crosstalk (signals from motor units of neighboring muscles) may result in misleading information about the investigated muscle. Ambient 60 Hz noise from power supplies (50 Hz for European power supplies) may result in power line noise three fold the magnitude of the sEMG itself. Inherent noise generated by electronic equipment can range from zero to thousands of Hz. Motion artifacts due to electrode or cable movement add noise to the EMG signal in the frequency range of 1 to 5 Hz.

EMG Physiology

Muscle contraction and relaxation is controlled by the central nervous system. The nervous system sends a signal through a motor neuron to a grouping of muscle cells, called fibers. That grouping of muscle cells, and the motor neuron that innervates them, is a motor unit — a basic building block of the neuromuscular system, the smallest functional part of muscle tissue. *The signal of the motor neuron causes a chemical reaction that changes the membrane potential of muscle fibers. If the threshold potential is reached a motor unit action potential (MUAP) occurs, causing the electrical activation to spread along the entire surface of the muscle fiber at a rate of approximately 3–5 m/s.* We can see the image of a motor neuron connected to a group of muscle fibers below.

Figure 1 – Motor Neuron Attached to a Motor Unit

Electromyography (EMG) is a technique that is used to detect and record MUAPs non– invasively by placing a conductive element (electrode) on the surface of the skin overlying the muscle of interest (this method is referred to as surface EMG) or directly inside the muscle (this invasive EMG detection method utilizes needles or fine wires). Inserted electrodes record from a very small region of muscle, making it possible to view individual MUAPs. On the contrary, surface electrodes tend to record from much larger regions of the muscle. Thus, individual MUAPs are not clearly visible, as many motor units tend to be contracting concurrently. Only the superposition (interference) pattern is recorded.

As mentioned before the amplitude of a sEMG signal may vary from less than 50 µV up to 30 mV (DeLuca, 1979). It is commonly accepted that most sEMG signals have frequency content between 0–500 Hz with dominant energy between 50–150 Hz. However, there exists content at up to 2000 Hz that may be useful

There are numerous physiological and non– physiological factors that influence sEMG signal interpretation, such as electrode shape, size, inter–electrode distance, skin contact and location over the muscle; motor unit physiology; subject's muscles' properties; etc. As a sEMG signal travels through different media it acquires noise.

There are several types of electrical noise which affect a sEMG signal:

1.Motion artifact. This type of noise is caused by the movement at the interface between the detection surface of the electrode and the skin. It generally lies in the 1–10 Hz frequency range and has a voltage comparable to the magnitude of the EMG.

Solution:

- A high–pass filter will be used in order to filtering frequencies in the 0–10 Hz range.
- Skin preparation can reduce the electrode–skin impedance and also helps to minimize motion artifacts.

2.DC offset potential due to skin and due to opamps. Oil secretions and dead skin cells increase impedance on the outermost layer of the skin, which cause DC voltage potential generation during skin and electrode contact of up to 200–300 mV. And as we know in real life opamps has DC offset potentials due to input offset voltage and input current differences.

Solution:

- A high–pass filter will be used in order to filtering frequencies in the 0–10 Hz range.
- Can be minimized with proper skin preparation.Usually skin cleaning involves use of special abrasive and conductive pastes to remove dead skin or fine sandpaper and alcohol swabs to clean the skin, all to lower skin impedance.

3.Ambient noise. Ambient noise lies in a wide range of frequencies but its dominant component is 50 Hz or 60 Hz which is the most common source of electrical noise in the EMG signal and corresponds to power line noise. Such noise results in a signal whose voltage can be larger than the EMG signal itself.

Solution:

- Proper skin preparation,
- Using a differential amplifier with a CMMR of at least 100 dB at 50/60 Hz can help attenuate this type of noise.
- Since the dominant energy of the EMG signal is located in the 50–150 Hz range some experts do not recommend the use of a 50 or 60 Hz notch filter as it partially removes frequency components adjacent to the unwanted ones.

4.Muscle crosstalk. Muscle crosstalk is a phenomenon in which signal recorded over one muscle was in fact generated by a neighboring muscle and conducted to the recording electrodes.

Solution:

- Crosstalk can be minimized by choosing electrode size and inter–electrode distances carefully, as well as via the placement of the electrodes. Smaller inter–electrode distances tend to lead to less crosstalk. But, overly small distances can lead to electrode shorting (e.g., due to sweat). The recommended inter–electrode distance is typically 1–2cm or the radius of the electrode. Electrode alignment with the direction of muscle fibers increases the probability of detecting the same signal

5.Inherent noise. Inherent noise of the electronics instrumentation. Any electronic equipment will generate noise up to thousands of Hertz. Although this type of noise cannot be eliminated, modern electronics tend to have noise less than 1.5 mV RMS (referred to the input) over the band from 20–500 Hz.

2. DESIGN

Typically, sEMG is acquired in two stages. The first (electrode–amplifier) stage includes signal transduction/detection and pre–amplification. The second (signal conditioner) stage provides further signal conditioning. An electrode–amplifier circuit that detects the EMG signal, amplifies and removes some of the unwanted noise.

In our design we will use an extra operation which is rectification, because we want to see our output signal as a DC signal and transmit it to PC by using arduino The reason why we want our output signal as DC is that, for human beings it is extremely easy to understand DC signals compared to AC ones.

Figure below illustrates the connection of a differential amplifier to the skin. Two inputs of the amplifier are connected to the electrodes. *Two signals are detected and the difference is amplified. Any "common" signals (such as power line interference) will be removed (or greatly attenuated) and the physiologic signal that is different at the two sites will be amplified.* Any signal that originates far away from the detection surfaces will appear as a common signal, while signals in their vicinity will be different and will be amplified.

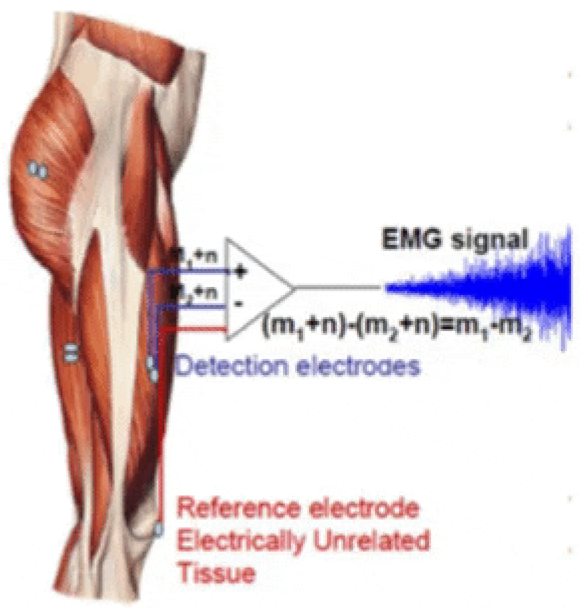


Figure 3 – Schematic of the Differential Amplifier Configuration

Reference electrode is usually connected to bone region away from muscles.The purpose of this electrode is measuring the body's own idle signal. Device will first do the amplification - subtraction operation by using Mid-Muscle and End-Muscle electrode signals.Then filtering and rectification operations and finally. Output signal will be subtracted from the body's neutral signal by this way we will get rid of the body's own noise.

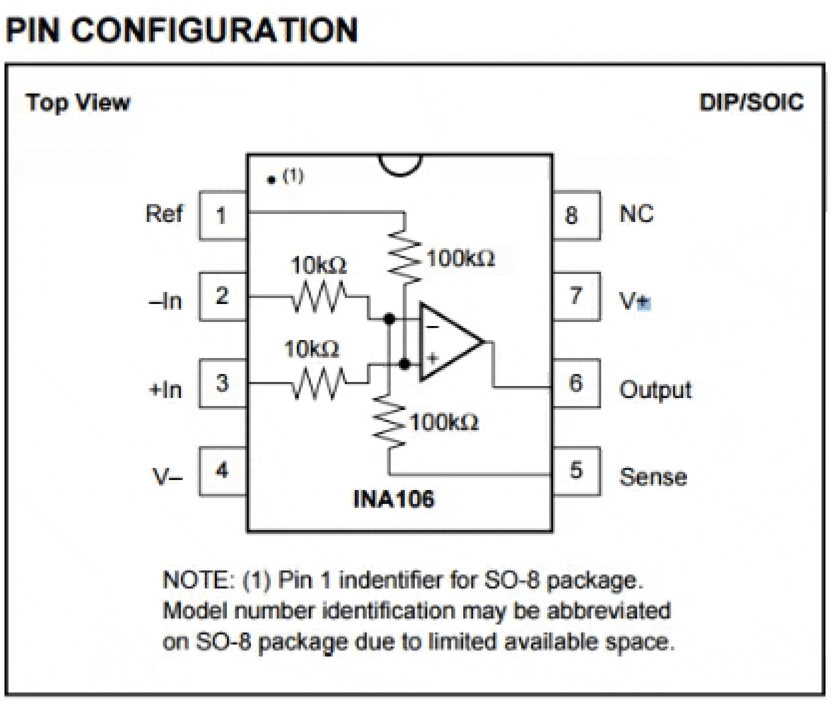
2.1. ELECTRODE-AMPLIFIER

First Stage - Signal acquisition - Subtractor:

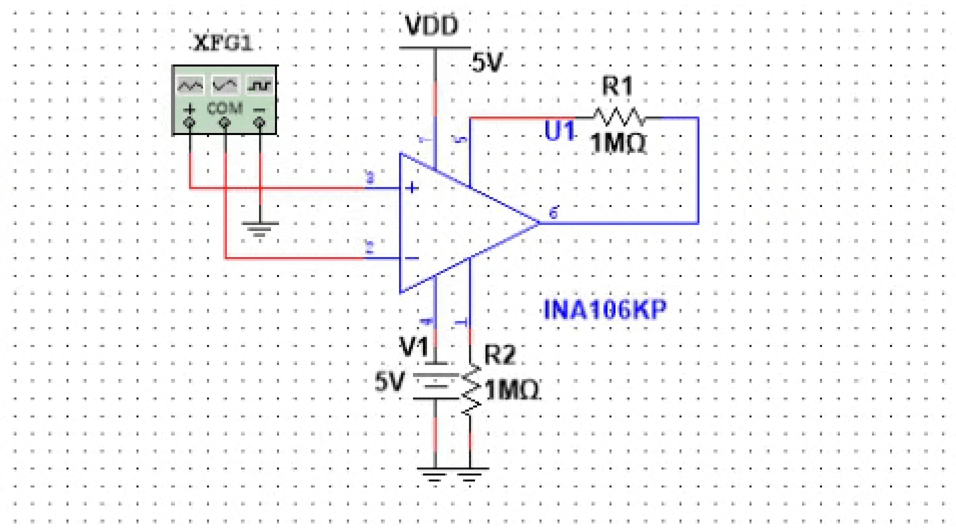
This stage is probably the most important stage for our circuit. Because our purpose in this stage is signal acquisition and if any error occurs in this stage and we can not manage to take emg signals and amplify it correctly, the rest stages will be compeletely meaningless.Thus we should use high quality IC for this stage.

To minimize current drawn from the subject and therefore to prevent attenuation or distortion of the signal, the input impedance should be as large as possible. An instrumentation amplifier is very suitable for this purpose since it rejects much of the common signal; the common mode interference is greatly attenuated.

Thus, in order to minimize errors and noise caused by opamp, we will use INA106KP IC for this stage which has high Common-Mode Rejection (86dB min). So our differential amplifier will amplify the difference signal and attenuate much of the common signal.



Stage 1 Drawing



Calculations

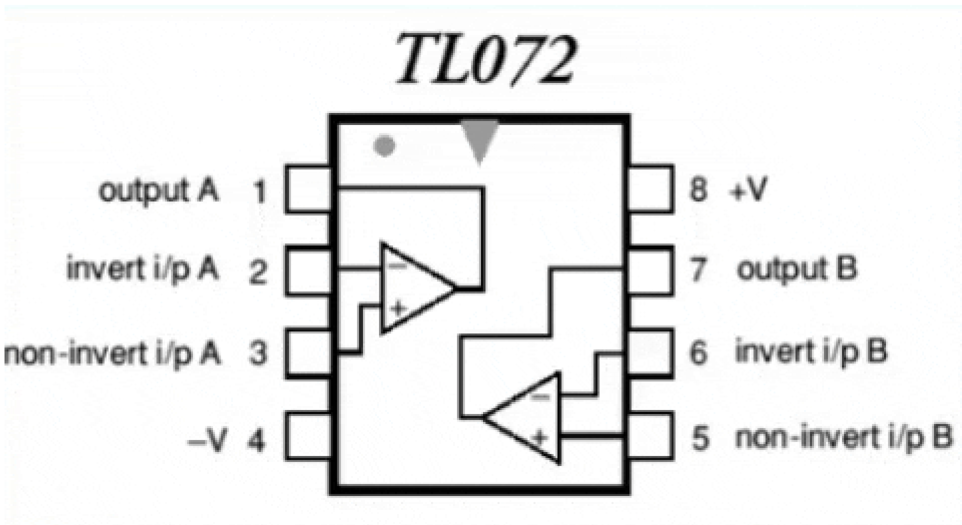
→ $V_O = \frac{R_2}{R_1}(V_1 - V_2) = \frac{1.1M\,\Omega}{10k\,\Omega}(V_{MID} - V_{END}) = 110\,(V_{MID} - V_{END})$

→ Thus our gain is **110**

2.2. SIGNAL-CONDITIONING

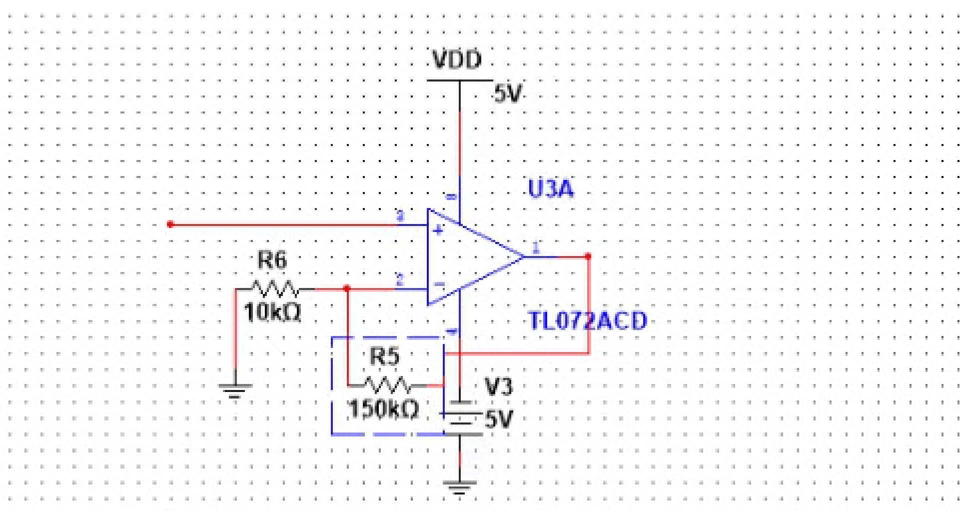
Second Stage - Non Inverting Amplifier

We can use normal quality opams for rest of the circuit since INA106KP is a bit expensive for student (about 50 liras) we will use TL072 IC's for rest of the circuit.



Purpose of this stage is further amplification of signal.

Drawing



Calculations

→ $V_O = (1 + \frac{R_2}{R_1})\,V_i = (1 + \frac{150k\,\Omega}{10k\,\Omega})\,V_i = 16\,V_i$

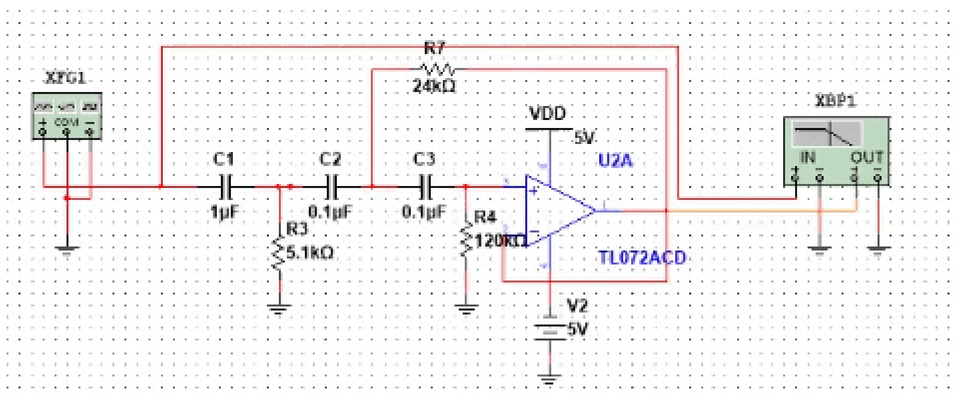
Thus our gain for second stage is **16** and our gain combined gain is 110*16 = **1760**

Third Stage - 3th Order Sallen Key High Pass Filter

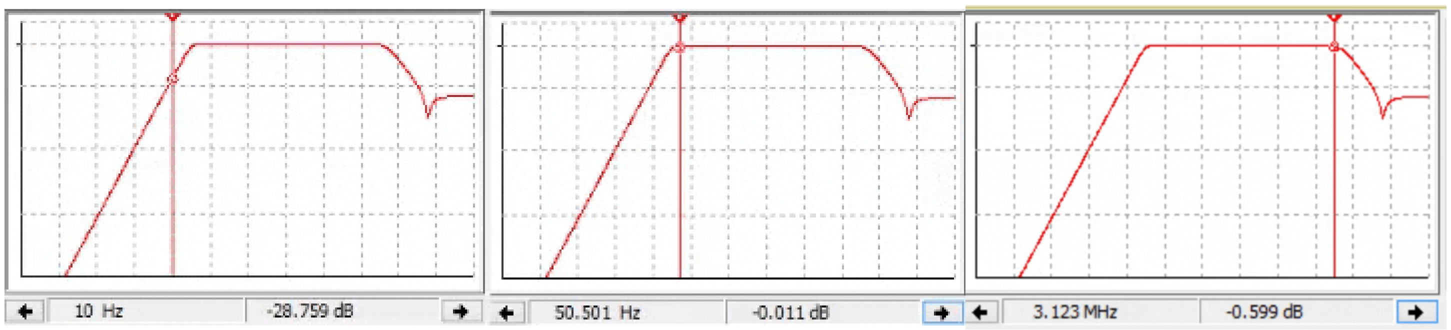
The purpose of this stage is by using 3th order filter, diminishing signal components with the frequency of 0-10 Hz. As we mentioned before, that portion of the signal contains motion artifact caused by movement at the interface between the detection surface of the electrode and the subject's skin. Also the DC offset potential (0 Hz) is also rejected by the high pass filter.

Using higher order filters can give better results for filtering because decay will be faster as order increases. But for our project, 3th order will be enough to eliminination.

Drawing



Bode Results



As we can see our filter attenuates signal components under 10Hz. and transmits our main signal (50Hz - 150Hz) until 3MHz without any attenuation.

Calculations:

As we can see, our 3th order filter consist of one 1st order filter cascaded with one 2nd order filter.

I want to set my cut-off frequency as 30 Hz in order to attenuate motion artifact effects (0-10 Hz) and DC offset voltage (0 Hz) and transmit signal components has dominant energy (50-150 Hz) without any attenuation.

i) First order filter calculations:

→ In order to our f_c = 30 Hz

→ $f_c = \frac{1}{2\pi RC}$ Let set our C = 1uF → $R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi 30\times 10^{-6}} = 5.3$ kOhm

→ Since there is no 5.3kOhm resistor in market we can say it approximately 5.1kOhm

ii) Second order filter calculations:

→ In order to our f_c = 30 Hz

→ $f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$ Let set our C_1 *and* C_2 = 0.1uF → $R_1 R_2 = 2814 \times 10^6\ Ohm^2$

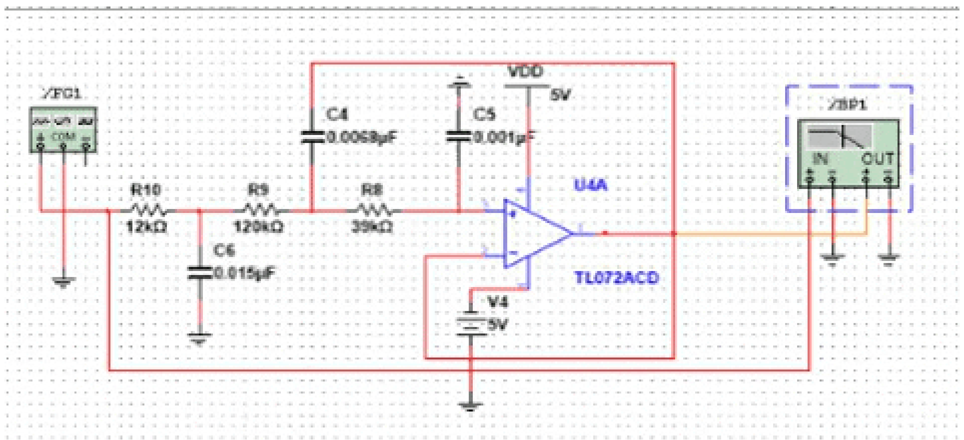
→ After some tryings on multisim i conclude R_1 = 24kOhm and R_2 = 120kOhm provides our condition and gives a good bode plot for us. $(24k \times 120k - 2880 \times 10^6)$

Fourth Stage - 3th Order Sallen Key Low Pass Filter

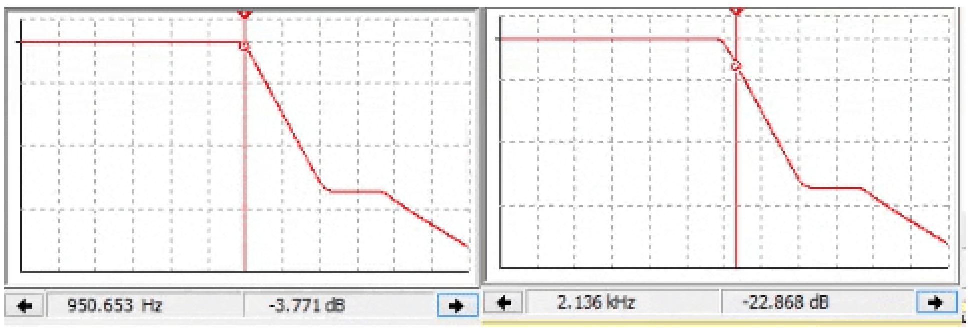
As we know it is commonly accepted that most sEMG signals have frequency content between 0–500 Hz with dominant energy between 50–150 Hz. However, there exists content at up to 2000 Hz that may be useful.

Thus the main purpose of this stage is, attenuate our signal components with frequencies bigger than 2000 Hz. To achieve that we will use a third order low pass Sallen Key filter.

Drawing



Bode Results



As we can see this filter transmits our signal components with frequency lower than 1kHz (Includes our dominant energy interval 0-150 Hz and 500 Hz too) almost without any attenuation. And blocks signal components with frequency higher than 2000 Hz.

As we mentioned before by using higher order filters we can obtain better bode plots for our purpose but for our project, 3rd order filters will be enough.

Calculations

As we can see, our 3th order filter consist of one 1st order filter cascaded with one 2nd order filter.

I want to set my cut-off frequency as 900 Hz.

i) First order filter calculations:

→ In order to our f_c = 900 Hz. I set our C= 0.015 uF after some tryings on multisim.

→ $f_c = \frac{1}{2\pi RC}$ Let set our C = 0.015uF → $R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 0.015 \times 10^{-6}}$ = 10.6 kOhm

→ Since there is no 10.6kOhm resistor in market we can say it approximately 12kOhm

ii) Second order filter calculations:

› In order to our f_c = 900 Hz

→ $f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$ Let set our C_1 *and* C_2 = 0.0068uF and 0.001uF

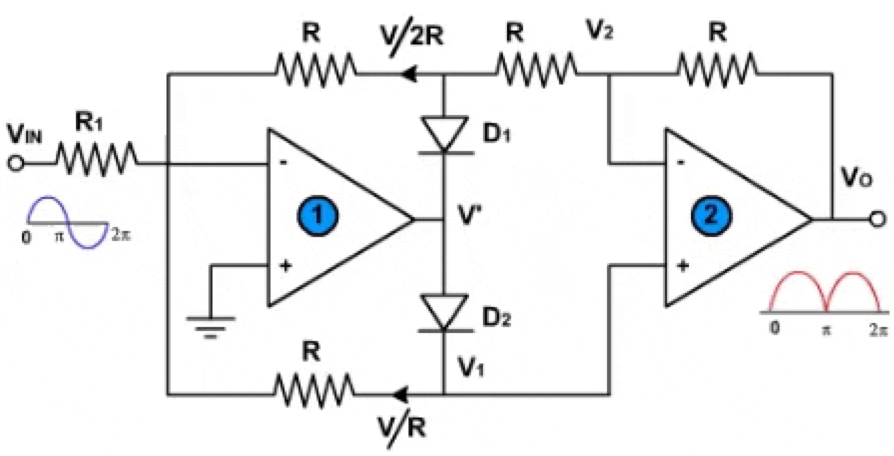
› $R_1 R_2 = 4599 \times 10^6\ Ohm^2$

→ After some tryings on multisim i conclude R_1 = 120kOhm and R_2 = 39kOhm provides our condition and gives a good bode plot for us. ($120k \times 39k = 4599 \times 10^6$)

2.3.RECTIFIER-AMPLIFIER

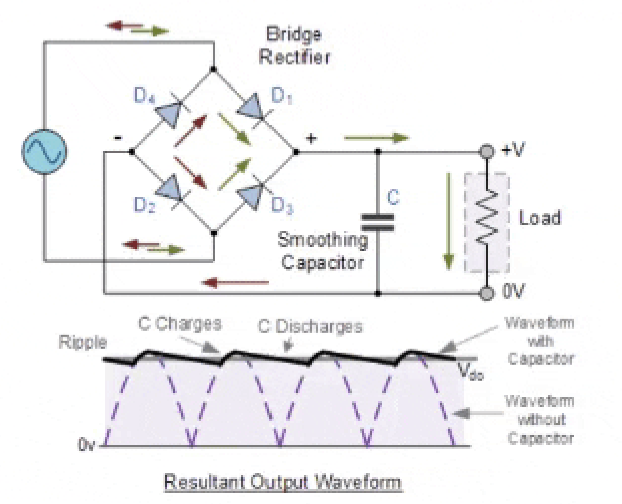
Fifth Stage - Full Wave Active Rectifier

In this stage firstly, I want to transform my AC signal to a rectified signal, then at next stage by using a low pass filter i want it to be look like a DC signal as much as i can. Active rectifier i will use for this operation is in the figure below.



I could have been use other types of full wave rectifiers such as figure below

Full-wave Rectifier with Smoothing Capacitor

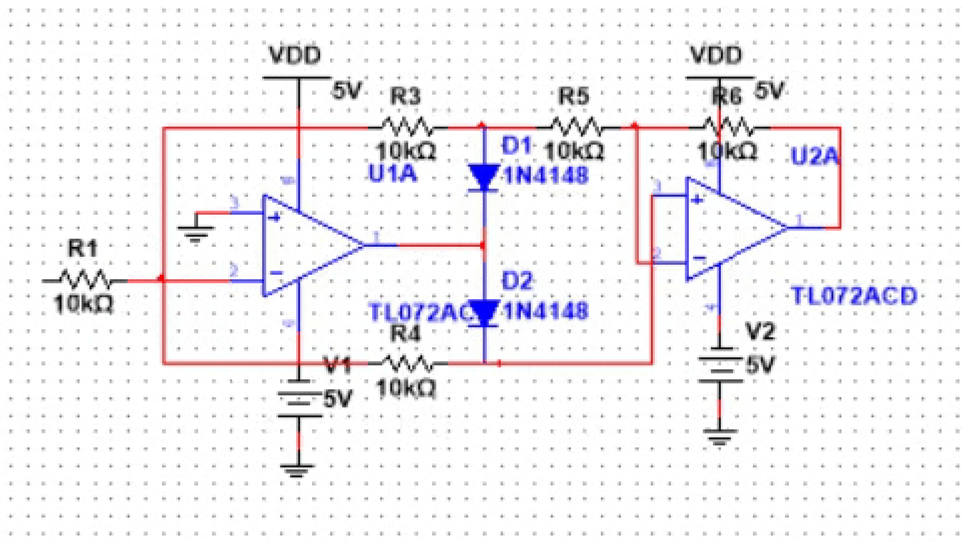


The reasons why I choose active rectifier in this stage are:

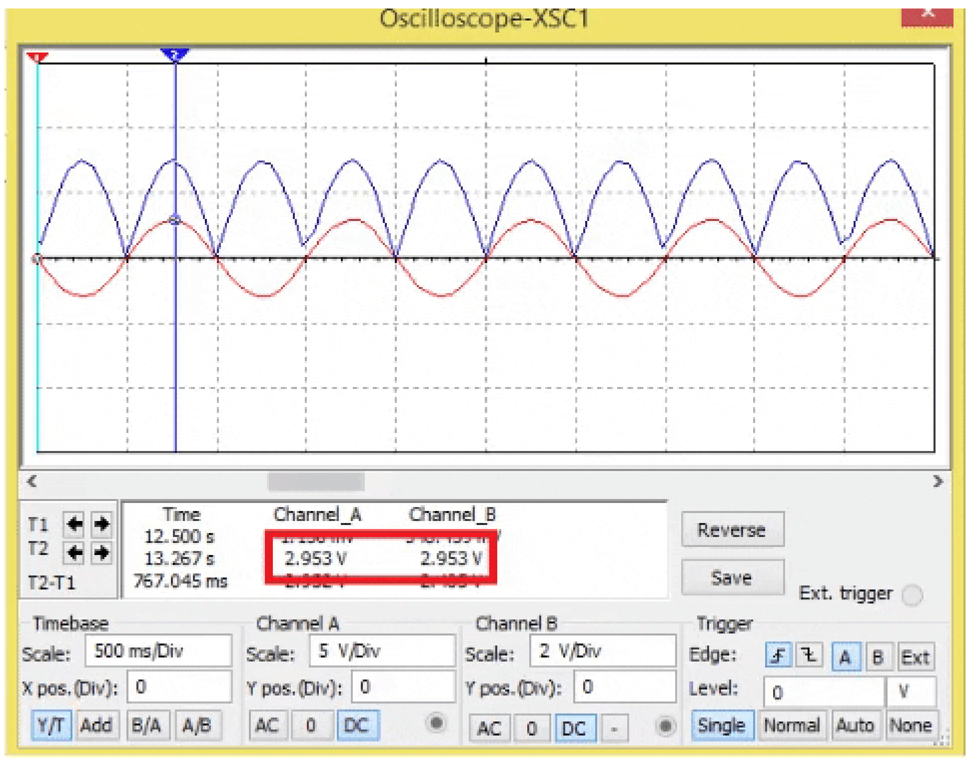
→ Easier to make calculations
→ Less voltage loss. Because we know $V_{dc} = 0.636\ (V_m - 2V_K)$ since our V_K = 0.7V for silicon diodes, and our V_m is about 3-4 Volts, 1.4 V is pretty large compared to 3 V.

→ But in active rectifier, $V_o = (R/R_1)\ V_i$ and $V_{dc} = 0.636\ V_m$ there is no voltage drop because of V_K.
→ Finally this circuit is easier to cascade with others.

Drawing



And we can see the output of rectifier to 3V input is almost 3V again.



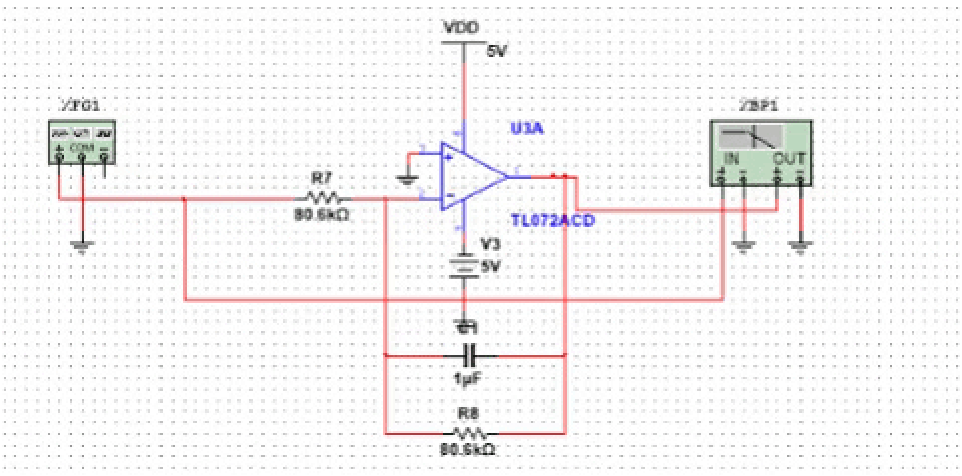
Calculations

→ Lets say gain of this stage will be 1.
→ If we set $R = 10\text{kOhm}$, then R_1 will be 10kOhm too.
→ Asssume we have 3V input for this stage.
→ $V_o = (R/R_1)\ V_i$ = 3V (Rectified) and $V_{dc} = 0.636\ V_m$ = 1.9 V. And remember Vm depends on our emg signal's magnitude, it means when i tighten my muscle, i will see a DC voltage (close to DC with some ripple) depends on my muscle signals amplitude.

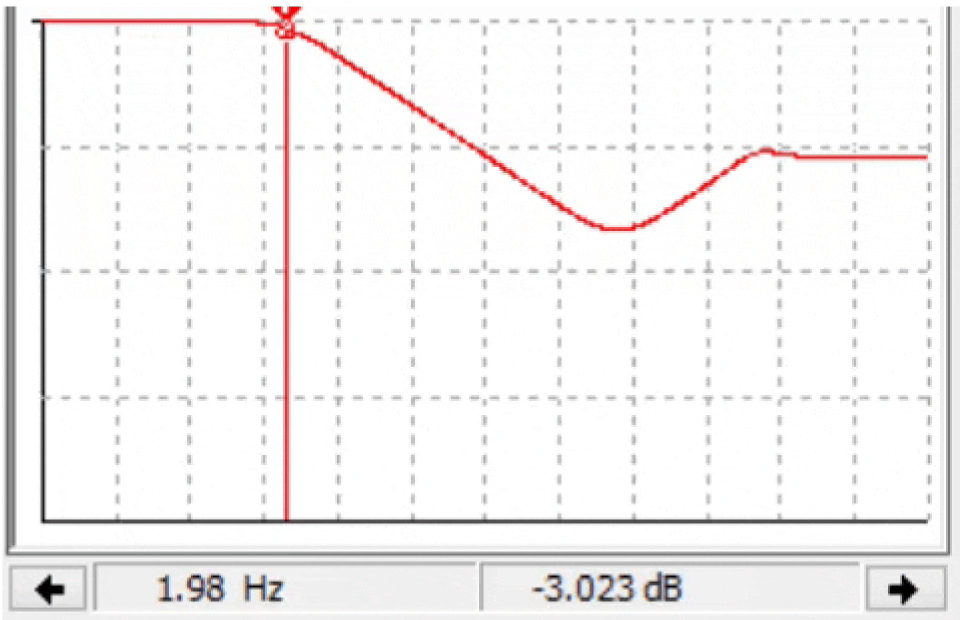
Sixth Stage - Active Low Pass Filter

The purpose of this stage is attenuate all most of the ac components in our rectified signal and take an DC output with relatively low ripple.

Drawing



Bode Result



Calculations

→ Since i want to block AC components, i wil set my cut-off frequency, f_c = 2Hz.

→ $f_c = \frac{1}{2\pi RC}$ Let set our C = 1uF → $R = \frac{1}{2\pi f_c C} = \frac{1}{2\pi 2\times 10^{-6}}$ = 79.6 kOhm

→ 79.6 kOhm ≃ 82 kOhm

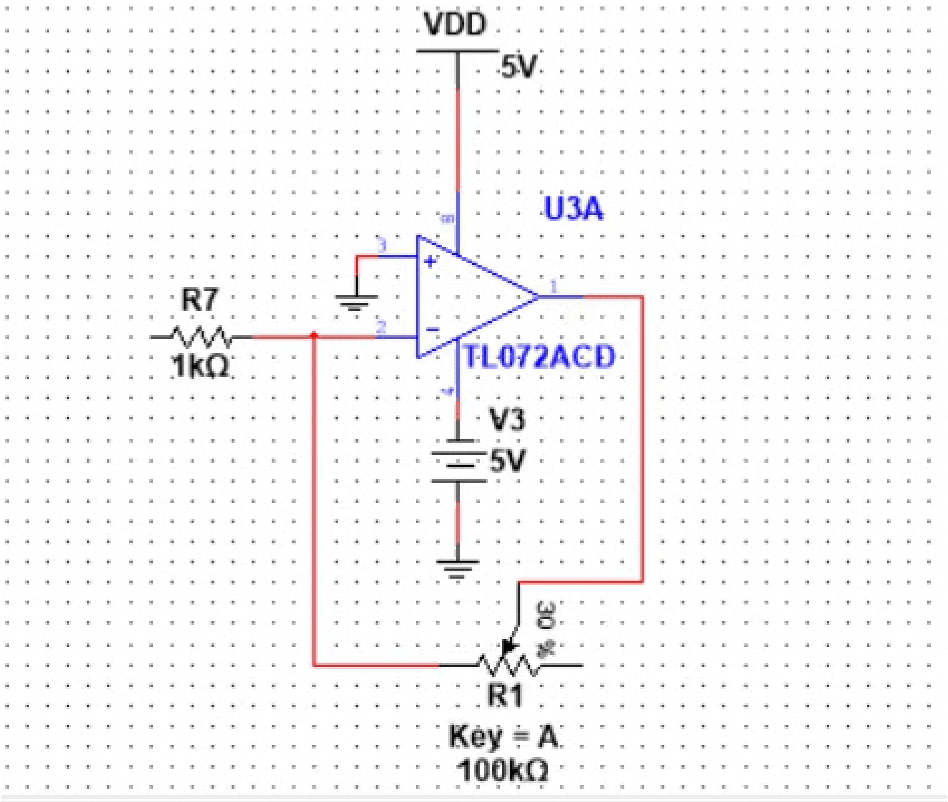
Seventh Stage - Inverter Amplifier

Since the stage 6 is an inverter low pass filter, i will put another stage to the end of our circuit which is inverter amplifier. There are two purposes for this stage:

1) I want a positive output signal.

2) I want to amplify my output if i needed. So i will use a potentiometer for this purpose.

Drawing



Calculations

→ $V_O = -\frac{R_2}{R_1}(V_i) = \frac{100k\,\Omega}{1k\,\Omega} = 100(V_i)$ max .

→ Thus our gain is between -1 and -100 depends on potentiometer.

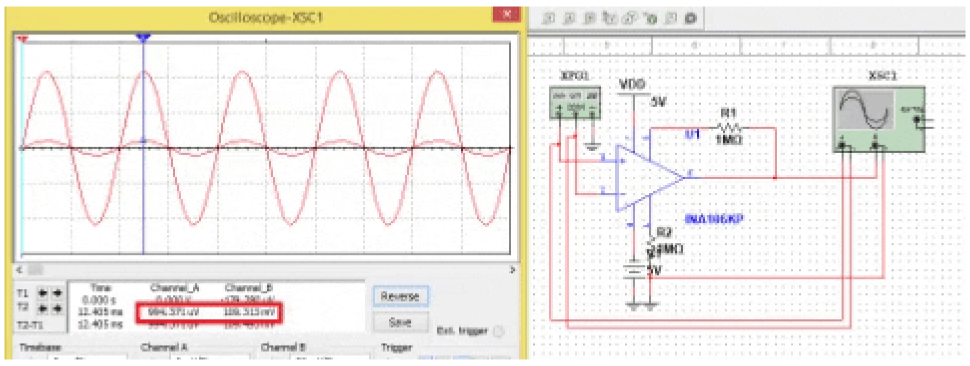
Supply Voltages

We will use +5V and -5V supply voltages for our circuit.

3. SIMULATION

First Stage - Signal acquisition - Subtractor:

The purpose of this stage was amplfying our emg signal. At design part we have set our gain as 110. Lets do the simulation and see the test results:



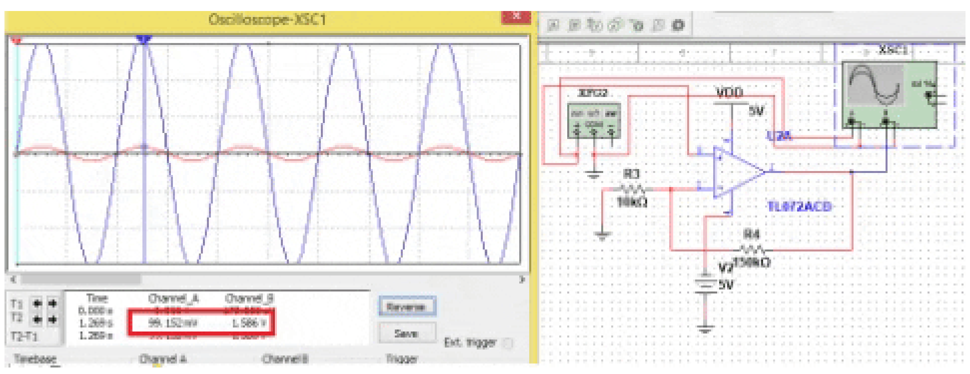
As we can see our simulation results are as expected for first stage.

Second Stage - Non Inverting Amplifier

The purpose for this stage was inverting amplification, and expected gain was 16.

$\rightarrow V_O = \left(1+\frac{R_2}{R_1}\right)V_i = \left(1+\frac{150k\ \Omega}{10k\ \ \Omega}\right)V_i = 16\ V_i$

Lets see the results:

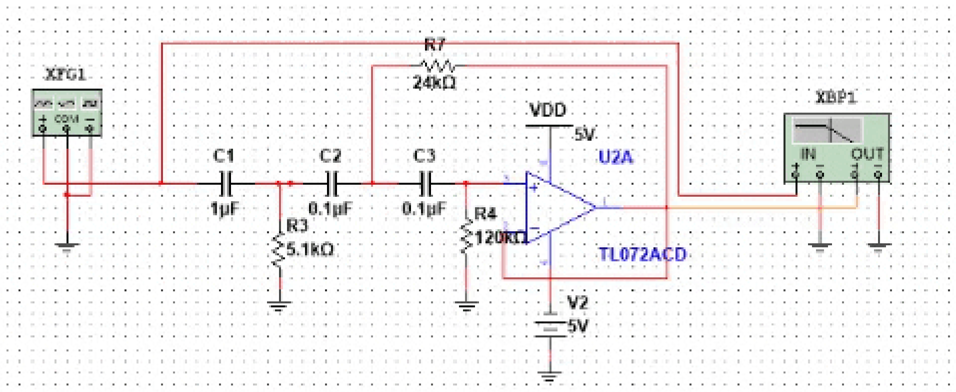


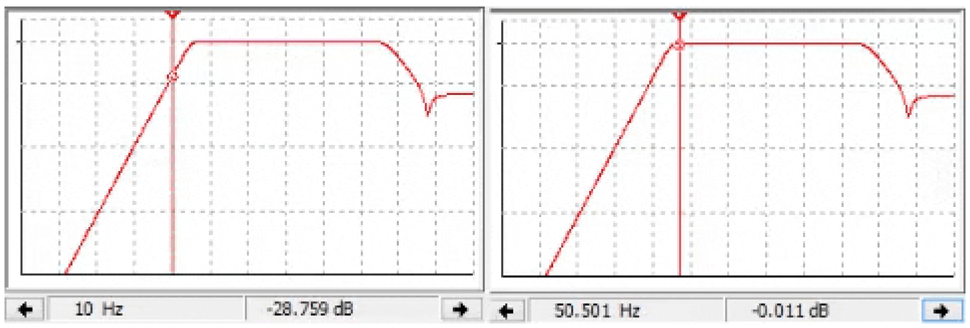
As we can see simulation results for second stage are supporting our design expectations.

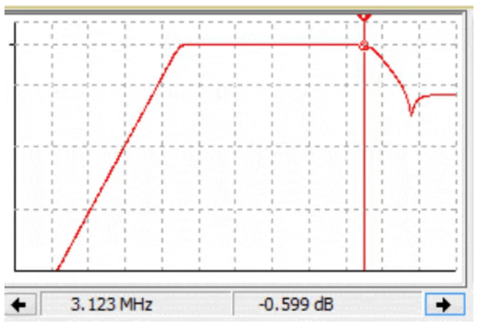
Third Stage - 3th Order Sallen Key High Pass Filter

The purpose of this stage was diminishing signal components with the frequency of 0-10 Hz. As we mentioned before, that portion of the signal contains motion artifact caused by movement at the interface between the detection surface of the electrode and the subject's skin. Also the DC offset potential (0 Hz) is also rejected by the high pass filter.

I already gave simulation bode plots for this stage i will give them again here below.



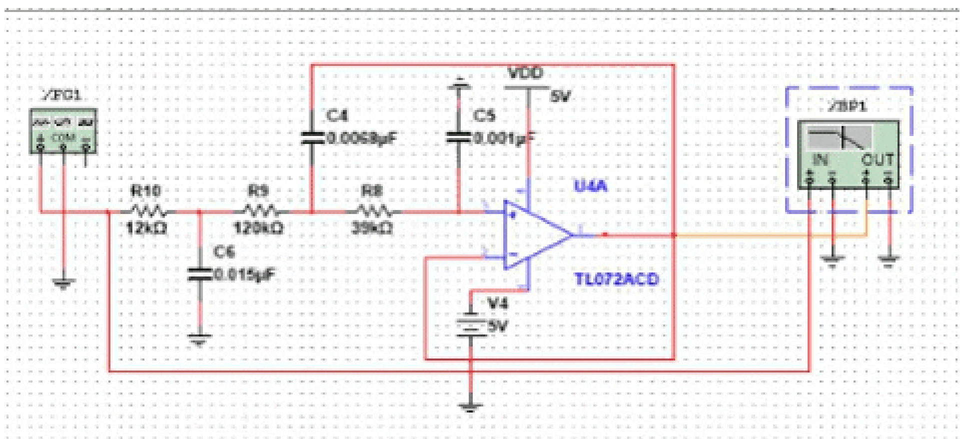




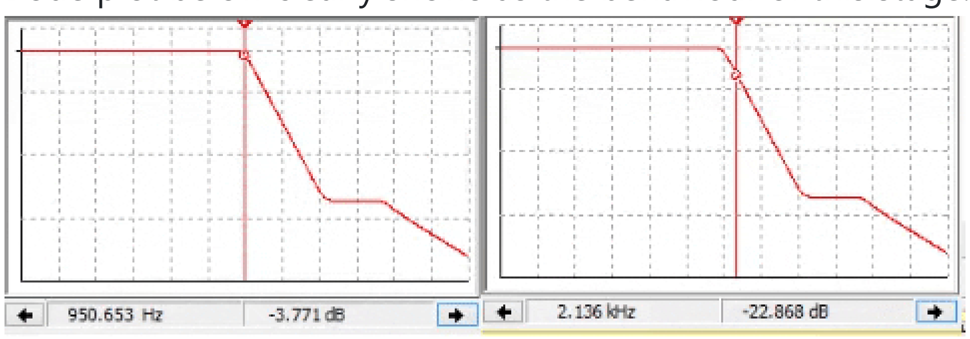
As we can see our filter attenuates signal components under 10Hz. We could have try these results by giving some different frequency inputs and checking outputs but bode plots is already telling us the results.

Fourth Stage - 3th Order Sallen Key Low Pass Filter

Main purpose of this stage was attenuating of our signal components with frequencies bigger than 2000 Hz.

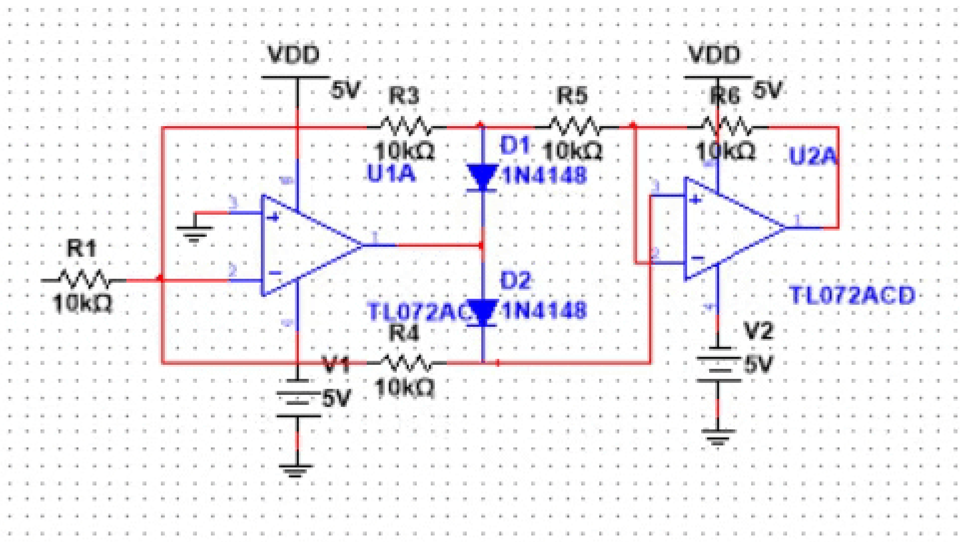


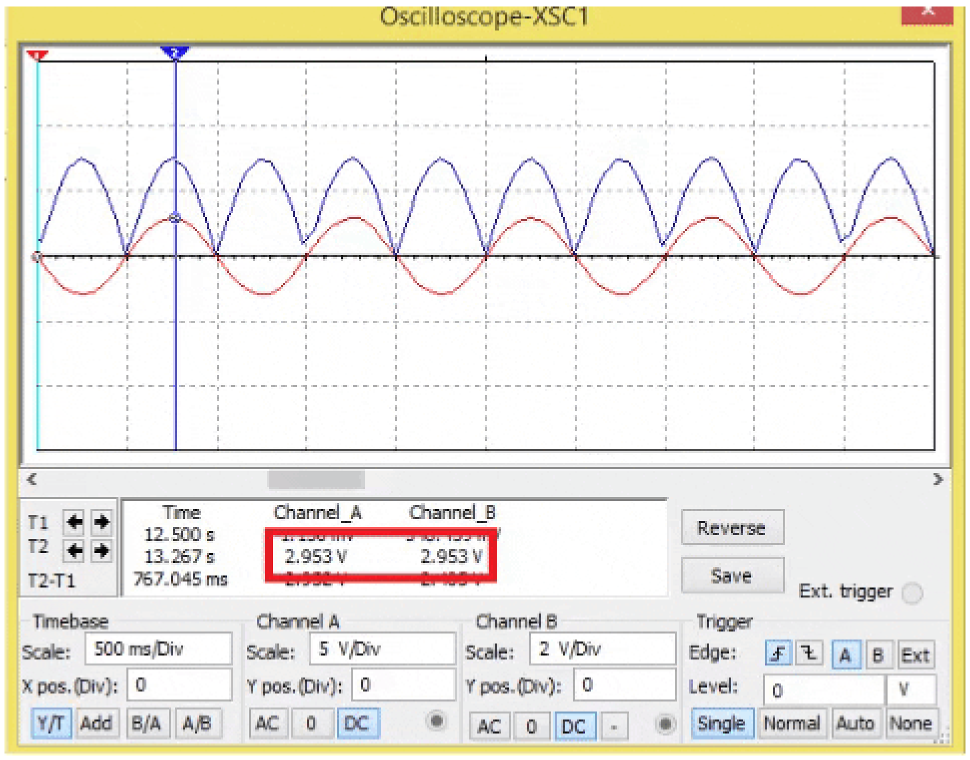
Bode plot below clearly shows us the behaviour of this stage.



As we can see this filter transmits our signal components with frequency lower than 1kHz (Includes our dominant energy interval 0-150 Hz and 500 Hz too) almost without any attenuation. And blocks signal components with frequency higher than 2000 Hz.

Fifth Stage Full Wave Active Rectifier

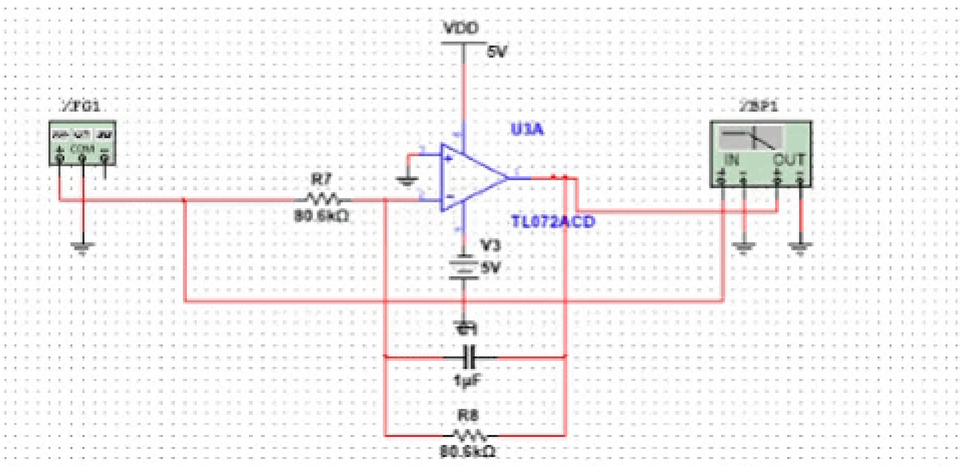


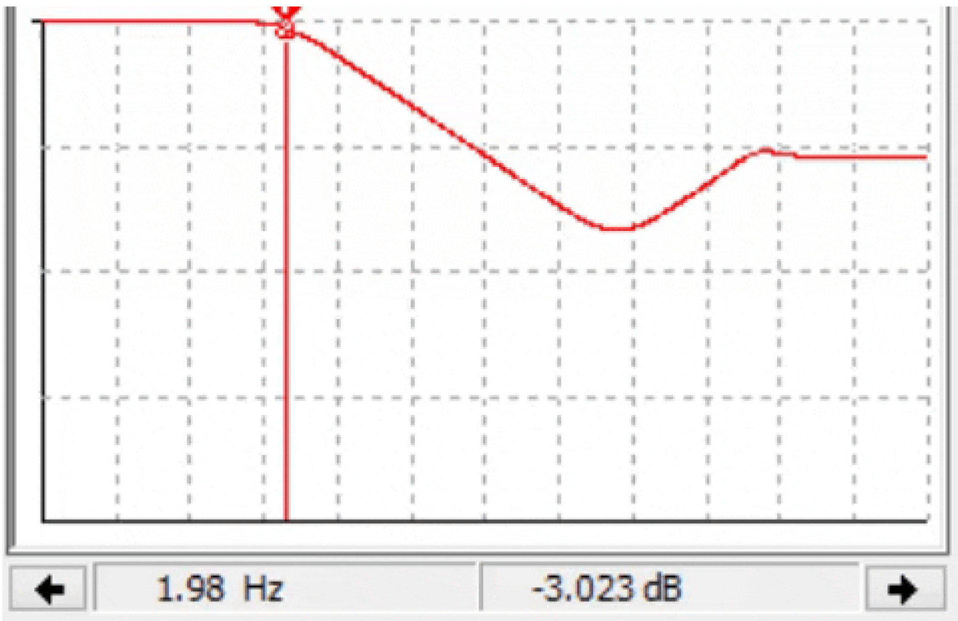


The purpose of this stage is attenuate all most of the ac components in our rectified signal and take an DC output with relatively low ripple.

Sixth Stage - Active Low Pass Filter

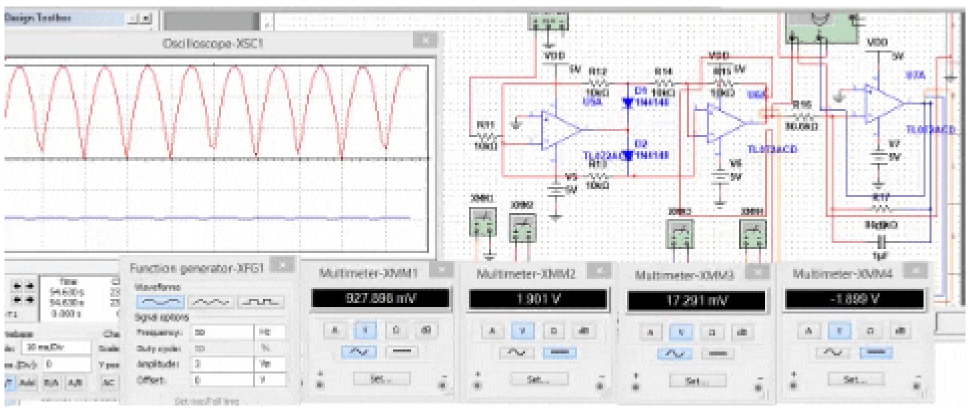
The purpose of this stage is attenuate all most of the ac components in our rectified signal and take an DC output with relatively low ripple.





Fifth and Sixth Stage Together

Result for 3V and 50 Hz sinusoidal input



→ First multimeter shows AC component of output of 5th stage(rectifier). Which should be equal to V_{rms} = 0.308V_m = 0.308 × 3 = 0.924 V ≅ 928 mV close enough!

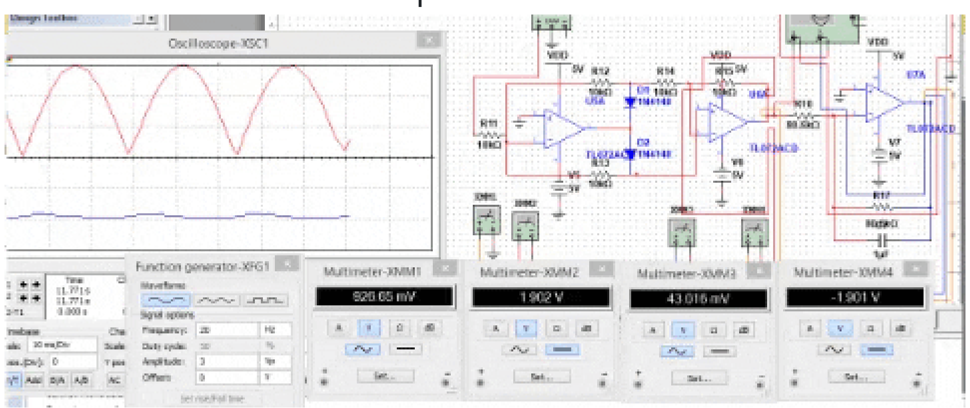
→ Second multimeter shows DC component of output of 5th stage(rectifier). Which should be equal to V_{dc} = 636V_m = 0.636 × 3 = 1.908 V ≃ 1.901 V close enough!

→ Third multimeter shows AC component of output of 6th stage(low pass filter). We can see our filter is filtered most ac component and the rest has only 17 mV magnitude.

→ Fourt multimeter shows DC component of output of 6th stage(low pass filter). We can see our filter is let our DC signal to pass almost without any attenuation and also we can see our DC component is inverted.

→ Our ripple , $r = \frac{V_{rms}}{V_{dc}} \times \%100 = \frac{17.291mV}{-1.899V} \times \%100$ = %0.9 which is really satisfying result for our purpose.

Result for 3V and 20 Hz input:



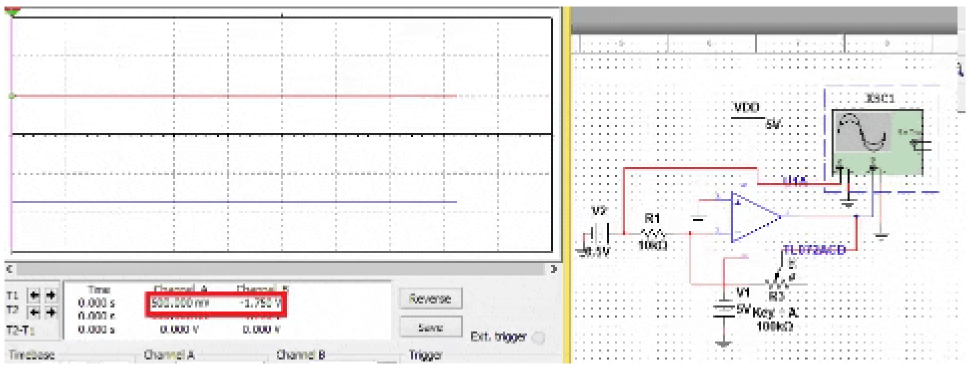
As we can see now our ripple has increased

$$\rightarrow r = \frac{43.06mV}{-1.899V} \times \%100 = \%2.2$$

Which is still enough for our expectation.

Seventh Stage - Inverter Amplifier

I had two purposes for this stage, obtaining a positive output signal and amplifying my output if i needed:

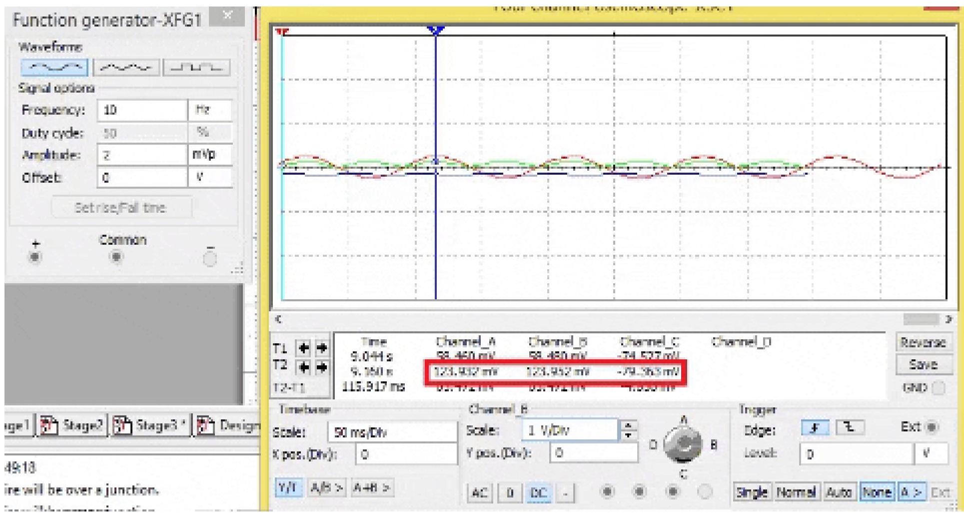


Overall Circuit

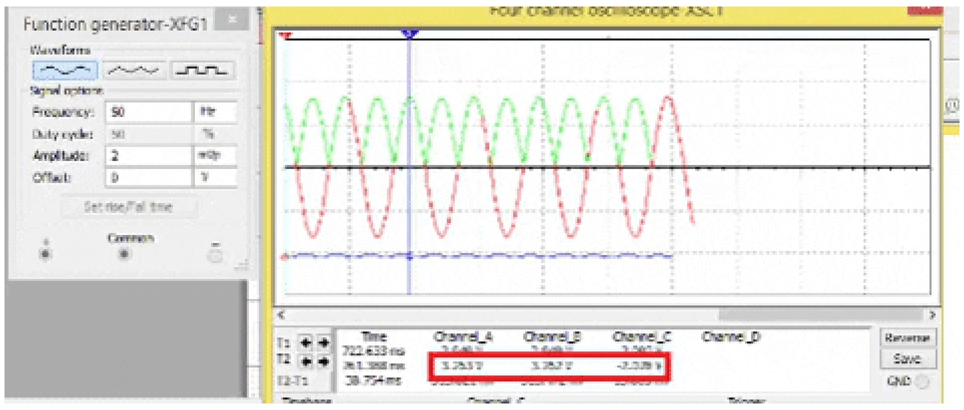
Now i will put combined system (from stage one to 6, last stage inverting amplifier is not involved) simulation results for different frequency inputs:

Red is output of 3rd order low pass filter and input of rectifier stage simply our nonrectified emg signal , Green is outputof rectifier stage, Blue is output of 6th stage (low pass filter) .

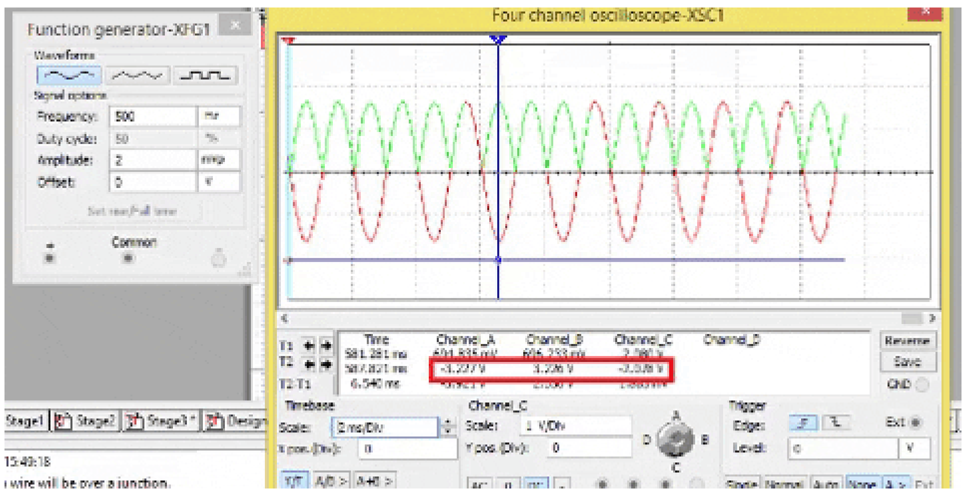
10Hz(In stopband, Attenuated)



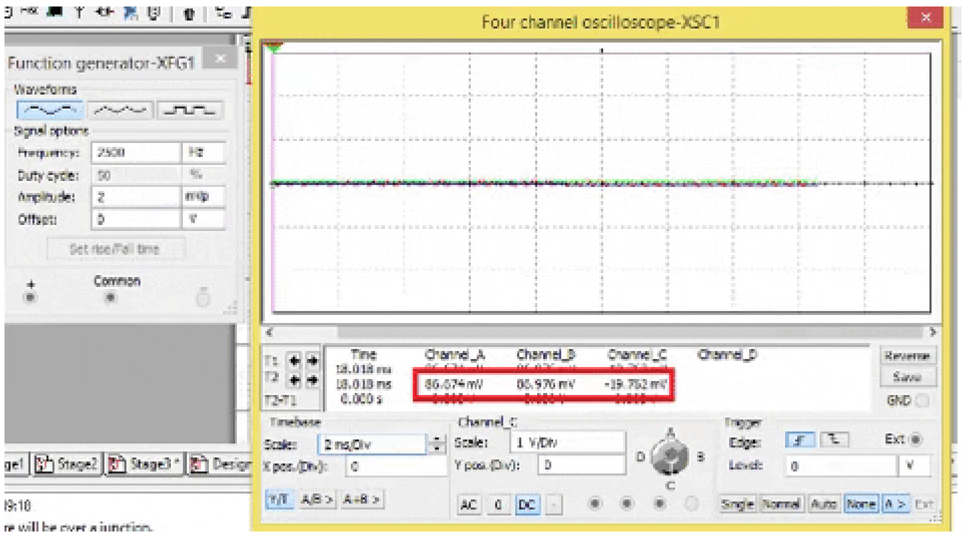
50Hz(In passband, Not Attenuated)



500Hz(In passband, Not Attenuated)



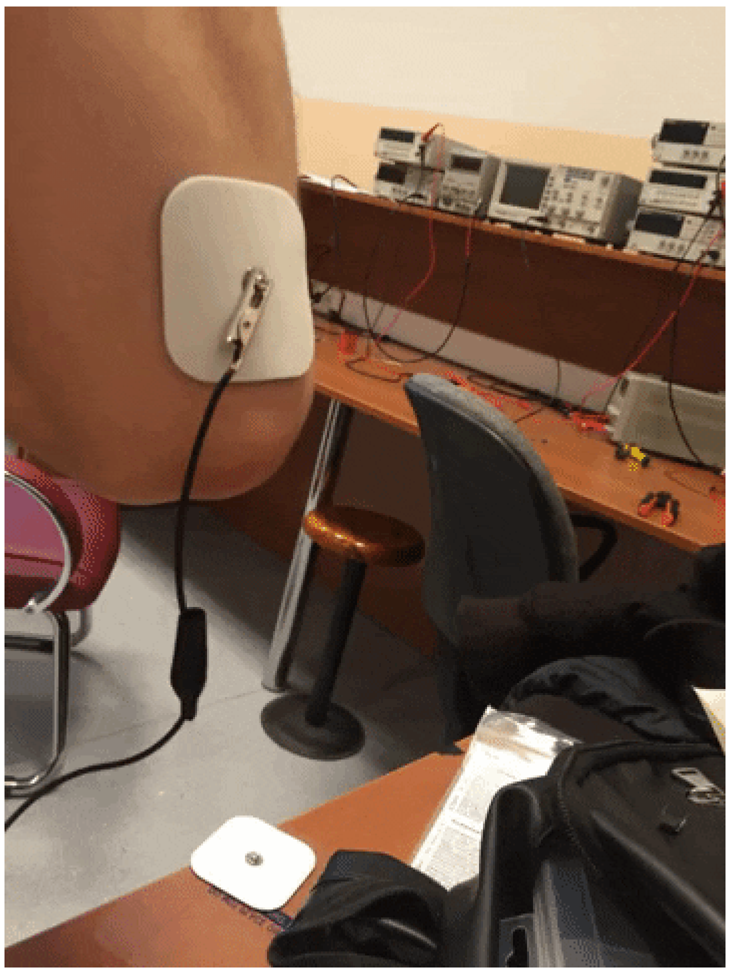
2500Hz(In stopband, Attenuated)



4. IMPLEMENTATION

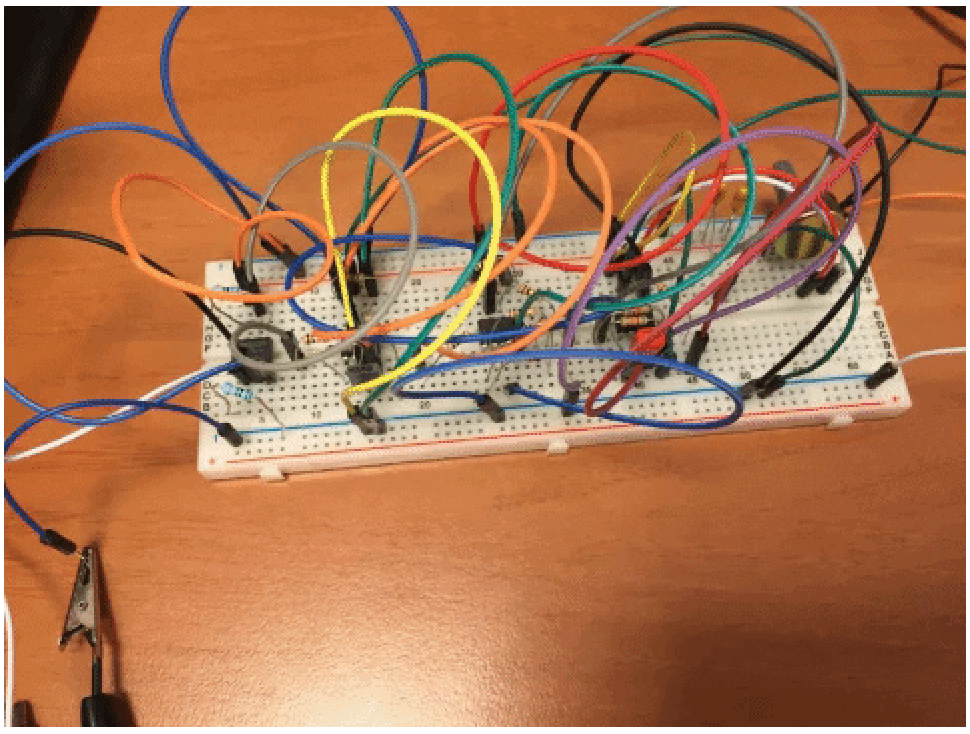
Electrodes

As we mentioned before we have used 3 electrodes; mid muscle, end muscle and reference electrodes



At the first picture above, the electrode on top is mid muscle electrode and other one is end muscle electrode, the last one on the second picture is called reference electrode.

Breadboard



Supplies

+5V and -5V supplies are used.

5. TEST RESULTS

Since I did my simulations by using a function generator signal input. I will do my tests in lab by using function generator signal again. It will give me a chance to compare my simulation and test results at the conclusion part. But of course at the end i will try circuit by connecting electrodes on my muscles.

First Stage - Signal acquisition - Subtractor:

Since the function generators in our lab can give minimum 80mV(rms) input, we used a voltage divider for testing this stage, because our expected gain was 110 and our supply voltages are +5V and -5V. By using voltage divider, we gave 10mV (150Hz) input to our first stage and we get 1.03 V which means approximately 103 gain.

Second Stage - Non Inverting Amplifier

For this stage we gave 200mV (150 Hz) input and we get 2.9V output. Which means 14.5 gain.

Third Stage - 3th Order Sallen Key High Pass Filter

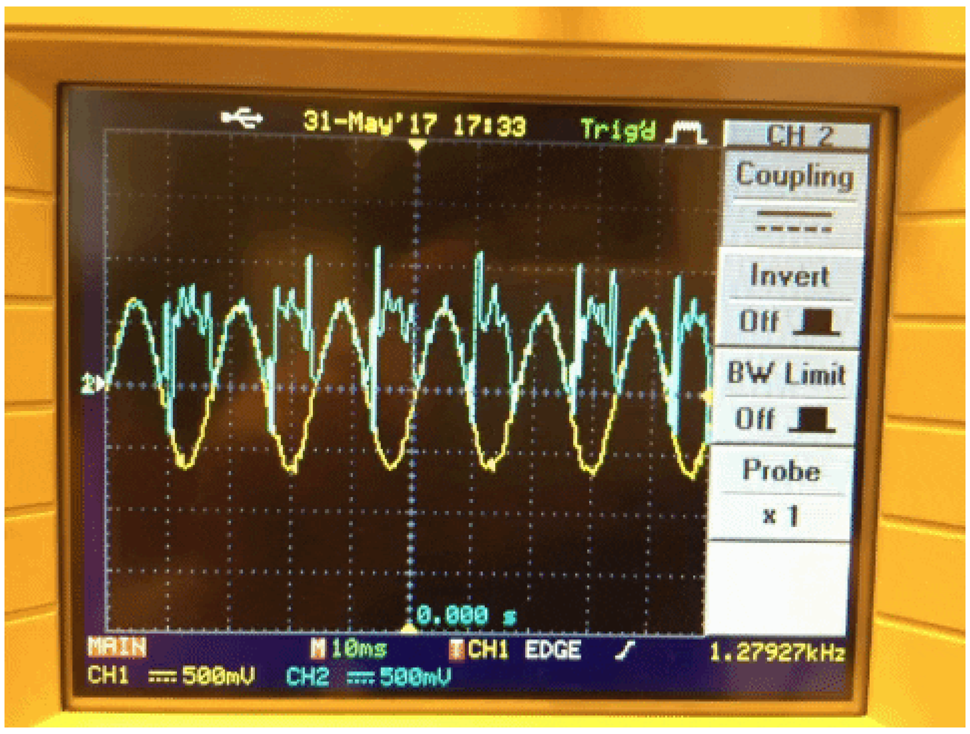
For this stage since we can not plot the bodeplots in lab, we gave 2 different inputs with different frequencies and measured output values.
→ 5Hz: For 3V input, approximately 15mV output.
→ 150Hz: For 3V input, approximately 2.9V output.

Fourth Stage - 3th Order Sallen Key Low Pass Filter

Again for this stage since we can not plot the bodeplots in lab, we gave 3 different inputs with different frequencies and measured output values.
→ 100Hz: For 3V input, approximately 2.9V output.
→ 500Hz: For 3V input, approximately 2.9V output.
→ 2kHz: For 3V input, approximately 300mV output.

Fifth Stage Full Wave Active Rectifier

For 3V(Vp) sinusoidal input, this stage gave us rectified signal with $V_{dc} = 1.7V \quad V_{rms} = 0.8V$



Here we can see rectified signal with some noise on it.

Fifth and Sixth Stage Together

For 3V(50Hz) sinusoidal input:

→AC component of output of 6th stage(low pass filter) is approximatly 30mV

→ DC component of output of 6th stage(low pass filter) is approximatly -1.7V

$$\rightarrow Our\ ripple, r = \frac{V_{rms}}{V_{dc}} \times \%100 = \%1.7$$

For 3V(20Hz) input:

$$\rightarrow r = \frac{100mV}{-1.7V} \times \%100 = \%5.8$$

6. CONCLUSION

Our main objective for this project was designing and implementing a Surface Electromyogram (EMG) Conditioning Circuit.

In our design we considered that most sEMG signals have a frequency content ranging from 0 to 500 Hz, with dominant energy between 50 to 150 Hz. However, content at up to 2000 Hz may be useful. The amplitude of the signal may vary from less than 50 µV up to 30 mV

For making a successful design, we should have eliminated noises from our signal. I will explain briefly how we solved problems below.

There are several types of electrical noise which affect a sEMG signal:

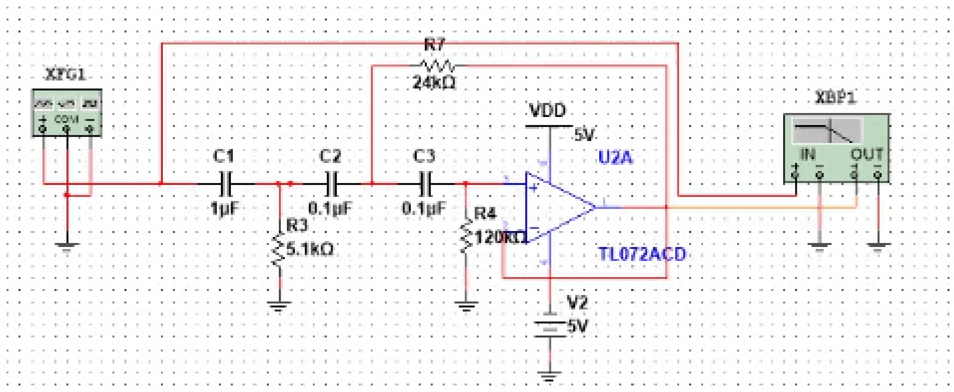
Motion artifact:

This type of noise is caused by the movement at the interface between the detection surface of the electrode and the skin. It generally lies in the 1–10 Hz frequency range and has a voltage comparable to the magnitude of the EMG.

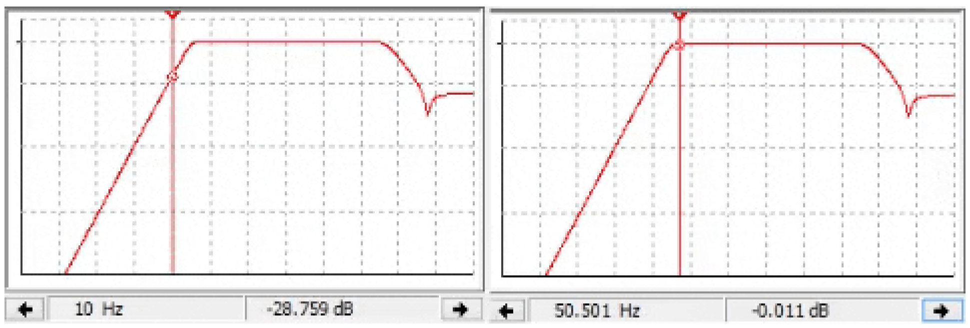
Solution:

- We used a 3th Order Sallen Key High Pass Filter which have f_c = 30 Hz in order to filtering frequencies in the 0–10 Hz range.

Drawing



Bode Results



DC offset potential due to skin and due to opamps:

Oil secretions and dead skin cells increase impedance on the outermost layer of the skin, which cause DC voltage potential generation during skin and electrode contact of up to 200–300 mV. And as we know in real life opamps has DC offset potentials due to input offset voltage and input current differences.

Solution:

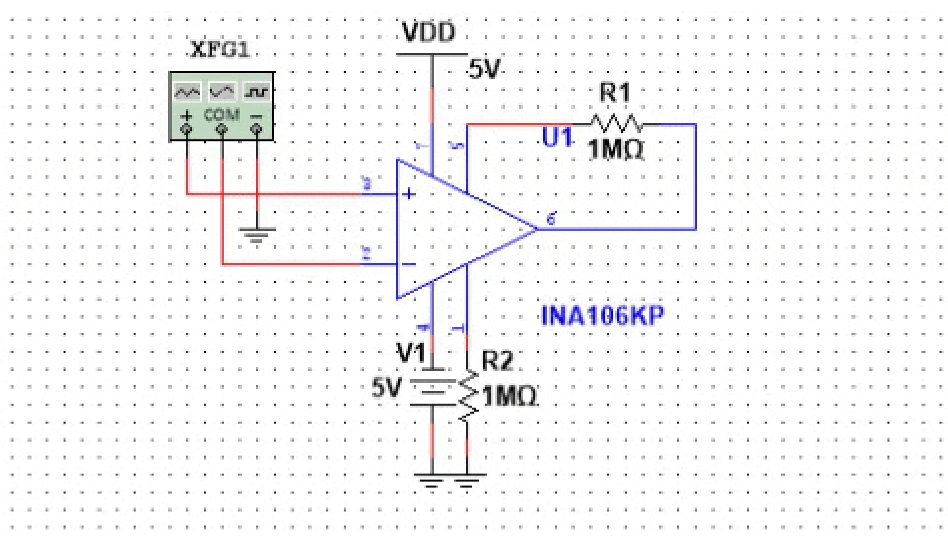
- Again we used a 3th Order Sallen Key High Pass Filter which have fcf_c = 30 Hz in order to filtering frequencies in the 0–10 Hz range.

Ambient noise:

Ambient noise lies in a wide range of frequencies but its dominant component is 50 Hz or 60 Hz which is the most common source of electrical noise in the EMG signal and corresponds to power line noise. Such noise results in a signal whose voltage can be larger than the EMG signal itself.

Solution:

- We used a high quality differential amplifier (INA106KP IC, has high Common-Mode Rejection ,86dB min) with a high CMMR in order to help attenuate this type of noise for this stage. So our differential amplifier amplified the difference signal and attenuate much of the common signal.



Body's neutral noise.

We used an extra reference electrode in order to get rid of this neutral noise. Reference electrode is usually connected to bone region away from muscles.The purpose of this electrode is measuring the body's own idle signal. Device will first do the difference amplification operation by using Mid-Muscle and End-Muscle electrode signals.Then filtering and rectification operations and finally. Output signal will be subtracted from the body's neutral signal by this way we will get rid of the body's own noise.

Comparing Simulation Results with Test Results

First Stage - Signal acquisition - Subtractor:

→ Simulation 110 Gain - Test 103 Gain
→ %6.36 error.
→ Considering %10 tolerance of circuit components, %6.36 error is quite acceptable.

Second Stage - Non Inverting Amplifier

→ Simulation 16 Gain - Test 14.5 Gain
→ %9.34 error.

→ Considering %10 tolerance of circuit components, %9.34 error is quite acceptable.

Third Stage - 3th Order Sallen Key High Pass Filter

Test Results

→ 5Hz: -20log(15mV/3V) = -46 dB
→ 150Hz: -20log(2.9V/3V) = -0.26 dB

Simulation

→ 5Hz corresponds -44 dB
→ 150Hz corresponds 0.018 dB

As we can see test and simulation results are pretty close.

Fourth Stage - 3th Order Sallen Key Low Pass Filter

Test Results

→ 100Hz: -20log(2.9V/3V) = -0.26 dB
→ 500Hz: -20log(2.9V/3V) = -0.26 dB
→ 2kHz: -20log(300mV/3V) = -20 dB

Simulation

→ 100Hz: -20log(2.9V/3V) = 0.006 dB
→ 500Hz: -20log(2.9V/3V) = 0.006 dB
→ 2kHz: -20log(300mV/3V) = -23 dB

As we can see test and simulation results are pretty close.

Fifth and Sixth Stage Full Wave Active Rectifier - Active Low Pass Filter

For 3V(Vp) sinusoidal input

For 3V(Vp) sinusoidal input

Output of stage 5:

Simulation: $V_{dc} = 1.908\text{ V}$ $V_{dc} = 1.7\text{V}$
Simulation: $V_{rms} = 0.924\text{ V}$ $V_{rms} = 0.8\text{V}$

For 3V(50Hz) sinusoidal input:

Output of stage 6 Test Results

→ AC component of output of 6th stage(low pass filter) is approximatly 30mV

→ DC component of output of 6th stage(low pass filter) is approximatly -1.7V

→ Our ripple ,

$r = \frac{V_{rms}}{V_{dc}} \times \%100 = \%1.7$

Output of stage 6 Simulation

→ AC component of output of 6th stage(low pass filter) is 17 mV

→ DC component of output of 6th stage(low pass filter) is -1.899V

→ Our ripple

$r = \frac{V_{rms}}{V_{dc}} \times \%100 = \%0.9$

For 3V(20Hz) input:

Test Results
$\rightarrow r = \frac{100mV}{-1.7V} \times \%100 = \%5.8.$

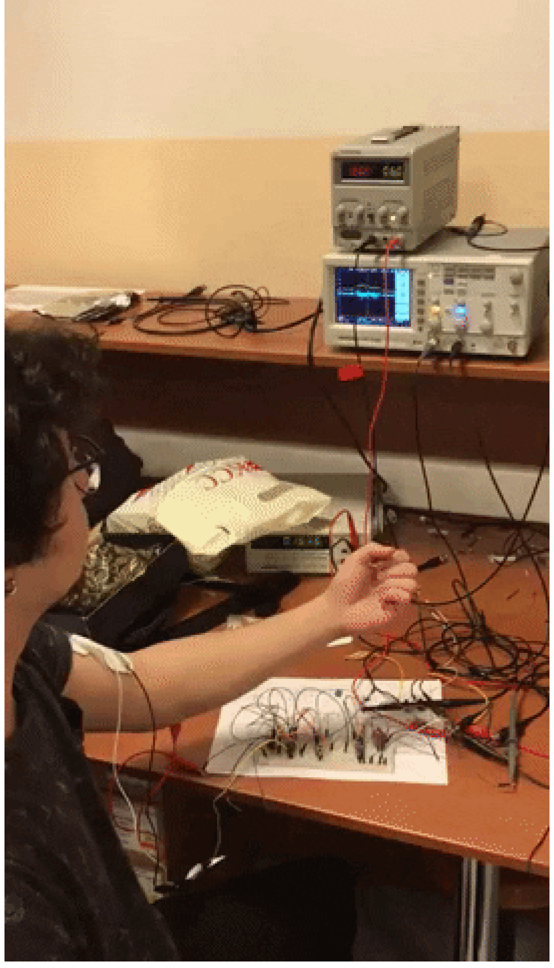
Simulation
$\rightarrow r = \frac{43.06mV}{-1.899V} \times \%100 = \%2.2$

Overall Circuit

→ Since I used a potentiometer in circuit it is not right to compare overall results numerically but as working logic, we can say it is working as expected.

→ Thus according to comparison results above we can say our design and test results are mostly compatible.

7. APPLICATION



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