PIEZOELETRIC SENSOR SIGNAL PROCESSING DESIGN AND APPLICATION FOR WEARABLE DEVICE

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PIEZOELECTRIC SENSOR SIGNAL PROCESSING DESIGN AND APPLICATION FOR WEARABLE DEVICE

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

Faculty of Electronic and Computer Engineering
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DECLARATION

I declare that this report entitled “Piezoelectric Sensor Signal Processing Design and Application for Wearable Device” is the result of my own work except for quotes as cited in the references.

Signature :

Author : … FONG YAN KEI………..

Date : ………23 Jun 2020……………

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with Honours.

Signature :

Supervisor Name : Assoc. Prof. Dr. Kok Swee Leong

Date : 1/7/2020

DEDICATION

Dedicated to my beloved family.

ABSTRACT

Piezoelectric sensor is an active sensor that has the potential to analyze the performance of skeletal muscle. It can produce electrical charges in response to mechanical stress. However, the signal generated in terms of current is too small and unreadable due to the higher impedance of the sensor. Furthermore, the signal generated is random with noises. Thus, a signal conditioning circuit which consists of a charge amplifier and a bandpass filter is designed to solve the problems. For signal processing, Fast Fourier Transform (FFT) is used to transform the signal from the time domain to the frequency domain in MATLAB. The signal of lifting movement for every 1 minute is successfully analyzed based on the frequency distribution in the frequency domain graph. The frequency of the signal drops from 146.1Hz to 139.2Hz. The drop in frequency shows the feature of muscle fatigue. Hence, the piezoelectric sensor can be utilized to detect muscle fatigue. Furthermore, the piezoelectric sensor can be built into accessories as it is flexible and light.

ABSTRAK

Sensor piezoelektrik adalah sensor aktif yang berpotensi untuk menganalisis prestasi otot rangka. Ia boleh menghasilkan cas elektrik sebagai tindak balas kepada tekanan mekanikal. Namun, isyarat yang dihasilkan dari segi arus terlalu kecil dan tidak dapat dibaca kerana impedans sensor terlalu tinggi. Tambahan pula, isyarat yang dihasilkan adalah secara rawak dengan bunyi. Oleh itu, litar pengkondisian isyarat yang terdiri daripada penguat cas dan penapis jalur lebar dirancang untuk menyelesaikan masalah tersebut. Untuk pemprosesan isyarat, Fast Fourier Transform (FFT) digunakan untuk mengubah isyarat dari domain masa ke domain frekuensi di MATLAB. Isyarat pergerakan mengangkat untuk setiap 1 minit telah berjaya dianalisis berdasarkan taburan frekuensi dalam grafik domain frekuensi. Kekerapan isyarat turun dari 146.1Hz hingga 139.2Hz. Penurunan frekuensi menunjukkan ciri keletihan otot. Oleh itu, sensor piezoelektrik boleh digunakan untuk mengesan keletihan otot. Selain itu, sensor piezoelektrik dapat dibina ke dalam aksesori kerana ia fleksibel dan ringan.

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LIST OF SYMBOLS AND ABBREVIATIONS

FFT	:	Fast Fourier Transform
PVDF	:	Polyvinylidene Difluoride
PZT	:	Lead Zirconate Titanate
EMG	:	Electromyography
CSV	:	Comma Separated Values
ESD	:	Electrostatic Discharge
ADC	:	Analog-to-Digital Converter
IDE	:	Integrated Development Environment
SPI	:	Serial Peripheral Interface
CLK	:	Serial Clock
MISO	:	Master Input Slave Output
MOSI	:	Master Output Slave Input
CS	:	Chip Select

LIST OF APPENDICES

CHAPTER 1:

INTRODUCTION

1.1 Overview

Piezoelectric sensor is a device that utilizes the piezoelectric effect. The electrical charges will be produced between its electrodes when there is a mechanical stress applied to it. The piezoelectric sensor does not need an external power supply to obtain an output signal. Hence, it is an active sensor.

The piezoelectric material is well matched to the needs of e-textile as it is small, flexible, light, and low cost. Thus, it is suitable for wearable technology. Besides, it is able to generate a readable voltage range from tens of millivolts to hundreds of volts based on the magnitude of the applied stimulus that can be produced easily (Edmison *et al.*, 2002).

The signal generated by the piezoelectric sensor is random with some noises. Therefore, it needs to undergo signal processing. Signal processing is important for extracting useful information from the signal, as well as produce a higher quality signal. Signal processing includes transformation and filtration of the signal.

1.2 Problem Statement

Piezoelectric sensor is a sensor that can produce an electric charge when there is a change in force, acceleration, pressure, temperature, or stain. The voltage produced by the piezoelectric sensor is about a few millivolts to volts. However, the current produced by the piezoelectric sensor is about a few nanoamperes to microamperes. Hence, the signal generated in terms of current is too low and not readable. To solve the problem, a charge amplifier circuit needs to be designed.

Furthermore, the signal generated by the piezoelectric sensor is difficult to determine and extract useful information, because it is random with noises. Hence, a filter needs to be designed, and signal processing is required to solve this problem. The signal will be transformed with the Fast Fourier Transform (FFT) method in MATLAB and analyzed based on the frequency distribution.

1.3 Objectives

There are three objectives that need to be achieved for this final year project:

1. To characterize the piezoelectric film sensor (PVDF, LDT0-028K).
2. To design and simulate a signal conditioning circuit for the piezoelectric film sensor (PVDF, LDT0-028K) using Multisim.

3. To analyze the signal with the Fast Fourier Transform (FFT) in MATLAB and evaluate the performance of the prototype.

1.4 Scope of Work

As for the limitation of the project, the piezoelectric film sensor (PVDF), which is LDT0-028K is chosen. This is because it has higher flexibility and sensitivity. Therefore, it is more comfortable to wear for users. The signals through muscle activity can be measured using LDT0-028K, such as the activity of lifting an object. The LDT0-028K will be placed at the biceps brachii to obtain signals.

The characterization of LDT0-028K will be done in a controlled environment. The experiment of characterization will be carried out in the laboratory with the room temperature of 28°C so that the signal generated from the sensor is not affected by the temperature changes from outside of the laboratory. Based on the theory of the piezoelectric sensor, the voltage should be directly proportional to the force applied on the sensor.

Next, the signal conditioning circuit will be designed and simulated using Multisim software. The Vcc of the TLV2772CD and the reference voltage of MCP3008 are set at 3.3V. The charge generated by LDT0-028K should be amplified and converted to the voltage signal at the range of 0V to 3.3V by the charge amplifier circuit. The microcontroller raspberry pi 3 will be used as a data acquisition center. Raspberry pi can write the data directly in a CSV file so that the file can be transferred directly to the MATLAB and doing the analysis.

After that, the signal will be analyzed with Fast Fourier Transform in MATLAB. The signal in the time domain should be able to transform into the frequency domain. The bandpass filter with a cut-off frequency between 34Hz to 408Hz is designed. Thus, the signal should be lined in the frequency range from 34Hz to 408Hz.

Lastly, this wearable electronic is suitable for healthy people, especially athletes. This prototype is tested for three months.

1.5 Thesis Outline

There are five chapters in the thesis for this project. Chapter 1 is the introduction. It covers the overview of the project, problem statement, objectives, and scope of work.

Chapter 2 is the literature review. It covers the discussions from the past research work until the recent findings by other researchers. Some background studies of the piezoelectric sensor are discussed as well.

Chapter 3 is the methodology. It covers the methodology used to complete this project. For example, block diagram, flow chart, hardware design, data acquisition and processing programming.

Chapter 4 is the results and discussion. It covers the results obtained from the experiments and simulations. The results are further analyzed and discussed.

Lastly, chapter 5 is the conclusion. It is the summarization of the research. It consists of the future work of this research as well.

CHAPTER 2:

BACKGROUND STUDY

2.1 Introduction of Piezoelectric Sensor

Piezoelectric sensor is characterized by having a transduction element made of piezoelectric material. Piezoelectric materials are non-conductive material. They can produce electricity due to mechanical stress. The piezoelectric effect occurs when there is an electrical charge generated in response to the mechanical stress applied to the piezoelectric material.

Piezoelectric materials can be separated into three groups, which are crystals, ceramics, and polymers (Bera and Sarkar, 2017). The examples of piezoelectric crystals are quartz, berilinite, gallium orthophosphate, and tourmaline. Barium titanate, lead zirconate titanate (PZT), and barium zirconate titanate are examples of piezoelectric ceramics. Polyvinylidene fluoride (PVDF) is an example of polymers.

The electricity produced by the piezoelectric material is called piezoelectricity. In 1880, piezoelectricity is discovered by two French scientists' brothers, Jacques and Pierre Curie. They found out that certain materials such as tourmaline, quartz, topaz, cane sugar, and Rochelle salt produce electric charges when there is mechanical stress applied to the (Gautschi, no date). The word "piezo" is an ancient Greek word, which means 'squeeze' or 'press'.

2.1.1 Piezoelectric Effect

There are two types of piezoelectric effects, which are direct piezoelectric effect and converse piezoelectric effect. The direct piezoelectric effect is the production of electricity when a piezoelectric ceramics or crystals are mechanically stressed, while the converse piezoelectric effect is to make piezoelectric ceramics or crystals shrink or expand when an electrical signal is applied (Garimella, Sastry and Mohiuddin, 2015). In 1881, Lippmann predicted the converse piezoelectric effect based on the thermodynamic considerations (Gautschi, no date). Figure 2.1 shows the concept of the direct piezoelectric effect and the converse piezoelectric effect.

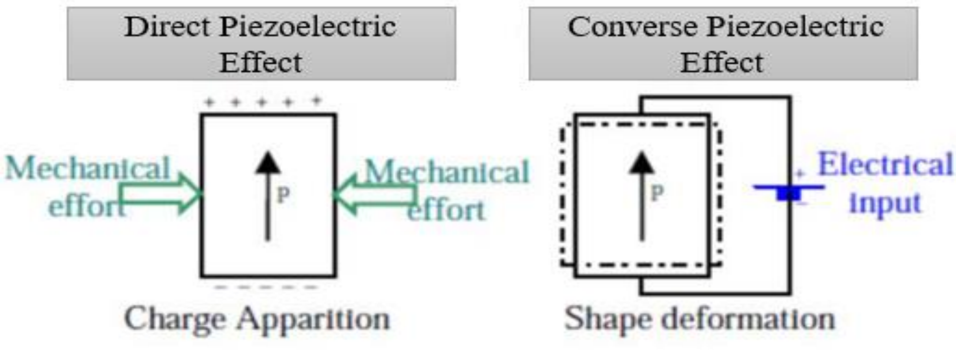


Figure 2.1: Direct Piezoelectric Effect and Converse Piezoelectric Effect (Garimella, Sastry and Mohiuddin, 2015)

The piezoelectric effect can be represented by the following equations (Roundy and Wright, 2004).

$$\{S\} = [s^E]\{T\} + [d]^t\{E\}$$

$$\{D\} = [d]\{T\} + [\varepsilon^T]\{E\}$$

Where,

$\{S\}$ = strain

$[s^E]$ = compliance at constant electric field

$\{T\}$ = stress

$[d]$ = piezoelectric charge coefficient

$\{E\}$ = electric field

$\{D\}$ = displacement vector (or electric flux density)

$[\varepsilon^T]$ = permittivity at constant stress

The relationship of voltage output and mechanical stress applied can be determined by following equation.

$$V_3 = d_{31}\frac{F_1}{A_1}A_3\frac{h}{\in^T{}_{33}\,A_3} = d_{31}\frac{F_1}{lh}\frac{h}{\in^T{}_{33}} = d_{31}\frac{F_1}{l\in^T{}_{33}}$$

Since stress = F/A , it can be concluded the voltage output is directly proportional to the stress applied to the piezoelectric sensor.

2.1.2 Comparison of Piezoelectric Material (PZT and PVDF)

The most common types of piezoelectric material are PZT and PVDF (Caliò *et al.*, 2014). Table 2.1 shows the comparison of PZT piezoelectric sensor and PVDF piezoelectric sensor.

Table 2.1: Comparison of PZT Piezoelectric Sensor and PVDF Piezoelectric Sensor

Characteristics	PZT Piezoelectric Sensor	PVDF Piezoelectric Sensor
Young's Modulus (GPa)	71	2 – 6
Density (g/cm^3)	8	1.78
Thickness (μm)	220 – 630	9 – 110
Piezo Charge Coefficient, $\lvert d_{31}\rvert$ (pC/N)	274	18 – 24
Piezo Charge Coefficient, $\lvert d_{32}\rvert$ (pC/N)	274	2.5 – 3
Piezo Charge Coefficient, $\lvert d_{33}\rvert$ (pC/N)	593	33
Dielectric Constant	3800	12 – 13
Curie's Temperature (℃)	230	80

The Young's Modulus of PVDF is generally lower than PZT as PVDF is a flexible polymer (Bera and Sarkar, 2017) while PZT is a ceramic with (JAFFE, 1958)(Bera and Sarkar, 2017). The Young's Modulus of PVDF is in the range of 2 – 6 GPa (Specialties, 2006)(Shen, Choe and Kim, 2007), whereas PZT has a higher of Young's Modulus which is equal to 71GPa (Sirohi and Chopra, 2000).

PVDF is lighter than PZT as the density of the polymer is lower than ceramic. The density of PVDF is equal to 1.78g/cm^3 (Specialties, 2006)(Bera and Sarkar, 2017), while PZT has about four times higher of density which is equal to 8g/cm^3 (DIH and FULRATH, 1978). Next, the thickness of PVDF is generally thinner than PZT. The thickness of PVDF is in the range of 9 – 110 μm (Specialties, 2006), while PZT has a thickness of 220 – 630 μm (Electronics, 2015).

For the piezo charge coefficient, the value of $|d_{31}|$, $|d_{32}|$, and $|d_{33}|$ for PVDF is lower than PZT. The piezo charge coefficient of PVDF for $|d_{31}|$, $|d_{32}|$, and $|d_{33}|$ is equal to 18 – 24 pC/N, 2.5 – 3 pC/N, 33 pC/N (Sirohi and Chopra, 2000), whereas the piezo charge coefficient of PZT for $|d_{31}|$ and $|d_{32}|$ is equal to 274 pC/N, whereas $|d_{33}|$ is equal to 593 pC/N (Sirohi and Chopra, 2000).

The dielectric constant of PVDF is lower than PZT. PVDF has a dielectric constant which is equal to 12 – 13 (Shen, Choe and Kim, 2007), while PZT has a higher dielectric constant which is equal to 3800 (Shen, Choe and Kim, 2007). The Curie's temperature of PVDF is lower than PZT as the ceramic has a higher withstand temperature compared to the polymer. PVDF has a Curie's temperature of to 80 ℃ (Shen, Choe and Kim, 2007), whereas the Curie's temperature of PZT is equal to 230 ℃ (Shen, Choe and Kim, 2007).

Figure 2.2 shows the photograph of ceramic based PZT piezoelectric sensor and polymer based PVDF piezoelectric sensor.

Figure 2.2: Photograph of (a) Ceramic based PZT Piezoelectric Sensor (Bell and Deubzer, 2018) and (b) Polymer based PVDF Piezoelectric Sensor (Sensors and Sensativity, 2008)

2.1.3 Application of Piezoelectric Material

Piezoelectric material can be used in a variety of applications, such as sensors, actuators, generators, and transducers. Piezoelectric sensor can generate an electrical signal when there is a change in force, speed, pressure, temperature, or strain. Hence, it is widely used for wearable technology. Wearable technology is a kind of electronic device that can be worn by users.

Fall detection is a popular application for wearable sensors. The sensor usually used for fall detection is accelerometers. The common types of accelerometers are piezoresistive, piezoelectric, and differential capacitive accelerometers (Yang and Hsu, 2010). Accelerometer can be used for activity recognition. The activity group with a difference level can be determined by the different positions of the sensor (Atallah *et al.*, 2011).

Glove is a potential wearable electronic to control the movement of a robot gripper. A motion-sensing glove can be developed using PVDF to control the robot gripper. The motion of the index finger can be used to control the movement of robot gripper

(Åkerfeldt, Lund and Walkenström, 2015). Furthermore, it is suitable for physical rehabilitation. It can be used to predict the recovery status of a patient.

Next, the wearable cardiorespiratory signal sensor device can be used to monitor sleep conditions (Choi and Jiang, 2006). The PVDF sensor can be placed at the abdominal circumference. The signal is collected from the abdominal muscle. It is suitable for the patient because the doctor and nurse can observe their cardiorespiratory signal during their sleep.

Besides, the fatigue in muscle can be detected using the piezoelectric sensor. For example, training for athletes can be set properly using wearable technology. The kinematic changes with fatigue in running can be monitored in the sports areas (Strohrmann *et al.*, 2012). The fatigue in muscle can be detected by analyzing the signal generated from the sensor. Muscle pain or muscle injury can be avoided since the training can be stopped immediately.

Lastly, the performance of the skeletal muscle can be analyzed using a piezoelectric film sensor (Cai *et al.*, 2015). The EMG and piezoelectric film sensor signals can be measured from the bicep muscle during different weightlifting. The reduction in the peak amplitude toward the end of measurement indicates the fatigue of the muscle. Furthermore, the transition of the high frequency to the low frequency is a feature of muscle fatigue (Shair *et al.*, 2017). In conclusion, muscle fatigue can be detected by observing the amplitude or the frequency of the signal.

2.2 Signal Conditioning Circuit

Signal conditioning is a vital process, which can manipulate an analog signal before it is suitable for further processing. The piezoelectric sensor needs a signal conditioning circuit to convert the electrical signal into a higher level before undergo signal processing. The charge generated by the piezoelectric sensor is too small. The charge generated by 1N force is at the range of tens or hundreds of picocoulombs. Hence, it needs a charge amplifier circuit to amplify the charge and convert it into a readable signal.

Normally, there will be a feedback resistor and capacitor in the charge amplifier circuit. The feedback capacitor can create an output that is proportional to the accumulation of input current over time, while the feedback resistor can prevent the amplifier from saturating. The gain only depends on the feedback capacitor. The output voltage of the charge amplifier can be expressed by a formula:

$$V_{out} = \frac{1}{C_f}\int -I\, dt = \frac{Q}{C_f}$$

Figure 2.3 shows the basic charge amplifier.

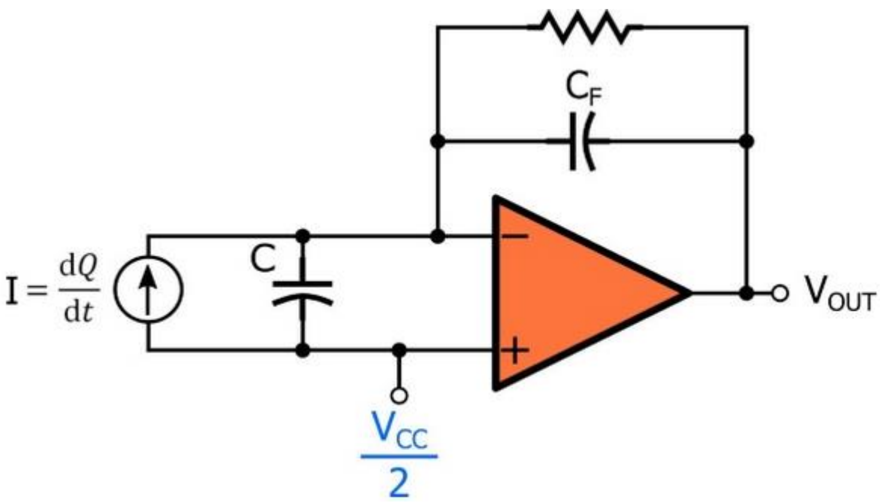


Figure 2.3: Basic Circuit of Charge Amplifier

2.2.1 Equivalent Circuit of the Piezoelectric Sensor

The equivalent circuit of the piezoelectric sensor can be made by a current source, capacitor, and resistor. The capacitor and the resistor connect parallel to the current source. Figure 2.4 shows the equivalent circuit of the piezoelectric sensor.

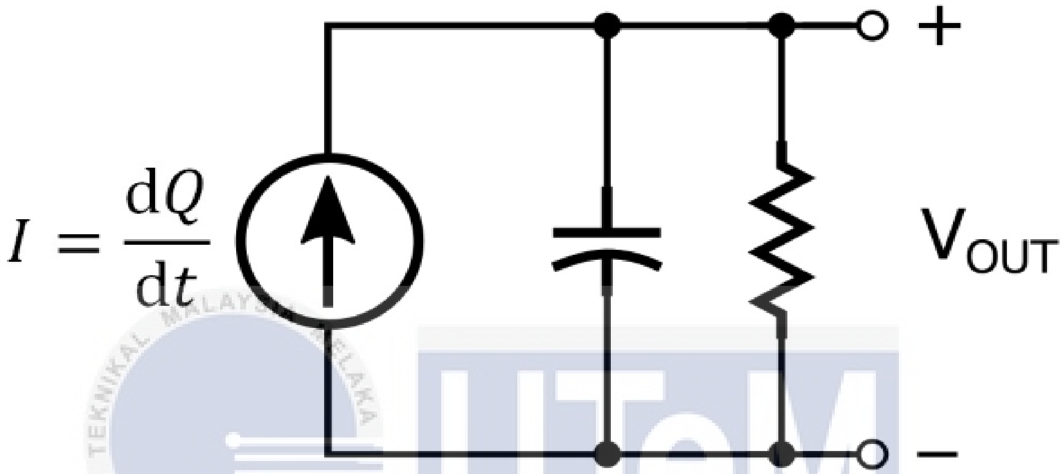


Figure 2.4: Equivalent Circuit of Piezoelectric Sensor

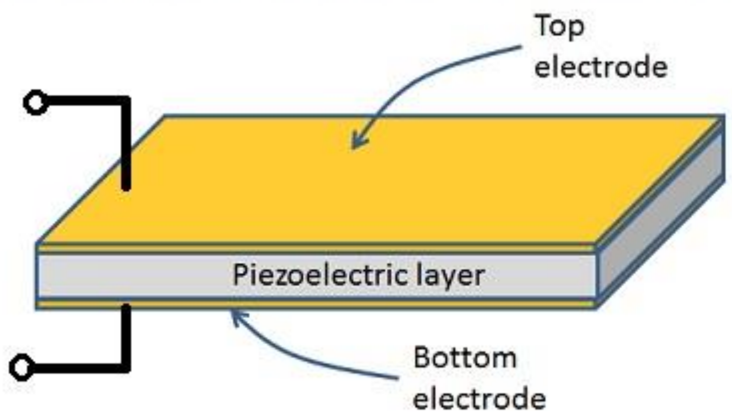


Figure 2.5: Illustration of Piezoelectric Sensor

The charge generated by the piezoelectric sensor is mobile. Thus, the current will be produced when the charge is moving in the circuit over time. The electric current is the rate of flow of charge, $I = dQ/dt$. This means the piezoelectric sensor can be modeled using a current source.

The electrical charge is generated at the piezoelectric layer when there is mechanical stress. The charge will then move to the electrodes and flow to the circuit. It is like a capacitor. Hence, the capacitor acts as a part of the equivalent circuit. Figure 2.5 shows the illustration of the piezoelectric sensor.

The charge generated by the piezoelectric sensor is movable, and it will not stay around. Moreover, there is a leakage of charge due to the piezoelectric material. It will make the charge to diminish gradually. To mimic this behavior, a resistor is added parallelly to the circuit. Therefore, the general representation of piezoelectric functionality is more accurate for the model.

2.3 Signal Processing

The wearable market is emerging around the world. Technology such as mounting a sensor into a clothing and wearable accessory to track the fitness level, heartbeat rate, breathing rate, sleeping pattern becomes more and more developed. Hence, signal processing is vital for collecting the information and translating it into useful data.

Signal processing is a process that can improve or optimize the efficiency and performance of the signal. Furthermore, various mathematical and computational algorithms can be applied to analog and digital signals through signal processing to produce a higher quality signal.

There are two main functions for signal processing, which are transformation and filtration. Signal processing can be used to transform a signal from the time domain to the frequency domain. Fast Fourier Transform (FFT) method is commonly used for signal analyzation. The examples of time domain signal and frequency domain signal are shown in Figure 2.6 and Figure 2.7.

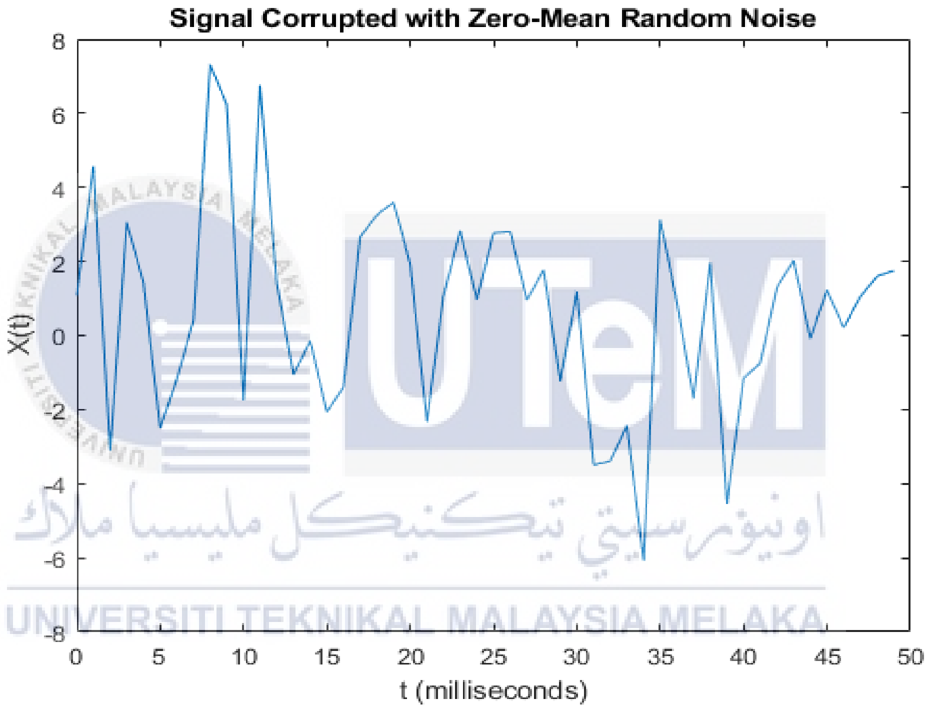


Figure 2.6: Noisy Signal in the Time Domain

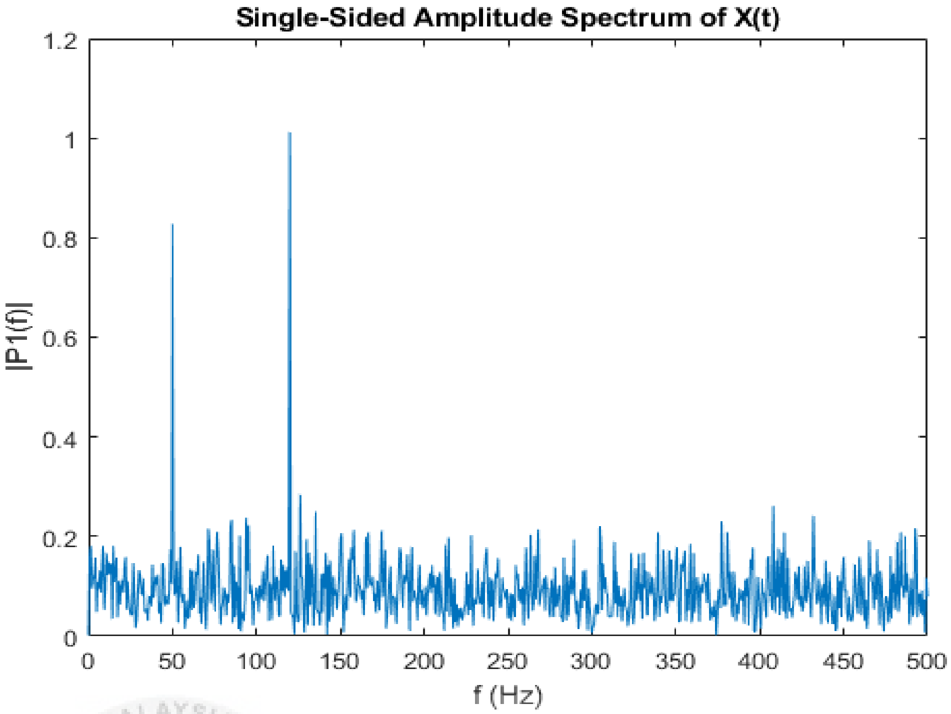


Figure 2.7: Fast Fourier Transform of the Noisy Signal

2.4 Conclusion

It can be concluded that PVDF is a better piezoelectric material for embedded into the electronic textile as it is flexible and light. It can also generate a readable signal with a proper signal conditioning circuit. The useful information can be extracted from the signal using the Fast Fourier Transform (FFT) method. The methodology for the studies is further discussed in the next chapter.

CHAPTER 3:

METHODOLOGY

3.1 Block Diagram

Figure 3.1 shows the block diagram of the project.

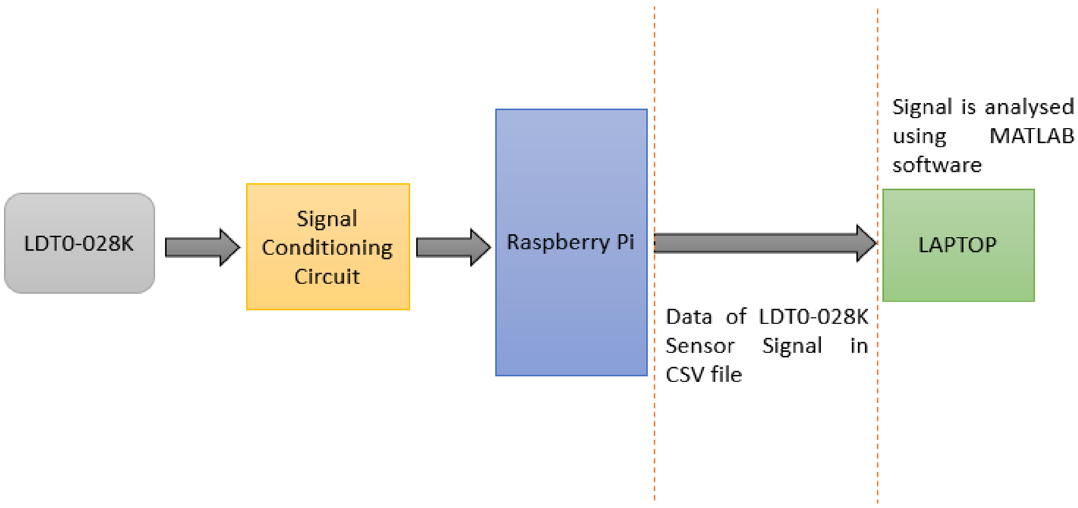


Figure 3.1: Block Diagram of the Project

In this project, LDT0-028K acts as a sensor to detect the signals caused by muscle activity, such as the activity of lifting a bottle of water (500ml). After that, a signal conditioning circuit is designed to amplify the charge and filter the noise of the signal. Before the signal pass to the raspberry pi, MCP3008 will convert it into the digital numbers which can be understood by the raspberry pi. Next, the digital numbers are written into a CSV file, and the file is transferred to the MATLAB. The signal is transformed from the time domain to the frequency domain with the Fast Fourier Transform (FFT). The signal is analyzed based on the frequency distribution in the frequency domain graph.

3.2 Project Flow

Figure 3.2 shows the project flow of the project.

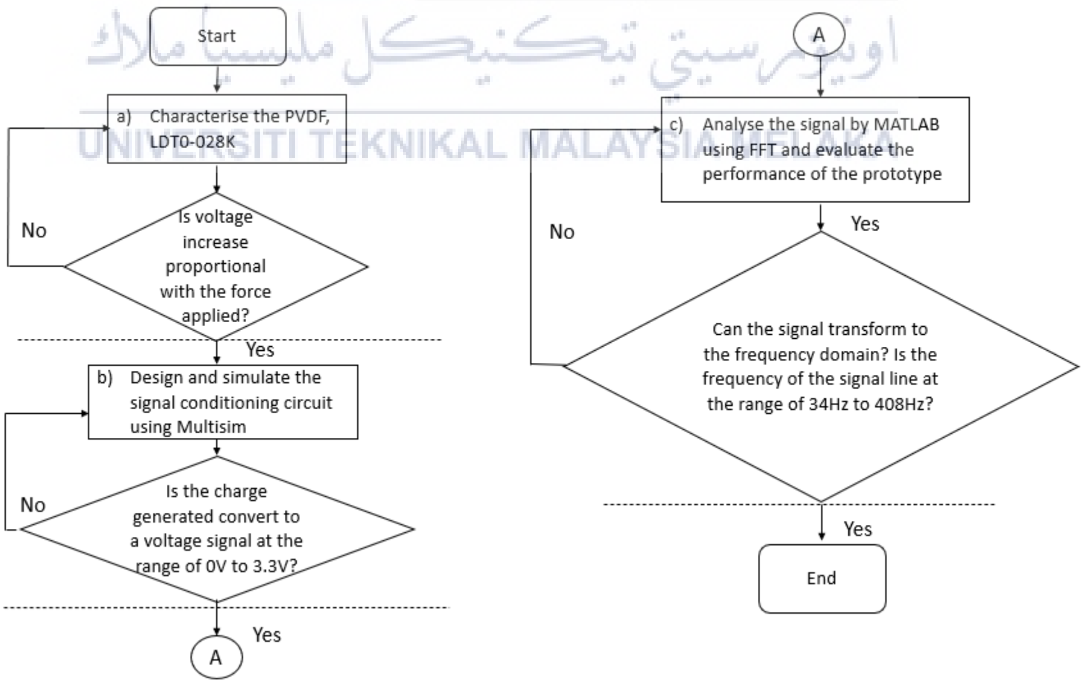


Figure 3.2: Project Flow of the Project

3.3 Hardware Design

Table 3.1 shows the list of components used in this project.

Table 3.1: Component Used in the Project

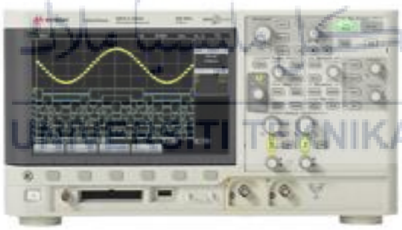
1	LDT0-028K
2	Raspberry Pi 3B
3	TLV2772CD
4	MCP3008
5	Resistor
6	Capacitor

Figure 3.3 shows the main components used in the project.

Figure 3.3: Main Components Used in the Project

3.3.1 Characterization of piezoelectric film sensor, LDT0-028K

The experiment of the characterization sensor is carried out in the laboratory. The equipment and component used in the experiment are LDT0-028K, strap, 110g plasticine, UHU glue, raffia string, binder clip, G-clamp, electronic balance, and oscilloscope. First, LDT0-028K is pasted on the strap using UHU glue. Next, G-clamp is used to clamp the tip of the strap with the table, so that the strap is fixed. 100g of plasticine is weighed using the electronic balance. Then, a raffia string and binder clip are used to tie another tip of the strap with the plasticine. LDT0-028K is connected to the oscilloscope. After that, the plasticine is dropped at the height of 45cm from the table. The output signal is shown on the oscilloscope. The peak to peak voltage is recorded, and the graph is plotted using Microsoft Excel. This experiment is repeated with the plasticine at 0g, 20g, 40g, 60g, and 80g. The equipment used in this project is shown in Figure 3.4, while the experiment set up is shown in Figure 3.5.



Oscilloscope

Electronic Balance

Digital LCR Meter

Figure 3.4: Equipment Used in the Project

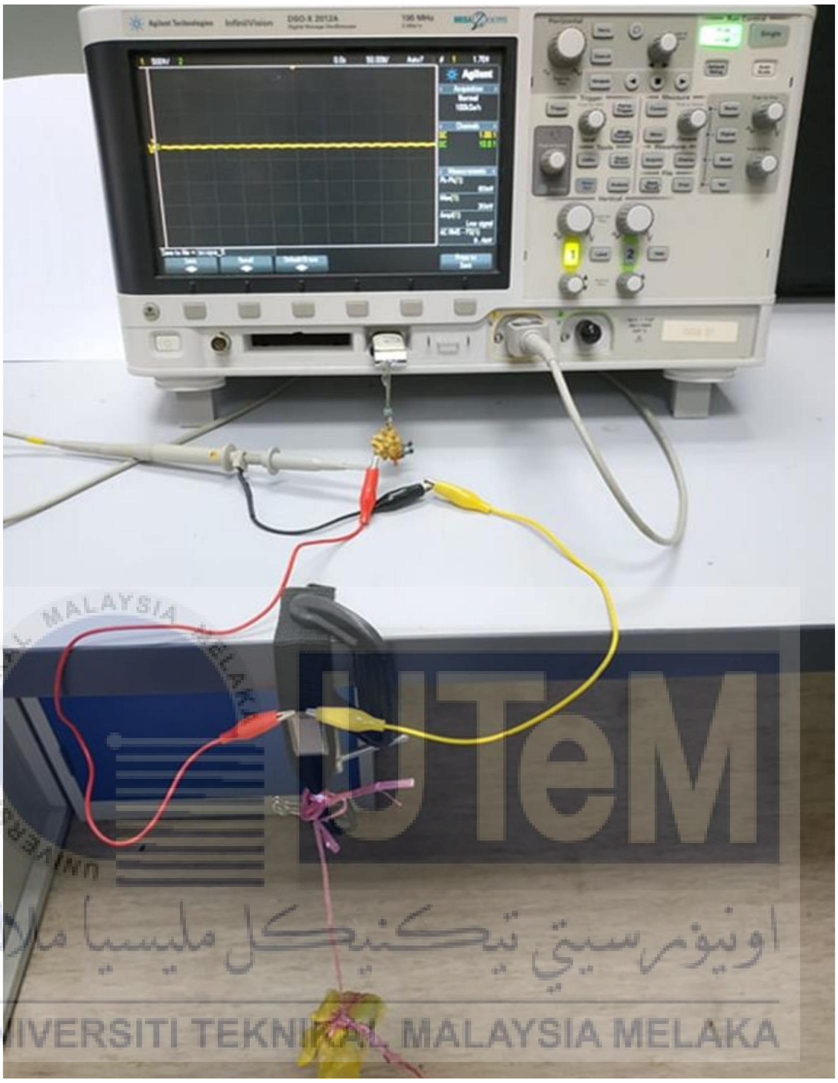


Figure 3.5: Experiment Set Up

3.3.2 Design and Simulation of Signal Conditioning Circuit

The signal conditioning circuit is designed in this project. The electronic components such as TLV2772CD, resistor, and capacitor are used for designing the circuit. A charge amplifier and a filter are designed to amplify the charge and filter the noise. The circuit is drawn and simulated using Multisim. The circuit design in

Multisim is shown in Figure 3.6, whereas the signal conditioning circuit connection is shown in Figure 3.7.

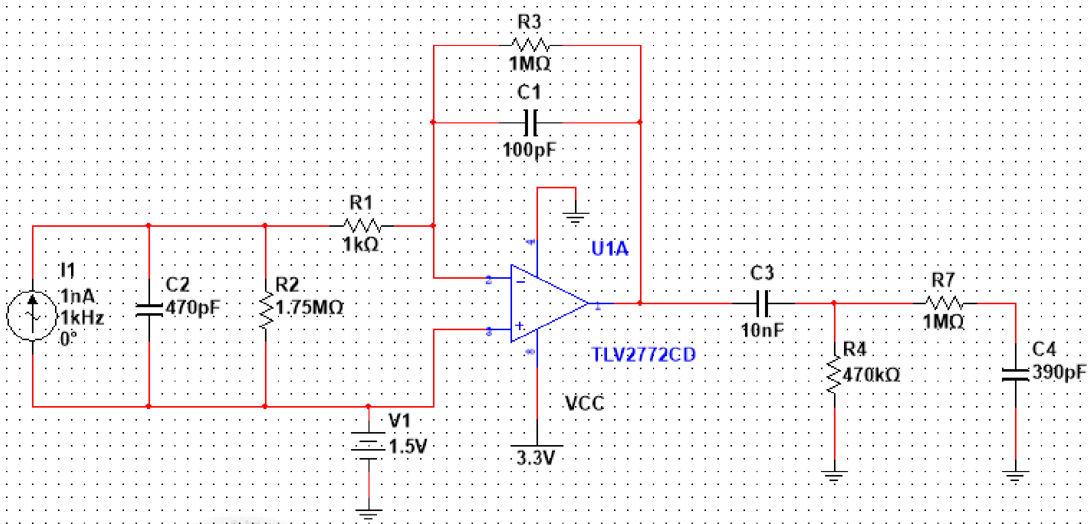


Figure 3.6: Design of Signal Conditioning Circuit

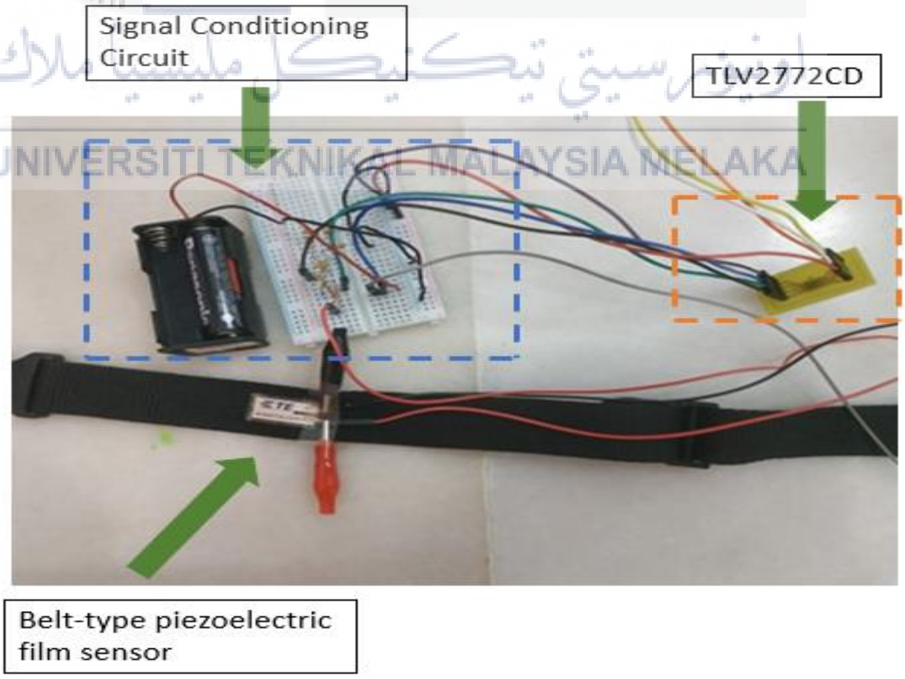


Figure 3.7: Signal Conditioning Circuit Connection

The signal conditioning circuit consists of two parts, which are the charge amplifier and filter. A charge amplifier is a circuit that can amplify the charge and convert it to the voltage. TLV2772CD is chosen in this project. It is suitable for the sensor that has high impedance, such as piezoelectric sensor. It has a high slew rate and bandwidth, rail to rail output swing, and the supply voltage range is 2.5V to 5.5V. Thus, the VCC of TLV2772 CD is set at 3.3V. The package pinouts of TLV2772CD is shown in Figure 3.8.

For the equivalent circuit of the piezoelectric sensor, a capacitor and a resistor are connected parallel to a current source. Before design an equivalent circuit for the piezoelectric sensor, a digital LCR meter is used to measure the resistance and capacitance of the sensor under a frequency of 1kHz. The resistance of the sensor equals to 1.75MΩ, while the capacitance of the sensor equals to 470pF. According to the datasheet of LDT0-028K, the range of resistance is from 1MΩ to 10MΩ (Piezo film sensors, 1999), whereas the range of capacitance is from 480pF to 500pF (Piezo film sensors, 1999). Figure 3.9 shows the equivalent circuit of the LDT0-028K.

Resistor R1 is designed to provide ESD protection for the circuit. It can prevent the problem associated with the amplitude peaking. The resistance value of R1 is at the range of 100Ω to 1kΩ. Thus, the resistance of R1 set as 1kΩ. Capacitor C1 is designed to accumulate the charge from the sensor. The capacitance value of C1 is at the range of 0.1nF to 10nF. The voltage output can be expressed by an equation, which is $V_{out} = \frac{1}{C_f}\int -I\,dt = \frac{Q}{C_f}$. The voltage output is inversely proportional to C_f. Thus, the capacitance value of C1 set as 0.1nF (100pF) in order to obtain a higher voltage output. Resistor R3 is designed to convert the charge or current into the voltage. It can also provide a negative DC bias path for the negative input since the capacitor acts as an open circuit during DC analysis. The resistance of R3 set as 1MΩ. The voltage gain of the amplifier can be calculated using a formula, $A_v = V_{p(out)}/V_{p(in)}$. To measure the voltage input and voltage output, an oscilloscope is connected to the charge amplifier circuit. The circuit is shown in Figure 3.10.

Next, a bandpass filter is designed in the simulation as shown in Figure 3.11. The circuit of the passive high pass filter is shown in Figure 3.12, while the circuit of the passive low pass filter is shown in Figure 3.13. The low cut-off frequency set as 34Hz, while the high cut-off frequency set as 408Hz. This happened when the capacitance of C3 and C4 are set as 10nF and 390pF. The value of resistor R4 and R7 can be determined using the formula of cut-off frequency, $f_c = 1/2\pi RC$. After that, a 0.1µF capacitor is connected between V_O and channel 0 of MCP3008. This can smoothen the output from the charge amplifier. The circuit diagram is shown in Figure 3.14.

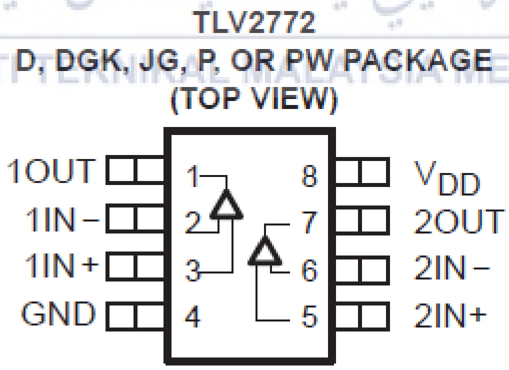


Figure 3.8: Package Pinouts of TLV2772CD

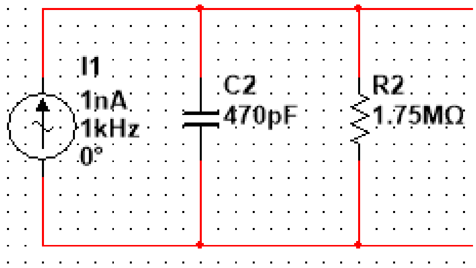


Figure 3.9: Equivalent Circuit of LDT0-028K

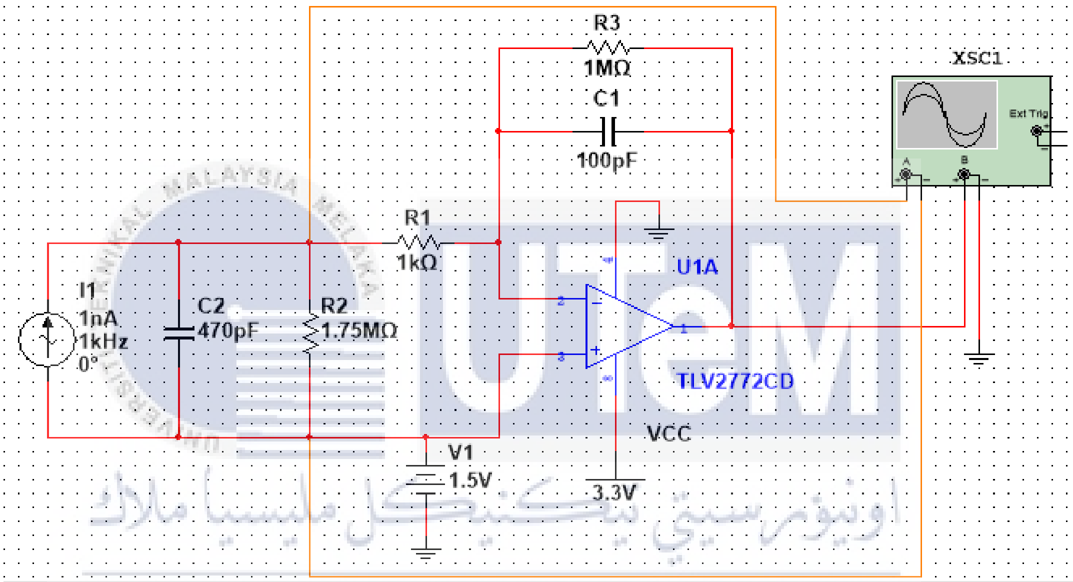


Figure 3.10: Charge Amplifier Circuit

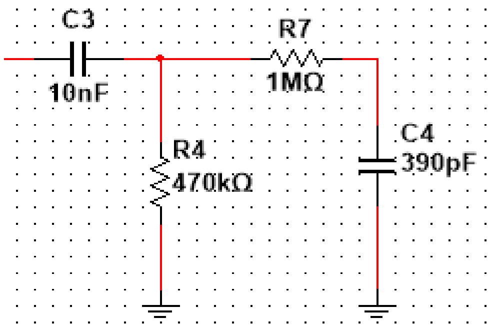


Figure 3.11: Bandpass Filter

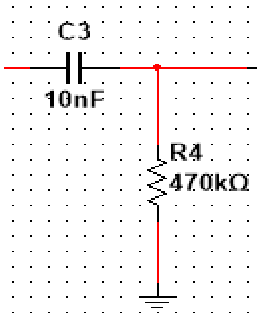


Figure 3.12: Passive High Pass Filter

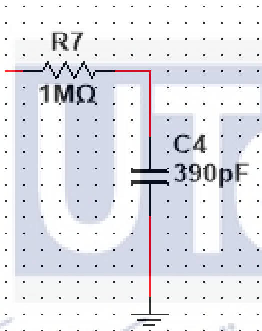


Figure 3.13: Passive Low Pass Filter

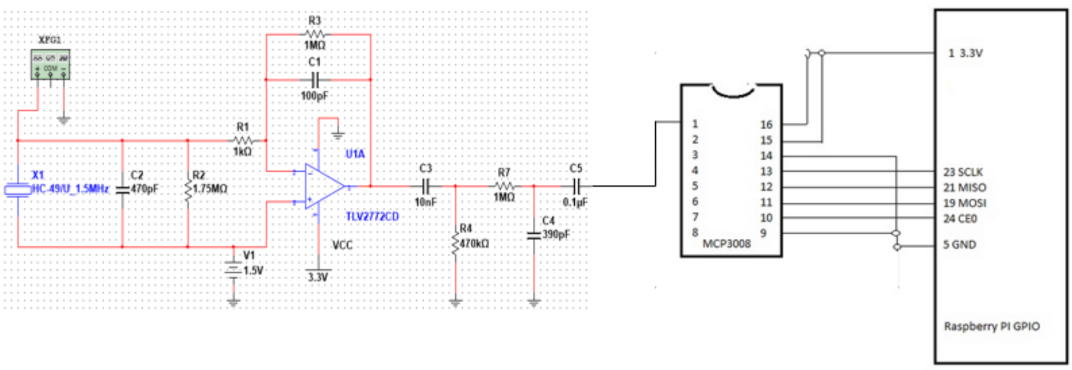


Figure 3.14: Circuit Connection of Signal Conditioning Circuit and MCP3008 with Raspberry Pi

3.3.3 Circuit Connection of the Hardware

Figure 3.15 shows the circuit connection of the hardware.

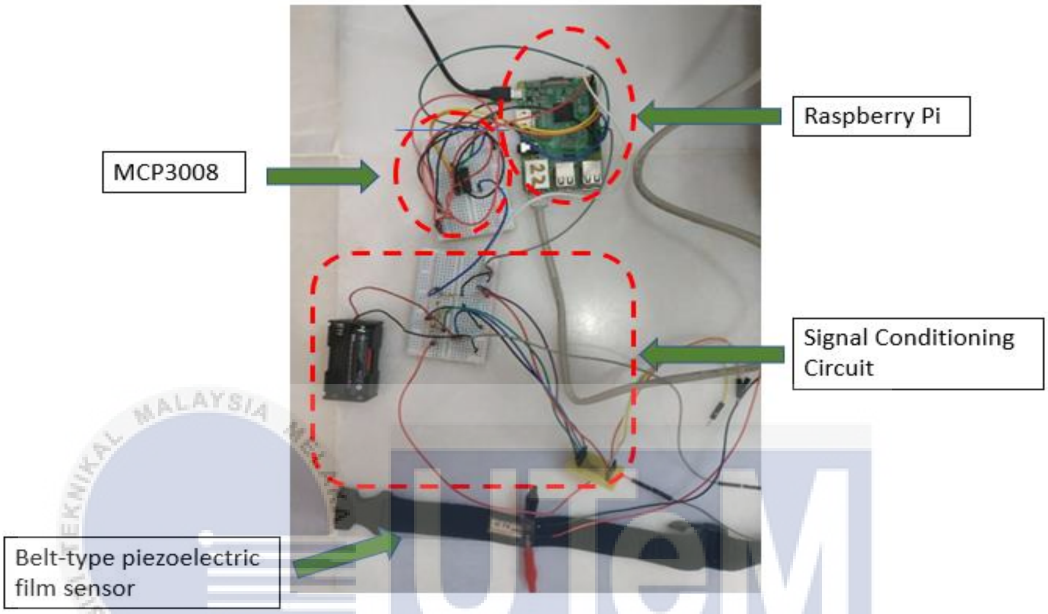


Figure 3.15: Circuit Connection of the Hardware

The hardware consists of belt-type piezoelectric film sensor, signal conditioning circuit, ADC (MCP3008), and a microprocessor (raspberry pi).

3.4 Data Acquisition and Processing Programming

Table 3.2 shows the list of software used in this project.

Table 3.2: Software Used in the Project

1	Thonny
2	MATLAB

Figure 3.16 shows the software used in the project.

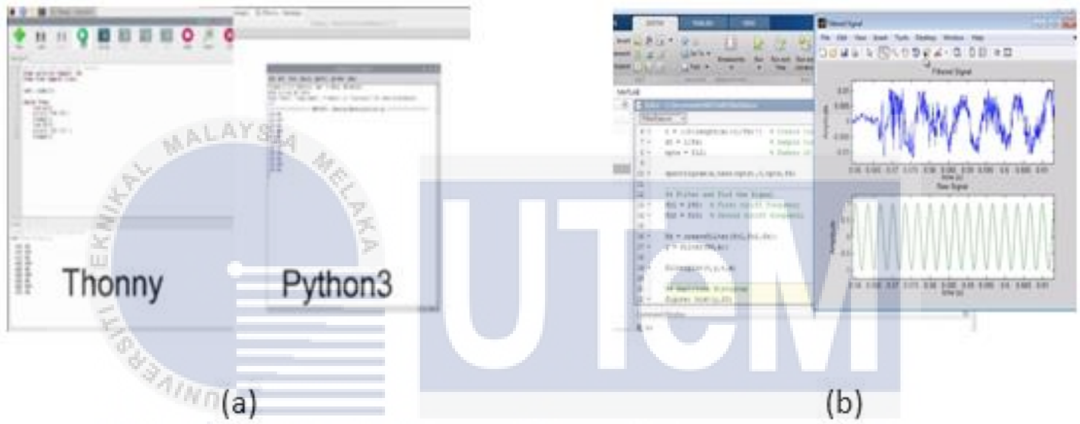


Figure 3.16: Software Used in the Project, (a) Thonny IDE and (b) MATLAB IDE

3.4.1 Signal Analysis

A CSV file is created to write the data from MCP3008 using python. The python code is typed in Thonny. Thonny is one of the integrated development environments (IDE) for python in raspberry pi. Next, the data file is imported to MATLAB. The code in MATLAB is executed, and the data is analyzed. The data of the signal is obtained from the biceps brachii. The movement of slow and fast elbow flexion and extension with a strong gripe during lifting a bottle of water (500ml) is repeated for 3 minutes. The signal will be transformed into the frequency domain with FFT in MATLAB, and it is analyzed based on the frequency distribution.

3.4.2 Python Code

```
import spidev                  # importing spidev module
from time import sleep         # from time module import sleep function
import os
import csv                     # importing csv module
import time                    # importing time module


csvfile = "piezo1.csv"         # create a csv file
f=open(csvfile,"w+")           # clear the data in csv file


spi = spidev.SpiDev()          # first open up SPI bus

spi.open(0,0)


piezoChannel = 0               # initialize where is the sensor
sleepTime = 0.001              # declare the time delay for the task execution


def analogInput(channel):                # function that read data from MCP3008
   spi.max_speed_hz = 1350000
   adc = spi.xfer2([1,(8+channel)<<4,0]     # first pull the raw data from the chip
   data = ((adc[1]&3) << 8) + adc[2]        # process the raw data into
                                              something we understand.
   return data
```

```
def ConvertVolts(data):                    # function that convert data to voltage
    volts = (data * 3.3) / float(1024)     # formula
    volts = round(volts, 2)                # round off to 2 decimal places
   return volts


while True:
    piezoData = analogInput(piezoChannel)
   piezoVoltage = ConvertVolts(piezoData)


    # print the piezo bit value and voltage
   print("Piezo bitvalue = {}; Voltage = {} V".format(piezoData, piezoVoltage))


   timeC=time.strftime("%I")+':'+time.strftime("%M")+':'+time.strftime("%S")

   read=[timeC,piezoData,piezoVoltage]


    # write data in the csv file that created
    with open(csvfile, "a")as output:
        writer=csv.writer(output,delimiter=",",lineterminator='\n')
        writer.writerow(read)                  # write 3 columns of data
    sleep(sleepTime)                           # collect data every 0.001 second
```

3.4.2.1 Explanation of Python Code

LDT0-028K is an analog sensor. Hence, the data needs to convert into the digital numbers, which can be understood by the raspberry pi using an ADC converter. To read the data from MCP3008, spidev module needs to be imported in this project. Serial Peripheral Interface (SPI) is a communication protocol. It can transfer data between raspberry pi and sensors. There are 4 sperate connections such as serial clock (CLK), Master Input Slave Output (MISO), Master Output Slave Input (MOSI), and Chip Select (CS) used to communicate with the target device by SPI.

Next, the sleep function needs to be imported from the time module. Hence, the time to collect data can be set. Furthermore, the csv module needs to be imported so that a CSV file can be created for the aim of writing data. Then, a function of reading data from MCP3008 is created. The data read in the form of bit value. To read the data in voltage, a function for the voltage conversion is created. A formula $voltage = (bit\ value * V_{ref})/1024$, $V_{ref} = 3.3V$ is required for MCP3008 to convert data into voltage. The voltage is then round off to 2 decimal places.

When there is no error, the function in the while true loop will be loop infinity. Therefore, the data can be collected every 0.001 seconds. The data of bit value and voltage will be printed at the Thonny Shell. At the same time, there are 3 columns of data will be written in the CSV file. The first column is time, the second column is bit value, and the third column is voltage.

3.4.3 MATLAB Code

```
X = ctranspose(piezo1);                  % Transpose the matrix


Fs = 1000;                               % Sampling frequency
T = 1/Fs;                                % Sampling period
NFFT = length(X);                        % Length of signal
t = (0:NFFT-1)*T;                        % Time vector


subplot(2,1,1)
plot(t(1:1001),X(1:1001))                        % Plot graph
title('Signal of LDT0-028K')
xlabel('Time (s)')                               % Label x-axis
ylabel('Voltage (V)')                            % Label y-axis


% Computes the DFT of X using FFT algorithm
Y = fft(X,NFFT);
% Remove the DC component for better visualization
Y(1) = 0;
Pyy = (1/(2*pi*NFFT)) * abs(Y).^2;       % Compute the power spectral density
f = Fs/NFFT*(1:NFFT/2);
subplot(2,1,2)
stem(f,Pyy(1:(NFFT/2)))                  % Plot graph
title('FFT for Spectral Analysis')
xlabel('Frequency (Hz)')                 % Label x-axis
ylabel('Pyy (mW/Hz)')                    % Label y-axis
```

3.4.3.1 Explanation of MATLAB Code

The data is transposed using the ctranspose function so that the size of the array matches the frequency vector. The sampling frequency, sampling period, length of the signal, and the time vector are required to declare. The sampling frequency in this project is declared as 1kHz. This is because the number of data collected in 1 second is equal to 1000.

Two graphs will be plotted in MATLAB. One is the time-domain graph and the other is the frequency-domain graph. For the frequency domain graph, FFT function is used to compute the discrete Fourier transform (DFT) of the reading using a fast Fourier transform (FFT) algorithm. Next, an equation $P_{yy} = (1/(2 * pi * NFFT)) * abs(Y).$^2 is used to computes the power spectral density, and NFFT is the length of the signal.

3.5 Conclusion

From the methodology, firstly the LDT0-028K is being characterized and follows enhancing the signal output with a signal conditioning circuit. Next, the signal is being transformed and analyzed with the FFT in MATLAB. The output of the experiment is explained in detail in the following chapter.

CHAPTER 4:

RESULTS AND DISCUSSION

4.1 Result for Characterization of Piezoelectric Film Sensor, LDT0-028K

Figure 4.1 show the signal of LDT0-028K measured by oscilloscope.

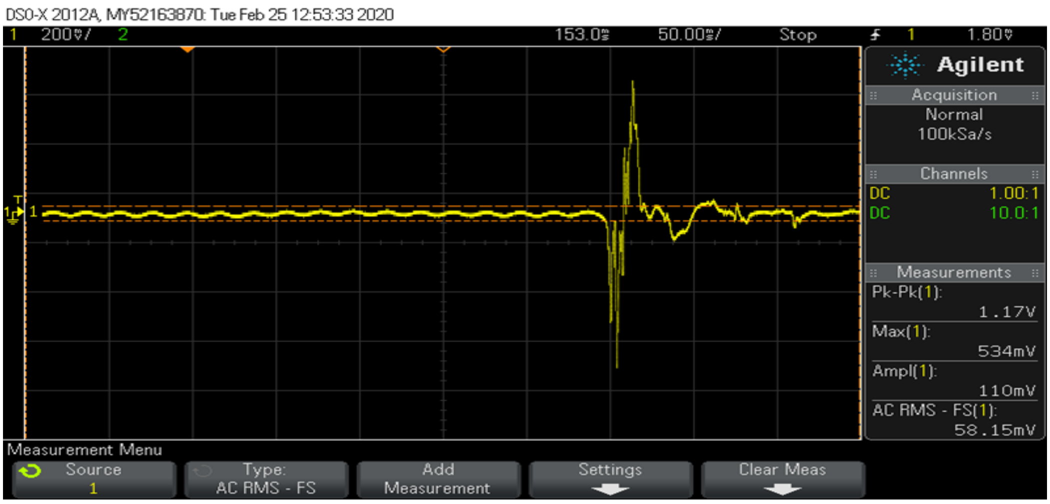


Figure 4.1: Signal of LDT0-028K Measured by Oscilloscope

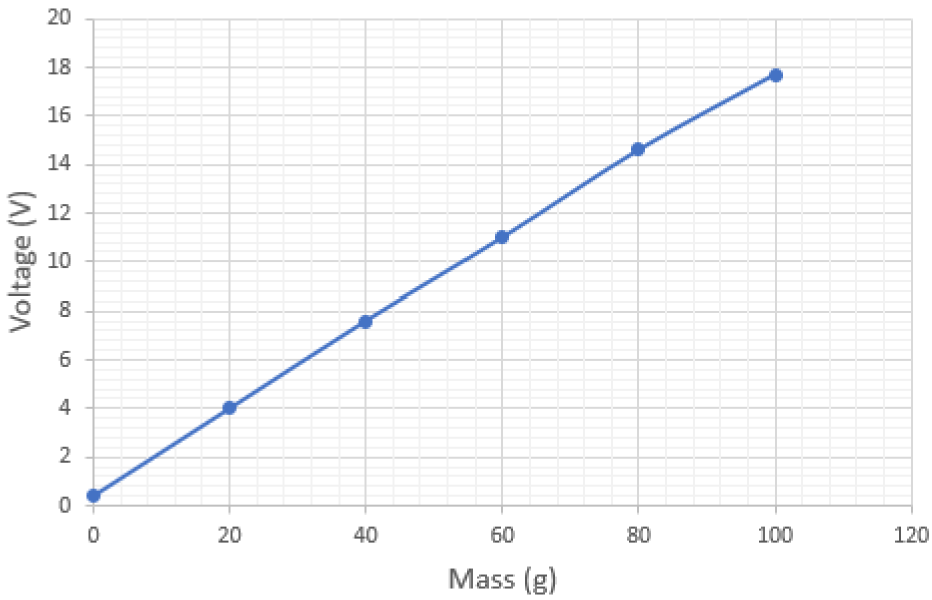


Figure 4.2: Graph of Voltage against Mass

After the data are collected using the oscilloscope, the graph of voltage against mass is plotted as shown in Figure 4.2. To obtain the relationship of the voltage and force applied, it needs to convert the mass (g) into the force (N). The mass is converted to the unit of kg before the force is calculated. Force can be calculated using a formula, which is $F = mg$. Due to the object in free fall, so $g = 9.81\,m/s^2$.

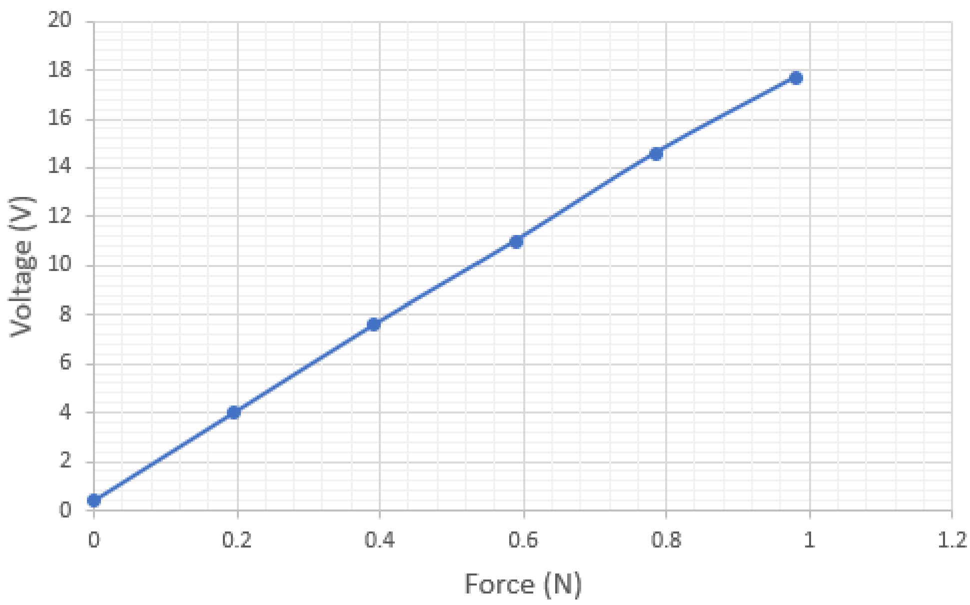


Figure 4.3: Graph of Voltage against Force

The graph as shown in Figure 4.3 is a straight-line graph. Hence, a straight-line equation can be obtained, which is $y = mx + c$. m can be calculated by using two coordinate points. $m = (y_2 - y_1)/ (x_2 - x_1) = (17.7 - 0.4)/(0.981 - 0) = 17.6V/N$. m is also referred to the sensitivity of the sensor. From the graph, the value of m is equal to $17.6V/N$, whereas c is approximately equal to 0. Therefore, the relationship between voltage and force can be concluded as the voltage is directly proportional to the force applied on the sensor. The result of the characterization of the sensor is in agreement with the theory, which is voltage output proportional to the force that applied on the sensor. It can be proved by the equation of the piezoelectric sensor, which is $V_3 = d_{31}F_1/l \in^T{}_{33}$. From the equation, $V_3 \propto F_1$.

4.2 Result for Simulation of Signal Conditioning Circuit

Figure 4.4 shows the simulation result for the voltage input of the sensor, while Figure 4.5 shows the simulation result for the voltage output of the sensor.

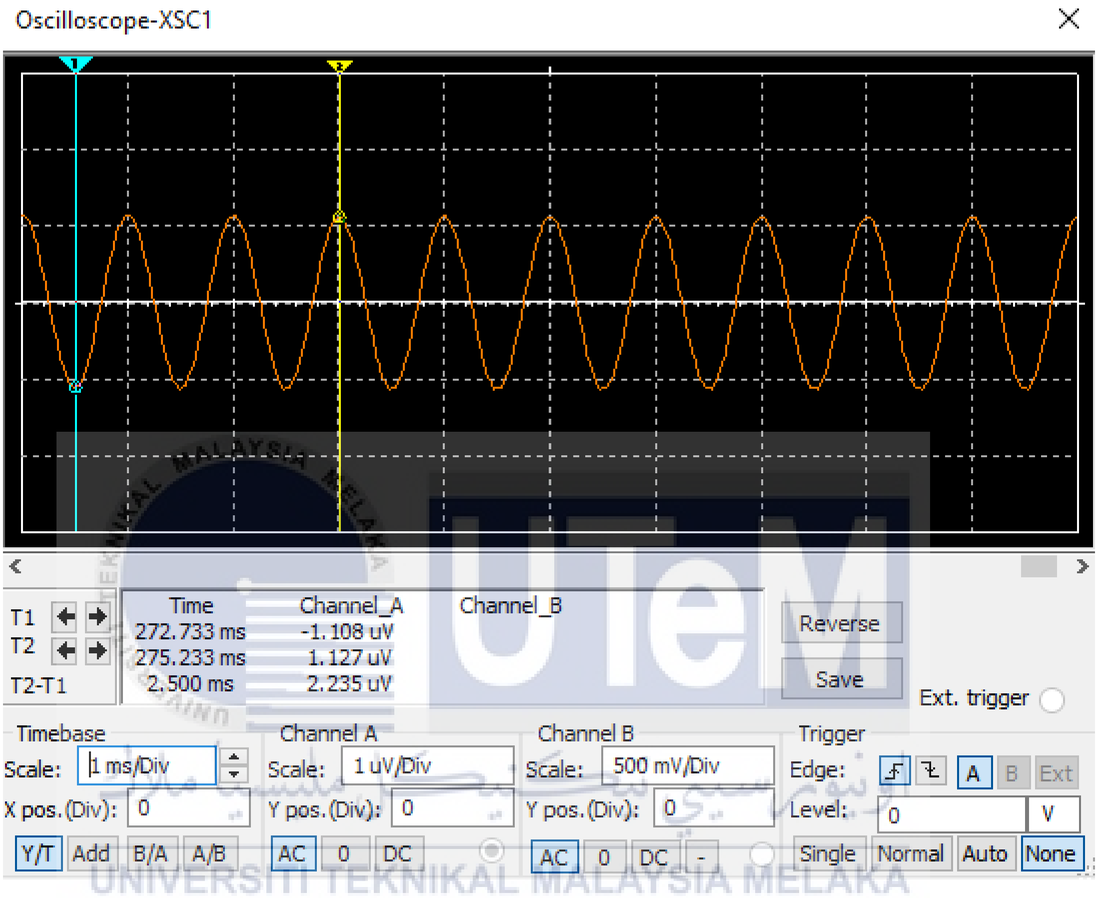


Figure 4.4: Simulation Result for Voltage Input with a Current Source at 1nA

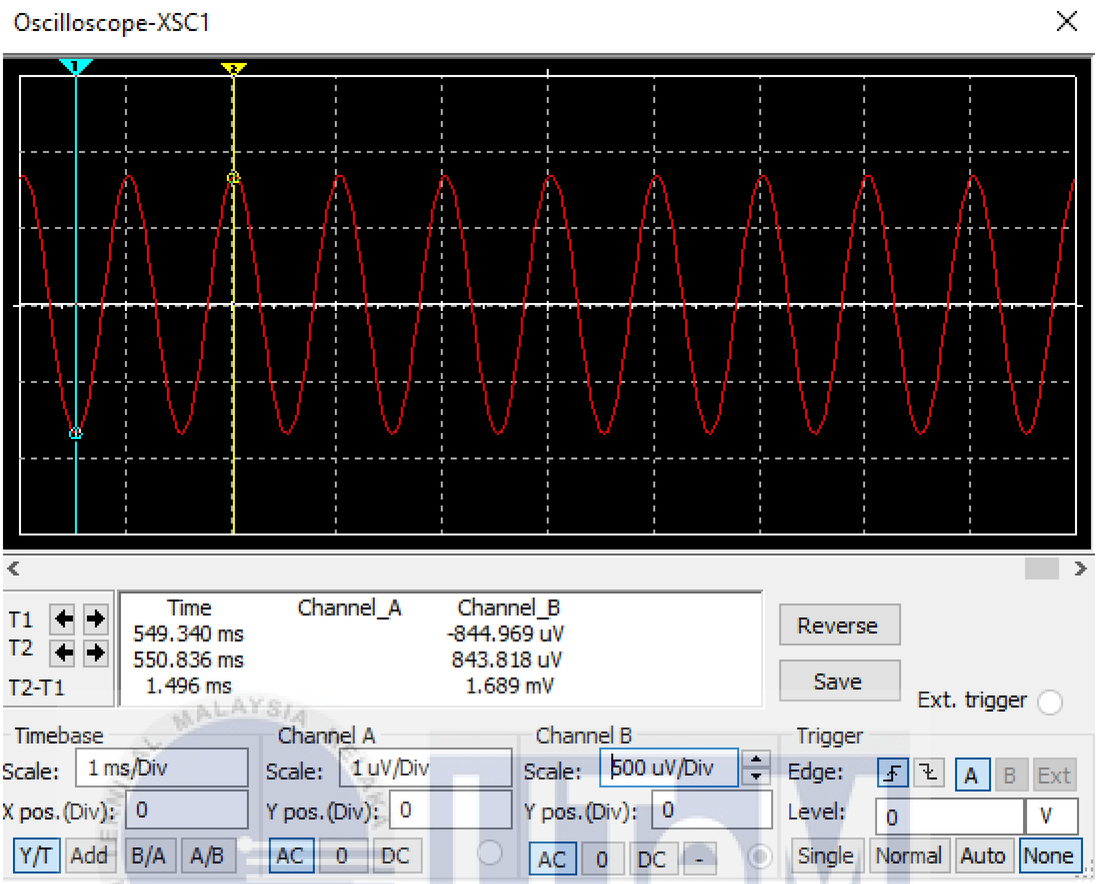


Figure 4.5: Simulation Result for Voltage Output with a Current Source at 1nA

The simulation results are obtained from the charge amplifier circuit as shown in Figure 3.10. The peak voltage input from the simulation as shown in Figure 4.4 is equal to 1.127μV, while the peak voltage output from the simulation as shown in Figure 4.5 is equal to 843.818μV. The voltage gain of the circuit can be calculated using a formula, $A_v = V_{p(out)}/V_{p(in)}$. $A_v = 843.818\mu/1.127\mu = 749$. Thus, the voltage gain of the circuit with the current source at 1nA is equal to 749.

Figure 4.6 shows the simulation result for the voltage input of the sensor, while Figure 4.7 shows the simulation result for the voltage output of the sensor.

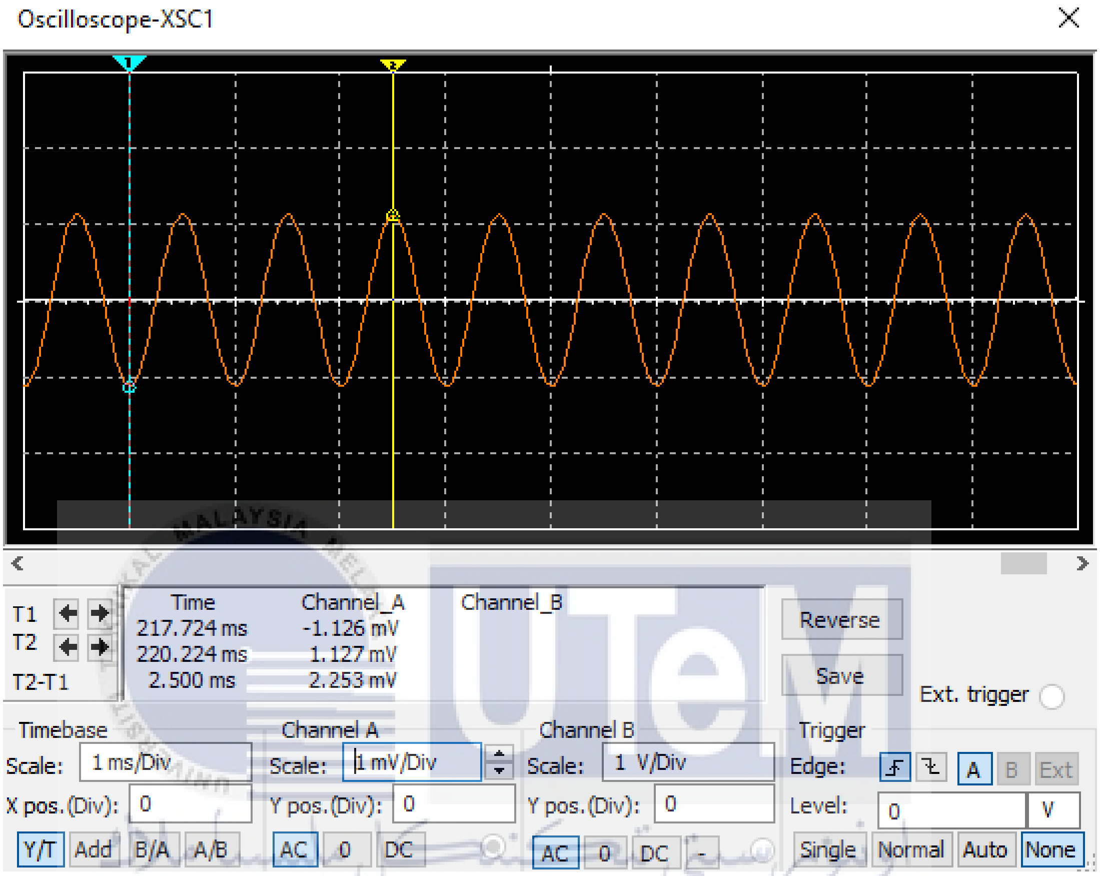


Figure 4.6: Simulation Result for Voltage Input with a Current Source at 1μA

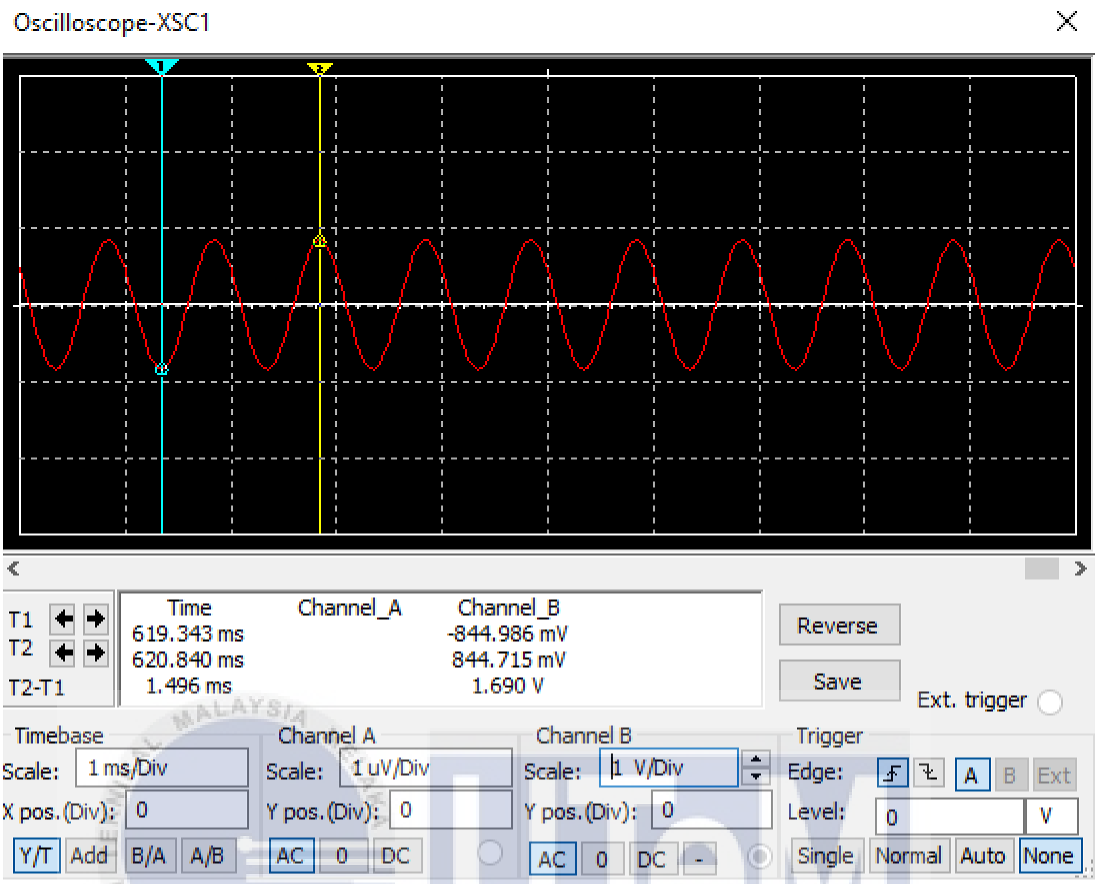


Figure 4.7: Simulation Result for Voltage Output with a Current Source at 1μA

The simulation results are obtained from the charge amplifier circuit as shown in Figure 3.10, but the value of the current source change to 1μA. The peak voltage input from the simulation as shown in Figure 4.6 is equal to 1.127mV, while the peak voltage output from the simulation as shown in Figure 4.7 is equal to 844.715mV. The voltage gain of the circuit can be calculated using a formula, $A_v = V_{p(out)}/V_{p(in)}$. $A_v = 844.715m/1.127m = 750$. Thus, the voltage gain of the circuit with the current source at 1μA is equal to 750.

In conclusion, the voltage output of the sensor is amplified successfully with the different values at the current source. The voltage gain of the designed charge amplifier circuit is around 750. For the hardware, the negative voltage output is removed since the negative voltage output cannot detect by MCP3008. Hence, the range of voltage output is in the range of 0V to 3.3V.

Figure 4.8 shows the simulation result of a high pass filter.

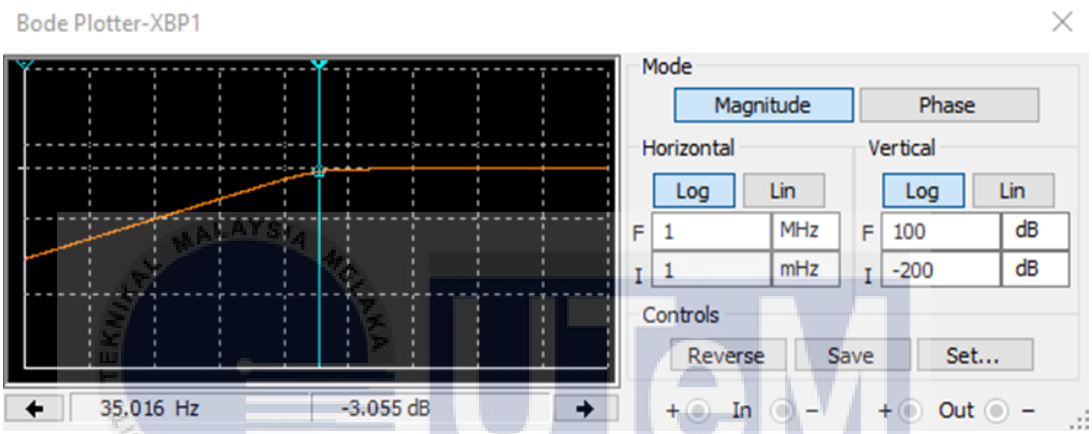


Figure 4.8: Simulation Result for a High Pass Filter with a Cut-Off Frequency at 35Hz

The simulation result is obtained from the passive high pass filter as shown in Figure 3.11. The cut-off frequency is taken at -3dB. The simulation result for the cut-off frequency as shown in Figure 4.8 is approximately 35Hz. There is a small difference in cut-off frequency for the simulation and calculation. The cut-off frequency can be calculated using a formula, $f_c = 1/2\pi RC$. $f_c = 1/2\pi(470k)(10n) = 34Hz$. The difference between them is equal to 1Hz, $35 - 34 = 1Hz$. This is probably due to the tolerance of the resistance and capacitance.

Figure 4.9 shows the simulation result of a low pass filter.

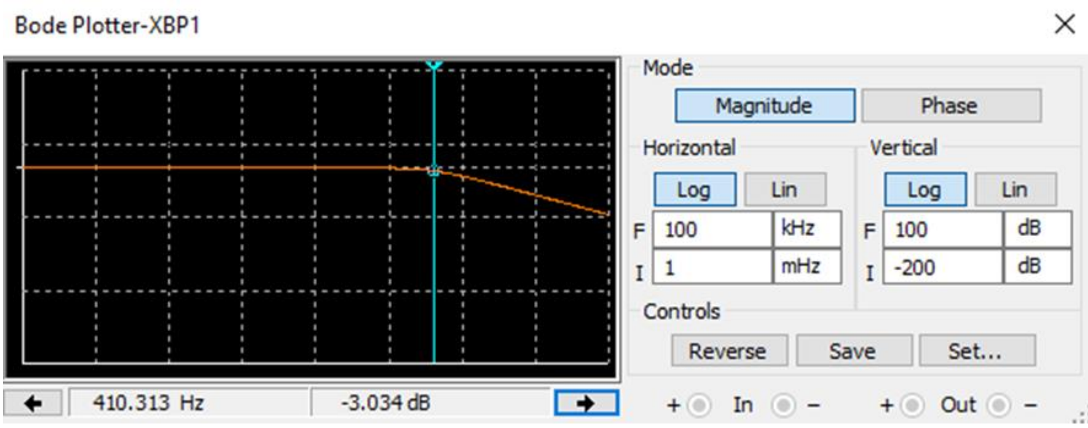


Figure 4.9: Simulation Result for a Low Pass Filter with a Cut-Off Frequency at 410Hz

The simulation result is obtained from the passive low pass filter as shown in Figure 3.12. The cut-off frequency is taken at -3dB. The simulation result for the cut-off frequency as shown in Figure 4.9 is approximately 410Hz. There is a small difference in cut-off frequency for the simulation and calculation. The cut-off frequency can be calculated using a formula, $f_c = 1/2\pi RC$. $f_c = 1/2\pi(1M)(390p) = 408Hz$. The difference between them is equal to 2Hz, $410 - 408 = 2Hz$. This is probably due to the tolerance of the resistance and capacitance.

Figure 4.10 shows the simulation result of a bandpass filter.

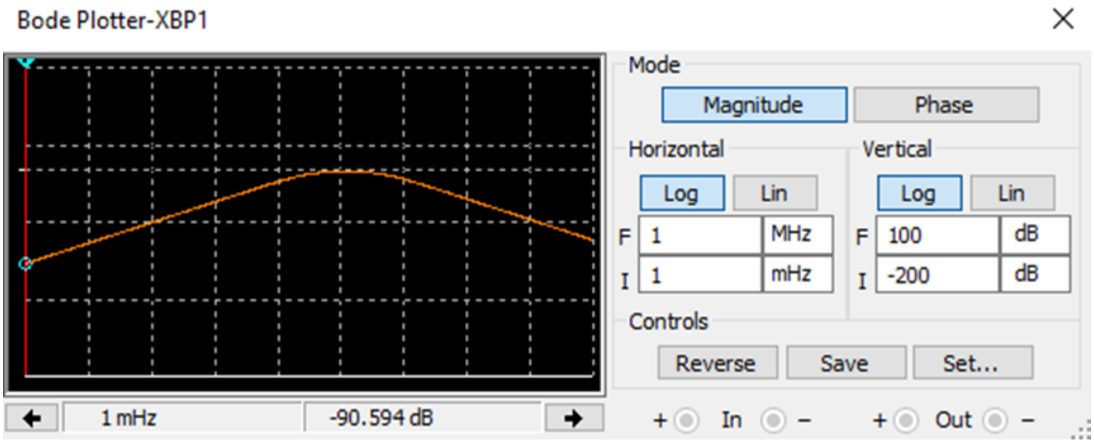


Figure 4.10: Simulation Result for a Bandpass Filter with a Cut-Off Frequency Between 35Hz to 410Hz

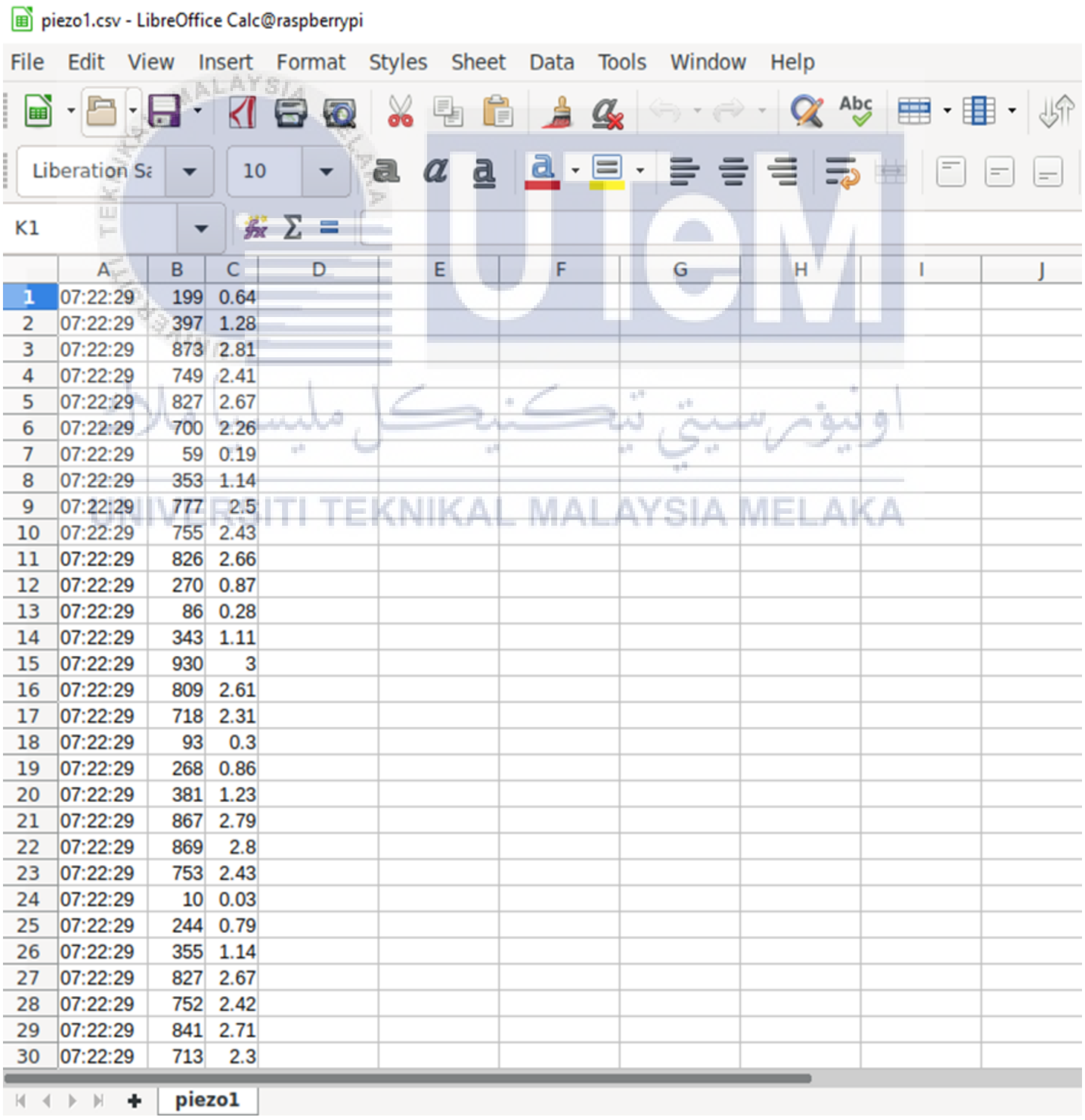
The combination of a passive high pass filter and a passive low pass filter will make a bandpass filter. The bandwidth of the bandpass filter can be calculated using a formula, $BW = f_H - f_L$. The value of f_H and f_L from the simulation result is equal to 410Hz and 35Hz. Hence, the bandwidth of the bandpass filter is equal to 375Hz.

4.3 Result for Signal Analysis

There is two part of coding in this project. One part of coding is python code, it can read the data and write them into a CSV file. Another part of coding is MATLAB code, it can plot the frequency domain graph with FFT.

4.3.1 Implementation of Python Code

Figure 4.11 shows the data collected from the sensor in a CSV file.



	A	B	C
1	07:22:29	199	0.64
2	07:22:29	397	1.28
3	07:22:29	873	2.81
4	07:22:29	749	2.41
5	07:22:29	827	2.67
6	07:22:29	700	2.26
7	07:22:29	59	0.19
8	07:22:29	353	1.14
9	07:22:29	777	2.5
10	07:22:29	755	2.43
11	07:22:29	826	2.66
12	07:22:29	270	0.87
13	07:22:29	86	0.28
14	07:22:29	343	1.11
15	07:22:29	930	3
16	07:22:29	809	2.61
17	07:22:29	718	2.31
18	07:22:29	93	0.3
19	07:22:29	268	0.86
20	07:22:29	381	1.23
21	07:22:29	867	2.79
22	07:22:29	869	2.8
23	07:22:29	753	2.43
24	07:22:29	10	0.03
25	07:22:29	244	0.79
26	07:22:29	355	1.14
27	07:22:29	827	2.67
28	07:22:29	752	2.42
29	07:22:29	841	2.71
30	07:22:29	713	2.3

Figure 4.11: CSV file with Data Collected

There are 3 columns of data in the CSV file. The time to collect the data is written in the first column of the file. Then, the bit value generated from the MCP3008 is written in the second column of the file. Next, the data for the voltage conversion is written in the third column of the file.

4.3.2 Implementation of MATLAB code

Figure 4.12 shows the connection between the raspberry pi and MATLAB.

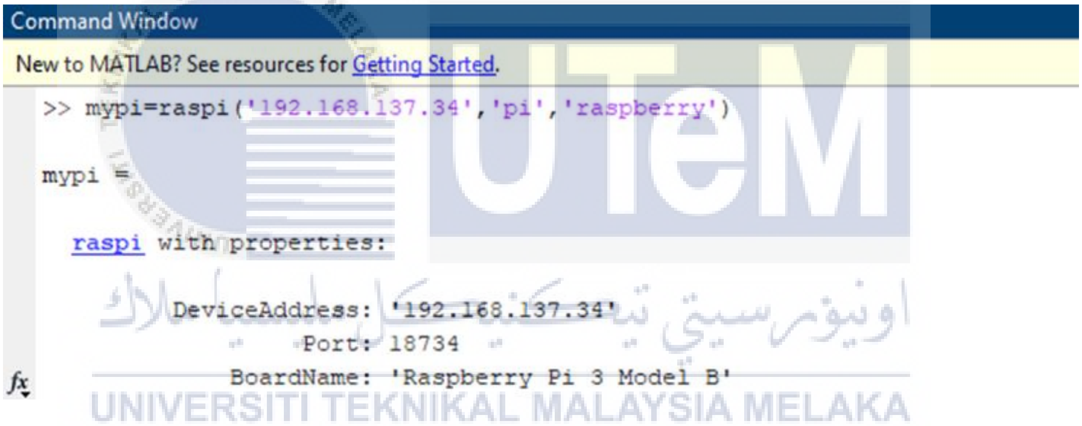


Figure 4.12: Create Connection to Raspberry Pi

Before implementing the MATLAB code, a connection is created between raspberry pi hardware and MATLAB using raspi function. The raspi function required some information, such as the IP address, username, and password of the raspberry pi. Moreover, the properties of the raspberry pi hardware can be displayed in the command window of MATLAB.

Figure 4.13 shows the getFile function in MATLAB.

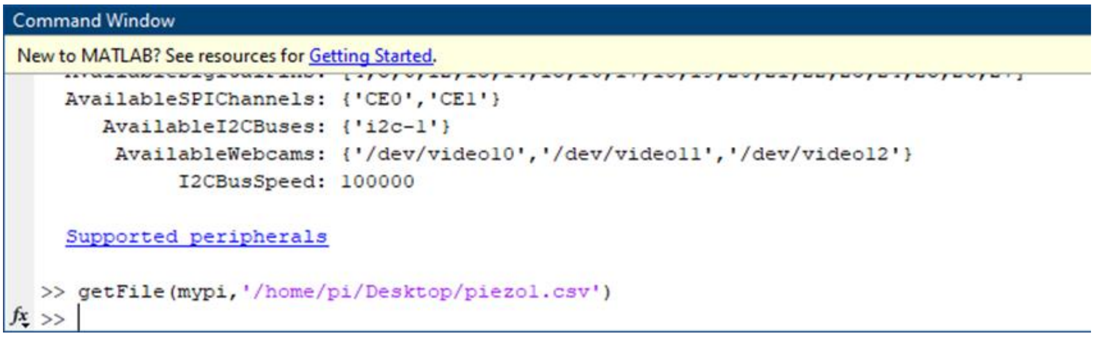


Figure 4.13: getFile Function in MATLAB

After setting up the raspberry pi hardware with MATLAB, the getFile function is typed in the command window of MATLAB. After this function is implemented, the CSV file named 'piezo1' is transferred from the raspberry pi to the MATLAB current folder on the laptop.

Figure 4.14 shows the piezo1.csv file in MATLAB current folder.

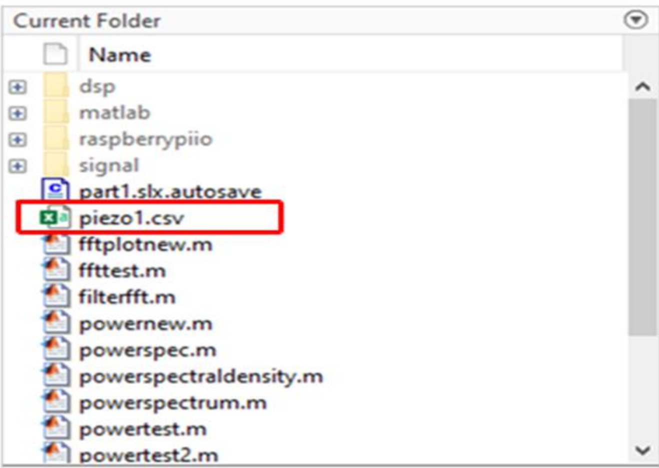


Figure 4.14: MATLAB Current Folder

The CSV file named 'piezo1' is transferred to the MATLAB current folder successfully.

Figure 4.15 shows the data import in MATLAB.

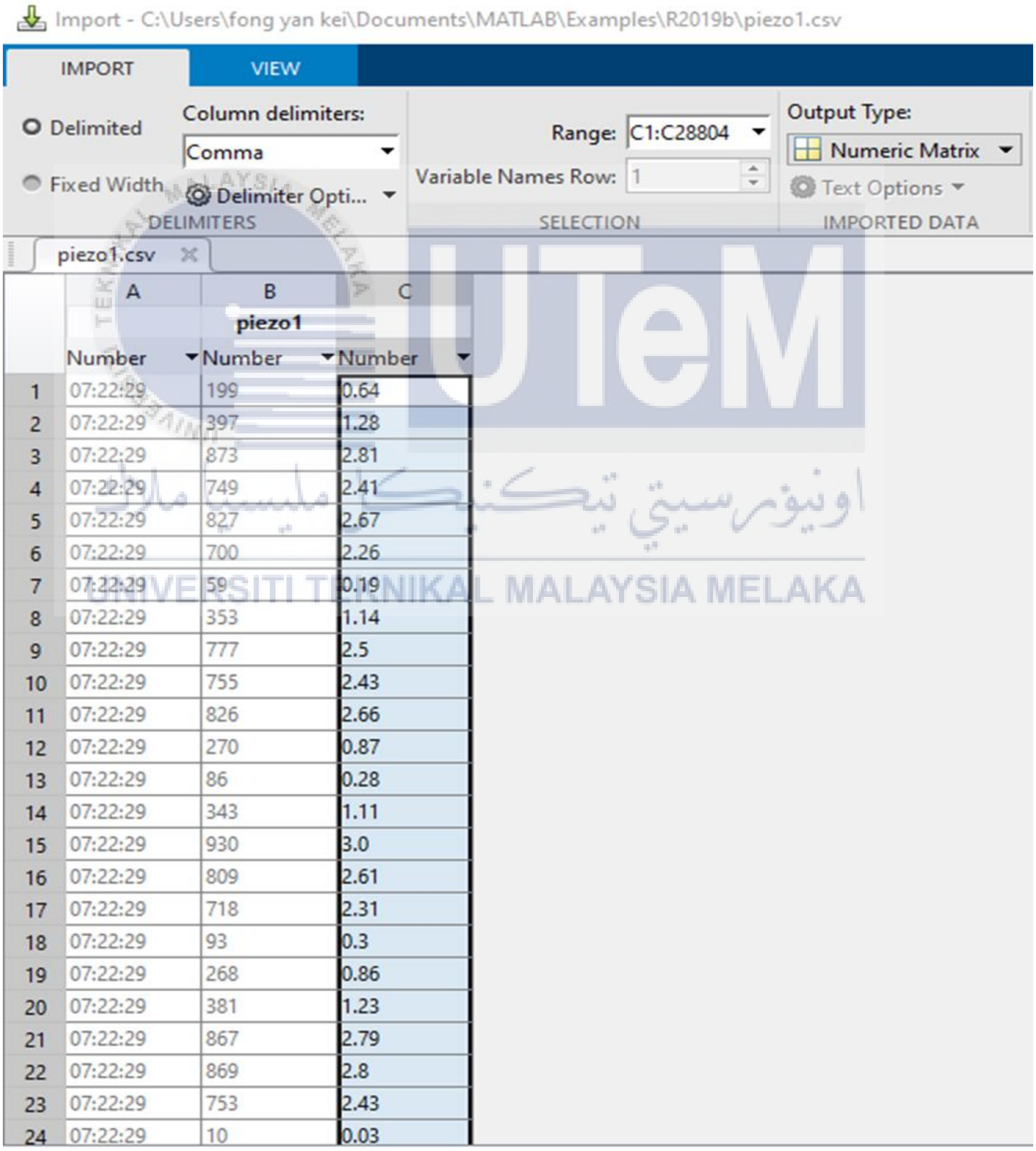


Figure 4.15: Data Import to MATLAB

The third column of the data is selected and imported to the MATLAB. The data will be divided into 3 parts, which are the first minute, second minute, and the third minute of the movement. Numeric matrix is chosen for the output type before importing the data. This is because the numeric matrix is easier to transpose using ctranspose function compared to the other type of output.

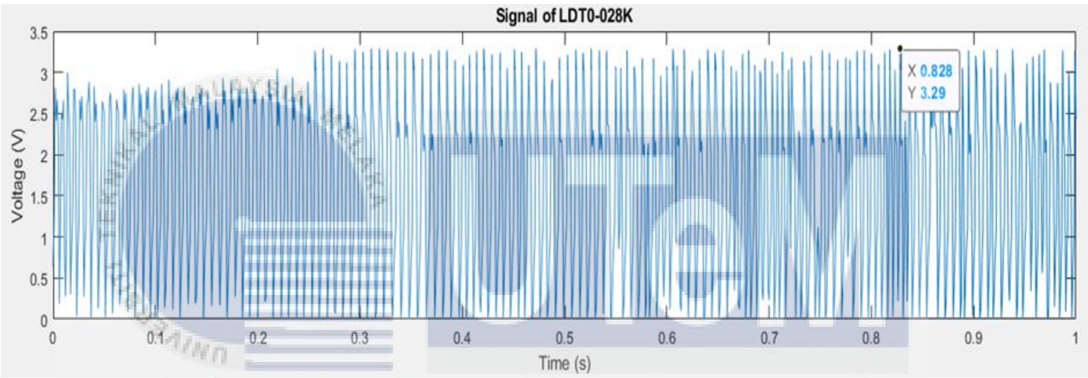


Figure 4.16: Time Domain Graph of LDT0-028K Sensor Signal for 1 Second

The time domain graph of LDT0-028K sensor signal for 1 second is plotted by MATLAB as shown in Figure 4.16. The highest voltage of the signal is equal to 3.29V. It will not exceed 3.3V because the reference voltage of MCP3008 set as 3.3V.

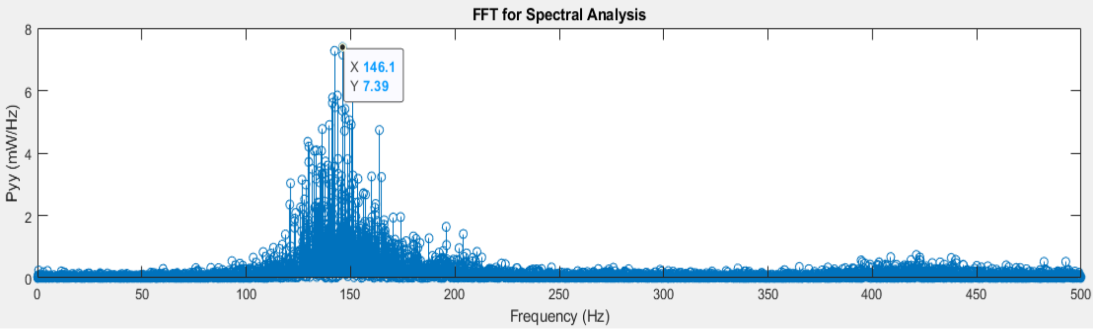


Figure 4.17: Frequency Domain Graph of LDT0-028K Sensor Signal at the 1st Minute

The frequency domain graph of LDT0-028K sensor signal at the 1st minute is plotted as shown in Figure 4.17. The time domain signal is transformed to the frequency domain using the fft function in MATLAB. The Pyy of the signal is equal to 7.39mW/Hz. The Pyy of the signal can be calculated by MATLAB using the formula of $P_{yy} = (1/(2 * pi * NFFT)) * abs(Y).\hat{}2$. The power spectral density is proportional to the absolute value squared of the Y. The frequency where the highest point located is equal to 146.1Hz.

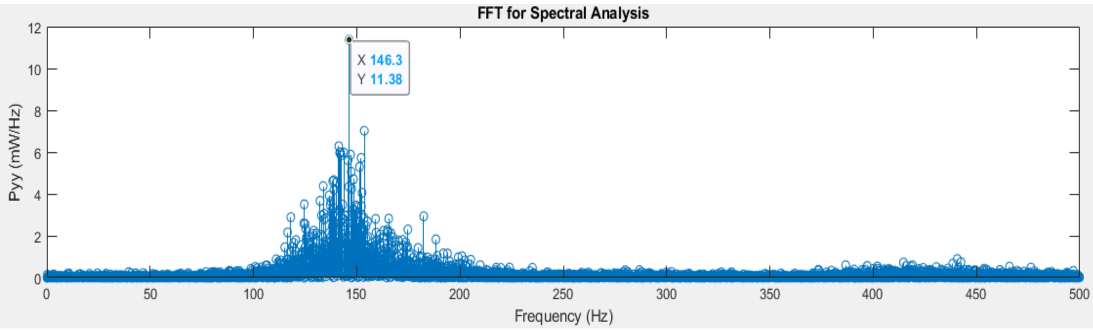


Figure 4.18: Frequency Domain Graph of LDT0-028K Sensor Signal at the 2nd Minute

The frequency domain graph of LDT0-028K sensor signal at the 2nd minute is plotted as shown in Figure 4.18. The time domain signal is transformed to the frequency domain using the fft function in MATLAB. The Pyy of the signal is equal to 11.38mW/Hz. The Pyy of the signal can be calculated by MATLAB using the formula of $P_{yy} = (1/(2 * pi * NFFT)) * abs(Y).\hat{}2$. The power spectral density is proportional to the absolute value squared of the Y. The frequency where the highest point located is equal to 146.2 Hz.

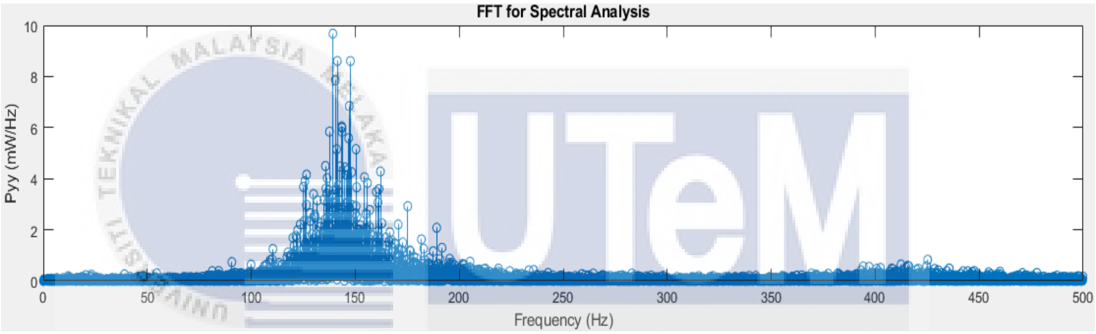


Figure 4.19: Frequency Domain Graph of LDT0-028K Sensor Signal at the 3rd Minute

The frequency domain graph of LDT0-028K sensor signal at the 3rd minute is plotted as shown in Figure 4.19. The time domain signal is transformed to the frequency domain using the fft function in MATLAB. The Pyy of the signal is equal to 9.676mW/Hz. The Pyy of the signal can be calculated by MATLAB using the formula of $P_{yy} = (1/(2 * pi * NFFT)) * abs(Y).\hat{}2$. The power spectral density is proportional to the absolute value squared of the Y. The frequency where the highest point located is equal to 139.2 Hz.

From the three frequency domain graphs of signal, the frequency of the signal is decreased from the 1st minute to the 3rd minute. The frequency of the signal is decreased from 146.1Hz to 139.2Hz. The transition of the signal from high frequency to low frequency indicate the feature of muscle fatigue. Therefore, it can be concluded the muscle starts to undergo fatigue at the 3rd minute.

4.4 Conclusion

From the results and discussion, the characterization of LDT0-028K from the experiment is in agreement with the theory of piezoelectric sensor, which is voltage output proportional to the force applied on the sensor. The simulation of output voltage in the charge amplifier circuit is at the range of 0V to 3.3V. From the simulation result, the designed bandpass filter has a cut-off frequency between 35Hz to 410Hz. The signal of lifting movement is transformed to the frequency domain with the FFT method in MATLAB successfully. The signal is located at the frequency range of 34Hz to 408Hz, and it is managed to analyze based on the frequency distribution in the frequency domain graph.

CHAPTER 5:

CONCLUSION AND FUTURE WORKS

5.1 Overview

A wearable belt-typed electronic is designed and tested in this project. The wearable belt-typed electronic consists of a piezoelectric film sensor, a signal condition circuit, and a microprocessor raspberry pi. The signal conditioning circuit made up of a charge amplifier circuit and a bandpass filter. The output voltage of the piezoelectric film sensor from the signal conditioning circuit is at the range of 0V to 3.3V. The time domain graph of the LTD0-028K sensor signal can be transformed to the frequency domain graph. The frequency range for LTD0-028K sensor signal caused by the movement of lifting a bottle of water (500ml) is lined at 35Hz to 410Hz. For the signal analysis, there is a transition of the signal from high frequency to low frequency. This shows the feature of muscle fatigue. It can be concluded that the prototype can perform in the detection of muscle fatigue.

5.2 Future Work

The wearable belt-typed electronic can be used to measure the piezoelectric film sensor signals caused by muscle activity. The real-time data of the piezoelectric film sensor signal can be obtained and uploaded to the cloud platform, such as ThingSpeak using IoT. Furthermore, the MATLAB analysis can be done in ThingSpeak. If any fatigue muscle is detected, a notification can be made by connecting the IFTTT app with ThingSpeak, so that it can alert the users.

Besides, a GUI can be made by the MIT App Inventor. The MIT App Inventor can be downloaded in the Google Play Store. The raspberry pi can be controlled with the GUI using the smartphone. This can enhance the interface between users and the electronic device. Figure 5.1 shows the wearable electronic using IoT.

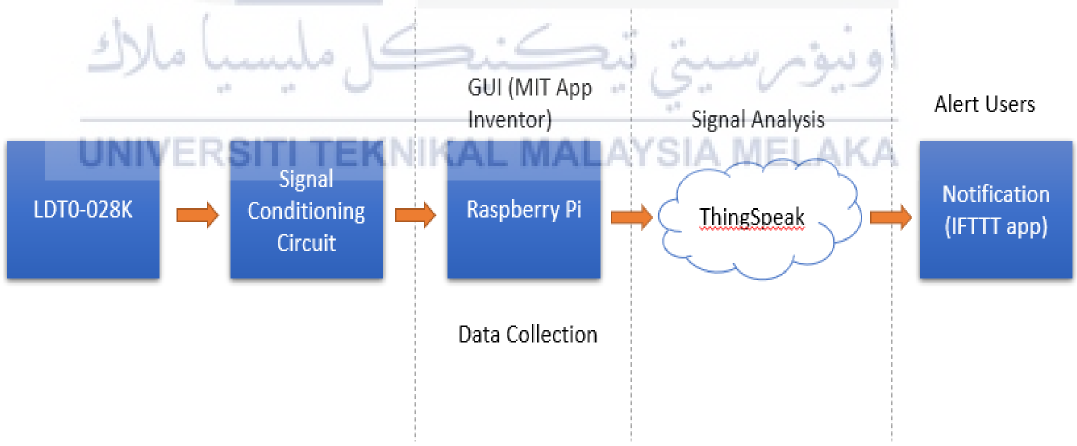


Figure 5.1: Wearable electronic using IoT

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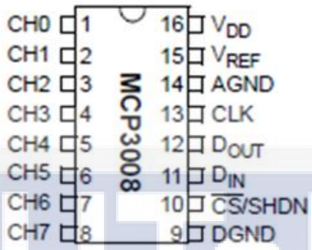
APPENDIX A

PDIP, SOIC



EQUATION 4-1: LSB SIZE CALCULATION

$$LSB\ Size = \frac{V_{REF}}{1024}$$

The theoretical digital output code produced by the A/D converter is a function of the analog input signal and the reference input, as shown below.

EQUATION 4-2: DIGITAL OUTPUT CODE CALCULATION

$$Digital\ Output\ Code = \frac{1024 \times V_{IN}}{V_{REF}}$$

Where:

V_{IN} = analog input voltage

V_{REF} = analog input voltage

When using an external voltage reference device, the system designer should always refer to the manufacturer's recommendations for circuit layout. Any instability in the operation of the reference device will have a direct effect on the operation of the A/D converter.