Sensing and Measurement Final Project

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***Abstract*— This project is about Measuring the grip of a metal glass using index and thumb fingers by piezoelectric sensors for each of these two fingers and surface electromyograms with two electrodes in the forearm muscle. In this project, the design and simulation of a combined processing circuit for analyzing the signals obtained from the measurements is also examined. The designed circuit contains low-pass and high-pass filters for filtering noise and distortions, which might have external source or caused by measurement mistakes, and an instrumentation amplifier to amplify the filtered signal to a level that can be processed. At the end, abnormal signal conditions are discussed and some solutions are provided.**

This project is about measuring the grip of a metal cup using the index and thumb fingers with a piezoelectric sensor for each of these two fingers and a two-electrode surface electromyogram on the forearm muscles. This project addresses an important topic in the field of biological sciences and biomedical engineering. Utilizing piezoelectric sensors and surface electromyography as precise tools for measuring mechanical forces and electrical activity of muscles can be very useful in biological and medical research and can improve our understanding of muscle function and internal body forces.

These methods can be used in diagnosing muscular and neurological diseases, designing implants and prostheses, and improving the quality of physiotherapy and rehabilitation processes. These methods are also applied in analyzing athlete performance, enhancing training methods, and measuring and monitoring muscle performance in professional sports.

An example of this system is a glove that measures hand forces and muscular activity. This glove has multiple piezoelectric sensors to measure mechanical forces in the fingers and a two-electrode surface electromyogram to measure electrical activity in the forearm muscles, and it supports wireless connectivity to computers or smart devices. This glove is used in medical and rehabilitation research, diagnosing and monitoring muscular and neurological diseases, improving sports performance, and motion analysis.

Next, we will design and simulate signals from the electromyogram and piezoelectric sensors, and for processing these signals, we will design and simulate a preprocessing circuit that includes a filter and amplifier tailored to the characteristics of the desired signal, with the ability to remove noise and interferences in the signal.

The following report provides details on the design and simulation processes of the signals and components mentioned, and includes images of all designs and outputs.

I. Project Background

A. Signal Specifications

A piezoelectric sensor will generate an electrical signal proportional to the force applied by the thumb and index finger on the glass (often in the range of 0-100 N). Piezoelectric sensors can have a broad frequency range (typically 1-1000 Hz).

The EMG signals are a representation of the electrical activity of the muscles in the forearm, specifically those involved in controlling the thumb and index finger. Typically, EMG signals lie within a frequency range of 10 Hz to 500 Hz, with most of the relevant muscle activity occurring between 20 Hz and 500 Hz. The amplitude of EMG signals varies depending on the intensity of muscle activity. In general, surface EMG signal amplitudes can range from microvolts (μV) to millivolts (mV). Low-level contractions may have signals in the range of 10-100 μV, while maximal voluntary contractions (MVC) can exceed 500 μV or more

B. Analog Circuit Specifcations

Piezoelectric Circuit:

- Amplifier: The output of the piezoelectric sensor is typically very small and requires amplification. So, we need a low-noise, high-precision op-amp with low input bias current.
- Low-pass Filter: After amplification, the piezoelectric signal may have high-frequency noise. A low-pass filter with a cutoff frequency of about 1-2 kHz can help to remove unwanted noise while maintaining the force-related signal.

EMG Circuit**:**

- Amplifier: The surface electromyogram signal is typically in the range of microvolts. So, an amplifier is needed to amplifies the differential signal between the two electrodes placed over the muscle.
- Band-pass Filter: The EMG signal often contains low-frequency noise (e.g., from motion artifacts). So, a band-pass filter is proper for isolating the relevant frequency range of the EMG signal.
- Rectifier: To track muscle activity, the raw EMG signal is often rectified (absolute value) and then processed to extract the envelope, which represents the muscle's overall activity over time. A precision rectifier circuit (often with an op-amp) is used for rectification, followed by a low-pass filter with a cut-

off frequency of about 2-10 Hz, to smooth the signal and obtain a representation of muscle activation.

Other Requirements**:**

- Buffer: It’s common to use buffer between the stages to prevent the load from affecting the signal.
- dual power supply: The amplifiers will require a dual power supply (±5V or ±12V) to ensure that both positive and negative parts of the signal are captured.
- Analog-to-Digital Convertor (ADC): For digital processing, the analog signals from the piezoelectric sensor and EMG electrodes must be converted to digital form. The principles of an ADC, include sampling, holding, and signal processing using operational amplifiers and switches. 12-bit to 16-bit ADCs are commonly used for this purpose to ensure that the signals are captured with sufficient resolution.
- Digital Isolator:
    - Optocoupler-Based Digital Isolator: This is the most common isolator in older circuits. Its inner circuit consists of LED for converting digital signal into light, Photodetector (Phototransistor or Photodiode + Amplifier) which Detects light and converts it back to an electrical signal and Pull-up Resistor in order to Ensure proper logic levels. When input is HIGH, LED turns ON, activating the phototransistor and pulling the output LOW. When input is LOW, LED turns OFF, phototransistor is OFF, and pull-up resistor pulls output HIGH.
    - Transformer-Based Digital Isolator: These are used for high-speed signal isolation and power transfer. Their inner circuit components are Pulse Transformer, CMOS Driver Circuit which shapes the signal into sharp pulses and Schmitt Trigger for cleaning up the received signal.
    - Capacitive-Based Digital Isolator: These use high-speed capacitors to transfer signals via an electric field. Their inner circuit consists of Coupling Capacitors for Transfer high-frequency digital pulses, Modulation Circuit which Converts slow signals into high-frequency pulses, Demodulation Circuit which Recovers the original digital signal and CMOS Logic Gates which Shapes the output signal.

C. *Common Methods of Design Similar Items*

- Piezoelectric sensors output a small charge proportional to the applied force, which needs to be converted into a voltage. A typical approach involves using operational amplifiers (op-amps) to convert the charge into a voltage, with a feedback capacitor to define the sensor's sensitivity.
- To measure the weak EMG signals from the muscles, We can use an instrumentation amplifier which has high common-mode rejection ratio (CMRR) to reject noise from other sources and low noise amplification. The gain is usually set in the range of 1000x to 2000x for adequate amplification of EMG signals, which typically range from 10 µV to 500 µV in muscle contractions.
- Low-pass filters are implemented either as an active filter using op-amps or with simple RC circuits.
- The band-pass filter can be realized using active filters (e.g., using op-amps) with specified cutoff frequencies or by cascading a low-pass and a high-pass filter implemented with simple RC circuits.

D. *Challenges and Points of Signal Registration and Design Process*

- Low Signal Amplitude: Both piezoelectric sensors and EMG signals are typically very weak, often in the microvolt range for EMG and in mV/N for piezoelectric sensors.
- Noise: Piezoelectric and EMG signals can be easily corrupted by motion artifacts and mechanical vibrations, respectively.
- For accurate muscle activity measurements, EMG electrodes must be placed precisely on the muscle belly. Misplacement of electrodes can lead to poor signal quality or even no signal if they are placed over a tendon or too far from the muscle.
- Both piezoelectric sensors and EMG systems need to be properly calibrated to provide accurate and reproducible measurements. Calibration often depends on factors such as the user's muscle characteristics or hand strength.
- Amplification : Amplifiers must have high precision because Insufficient gain or nonlinear amplification may distort the signal.
- Power line interference (50 Hz or 60 Hz) can contaminate both types of signals.
- Temperature and Humidity Sensitivity**:** Piezoelectric sensors are sensitive to temperature fluctuations, which can cause drifts in the output.
- Electrode Impedance**:** EMG electrode impedance may vary with skin moisture or sweat, leading to unstable signals.

II. Designing and Simulation

A. *Signals Simulation*

The piezoelectric signal is considered as a sinusoidal signal with variable amplitude and frequency, and the electromyogram signal is considered as a combination of two sinusoidal signals that represent rest time and activity time, so that 3 seconds for rest and 7 seconds for activity is considered.

In order to simulate noise, a Gaussian White noise is added to the piezoelectric signal. A non-linear distortion is also added to the piezoelectric signal by adding the cube of the signal to it. This process has been done for the EMG signal with the difference that the distortion is simulated by adding the adding the square if the signal to it.

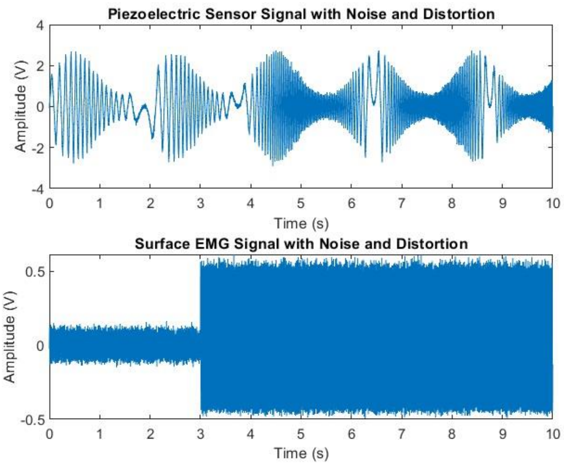
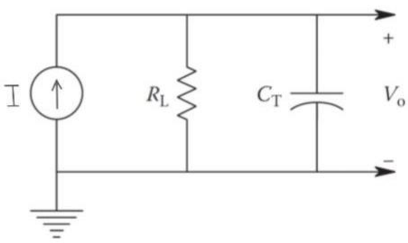


Figure 1: Simulated Signals with Noise and Distortion

B. Circuit Design and Simulation

- Since the generated signals are .txt files, we use PWL (Piecewise Linear) sources to apply them to the circuit. The measurement is done with two electrodes and two piezoelectric sensors. So, for each circuit two sources are needed.
- For the EMG circuit, two voltage sources are used, which the generated electrode signals are applied to them.
- The electrical equivalent circuit of a piezoelectric sensor is as below:



Each Piezoelectric signal is applied to a current source so, for each piezoelectric signal we should have a separated circuit. Since the circuits are similar, for simplicity just one is simulated.

- After each voltage source in the EMG circuit and after the equivalent circuit in piezoelectric circuit, the related filter is placed to filter the noises. The filters are simulated using simple RC circuits. For the band-pass filter, a low-pass and high-pass filter are cascaded with a buffer between them in order to prevent the load from affecting the signal.
- For amplification, we use instrumentation amplifier which has high CMRR and low noise amplification. There are several instrumentation amplifier ICs, but we used three LT1014 op-amps to model it.
- Two voltage sources with DC value of ±15v are used as the power supplies of the amplifiers.
- For the EMG circuit, Another filter is used after the amplifier to filter the amplification noise and eliminate the DC offset.
- Digital Isolator:
- Analog to Digital Converter:
  - Voltage Sources: We use two DC voltage sources (5v), a source as sine wave generator, a source as pulse generator and a reference voltage source (3v).
  - Switches: The switches have an on resistance of 1 ohm, off resistance of 1 megaohm, threshold voltage of 0.5v, and hysteresis voltage of -0.4v.
  - Operational Amplifiers
    - A_1: Sample-and-hold function, controlled by the pulse generator V_5.
    - A_2: An inverter.
    - U_1, U_2, U_3: LT1001 Operational amplifiers, powered by V_{cc}.
  - Resistors
  - Clock Source: Providing 5v.
  - Operation: The sine wave from V_3 is sampled by the sample-and-hold amplifier A_1, controlled by the pulse generator V_5. The sampled signal is then processed by operational amplifiers U_1, U_2, and U_3, which simulate the ADC process. Switches S_1, S_2, S_3, and S_4 route the sampled signal through the circuit, controlled by the clock and other signals. Resistors R_1 to R_6 form part of the feedback and signal conditioning network for the operational amplifiers.

C. Software Introduction

The signals are simulated using MATLAB.

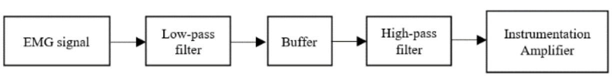
MATLAB is a high-level programming language used by scientists and engineers, designed for numerical computation, data analysis, visualization, and programming. Unlike most programming languages, MATLAB operates primarily on matrices and arrays, simplifying operations like linear algebra calculations. It also offers extensive plotting and graphical capabilities for data visualization in 2D and 3D.

The Analog circuit is simulated using LTspice.

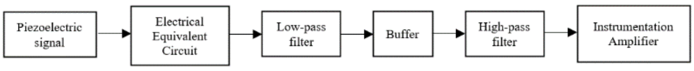
LTspice is a free circuit simulation tool that allows users to model, analyze, and simulate electronic circuits. It's used by engineers in many fields, including power electronics, audio electronics, and digital electronics. It has many features such as various types of analysis (nonlinear DC, nonlinear transient, and linear small-signal AC circuit analysis), noise simulation and Calculating the heat dissipation of components.

D. Circuit Block Diagram

- EMG circuit:



- Piezoelectric circuit:



E. *Designing Calculations*

- Low-pass filter:

$$f_{LP} = 200\ Hz = \frac{1}{2\pi RC} \rightarrow R = 20k\Omega\,, C = 41nF$$

- High-pass filter:

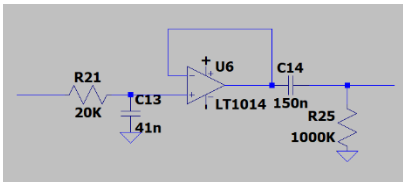
$$f_{HP} = 1\text{Hz} = \frac{1}{2\pi RC} \rightarrow R = 1000k\Omega\,, C = 150nF$$

- Instrumentation amplifier:

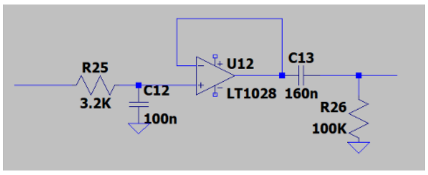
$$Gain = \left(1 + \frac{2R_2}{R_1}\right)\frac{R_4}{R_3} = \left(1 + \frac{2 \times 10k}{2.22k}\right)\frac{10k}{10k} \approx 20$$

F. *Circuit Sections Separately:*

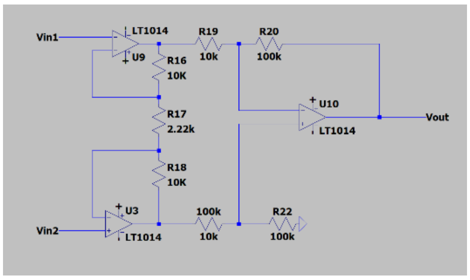
- Low-pass filter, Buffer, High-pass filter:
  - Piezoelectric:



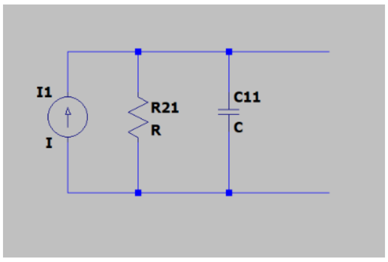
  - EMG:



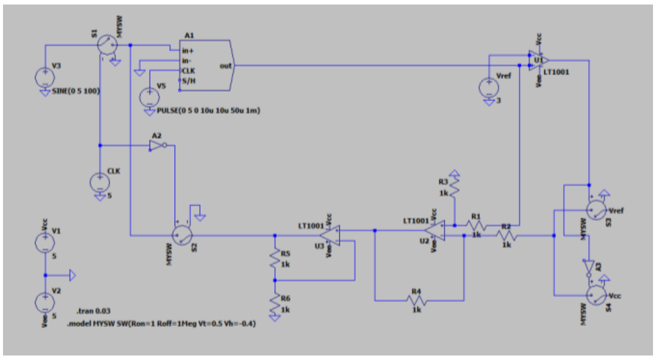
- Instrumentation amplifier:



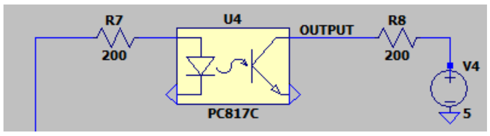
- Electrical Equivalent circuit of the Piezoelectric sensor:



- Analog to Digital Converter:

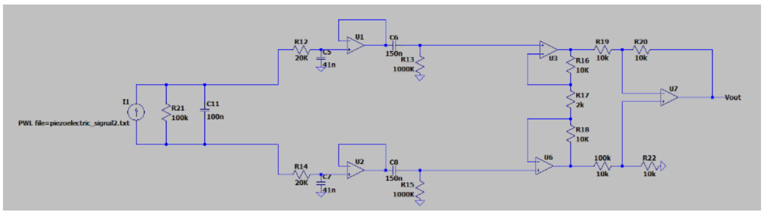


- Digital Isolator:

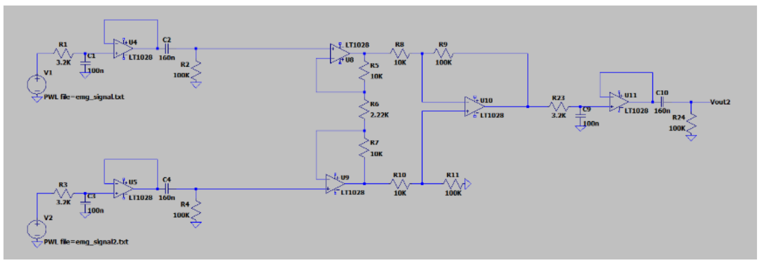


G. *Complete Designed Circuit:*

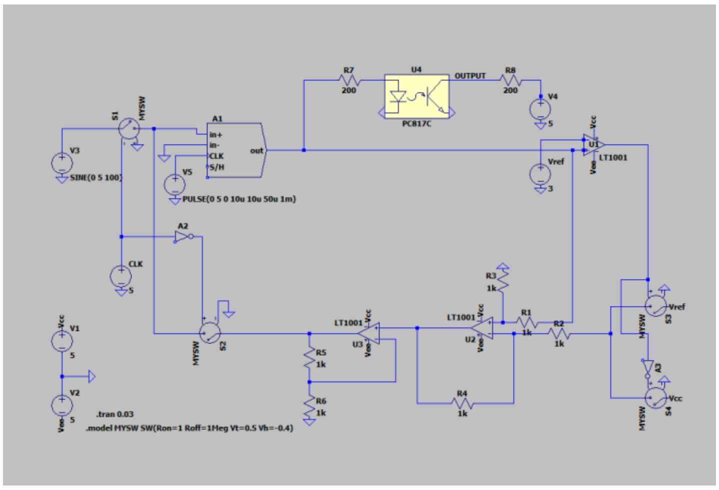
- Piezoelectric Circuit:



- EMG circuit:



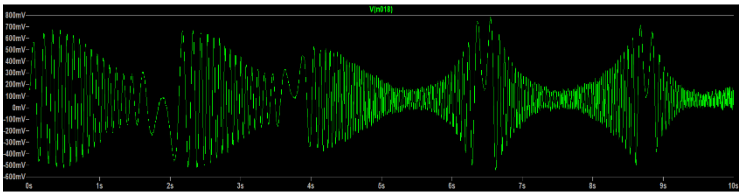
- ADC and Digital Isolator



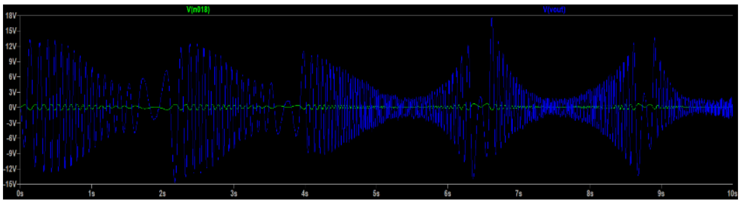
III. SIMULATION RESULTS

A. *Piezoelectric Circuit*

- Input signal

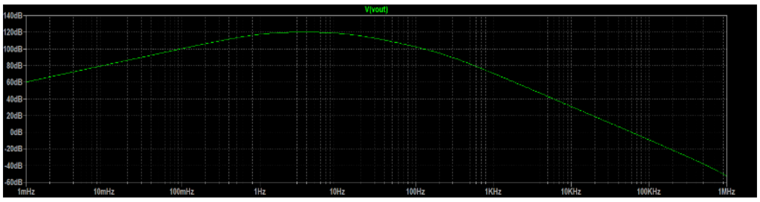


- Output signal:

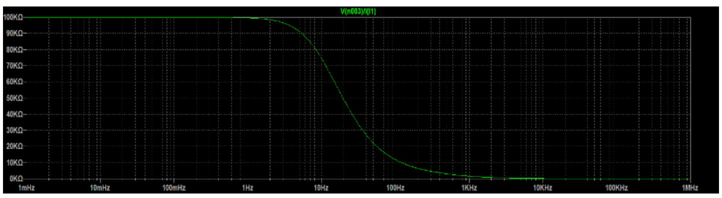


- $Gain = \frac{12v}{600mv} = 20$

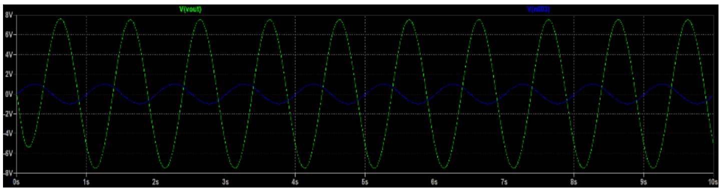
- Frequency response of the whole circuit:



- $R_{in} = 100K\Omega$

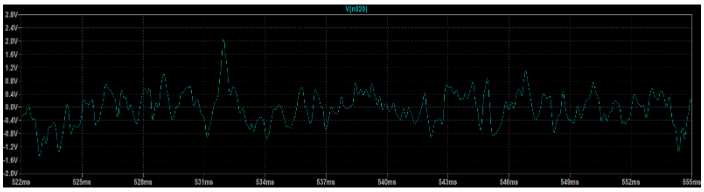


- Common Mode Rejecion Ratio:



$$CMRR = 20\log\left(\frac{1}{7.7}\right) = -17.73\ dB$$

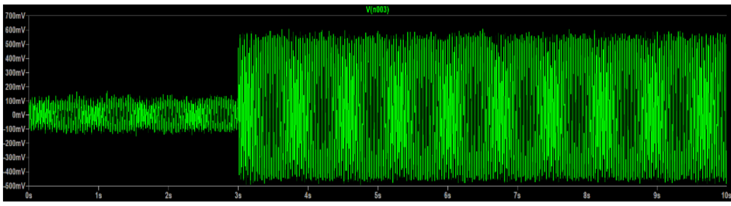
- Signal to Noise Ratio:



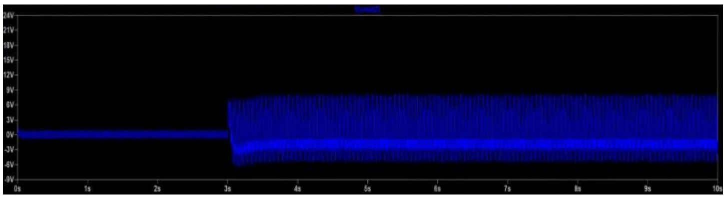
$$SNR = \frac{4}{2.4} = 1.6$$

B. *EMG Circuit*

- Input signal:

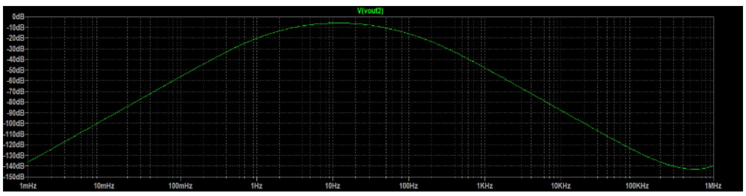


- Output signal:

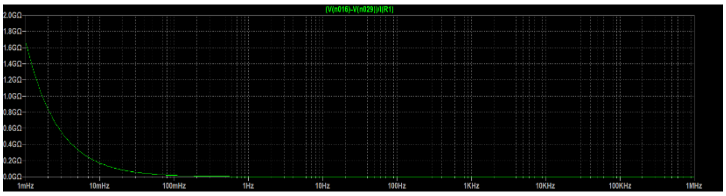


- $Gain = \frac{7v}{700mv} = 10$

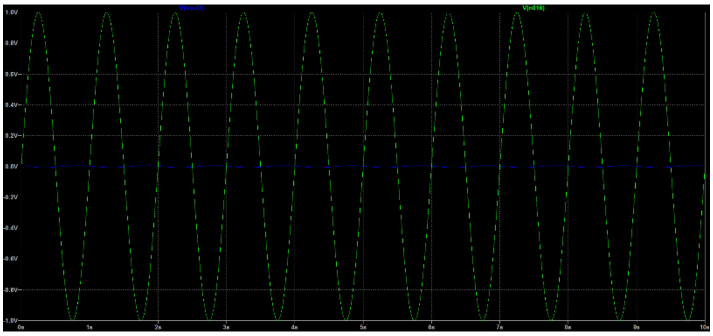
- Frequency response of the whole circuit:



- $R_{in} = 1.6G\Omega$

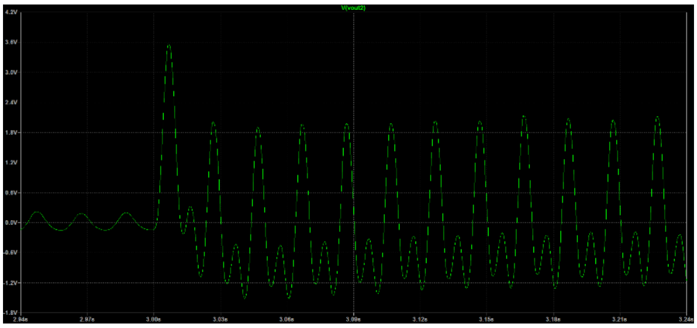


- Common Mode Rejection Ratio:



$$CMRR = 20 \log\left(\frac{6 \times 10^{-3}}{1}\right) = -44.44\ dB$$

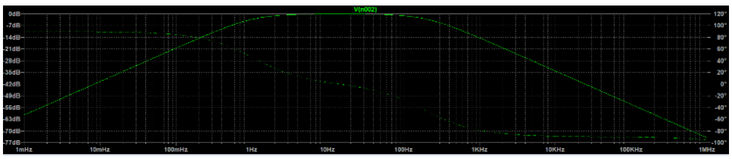
- Signal to Noise Ratio:



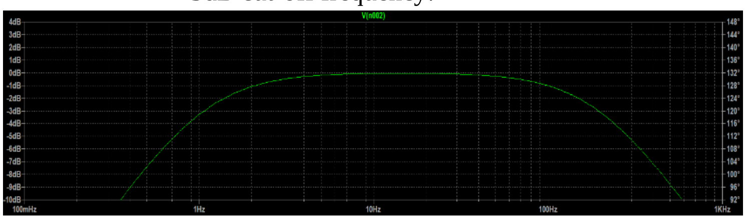
$$SNR = \frac{3.5}{3} = 1.17$$

C. Filter

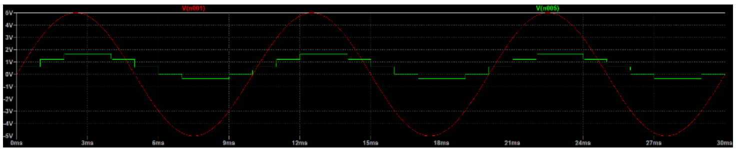
- Bandwidth: 10-200 Hz



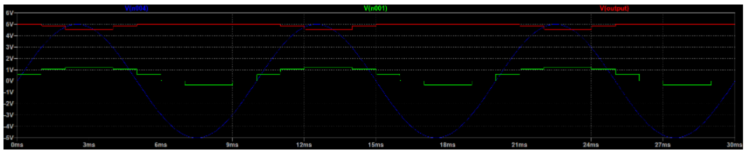
- -3dB cut-off frequency:



D. ADC



E. Digital Isolator



IV. ABNORMAL SIGNAL CONDITIONS AND FACTORS

A. Noise and External Factors

B. Measurement Conditions

- Electrode Placement: Incorrect positioning of electrodes can result in poor signal quality or cross-talk from adjacent muscles.
- Sensor Placement: Incorrect placement or loose attachment of the sensor can lead to inconsistent readings.
- Electrode Contact: Poor contact between the electrodes and the skin can lead to signal loss or noise.
- Muscle Fatigue: As the muscle fatigues, the EMG signal characteristics can change, affecting the measurement.

V. HARDWARE SOLUTIONS FOR ABNORMAL CONDITIONS

A. Noise and External Factors

- Use 50Hz Notch filter for power line
- Use Low-pass filter for eliminating high frequency mechanical vibrations
- Ensure that electrodes placement are correct and stable in order to reduce sudden movements.

B. Measurement Conditions

- Implementing self-calibration mechanism to adjust the changes in the cup holding position
- Use differential signal processing to compensate for changes in skin electrical conductivity
- Use Real-time monitoring in order to detect the process of muscle fatigue

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