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DESIGN AND MANUFACTURING OF A SMALL-SCALE ENERGY HARVESTING DEMONSTRATION MODEL FOR VIBRATIONS LAB

A Project Report

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DECLARATION

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ACKNOWLEDGEMENT

We are thankful to Allah Almighty, the most Merciful and the most Beneficent, for the blessings, courage, and the intellect He has bestowed us with, because of which it became possible for us to accomplish such a crucial and remarkable goal. We are thankful to our parents and the family for their constant support and encouragement through each thick and thin. We are much obliged to our supervisor Dr. Rashid Naseer for their continuous guidance and the valuable time they spent on providing us the support and the encouragement through each stage. without their efforts we would have never been able to achieve that much. Moreover, we are grateful to all our fellows, course mates and friends who supported us both intellectually and emotionally with their excellent co-operation and support during this study. Our sincere thanks to all the lecturers and members of the staff of the Department of Mechanical Engineering, CEME, who helped us in many ways and made our education journey at CEME pleasant and unforgettable. We are hopeful that this project will add value to the peoples' life and would be developed further to adopt this technology on a massive level.

Lastly, we would like to thank any person which contributes to our final year project directly or indirectly. We would like to acknowledge their comments and suggestions, which was crucial for the successful completion of this study.

ABSTRACT

The increasing demand of energy has highlighted the exploration of alternate sources of energy. Non- renewable energy sources such as fossil fuels will run out one day. Moreover, the potential harm done to the environment with their consumption has risen the need of green and environmentally friendly energy sources. Piezoelectric based energy harvesters are gaining popularity in this regard due to their light weight, ease of application, flexibility, and environment friendly nature. Piezoelectric materials produce an electric current when placed under mechanical stress.

In this project, we will create a small-scale demonstration model to depict the phenomenon of piezoelectric energy harvesting. The model will be used afterwards as a lab equipment in the Vibrations lab. The mechanical loading on the piezoelectric material will generate electric current. The generated current can be used either to light up an LED or to charge a battery so that energy can be stored for future use. The internal circuit consisting of Arduino UNO and multiple sensors will be used to find the numeric values of concerned parameters and to plot their respective graphs. The demonstration model can store data on an SD card or it can be shown on the display screen. The model is a good addition to the Vibrations Lab and will provide future students with an insight of this growing field of energy harvesting.

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Chapter 1: Introduction

1.1. Background

The consumption of fossil fuels and the increase in environmental pollution have necessitated the development of green and renewable ways to harvest energy from nature. For instance, the power generation from water has mainly contributed to the daily energy consumption however, it mainly exists in the form of hydropower, where a large altitude and the construction of big dams are needed. In 2020, global hydropower consumption reached its peak, at some 38.2 exajoules. Thermal power plants convert fossil fuel energy to electricity. For this purpose, large coal power plants are required which account for 50% of global final energy consumption in 2018 and contribute 40% of global carbon dioxide (CO2) emissions. [1]

The increasing electricity demand and the increased consumption of non-renewable energy sources have forced researchers to explore alternative energy sources that can harvest energies available in the ambient environment. Renewable electricity technologies have scaled up, from a total global supply of 1,454 GW in 2011 to 2,167 GW in 2017 [2], which is quite low as compared to hydropower or thermal power energy production.

Mechanical energy is widely abundant in the ambient environment that can be captured and converted into useful electric power. Various energy harvesting techniques have been repeatedly proposed by researchers in the past to utilize the ambient sources of energy like wind [3], solar [4], sound [5], heat [6], wave [7], vibration energies [8] and their synergic combination [9]. To devise ways to transform vibrational energy into electric energy, many exploratory research works have been carried out by research scholars from different countries in recent years. At present, the devices that collect environmental vibrational energy can be divided into electromagnetic type [10], electrostatic type [11], and piezoelectric type according to the difference in transformation principles [12].

One such method that can capture the stress/strain on different materials and convert it into useful electric power is the use of piezoelectric transducers. The principle is based on the positive piezoelectric effect of piezoelectric material: when piezoelectric material deforms under external force (pressure or stress), an inside polarization phenomenon occurs, and charges of different polarity accumulate on two opposite surfaces. If an intermittent external force is continuously exerted on a piezoelectric material, the charges appearing on the surfaces are simultaneously collected by the charge collector and stored in energy storage equipment, and then the transition from mechanical energy to electric energy is realized. Therefore, piezoelectric power generation is a new type of green power generation without pollution, electromagnetic interference (EMI), thermal radiation, and noise. [13]

In the late nineteenth century, it was discovered by the Curie brothers that several natural materials, including quartz and Rochelle salt, showed an interesting property. Piezoelectric materials are those that possess the ability to produce an electric field when subjected to mechanical stress. This ability is referred to as the piezoelectric effect [14]. On the other hand, piezoelectric materials also exhibit the inverse piezoelectric effect, the production of mechanical strain when subjected to the electric field. Elvin et al. carried out both experimental and theoretical analyses of a simple mechanical strain energy sensor with wireless communication [15]. H. W. Kim investigated the capability of harvesting the electrical energy from mechanical vibrations in a dynamic environment through a ‘‘cymbal’’ piezoelectric transducer [16]. Targeted mechanical vibrations lie in the range of 50–150 Hz with a force amplitude in the order of 1 kN (automobile engine vibration level). Ericka et al. investigated ways to improve the power harvested from ambient vibrations with a unimorph membrane transducer, which consisted of a circular PZT layer bonded to a circular brass layer and was attached to the inner surface of a thick aluminum ring [17]. Petr Sadilek and Robert Zemcik (2010) performed a frequency response analysis of hybrid AL. Beam with piezoelectric actuators using the finite element method [18]. Piezoelectric materials have been used to actuate active structures, pump fluid, sense strains [19] - [20], generate ultrasonic waves in structural health monitoring of components [21] [22], provide active motion or vibration control to structures, in noise suppression, to create and detect sound and to generate electricity in energy harvesting applications [23]. The ultimate objective of many researchers is how to use the natural energy sources to generate inexhaustible electric energy and to operate self-powered devices including microelectromechanical systems or actuators [24] [25], health monitoring and wireless sensors [26], cameras [27], pacemakers [28], cell phones [29], or replacing small batteries that have a finite life span or would require hard and expensive maintenance [30]. Therefore, the target of energy harvesting is to operate autonomous powered electronic devices over their lifetime. For powering electronic devices, mechanical energy has received the most attention because it can be found in many places where thermal or light energy is not suitable. Piezoelectric transduction is the most suitable for harvesting mechanical energy through converting wasted vibrations to electrical energy such as used in MEMS devices [25] and wireless sensors [26] mostly because it can effectively be placed in small volumes and it can be used to harvest energy over a wide range of frequencies. Piezoelectric-based energy harvesters are gaining popularity due to their light weight, ease of application, and flexibility. The goal of this paper is to investigate the behavior of piezoelectric energy harvesting and to design and manufacture a demonstration model that will depict this phenomenon. The model will demonstrate the generation of electric current and potential difference concerning the applied force along with their relationship to the input parameters. Hence, parametric studies for input and output parameters can be conducted.

1.2. Motivation

The motivation behind choosing the FYP of creating a small-scale demonstration model for piezoelectric energy harvesting is to show the university undergraduate students how wasted energy in everyday life can be saved in a sustainable manner which can later be reutilized for different purposes. Another aim includes the introduction of piezoelectric materials, as they are a source of environmentally friendly energy. Piezoelectric energy harvesting causes no damage to the environment, requires less capital, has ease of application, is flexible, and can be applied on a larger or a smaller scale as required. In developing countries, there is a wide field of research and application of green energy and one of its direct sources can be the energy obtained from vibrations. Harvesting wasted energy using vibrations is an upcoming field of interest and the project will help in inculcating the interest as well as better understanding in students. As in Pakistan, the concept of green energy is still new, therefore a lot of research and applied work is required to excel in the future.

1.3. Objectives

- To design the outer frame and internal circuit of the demonstration model.
- To manufacture the demonstration model within the available resources.
- To demonstrate the phenomenon of piezoelectric energy harvesting.
- To carry out parametric studies.

1.4. Demonstration Model

The demonstration model of an object is similar to a small-scale prototype used to show the actual working and performance of the object. In laboratory equipment, the demonstration models are used to depict a phenomenon on a small scale. The purpose of creating a piezoelectric-based demonstration model is to show the basic phenomenon on which the material functions. The material, when placed under stress or strain, produces electrical energy. The demonstration model is designed in such a way that it will show how the generated piezo-electric energy can be harvested. The demonstration model will show the behavior of piezoelectric materials under the application of stress only.

The first demonstration of the direct piezoelectric effect is shown in Figure 1. It was made in 1880 by the brothers *Pierre Curie* and *Jacques Curie* [31]. They combined their knowledge of pyroelectricity with their understanding of the underlying crystal structures that gave rise to pyroelectricity to predict crystal behavior and demonstrated the effect using crystals of tourmaline, quartz, topaz, cane sugar, and Rochelle salt (sodium potassium tartrate tetrahydrate). Quartz and Rochelle salt exhibited the most piezoelectricity.

Figure 1 Piezoelectric quartz device that belonged to the Curie Laboratory courtesy of the Curie Museum

Chapter 2: Piezoelectric Materials

2.1. Introduction

Piezoelectric materials are materials that produce an electric current when they are placed under mechanical stress. The piezoelectric process is also reversible, so they will change shape slightly on the application of the electric current shown in Figure 2. Piezoelectric materials are the class of dielectric materials that can be polarized, in addition to an electric field.

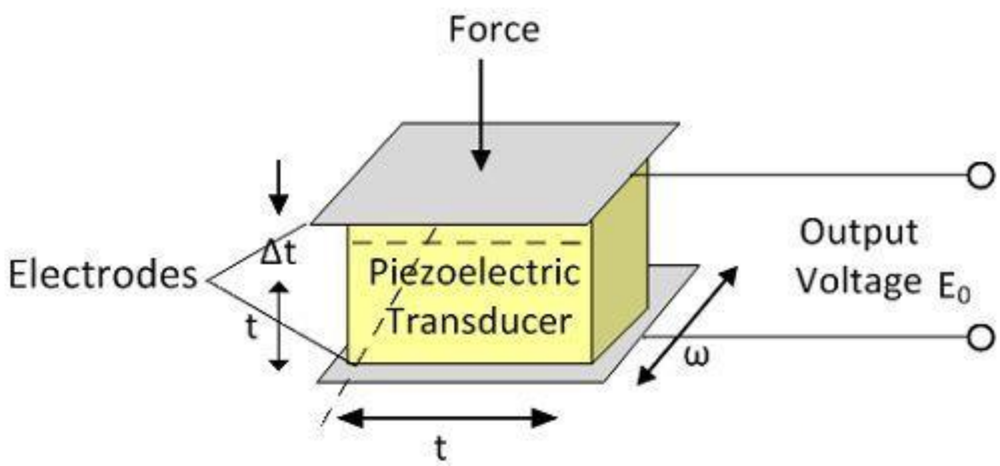

Figure 2 Piezoelectric phenomenon: Material deformation generates output voltages

2.2. Naturally existing and Manmade Synthetic Materials

Naturally occurring materials contain crystals that are anisotropic dielectrics with the non-centrosymmetric crystal lattice. Crystal materials like Quartz, Rochelle salt, Topaz, Tourmaline-group minerals, and some organic substances such as silk, wood, enamel, bone, hair, rubber, and dentin comes under this category. On the other hand, materials with ferroelectric properties are used to prepare synthetic piezoelectric materials. Manmade materials are grouped into five main categories – Quartz analogs, Ceramics, Polymers, Composites, and Thin Films.

In polymers, we have the materials like Polyvinylidene difluoride (PVDF). Similarly, for composites, piezo composites are the upgrade of piezopolymers. They can be of two types; *Piezo polymer* in which piezoelectric material is immersed in an electrically passive matrix. Piezo composites are made by using two different ceramics example BaTiO3 fibers reinforcing a PZT matrix. The manmade piezoelectric with crystal structure as perovskite: Barium titanate, Lead titanate, Lead zirconate titanate (PZT), Potassium niobate, Lithium niobate, Lithium tantalate, and other lead-free piezoelectric ceramics. The branch distribution is shown in Figure 3.

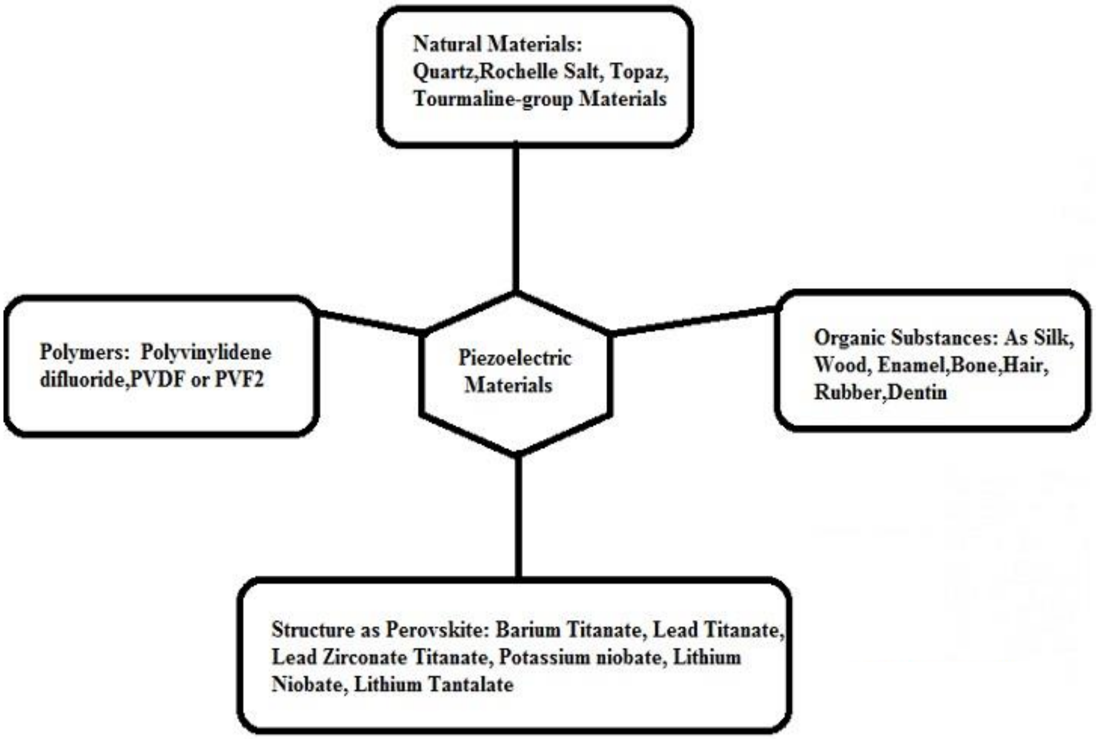

Figure 3 A Classification Diagram for Piezoelectric Materials

Piezoelectric ceramics are the materials commonly selected for piezoelectric elements used in energy harvesting devices because of their low cost, good piezoelectric properties, and ease of use in energy harvesting devices. Amongst all the piezoelectric ceramics, PZT is important because of its excellent piezoelectric properties and high Curie temperatures (the critical temperature above which piezoelectric materials lose their piezoelectricity). Based on a wide range of material property requirements for piezoelectric materials, over the last few decades, PZT has been expanded into a large family of ceramics that cover a broad range of properties by modifying its chemical composition or fabrication processes. PZT-5H and PZT-5A are some of the more frequently used ones. While piezoelectric ceramics in the form of thin layers have been favorable in piezoelectric energy harvesting studies based on vibrations, piezoelectric ceramic stacks can be used in energy harvesting from mechanical impacts.

PVDF (polyvinylidene difluoride) is the most frequently used piezoelectric polymer. It is a semi-crystalline polymer with a repeating unit of (CH_2-CF_2) and it contains about 50% crystals that are embedded in an amorphous matrix. Piezoelectric polymers are flexible and easy to deform, which makes them resilient to mechanical shock and also allows them to be easily mounted to curved surfaces. As varying forces are applied to the piezoelectric materials, different voltage readings corresponding to the force are displayed.

2.3. Comparison between PZT and PVDF

The proper choice of the piezoelectric material is of prime importance. An analysis of the two most commonly available piezoelectric materials - PZT and PVDF, tells us that the voltage from PZT is greater than that of PVDF. The criterion for selection was better output voltage for various pressures applied. The results tell that PZT is better than the PVDF as shown by the voltage-current graph [32].

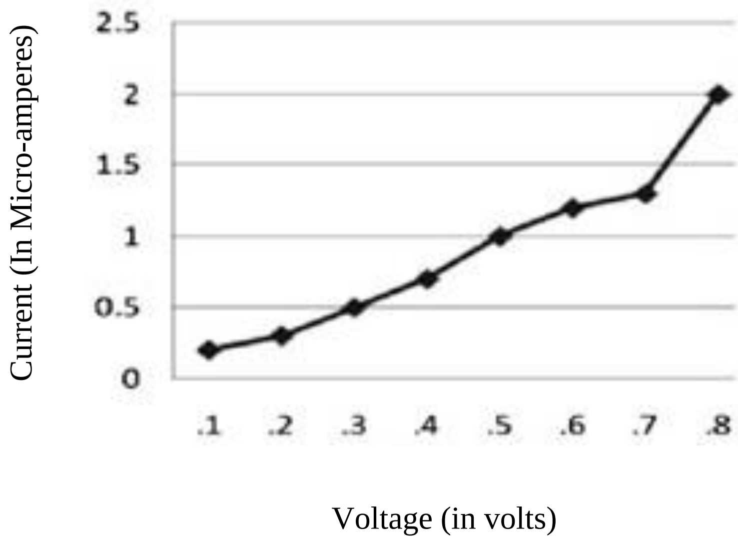

Figure 4 Voltage Current graph of PZT Materials [32]

2.4. Material Properties

Material properties that control the performance of piezoelectric energy harvesters are dielectric constant, piezoelectric strain coefficient, electro-mechanical coupling coefficient, young modulus, density, and electrical and mechanical quality factors. The above-mentioned favorable properties cannot be associated with one single material. However, lead-based materials have been reported for their best performance among all the known piezoelectric materials It is to be noted that lead has a negative impact on the environment because of its toxicity. Most countries have barred the use of lead in all applications. In this context, scientists are now working toward new materials with comparable or better performance than lead-based materials. Several lead-free piezoelectric ceramics are reported for various promising device applications. $K_{0.5}Na_{0.5}NbO_3$ (KNN)-based materials are promising piezoelectric materials for futuristic applications.

Chapter 3: Energy Harvesting

3.1. Introduction

Energy harvesting is defined as capturing minute amounts of energy from one or more of the surrounding energy sources, accumulating them, and storing them for later use. With recent advances in wireless and MEMS technology, energy harvesting is highlighted as the alternative to the conventional battery. The replacement or recharging of the battery is inefficient and sometimes impossible. Therefore, a great amount of research has been conducted about energy harvesting technology as a self-power source for portable devices or wireless sensor network systems. Human beings are already harvesting energy in the form of the windmill, watermill, geothermal and solar energy. The energy came from natural sources, called renewable energy, is emerged as a future power source. Since the renewable energy harvesting plants generate kW or MW level power, it is called macro energy harvesting technology. Micro energy harvesting technology is mostly based on mechanical vibration, mechanical stress and strain, thermal energy from furnace, heaters and friction sources, sunlight or room light, human body, and chemical or biological sources, which can generate *mW* or µW level power.

Vibration-based energy harvesting has received growing attention over the last decade. The research motivation in this field is due to the reduced power requirement of small electronic components, such as the wireless sensor networks used in passive and active monitoring applications. The ultimate goal in his research field is to power such small electronic devices by using the vibrational energy available in their environment. If this can be achieved, the requirement for external power sources, as well as the maintenance costs for periodic battery replacement and the chemical waste of conventional batteries, can be reduced.

The piezoelectric transducers can convert mechanical vibration into electrical energy with a very simple application structure. Among the available vibration energy harvesting methodologies, piezoelectric-based approaches are widely recognized because of the relatively high energy density. Piezoelectric materials have been explored significantly for a diversified range of sensor, actuator, and energy harvesting applications. [33]

3.2. Power Generation from Shoe Mounted Device

Walking is the most common activity in day-to-day life. When a person walks, he loses energy on the road surface through footfalls on the ground during every step. A 68 Kg person, walking with a normal stepping frequency of 2 steps/ sec., delivers the energy of about 70 watts to the ground. A new startup called Sole Power has come up with a shoe insert that creates power as you walk. It is envisaged that this power will be sufficient to charge cell phones and other smart electronic devices. The power-generating shoes are of special interest to the army as soldiers are often stationed at places where electricity is not available. The continuous march of soldiers and training drills can produce sufficient energy which can be used or stored afterward.

The piezoelectric device is fixed on a base with rivets on one side, and spring is inserted between the piezoelectric device and the base. A basic model is shown in Figure 5. The advantage of this structure is the second-generation effect. The first-generation effect occurs when the PEH is pushed. During this period, the spring is compressed. Alternatively, the second-generation effect occurs during the recovery period of the spring. [34]

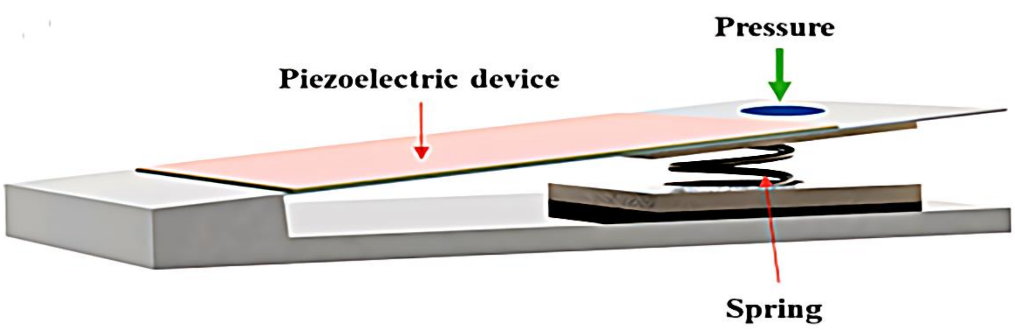

Figure 5 Footstep Power Generation [32]

3.3. Power generation from Roads

The piezoelectric energy-generating roads have been proposed in various cities of the world [35]. The design is based on the positive effect of piezoelectricity that is produced in response to mechanical stress applied to some solid materials like crystals and ceramics. The design proposes the placement of piezoelectric sensors beneath the road surface which would produce electricity from the vibration caused by the movement of vehicles on road. When applied on road, the piezoelectric technology could produce up to 44 megawatts of electricity per year from one kilometer stretch of the road and meet the energy demand of about 30,800 households

[35]. Another research conducted to gauge the energy harvested from road pavements showed that the maximum voltage that could be reached is 65.2 V. The primary wheel rolling impact could produce electric energy of 0.23 mJ. The electric capacity of 0.8 kW/h could be produced per day, which can at least meet the demand for signal lights. [36]

Roadways are a great energy source due to the loads exerted by the millions of vehicles passing on them which produce a significant number of vibrations. These vibrations can be used to generate sufficient electricity to power traffic lights, structural health monitoring (SHM) systems, and charge electric vehicles. The roads which produce electricity by application of mechanical energy when the vehicle moves over the road, those roads are called piezoelectric roads. Piezoelectric materials are among the smart materials used to harvest road vibrations as they generate an electrical voltage when induced by time-varying stress or strain. These materials are commonly shaped in the form of disks, plates, rings, and cylinders and can be embedded in types of cymbals, piles, stack, and cantilevers in asphalt pavements. Piezoelectric disks are suggested as an efficient stress-based energy harvester in asphalt pavements for their operation at lower frequencies. However, they may degrade both electrically and mechanically over time due to the induced cyclic stress [35]. Therefore, it is necessary to consider these effects while designing a piezoelectric energy harvester. The piezoelectric phenomenon is demonstrated in Figure 6.

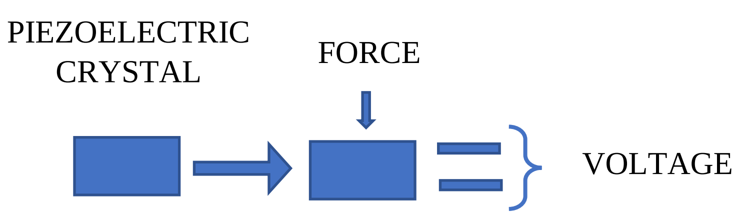

Figure 6 Demonstration of Force on Piezoelectric Crystal

3.4. Energy harvesting by Flow Induced Vibration

Wind energy is available all over the world. The continuous air flow produces vibrations which can be harvested using piezoelectric materials. The work done in this field is only been limited to the study of such vibrations which opens the field of application of these vibrations to our use. [39]

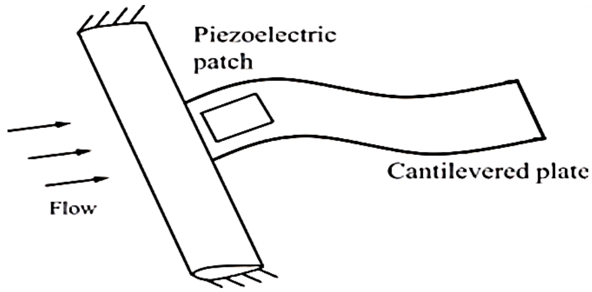

Figure 7 Energy Harvesting by Flow Induced Vibrations [39]

Generally, for vibrations in steady flow, the mutual interaction between fluid and structure is the most commonly observed scenario where structures become unstable as the flow velocity exceeds a critical value and undergo self-excited oscillations [39]. The energy harvesting model for Flow Induced Vibrations is shown in Figure 9. Air flow on a bluff body such as a cylinder makes it to vibrate. These vibrations can produce stress and strain on piezoelectric materials producing electric charges. These charges can be accumulated by means of a capacitor and other energy storing devices. The stored can afterwards be utilized to power devices such as an electric bulb or a surveillance camera.

3.5. Power from Vehicle Vibration/Suspension

Moving vehicles are subjected to different disturbances such as road irregularities, braking forces, acceleration forces, and centrifugal forces on a curved road which cause discomfort to the driver and passengers and influence maneuverability. Passive suspensions, composed of viscous hydraulic shock absorbers and springs in parallel, have been widely used to suppress the vibration by dissipating the undesired mechanical energy into heat waste. Reducing vehicle energy losses is necessary for improving fuel economy, reducing emissions, and supplying other power demands of the system [37]. In addition to improving engine and powertrain efficiency, we may also harvest the energy wasted in vehicles including the recovery of wasted heat energy, regenerative braking energy, and vibrational energy on shock absorbers. The power capacity is related to the vibration intensity levels meaning that the aggressive vibrations can collect more power and save more fuel which manifested obviously in case of heavy trucks and off-road vehicles. The power generation of different vehicles is shown in Figure 7. For example, as for the fuel cost saving, harvesting the otherwise dissipated energy from small road bumps in Wal-Mart trucks could save $13 million a year. [38]

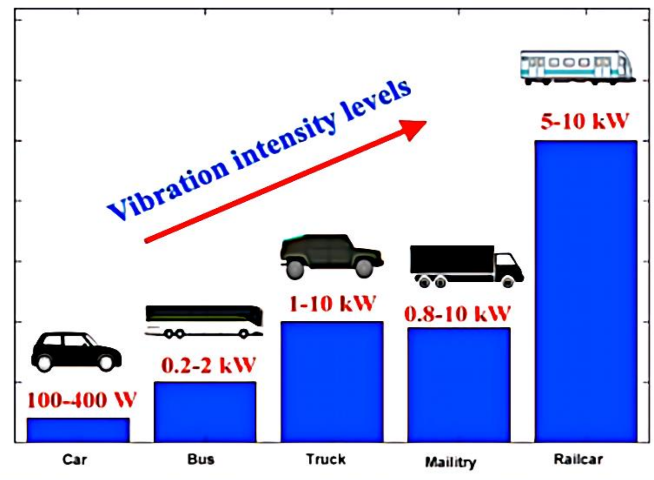

Figure 8 Power Generation from Suspensions of different vehicles [37]

As the wheel moves, the kinetic energy of the upward motion is converted into potential energy in the spring. This energy is stored in the compressed spring, and can be transferred to either the chassis or back to the wheel as kinetic energy through extension of the spring. Due to the greater inertia of the sprung mass, this energy does not cause quick acceleration of the chassis. The suspension allows the wheel to move relatively independent of the chassis, using the spring as a buffer between bumps in the road and bumps in the seat. The energy wasted at vehicle suspension system can be scavenged and stored in onboard vehicle batteries for improving mileage of electric vehicles. The lumped parameter model is shown in Figure 8.

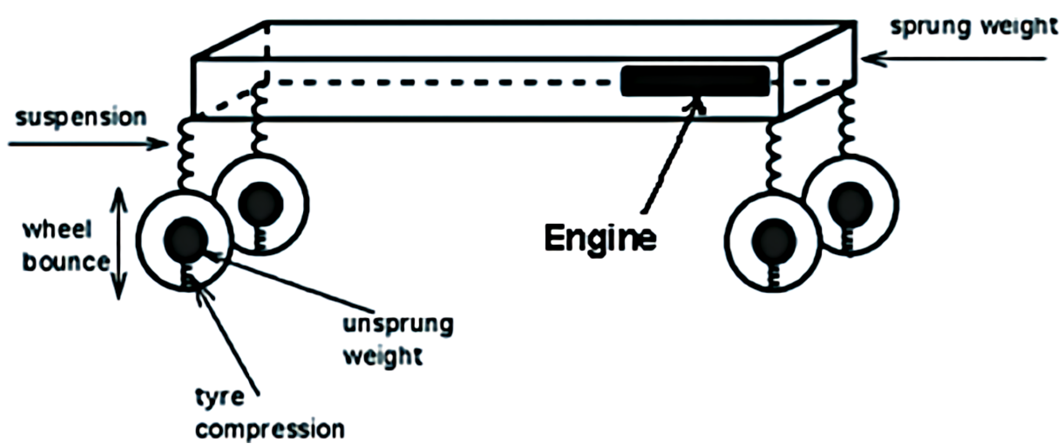

Figure 9 Lumped Parameter Model for Suspensions of Vehicles

Chapter 4: Methodology

The purpose of the project is to manufacture an experimental model that depicts the behavior of piezoelectric materials under loading. The methodology to be followed includes the completion of structural design that gives the basic idea of the project outlook. For this purpose, the CAD Model of the project is the initial step followed by its fabrication. The assembly of hardware components i.e., fitting of internal circuits in the outer frame and the internal circuit construction, the software portion which comprises of the coding to be done on a software. The fabrication of outer frame and the final testing of the model.

4.1. Flow Chart

The purpose of the flowchart is to describe the step-by-step procedure to be followed for the completion of the project. It simply describes the various steps of the project in a sequential order.

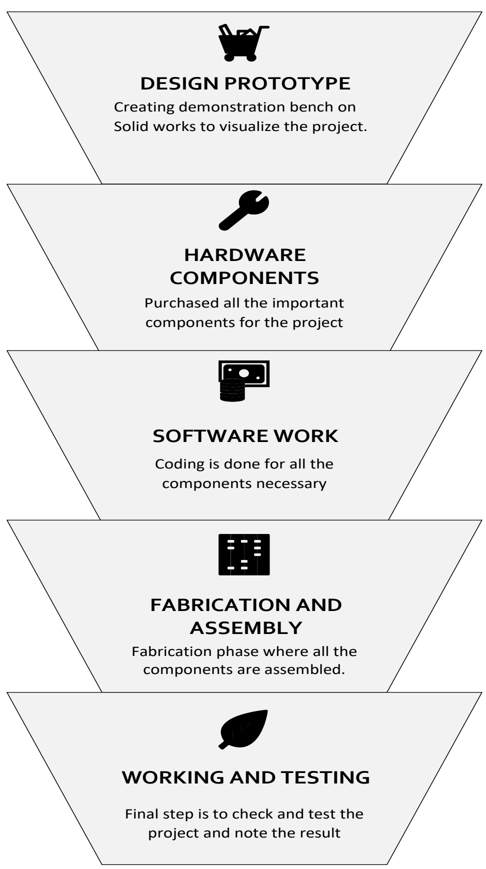

Figure 10 Step-by-Step Project Methodology

4.2. Block Diagram

The block diagram of the internal circuit shows how the demonstration model is supposed to work and it is prepared according to needs and requirements of the Final Year Project. The current through piezoelectric bank will be converted into DC by the help of a rectifier. The DC obtained, then can be supplied to the rechargeable battery or an LED. Arduino UNO takes input of current, voltage and load from sensors and then to display the output in the form of graphs that can either be displayed on screen or stored in a SD card. The block diagram gives the complete idea of the objectives to be accomplished from the circuit.

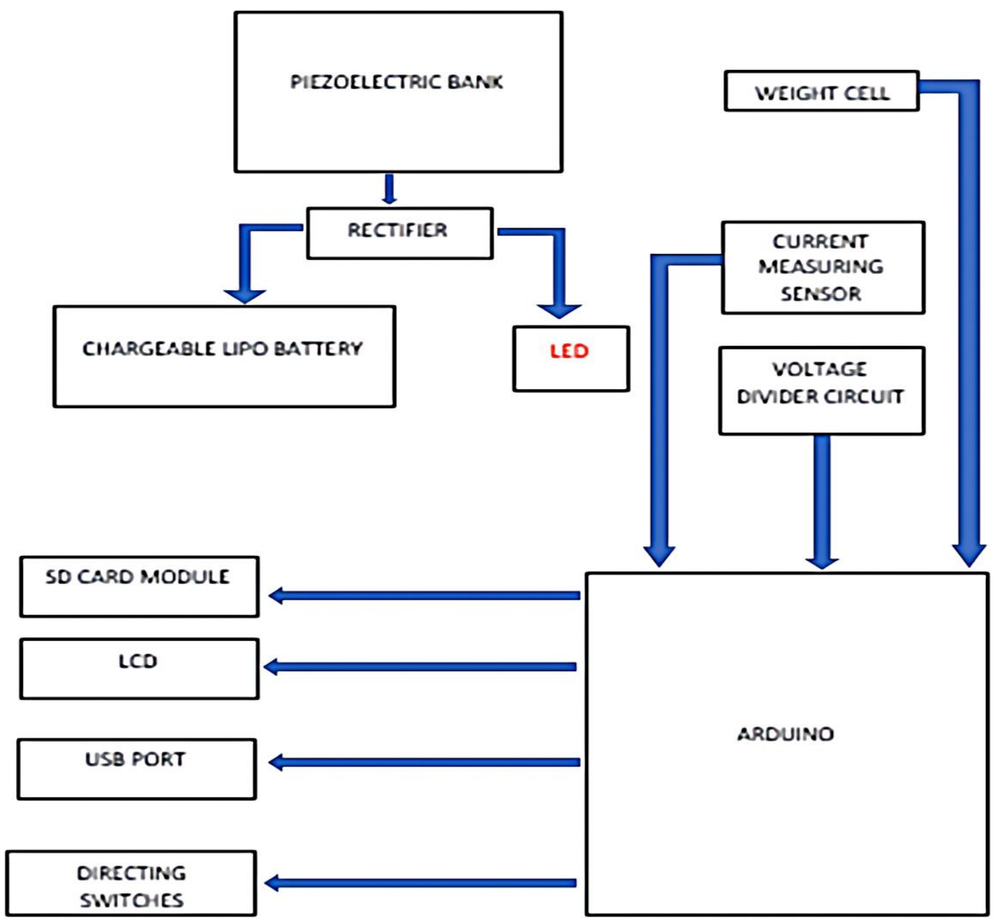

Figure 11 Block Diagram of Internal Circuit

Chapter 5: Internal Circuit Design

5.1. Circuit Diagram

The internal circuit diagram is shown in the Figure 12. The major components of the circuit and their respective connections are shown in the circuit diagram.

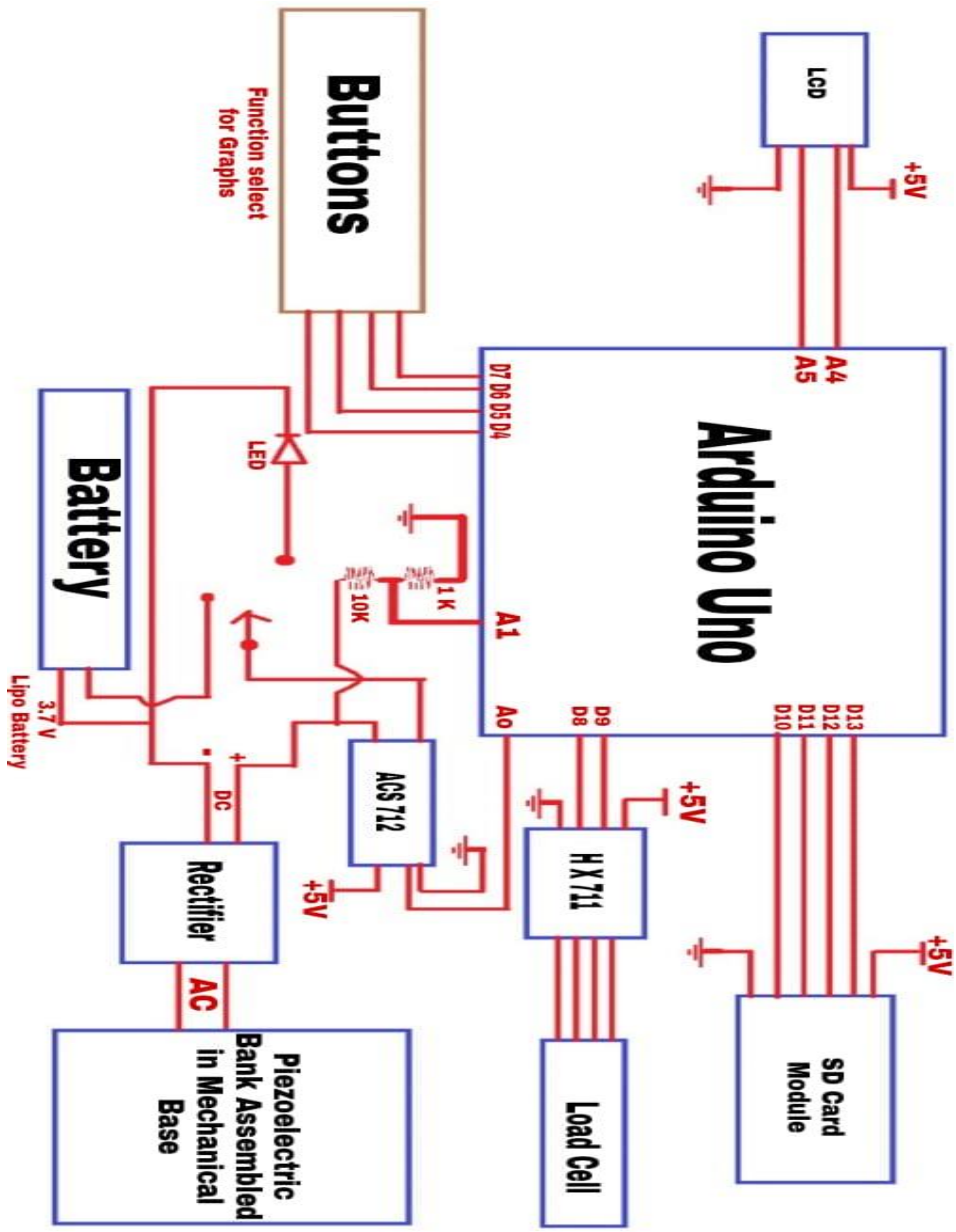

Figure 12 Circuit Diagram of the Project

5.2. Working of the Circuit

The circuit diagram gives the clear idea of how the circuit will work and the generated charge through piezoelectric materials will be utilized to perform the desired objectives. The piezoelectric bank, consisting of multiple piezoelectric materials, will generate charge on the application of mechanical stress. The load cell is used to measure the applied weight. The purpose of load/weight cell is to digitalized the values of applied load. The amplifier HX711 is attached with the load cell. The charge generated through the piezoelectric bank will be in AC. Therefore, bridge rectifiers are used to convert AC into DC. A toggle switch is used to direct the direct current produced from the rectifier. The current can either be used to light the LED or to charge the LiPo battery. The generated DC is then directed to the Hall-Effect sensor (ACS712) which measures the current. A Voltage-Divider circuit is used to measure the voltage of the generated current. A variable resistor of known resistance is used for the construction of Voltage-Divider circuit. The Arduino UNO works as the brain of the circuit. It takes measured values of load, current and voltages from the sensors, calculate the power readings in milli watts, and then plot the graph for these values. The physical assembly of the circuit for testing is shown in Figure 13.

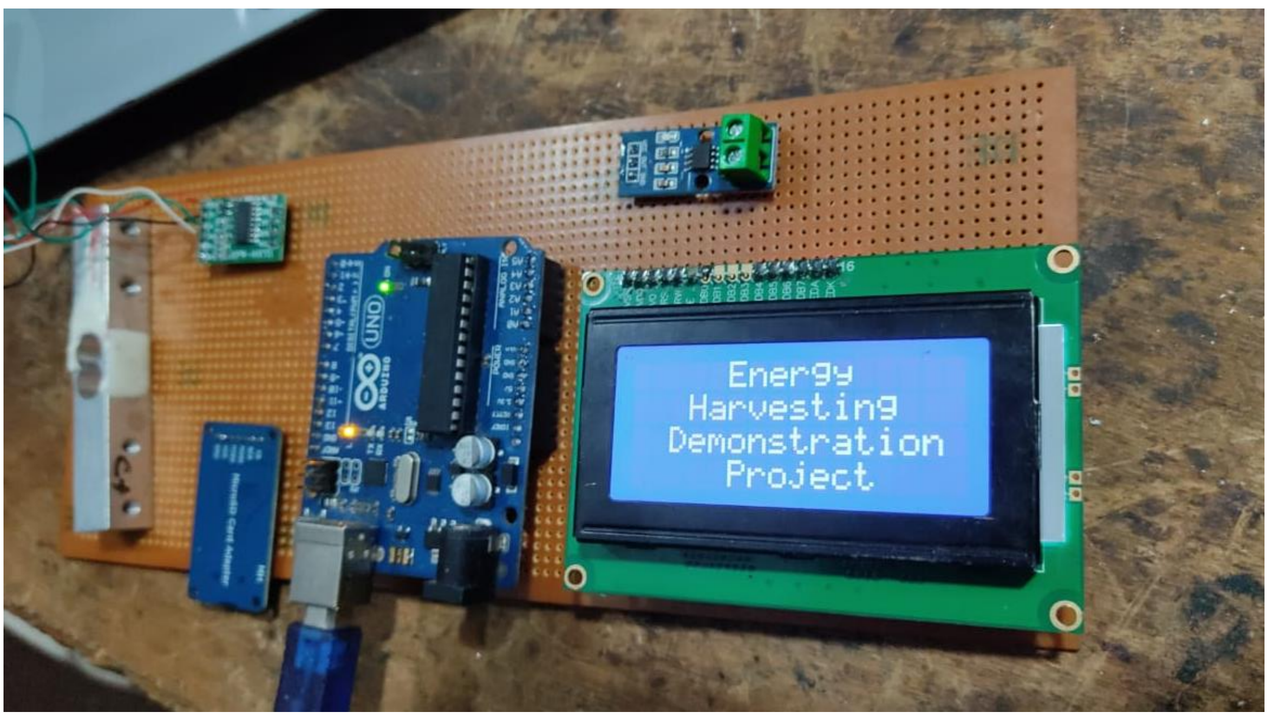

Figure 13 Physical Assembly of Circuit (Testing Phase)

A 16x4 LCD is used for the Arduino display. The LCD shows the changing values of the concerned parameters after every second. The I2C display protocol is used in the current circuit due to which six connection wires of LCD to Arduino can be reduced to only two connections. The graphs are generated through the function select buttons. The circuit can generate the graphs of voltage, current, load and power with reference to the number of samples in the serial plotter of the Arduino IDE. The readings of the experiment can be stored in the SD card or can be saved in an excel sheet and shown in real time when the setup is attached to a computer. The SD card module uses SPI (Serial Peripheral Interface) protocol and stores data in the SD card.

5.3. Components

5.3.1. Arduino UNO

Arduino UNO is a low-cost, flexible, and easy-to-use programmable open-source microcontroller board that can be integrated into a variety of electronic projects. This board can be interfaced with other Arduino boards, Arduino shields, Raspberry Pi boards and can control relays, LEDs, servos, and motors as an output. Arduino UNO features AVR microcontroller Atmega328, 6 analogue input pins, and 14 digital I/O pins out of which 6 are used as PWM output.

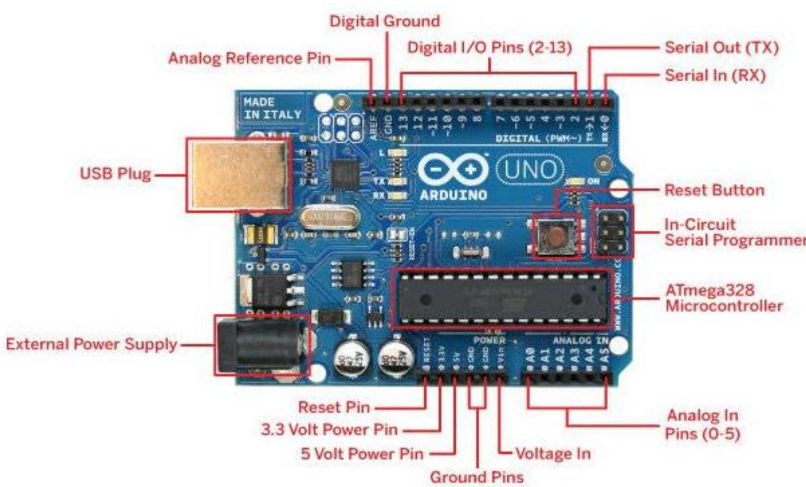

Figure 14 Arduino UNO

The board contains a USB interface i.e., USB cable is used to connect the board with the computer and Arduino IDE (Integrated Development Environment) software is used to program the board. The unit comes with 32KB flash memory that is used to store the number of instructions while the SRAM is 2KB and EEPROM is 1KB. A detailed description of an Arduino Uno is shown in Figure 14.The operating voltage of the unit is 5V which projects the microcontroller on the board and its associated circuitry operates at 5V while the input voltage ranges between 6V to 20V and the recommended input voltage ranges from 7V to 12V.

5.3.2. LCD Module (16 x 4)

LCD (Liquid Crystal Display) is a type of flat panel display which uses liquid crystals in its primary form of operation. LEDs have a large and varying set of use cases for consumers and businesses, as they can be commonly found in smartphones, televisions, computer monitors and instrument panels. LCDs were a big leap in terms of the technology they replaced, which include light-emitting diode (LED) and gas-plasma displays. LCDs consume much less power than LED and gas-display displays because they work on the principle of blocking light rather than emitting it. Where an LED emits light, the liquid crystals in an LCD produces an image using a backlight. A 16x4 display LCD is shown in Figure 15. The LCD uses I2C module to communicate with the arduino.

Figure 15 LCD (16x 4)

Table 1 Specification of display for LCD (16x4)

Item	Standard Value	Unit
Module Dimension	87.0 x 60.0	mm
Viewing Area	62.0 x 26.0	mm
Active Area	56.2 x 20.8	mm
Dot Size	0.55 x 0.55	mm
Character Size	2.95 x 4.75	mm

5.3.3. SD Card Module

The SD and micro-SD card modules allow communication with the memory card to write or read information on them. The module interfaces in the SPI protocol. A detailed description of the SD Card module is shown in Figure 16.

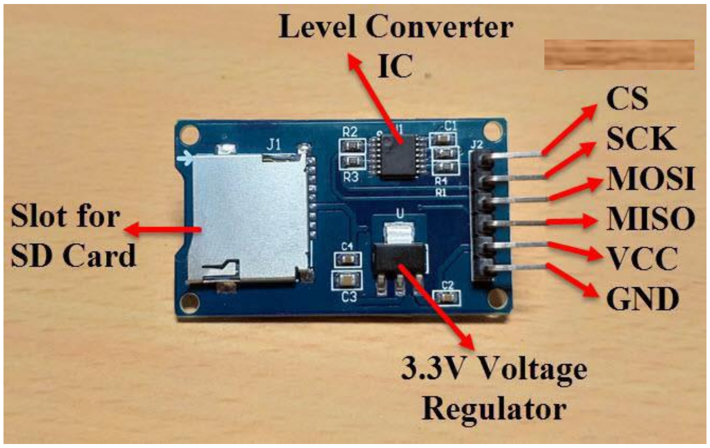

Figure 16 SD Card Module

To use these modules with Arduino SD library is required which is installed on the Arduino application by default. These modules cannot handle high-capacity memory cards. Usually, the maximum identifiable capacity of these modules is 2GB for SD cards, and 16GB for micro-SD cards. The module contains 6 pins for power and communicating with the controller. The table below describes the pin type and roll of each pin on the module.

Table 2 Description of Pins in SD Card Module

Pin Type	**Pin Description**
GND	Ground
VCC	Voltage input
MISO	Master in Slave Out (SPI)
MOSI	Master Out Slave In (SPI)
SCK	Serial Clock (SPI)
CS	Chip Select (SPI)

5.3.4. Hall Effect Sensor (ACS 712)

The purpose of the Hall Effect sensor is to measure the current values. It follows the principle that when an electric current flows through any material, the electrons within the current naturally move in a straight line, with the electricity creating its own magnetic field as it charges. If the material is placed between the poles of a permanent magnet, instead of moving in a straight line, the electrons will instead deviate into a curved path as they move through the material. This happens because their own magnetic field is reacting to the contrasting field of the permanent magnet. As a result of this new curved movement, more electrons are then present at one side of the electrically-charged material. Through this, a potential difference will appear across the material at right angles to the magnetic field, from both the permanent magnet and the flow of the electric current. Using semiconductors (such as silicon), Hall effect sensors work by measuring the changing voltage when the device is placed in a magnetic field. In other words, once a Hall effect sensor detects that it is now in a magnetic field, it is able to sense the position of objects.

Figure 17 ACS 712 Hall effect sensor

The ACS712 (as shown in Figure 17) is a fully integrated, hall effect-based linear current sensor with 2.1kVRMS voltage isolation and an integrated low-resistance current conductor. Technical terms aside, it’s simply put forth as a current sensor that uses its conductor to calculate and measure the amount of current applied.

5.3.5. Supply Adapter

A supply adapter or an AC adapter provides power supply to the electronic devices. Power adapters plug into a wall outlet and convert AC to a single DC voltage. The supply adaptor will be used in the circuit to power the Arduino when the Arduino is not powered by the USB interface.

5.3.6. LED

A light-emitting diode (LED) is a semiconductor device that emits light when an electric current is passed through it. Light is produced when the particles that carry the current (known as electrons and holes) combine together within the semiconductor material. As the direct recognition mode on piezoelectric power in this task, light-emitting diodes should take full consideration of the performance parameters of visual acuity, luminance, specified working condition and service life, of which the visual acuity of red light and green light in emitting colors is good.

5.3.7. LiPo Battery

A lithium polymer battery, or more correctly lithium-ion polymer battery is a rechargeable battery of lithium-ion technology using a polymer electrolyte instead of a liquid electrolyte. High conductivity semisolid (gel) polymers form this electrolyte. In the circuit, the purpose of LiPo battery is to store the current generated from the piezoelectric transducers thus showing the phenomenon of energy harvesting. A typical LiPo battery is shown in Figure 18.

Figure 18 LiPo Battery

5.3.8. Switches

The circuit consists of a main supply switch, a toggle switch and a few functions select switches. The main supply switch is responsible for turning the circuit ON or OFF. The toggle switch is used for shifting the circuit from lighting up LED to charging the battery and vice versa.

The function select switches are used to select various parameters for plotting the graph in the serial plotter of Arduino IDE.

5.3.9. Digital Voltmeter

Digital Voltmeter displays the voltage readings of a circuit numerically. Initially analog voltmeters were used to take the readings of the voltage in which a pointer or indicator moves across a scale in proportion to the voltage of the circuit. The digital voltmeter is used to display the voltage in the circuit apart from the values shown on the LCD Screen.

5.3.10 Variable Resistor

A 10k ohm 103 type variable resistor/potentiometer is used in the voltage-divider circuit. The variable resistors are used in various applications as they are flexible in changing the voltage values according to the requirement. In the circuit, variable resistor helps in measuring voltages and communicate the values to the Arduino board. The variable resistor used in the circuit is shown in figure 19.

Figure 19 10k ohm Horizontal-type Variable Resistor

Chapter 6: Piezoelectric Transducers Press

6.1. Introduction

Piezoelectric transducer press consists of upper and lower wooden frame. The lower wooden frame is mounded on load cell which is place in the middle of demonstration bench. The force is applied on upper wooden frame because of this force the spring compresses the piezoelectric transducers, and a potential difference is generated across the material. The transducers are arranged in a series and parallel combination to increase the amount of current generated and balance the high values of potential difference.

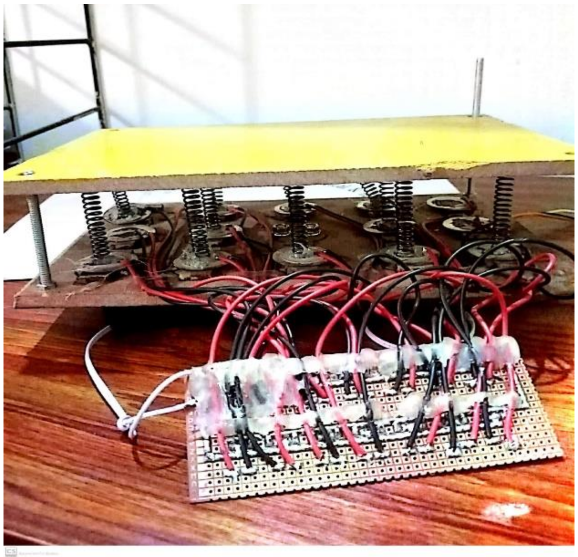

Figure 20 Piezoelectric Transducer Press (Testing Phase)

6.2. Piezoelectric transducer (Disc Type)

Piezoelectric discs generate voltage with applied force on it. These discs are shown in figure 20. They can be manufactured with two different procedure – unimorph and bimorph. Unimorph piezo discs are having one active piezoelectric layer and one non active layer, whereas bimorph piezo discs are having two active piezoelectric layers. The faces of the piezo disc are metallized, and the layers are bonded with either a conductive or nonconductive substrate, which acts as a base and stabilizer for the piezo circular disc. Unimorphs deform in a single direction when activated to generate the desired mechanical or electrical output. Piezo bimorphs are constructed of two active piezo ceramic layers with a passive metal substrate sandwiched in between. When a voltage is applied, the piezo disc deforms or contracts, bending the metal with it. The most displacement occurs at the center of the piezo ceramic disc, forming a dome or bowl. When this current is released, the metal springs back to its original state. Piezo ceramic discs are small, thin, lightweight, and quiet. They are highly efficient with low power consumption and fast response time.

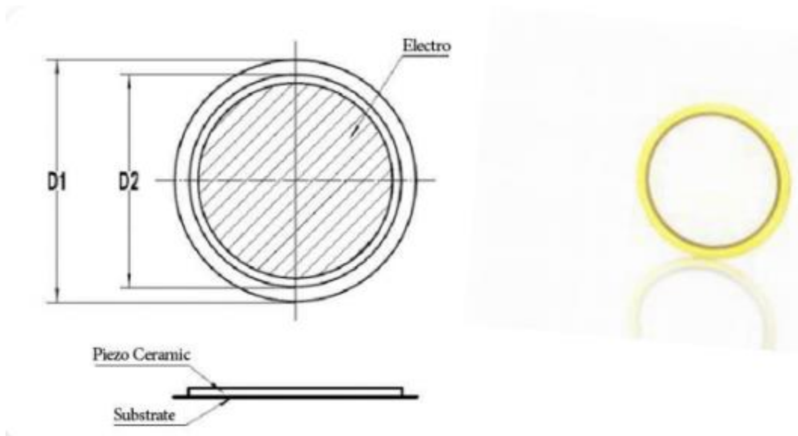

Figure 21 Piezoelectric Disc

6.3. Parallel Combination

The current generated from piezoelectric material is alternating current. The alternating current and voltage are converted to DC for usage. The piezoelectric discs are connected in parallel connection to increase the amount of current obtained. The maximum value of voltage through a single piezoelectric disc is 5-7 V. which is quite suitable but the current drawn is in micro-amperes. The current in series remains the same while the voltage in parallel remains the same. Therefore, parallel connections are used to improve the amount of current. In the circuit 14 piezoelectric discs are connected in parallel to increase the amount of current into milli-amperes.

The force applied must be the same on each crystal else the extra voltage from one crystal may affect the other crystals causing an inverse piezoelectric effect. The inverse piezoelectric effect converts electrical energy to mechanical energy. The main result of the discussion is to get a large amperage; therefore, a lot of parallel connections are made.

6.4. Load Cell

A load cell is a transducer which convert force into electrical output. This straight bar load cell can translate up to 10kg of pressure into an electrical signal. Each load cell can measure the electrical resistance that changes in response to, and proportional of, the strain applied to the bar.

With this gauge, it is possible to tell how heavy an object is, if an object's weight changes over time. Each straight bar load cell is made from an aluminum-alloy and can read a capacity of 10kg.

Figure 22 Load Cell position (Testing Phase)

The Load cell used in our project can measure load up to 10 kg. The load is applied on upper wooden frame with the push of hand which is sensed by the sensor and the load value is shown on LCD and the graph is plotted.

6.5. Helical Springs

The helical springs act as a bridge between upper wooden frame and the piezoelectric discs. When an upward force is applied, the springs are compressed. In this way, energy is stored in the springs. The stored energy is then used to compress the piezoelectric discs which produces the electric current. Another important feature of the springs is that it acts as a damper. The spring used is of very small diameter less than 0.5cm approximately.

6.6. Rectifier

A rectifier is an electrical component that converts alternating current (AC) to direct current (DC). A rectifier is analogous to a one-way valve that allows an electrical current to flow in only one direction. The process of converting AC current to DC current is known as rectification. The main rectifiers used with piezoelectric transducers are full wave rectifiers and bridge rectifiers.

Chapter 7: CAD Model and Fabrication

7.1. CAD Model

CAD (Computer Aided Design) or 3D Modelling is an essential and foremost component of designing process. Engineers, architects, and even artists utilize computers to assist in design projects. It basically gives the idea of the product in digital imagery and allows designers to test, refine and manipulate virtual products prior to their production. These high-quality 3D designs are identical in dimension and detail to the desired finished product, ensuring quality and accuracy for production.

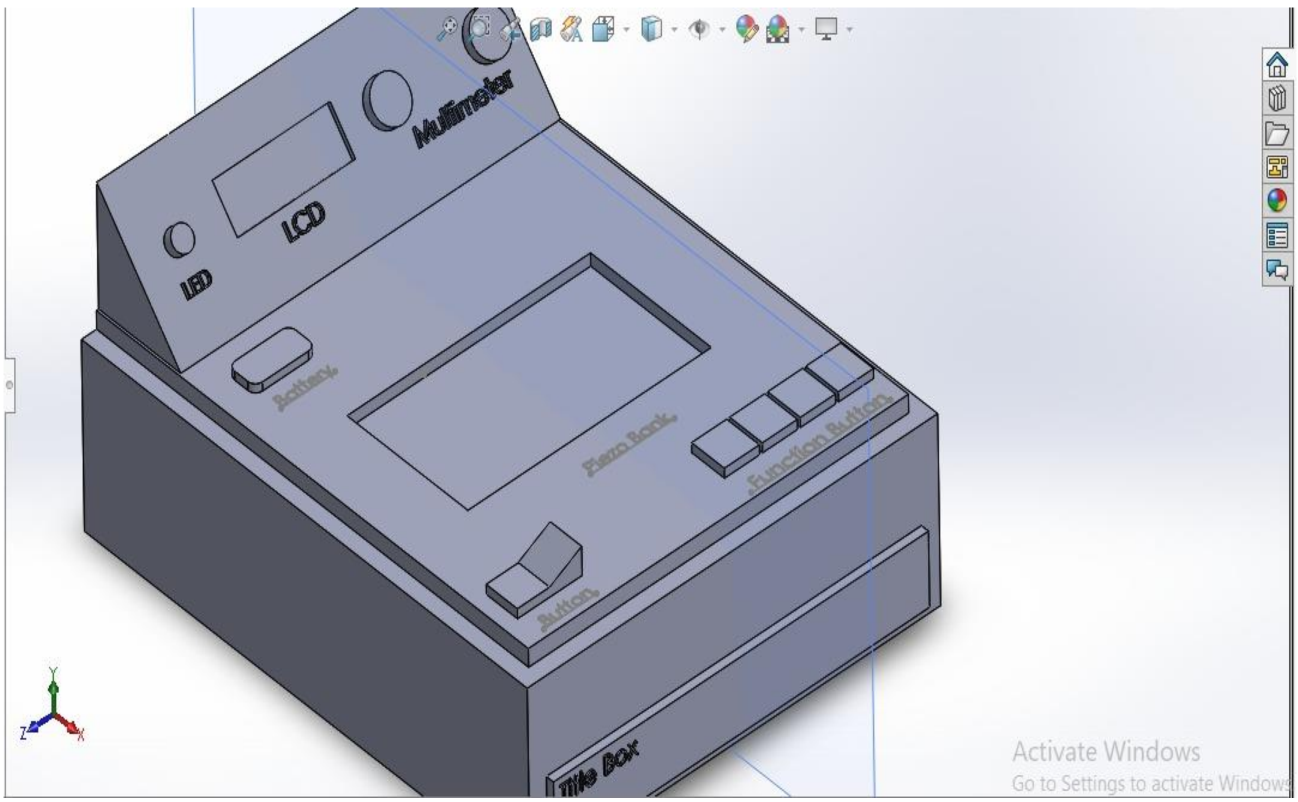

Figure 23 3D CAD Model on SolidWorks

The 3D CAD model of the project is shown in Figure 22. It is designed using Solid works to show the major components involved in the project and the give a realistic picture to our project. The components involved includes the Piezoelectric sensor press which is the main working area of the project. The press is placed at the center of the model on which weight could be added. The switches which include the Function Select switch and the Toggle switch is placed near the access of the user so that the user does not have to go beyond the piezoelectric sensor press plate to reach the switches. The display equipment which includes the LCD, Multi-meter screens and the LED is designed to be placed on an elevated surface. The reason behind the elevated surface is providing for the ease of the user. The user can easily see the displayed values of current and voltage from it and does not have to bend over the entire model to see them. A battery is also displayed to show the position of the battery in the model. The title box is present on the front side. The title box will represent the title of the project.

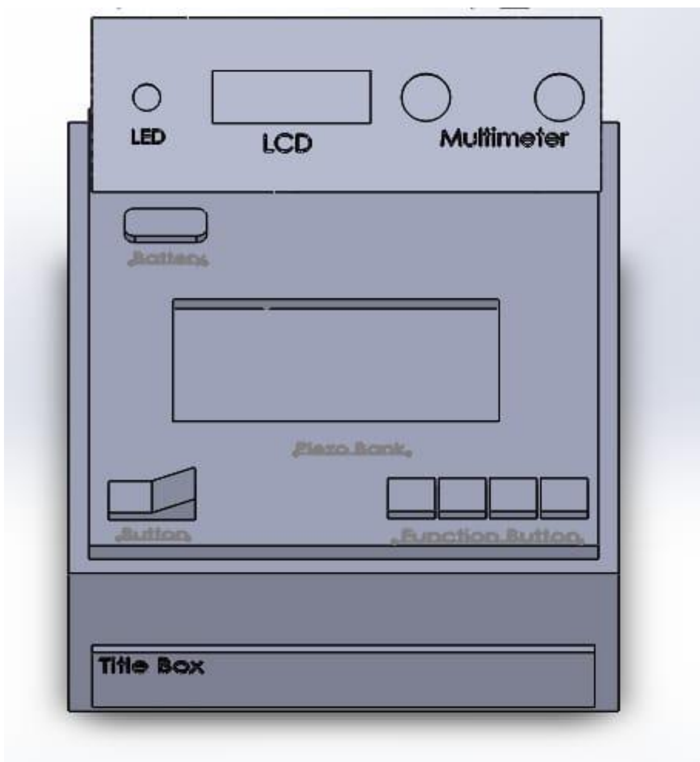

Figure 24 Top view of CAD Model on SolidWorks

The top view of the 3D model clearly shows all the components, their sizes and location in the demonstration model. Most of the area is covered by push-board located at the middle, where the load can be applied and parametric results can be seen on LCD.

7.2. Fabricated Outer Frame

7.2.1. Material Selection

From the market survey, multiple options were available for the material selection but for the model some critical properties such as high strength and robust nature was required. Due to this reason, the chosen material was mild steel. The mild steel is found to have the required properties. A few of them includes high tensile strength, high impact strength, good ductility and weldability.

Table 3 Properties of Mild Steel

Properties	Values
Young’s Modulus	200GPa
Poisson’s Ratio	0.31
Density	7750 Kg/m^3
Tensile Yield Strength	320 MPa
Tensile Ultimate Strength	400 MPa

7.2.2. Operations

To give the raw sheet of MS our desired shape and size, various operations are performed depending on the part of the model. Bending, cutting, drilling and welding are performed in the making of the outer frame. After the completion of the raw frame construction, the frame is polished to give a fine outlook. The last step involved was the painting of the model in blue and white.

7.2.3. Powder Coated Paint

The final frame work is painted used the powder coating. Powder coatings can produce much thicker coatings than conventional liquid coatings without running or sagging. Powder coated items generally have fewer appearance differences than liquid coated items between horizontally coated surfaces and vertically coated surfaces. Curing time is also significantly faster with powder coatings compared to liquid coatings especially when using ultraviolet cured powder Coatings or advanced low bake thermosetting powders.

7.2.4. Upper Lid and Bottom Frame

The upper lid of the demonstration model is colored blue. It contains the cavities of all the display and input modules and switches. An 18-Gauge metal sheet is used in its construction which has a thickness of 1.2 mm. The operations of cutting and bending are carried out in its manufacturing. All the interactive components are placed on the horizontal plate while the display components are placed on the elevated surface.

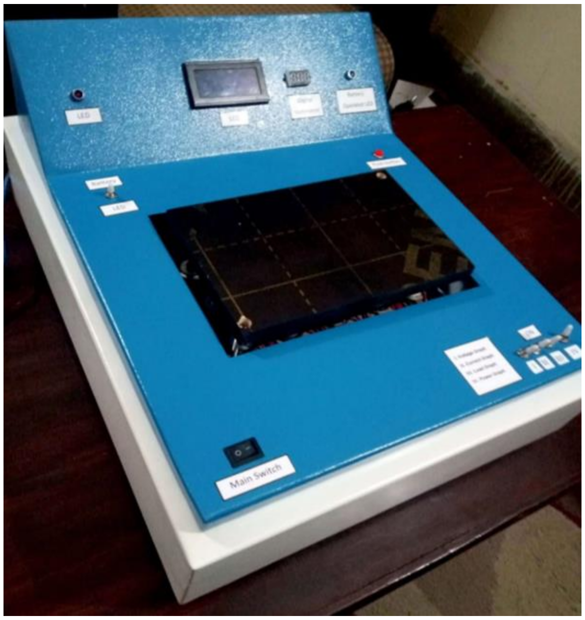

Figure 25 Fabricated Model

The bottom frame of the model is painted in white. It is simply an uncovered box with cavities made for connections at the rear.

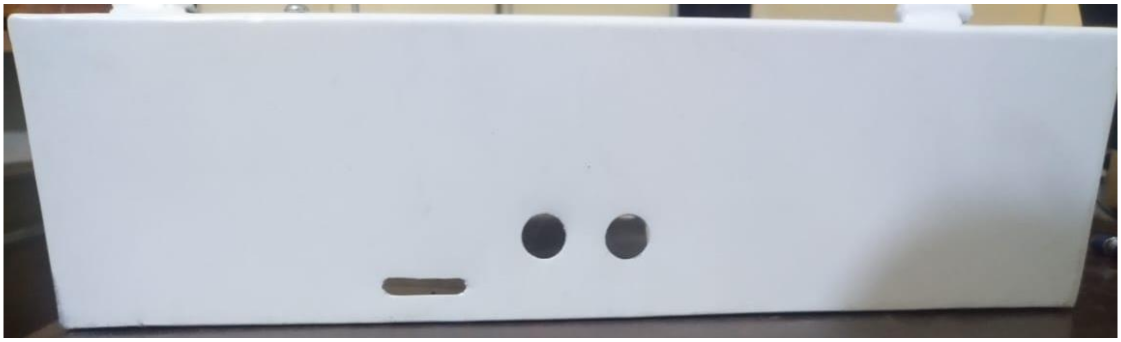

Figure 26 Bottom Frame (Rear View)

Chapter 8: Parametric Studies

8.1. Introduction

The parametric studies are conducted to observe the behavior of different parameters involved in our project and to study their relationships and dependencies on each other. For this purpose, graphs of the underlying parameters are drawn in the serial plotter of Arduino IDE. The serial plotter is a versatile tool for keeping record of different data sent to the Arduino. It is a greater visual tool that helps in understanding and comparing data much effectively.

8.2. Serial Plotter Graphs

The serial plotter graphs are obtained by the Arduino IDE interface. On the y-axis, the required parameter is placed and the x-axis contains the number of samples. In this way, any change in the required output can be monitored with respect to time. If the frequency of vibrations is kept at the same rate as the samples then graph will show the relation of concerned parameter with respect to frequency vibrations.

8.2.1. Voltage Graph

To obtain the voltage graph, turn the switch I of function select switch ON. For the given number of samples in Figure 27, we see that the voltage values remain in the bandwidth of 2.35 to 2.6 V range with the peak value of about 6V.

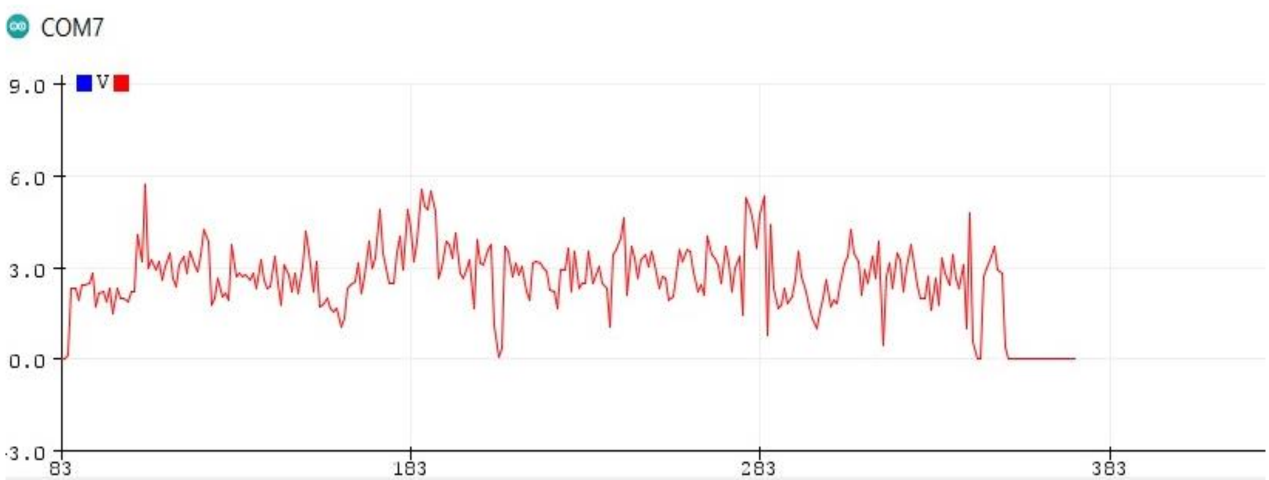

Figure 27 Voltage Graph

8.2.2. Current Graph

To obtain the current graph, turn the switch II of function select switch ON. For the graph in Figure 28, we see that the current values are obtained in milli amperes and remain in the bandwidth of 10 to 18 mA.

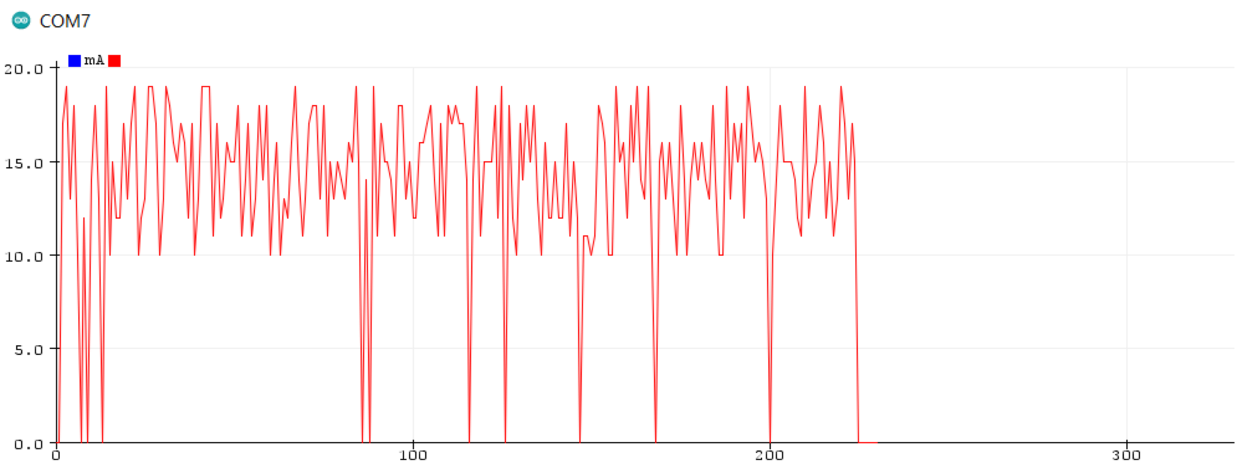

Figure 28 Current Graph (milli ampere)

8.2.3. Power Graph

To obtain the power graph, turn the switch III of function select switch ON. The power is calculated in milli watts as a product of both potential difference and current. It is given by the relation:

$$P = V * I$$

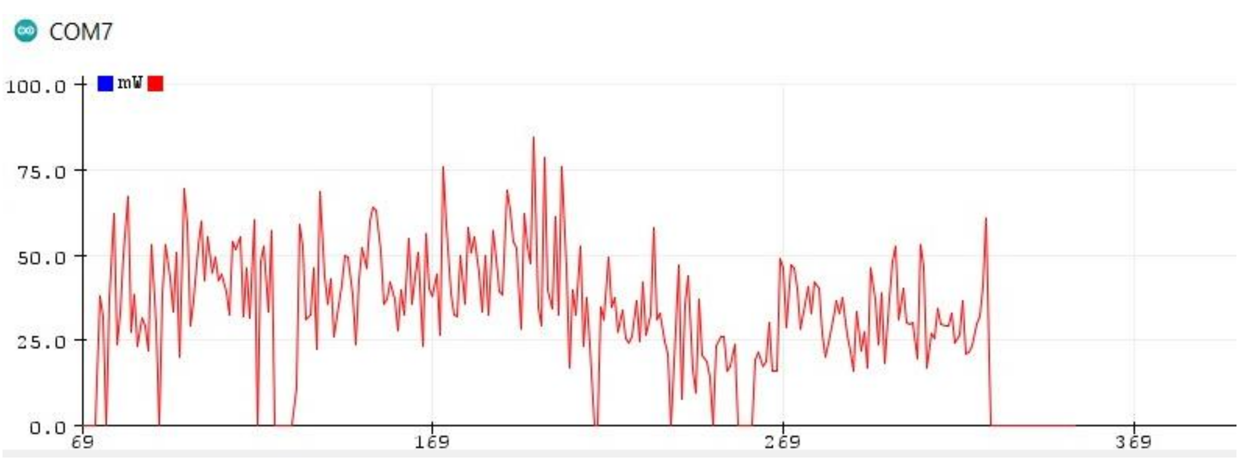

Figure 29 Power Graph

8.2.4. Load Graph

To obtain the load graph, turn the switch IV of function select switch ON. The load graph demonstrates the load cell readings with respect to the number of samples.

Figure 30 Load Readings

8.3. MATLAB Graphs and RMS value

The graphs obtained through MATLAB can be the same as obtained through the serial plotter i.e., between a concerned parameter and the number of samples or as a comparison between two concerned parameters i.e., by plotting one parameter on the x-axis and the other on the y-axis. Another important aspect of using MATLAB is the calculation of RMS value. The data obtained from the piezoelectric energy harvester has a continuously changing values of concerned parameters. To calculate the rms value is necessary to get a root mean square of the data. The function **y=rms(x)** returns the root-mean-square (RMS) value of the input, x. The parameters data is stored in a row or column vector in x then y gives a real-valued scalar RMS value. The RMS value of sample data in Table 4 is calculated using MATLAB.

8.4. Test Results

The values of the test result can be obtained directly from the personal computer in which data is stored in a directory or from the SD card. The data represent values of concerned parameters such as voltage, current, load and power output. The test results for an experiment conducted with 63 samples are given in Table 4.

Table 4 Test values for sample vibrations

Sr. No.	Voltage (V)	Current (mA)	Load (kg)	Power (mW)
1	2.12	13	4.98	27.51
2	1.97	16	5	31.52
3	1.57	15	5.5	23.53
4	1.86	15	5.26	27.9
5	1.77	18	4.35	31.92
6	1.98	11	4.94	21.75
7	1.57	14	5.05	22.01
8	1.66	17	5.36	28.17
9	1.89	11	4.38	20.76
10	1.69	13	4.44	21.91
11	1.34	18	4.34	24.16
12	1.44	14	4.15	20.19
13	1.52	18	3.76	27.29
14	1.61	10	4.2	16.13
15	1.82	14	4.43	25.52
16	1.3	16	4.16	20.76
17	1.44	10	4.58	14.36
18	1.13	13	4.59	14.67
19	1.47	12	3.86	17.59
20	1.45	16	3.04	23.15
21	1.65	19	4.81	31.42
22	1.47	14	4.58	20.55
23	1.19	11	4.72	13.11
24	1.19	13	5.07	15.48
25	1.51	17	4.86	25.59
26	1.69	18	4.72	30.47
27	1.61	18	4.33	29
28	1.7	13	4.24	22.16
29	1.55	18	3.96	27.96
30	1.73	11	4.46	19.03

31	1.35	15	4.37	20.28
32	1.06	13	4.39	13.82
33	1.45	15	4.33	21.78
34	1.65	14	4.28	23.09
35	1.52	13	4.7	19.77
36	1.48	16	4.35	23.61
37	1.27	15	4.31	18.99
38	1.29	19	4.56	24.51
39	1.63	15	4.68	24.49
40	1.12	14	4.73	15.64
41	1.13	19	4.53	21.53
42	1.37	11	4.77	15.05
43	1.03	17	4.79	17.49
44	0.52	15	4.87	7.74
45	1.94	15	3.97	29.06
46	1.44	14	4.1	20.18
47	1.62	11	3.93	17.83
48	1.51	18	3.94	27.26
49	1.75	18	5.21	31.57
50	1.86	13	5.45	24.19
51	1.69	15	5.37	25.3
52	1.63	12	4.84	19.58
53	1.88	12	4.28	22.56
54	1.5	16	4.27	24.04
55	1.35	16	4.49	21.52
56	1.61	17	4.37	27.43
57	1.51	18	4.58	27.26
58	1.6	14	4.77	22.47
59	1.51	11	4.16	16.65
60	1.4	17	4.18	23.76
61	1.33	11	4.39	14.62
62	1.76	18	4.83	31.65

8.4.1. Comments

The readings of the test experiment correlates that output parameters current, voltages and power to the input parameter. The RMS value of data in Table 4 is found out to be

$\boldsymbol{V}_{\mathbf{rms}}$ = 1.54 V

$\boldsymbol{I}_{\mathbf{rms}}$ = 14.98 mA

$\boldsymbol{P}_{\mathbf{rms}}$ = 22.96 mW

$\boldsymbol{L}_{\mathbf{rms}}$ = 4.51 kg

The voltage reading of a single piezoelectric disc was between 5-7 V. The voltage is reduced as the discs are working as a source in the circuit. The change in the potential difference of a source or battery is given by the relation:

$$V = E - IR$$

The load resistance is R, the current drawn is I and the actual potential or emf is given by E. The piezoelectric discs are connected in parallel so the current drawn from the circuit is increased. Hence, the actual potential will be subtracted by a factor IR from the relation $E - IR$. Due to the this drop the voltage values are in the given range. Moreover, the current and voltage values are highly dependent on the load applied and the frequency of its application. The current generated by the piezoelectric generator increases with the increase in the loading frequency and with the increase in the applied load. The load values fluctuate to some extent as the input load is provided in the form of vibrations and not as a constant load. Therefore, some fluctuations in the data values can be observed. The power obtained also varies directly with the applied load. There is a maximum value of current and power that can be generated by the piezoelectric discs, above which increase in load will not cause any increase in the numeric values.

Chapter 9: Summary and Limitations

9.1. Summary

A piezoelectric energy harvesting demonstration model's main purpose is to convert mechanical vibrations into electrical energy. The force due to compression generates potential difference across the piezoelectric transducers. These transducers are arranged to give significant current values to compensate the low current values of individual transducers. A rectifier converts the alternating current from piezoelectric press to direct current which is used to light up the LED or charge the battery. In the internal circuit, Arduino UNO is the heart of the model. It receives data form various sensors such as load readings from load sensor, current reading from Hall-effect sensor, and potential difference values from the voltage divider circuit. These data values are then stored and used to generate graphs of different parameters. The design of the exterior frame is made keeping in view various factors such as ease of access, operational feasibility and flexible usage.

9.2. Limitations

- Maximum load capacity of the used load cell is 10kg so applied load should be less than the maximum value.
- Applied force must be perpendicular to the piezoelectric press. Any lateral force can cause the shearing of the sensitive piezoelectric transducers, thus resulting in their damage.
- The current generated by the piezoelectric disc is quite low, generally in the order of milli ampere. Therefore, power produced is low.
- SD card is required to store the parametric values as a storage device. Data will not be displayed on the computer screen if SD card is not present.
- The demonstration model will also not work in the absence of SD card.

Chapter 10: Recommendations for Future Work

- The currently used piezoelectric discs are low power generating. It has been demonstrated from our project that the maximum power obtained is in milli watts which is quite low and not feasible to be operational in daily life. Therefore, there is a need of creating new piezoelectric materials that has greater power producing capability.
- The cantilever beam or rectangular piezoelectric layer is still new in the market. The demonstration model could be further updated by including the energy generation procedure of piezoelectric layer as well.
- The piezoelectric discs can be easily replaced with any new piezoelectric material that works on the same phenomenon. Thus, the project can be used to carry out the parametric studies on new materials.
- Further advancements can be done by replacing the laptop for real-time graphs with an oscilloscope or some other data acquisition device.
- The mechanical vibrations are produced by hand in the model. In future, a device can also be created with the sole purpose of generating vibrations in the demonstration model.

Chapter 11: Conclusions

We have successfully covered all the deliverables of our project. The demonstration model, depicting the phenomenon of piezoelectric energy harvesting, is designed and manufactured within the limited resources. The outer frame is robust in nature and the internal circuit is quite reliable for the model to be placed as a demonstration model. The parametric studies are conducted by the graph plots. The numerical values of the concerned parameter can be displayed on the screen or stored in the SD card.

The test data showed that there is a voltage drop due to parallel arrangement of piezoelectric discs as they are connected in parallel, the current generated by the piezoelectric generator increases with the increase in the loading frequency and with the increase in the applied load. The voltage signal also increases with the increase in the load but the readings are shown constant as the maximum value of possible voltages can be easily obtained. The power output is in milli watts which is used to turn ON the LED or it can be stored as electrical energy in a battery.

References

[1] P. R. Vikas Bavane, "Energy Analysis of Thermal Power Plant," *International Journal of Research in Advent Technology (IJRAT),* 2017.

[2] A. H. J. A. Shahrouz Abolhosseini, "A Review of Renewable Energy Supply and Energy Efficiency Technologies," *Discussion Paper No. 8145,* 2014.

[3] K. W. J. &. Y. D. Yang, " A double-beam piezo-magneto-elastic wind energy harvester for improving the galloping-based energy harvesting.," *Applied Physics Letters,* 2019.

[4] H. Y. H. J. &. K. S. W. Ryu, "Hybrid energy harvesters: toward sustainable energy harvesting.," *Advanced Materials,* 2019.

[5] H. Q. L. Z. Z. &. Y. J. Pan, "Kinetic energy harvesting technologies for applications in land transportation: A comprehensive review.," *Applied Energy,* 2021.

[6] M. S. L. M. M. H. C. &. B. L. Thielen, "Human body heat for powering wearable devices: From thermal energy to application.," *Energy conversion and management,* 2017.

[7] L. J. T. L. P. S. J. J. H. C. Z. W. .. &. W. Z. L. Xu, "Coupled triboelectric nanogenerator networks for efficient water wave energy harvesting.," *ACS nano,* 2018.

[8] L. &. Y. Y. Zhao, " An impact-based broadband aeroelastic energy harvester for concurrent wind and base vibration energy harvesting.," *Applied Energy,* 2018.

[9] M. &. Y. E. M. Kang, "Coupling of piezo-and pyro-electric effects in miniature thermal energy harvesters.," *Applied Energy,* 2020.

[10] D. P. n.-E. a. F. Y. M. Yang, "Wind power generation in China: Understanding the mismatch between capacity and generation," *Renewable Energy,* pp. 145-151, 2012.

[11] Z. X. C. a. J. Z. P. R. Li, "High dielectric performance of Polyamide66/poly(vinylidene fluoride) flexible blends induced by interfacial copolymer for capacitors," *Polymers,* pp. 2-10, 2016.

[12] Q. Q. G. Z. L. S. a. J. Z. P. 9R. Li, "Effects of conductive carbon black on PZT/PVDF composites," *Ferroelectrics,* pp. 176-186, 2018.

[13] X. Sun, "An Overview on Piezoelectric Power Generation System for Electricity Generation," *Journal of Power and Energy Engineering,* 2017.

[14] e. a. J. Qiu, "Fabrication of piezoelectric ceramic fibers by extrusion of Pb(Zr, Ti)03 powder and Pb(Zr, Ti)03 sol mixture," *Smart Materials.*

[15] A. A. E. M. S. Niell G Elvin, "A self-powered mechanical strain energy sensor, Institute Of Physics Publishing," *Smar Matter, Structure*, vol. 10, pp. 293-299, 2001.

[16] S. J. T. &. C. W. Kim, " Harvesting energy from a cantilever piezoelectric beam," *Proceedings of SPIE – The International Society The International Society*, pp. 259-268, 2004.

[17] M. V. D. C. F. P. G. &. S. Ericka, " Energy harvesting from vibration using a piezoelectric membrane," *Journal of Physics IV France*, pp. 187-193, 2005.

[18] R. Z. PetrSadilek, "Frequency Response Analysis Of Hybrid Piezoelectric Cantilever Beam, engineering Mechanics," *Materials Today: Proceedings 5* , pp. 4309-4316, 2018.

[19] e. a. M. Martinez, "Finite Element Analysis of Broken Fibre Effects on Hollow Active Fibre Composites,," *Journal of Intelligent Material Systems and Structures*, vol. vol 21, 2010.

[20] N. S. ,. M. Egashira, "Local Strain Sensing Using Piezoelectric Polymer," *Journal of Intelligent Materials and Systems and Structures*, p. Vol. 4, 1993.

[21] e. a. M. Kobayashi, "Structural Health Monitoring of Composites Using Integrated and Flexible Piezoelectric Ultrasonic Transducers," *Journal of Intelligent Materials and Systems and Structures*, vol. Vol. 20, 2009.

[22] e. a. A. J. Brunner, " Piezoelectric Fiber Composites as Sensor Elements for Structural Health Monitoring and Adaptive Material Systems," *Journal of Intelligent Materials and Systems and Structures*, vol. Vol. 20, 2009.

[23] Y. Zhang, "In Situ Fatigue Crack Detection using Piezoelectric Paint Sensor,," *Journal of Intelligent Materials and Systems and Structures.*

[24] S. P. K. A. S. M. C. L. H. R. T. G. J. F. L. e. a. Gurav, "Uncertainty-based design optimization of a micro piezoelectric composite energy reclamation device," in *the tenth AIAA/ISSSMO multidisciplinary analysis and optimization conference*, 2004.

[25] P. Muralt, "Ferroelectric thin films for micro-sensors and actuators: a review.," *Journal of Micromechanics and Microengineering*, vol. 10, p. 136–146, 2000.

[26] D. J. &. G. B. L. Inman, "Towards autonomous sensing.," in *The SPIE on smart structures and materials conference*, 2006.

[27] A. &. B. N. Abdelkefi, "Nonlinear analysis and power improvement of broadband low-frequency piezomagnetoelastic energy harvesters," *Nonlinear Dynamics*, no. 25, pp. 1-16, 2015.

[28] A. &. I. D. J. Karami, "Powering pacemakers from heartbeat vibrations using linear and nonlinear energy harvesters," *Applied Physics Letters*, 2012.

[29] N. A. A. &. P. S. Sharpes, "Comparative analysis of one-dimensional and two-dimensional cantilever piezoelectric energy harvesters.," *Energy Harvesting Systems,* vol. 1, pp. 209-216, 2014.

[30] I. D. D. H. M. S. E. P. &. D. M. W. Capel, "The amelioration of the suffering associated with spinal cord injury with subperception transcranial electric simulation," *Spinal Cord,* 2003.

[31] J. C. Pierre Currie, ""Develpoment, via compression, of electric polarization in hemihedralcrystals"," Bullein de la Societe Minerologique de France, 1880.

[32] M. D. D. C. A. D. D. M. Shrimoyee Poddar, "Footstep Voltage Generator using Piezoelectric Transducer," *International Journal of Scientific & Engineering Research* , vol. Volume 8, no. Issue 3, March-2017.

[33] P. P. Vahid Jamadar, "Analysis of Vibration Energy Harvesting from Power Consuming Devices," *IARJSET 4(1):26-29,* 2017.

[34] A. P. K. Kiran Boby, "Footstep Power Generation Using Piezo Electric," *International Journal of Engineering and Innovative Technology (IJEIT),* 2014.

[35] M. D. H. S. G. Erfan Hamsayeh Abbasi Niasar, "Roadway piezoelectric energy harvester design considering Electrical and Mechanical Performances," vol. 234, no. 1, 2020.

[36] Y. Y. B. Z. e. a. Rui Li, "Harvesting energy from pavement based on piezoelectric effects: Fabrication and electrical properties of a piezoelectric vibrator.," *Renewable Sustainable Energy,* 23 October 2018.

[37] L. X. M. K. A. A. A. E. J. M. G. Y. L. L. Z. Mohamed A.A. Abdelkareem, "Vibration energy harvesting in automotive suspension system: A detailed review," *Applied Energy,* 2018.

[38] C. D. More, "Power from Bumps in the Road," in *MIT News*, 9 February 2009.

[39] H. R.Naseer, "Piezomagnetoelastic energy harvesting from vortex-induced vibrations using monostable characteristics," *ScinceDirect,* 2017.

[40] J.-H. K. Heung Soo Kim, "A Review of Piezoelectric Energy Harvesting Based on Vibration," *International Journal of Precision Engineering and Manufacturing* , 2011.

Appendices

Code for Arduino

```
#include "HX711.h"
#include <SPI.h>
#include <SD.h>
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27,16,4);
const int LOADCELL_DOUT_PIN = 3;
const int LOADCELL_SCK_PIN = 2;
String sd_data_out="";
bool data_dump_flag=false;

HX711 scale;
File myFile;
unsigned long voltage_0=0;
 double voltage_1=0.000;
  double voltage_2=0.00;
  double voltage_out=0.00;
  double current_out=0.00;
  double load_out=0.00;
  double power_out=0.00;
 bool key_1=false;
 bool key_2=false;
 bool key_3=false;
 bool key_4=false;
void setup() {
    Serial.begin(38400);
    lcd.init();
    lcd.backlight();
    setting_loadcel();


    if (!SD.begin(4)) {
    Serial.println("initialization failed!");
    while (1);
    }
    SD.remove("pizo.txt");
    pinMode(5,INPUT);pinMode(6,INPUT);pinMode(7,INPUT);pinMode(9,INPUT);
    Serial.println("...............");
}


void loop() {

key_1=digitalRead(5);
key_2=digitalRead(6);
key_3=digitalRead(7);
key_4=digitalRead(9);
```

```
//Serial.println(key_1);
//Serial.println(key_2);
//Serial.println(key_3);
//Serial.println(key_4);
//Serial.println("***********");
voltage_out=volatge_measurement();
current_out =current_measurement();
load_out=load_cell_read();
power_out=voltage_out*current_out;
sd_data_out=sd_data_string(String(voltage_out),String(current_out),String(load_out),String(power_out));

if(load_out<0){load_out=0.00;}
//Serial.println(data_dump_flag);
if(data_dump_flag==true){sd_card_write(sd_data_out);data_dump_flag=false;}
Serial_display();
lcd_disp(String(voltage_out),String(current_out),String(power_out),String(load_out));

delay(1);
}

double volatge_measurement()
{

  voltage_0=0.00;
      for(int i=0;i<300;i++)
    {
     voltage_0 +=analogRead(A1);
     delay(1);
      }
     voltage_1=voltage_0/250.000;
     double voltage_2=(3.00/300.00)*voltage_1;
    return voltage_2;

  }

double current_measurement()
{
    unsigned int x=0;
    float AcsValue=0.0,Samples=0.0,AvgAcs=0.0,AcsValueF=0.0;
    double current_out_0=0.00;

      for (int x = 0; x < 150; x++){ //Get 150 samples
      AcsValue = analogRead(A0);     //Read current sensor values
      Samples = Samples + AcsValue;  //Add samples together
      delay (1); // let ADC settle before next sample 3ms
    }
    AvgAcs=Samples/150.0;//Taking Average of Samples

    //((AvgAcs * (5.0 / 1024.0)) is converitng the read voltage in 0-5 volts
    //2.5 is offset(I assumed that arduino is working on 5v so the viout at no current comes
    //out to be 2.5 which is out offset. If your arduino is working on different voltage than
```

```
   //you must change the offset according to the input voltage)
   //0.185v(185mV) is rise in output voltage when 1A current flows at input
   AcsValueF = (2.5 - (AvgAcs * (5.0 / 1024.0)) )/0.185;
   if((voltage_out*10)>=5)
   {
    current_out_0 =random(10,20);
    data_dump_flag=true;
     }
    else
    {
     current_out_0=0.00;
     }
   //Serial.println(AcsValueF);//Print the read current on Serial monitor
   delay(1);
  return current_out_0;

 }

void  setting_loadcel()
 {
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  scale.set_scale(226024.f);                      // this value is obtained by calibrating the scale with known weights; see the
README for details
  scale.tare();               // reset the scale to 0
/*
  Serial.println("After setting up the scale:");

  Serial.print("read: \t\t");
  Serial.println(scale.read());                // print a raw reading from the ADC

  Serial.print("read average: \t\t");
  Serial.println(scale.read_average(20));       // print the average of 20 readings from the ADC

  Serial.print("get value: \t\t");
  Serial.println(scale.get_value(5));   // print the average of 5 readings from the ADC minus the tare weight, set with
tare()

  Serial.print("get units: \t\t");
  Serial.println(scale.get_units(5), 1);        // print the average of 5 readings from the ADC minus tare weight, divided
            // by the SCALE parameter set with set_scale

  Serial.println("Readings:");
  */
  }

  double load_cell_read()
  {
//      Serial.print("one reading:\t");
//    Serial.print(scale.get_units(), 1);
//    Serial.print("\t| average:\t");
    double load_c1=scale.get_units(10);
//    Serial.println(scale.get_units(10), 1);
```

```
   //Serial.println(load_c1);
   return load_c1;
   }
 void Serial_display()
 {

   if(key_1==true && key_2==true && key_3==true && key_4==true)
   {
//      Serial.print("Voltage_out: ");Serial.print(voltage_out);Serial.println(" V");
//      Serial.print("Current _out: ");Serial.print(current_out);Serial.println(" mA");
//      Serial.print("Load_out: ");Serial.print(load_out);Serial.println(" kg");
//      Serial.println("..................");
      Serial.print("V: "); Serial.print(voltage_out); Serial.print("  ");
      Serial.print("mA: "); Serial.print(current_out); Serial.print("  ");
      Serial.print("mW: "); Serial.print(power_out); Serial.print("  ");
      Serial.print("kg: "); Serial.print(load_out); Serial.print("  ");
      Serial.println("");

//      Serial.print Serial.print(voltage_out);
//      Serial.print(current_out);
//      Serial.print(load_out);
   }
   else
   {
   if (key_1==true)
   {
     Serial.print("V: "); Serial.println(voltage_out); Serial.println("");
     }
   else if (key_2==true)
   {
     Serial.print("mA: ");Serial.println(current_out); Serial.println("");
     }
   else if (key_3==true)
   {
     Serial.print("mW: ");Serial.println(power_out);Serial.println("");
     }
    else if (key_4==true)
   {
     Serial.print("kg: ");Serial.println(load_out); Serial.println("");
     }
   }
  }

 void sd_card_write(String data_dump)
 {

    myFile = SD.open("pizo.txt", FILE_WRITE);
   // if the file opened okay, write to it:
   if (myFile) {
   myFile.println(data_dump);
   //Serial.println("wriitng data");
   delay(1);
```

```
   }
   // close the file:
   myFile.close();
   delay(1);
   //Serial.println("done.");


}
String sd_data_string(String v_s,String i_s,String p_s,String l_s)
{
 String sd_data_f=v_s+String(":")+i_s+String(":")+p_s+String(":")+l_s+String(":");
 //Serial.println(sd_data_f);
 return sd_data_f;
 }
void lcd_disp(String volt,String ampere,String power,String load)
{
 lcd.clear();
 lcd.setCursor(0,0);lcd.print("pizo harvesting");
 lcd.setCursor(0,1);lcd.print("V:");lcd.print(volt);lcd.setCursor(8,1);lcd.print("C:");lcd.print(ampere);
 lcd.setCursor(-4,2);lcd.print("P:");lcd.print(power);lcd.setCursor(4,2);lcd.print("L:");lcd.print(load);
 }
```

Outer Frame Dimensions

Upper Lid

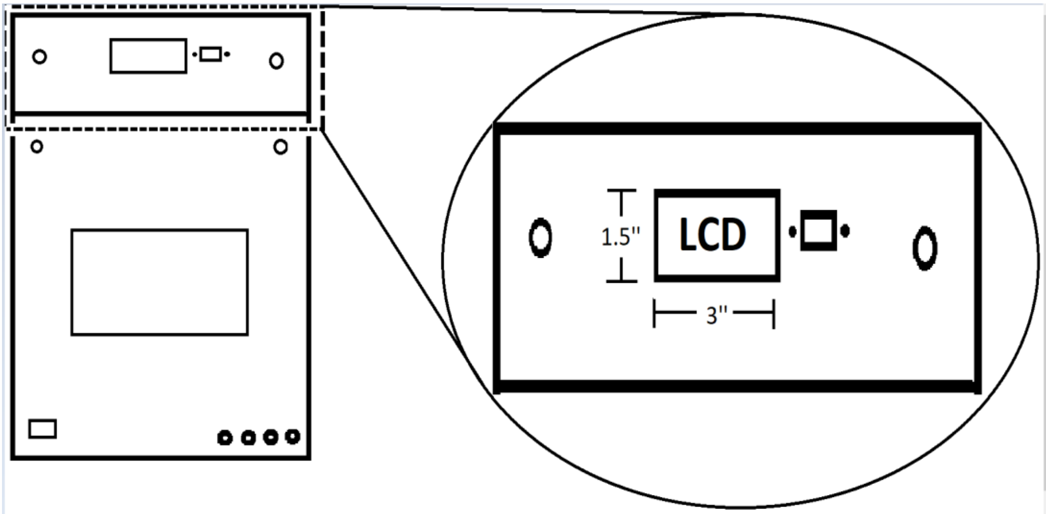

Figure 31 Upper Lid (Top View)

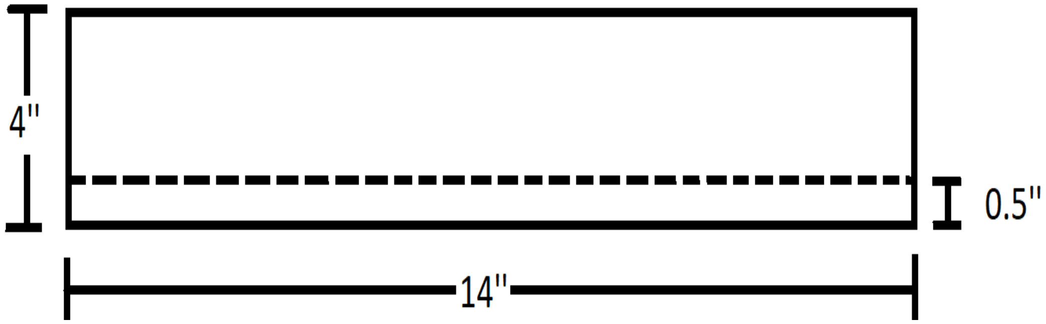

Figure 32 Front View

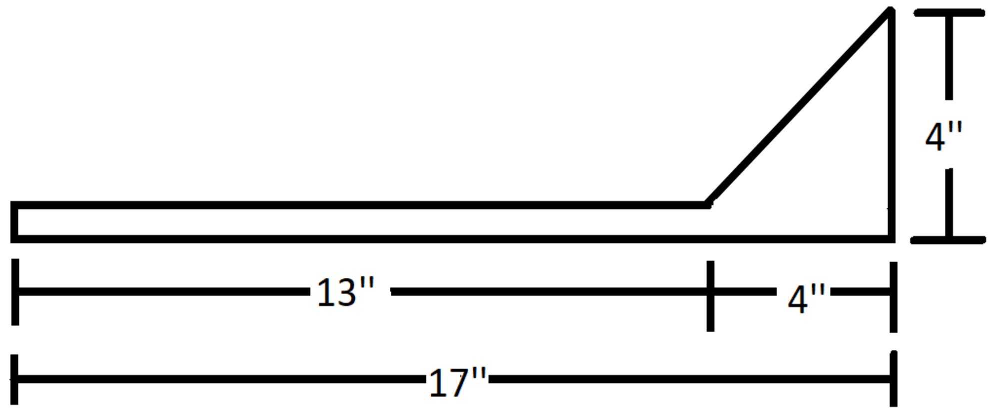

Figure 33 Side View

Bottom Frame

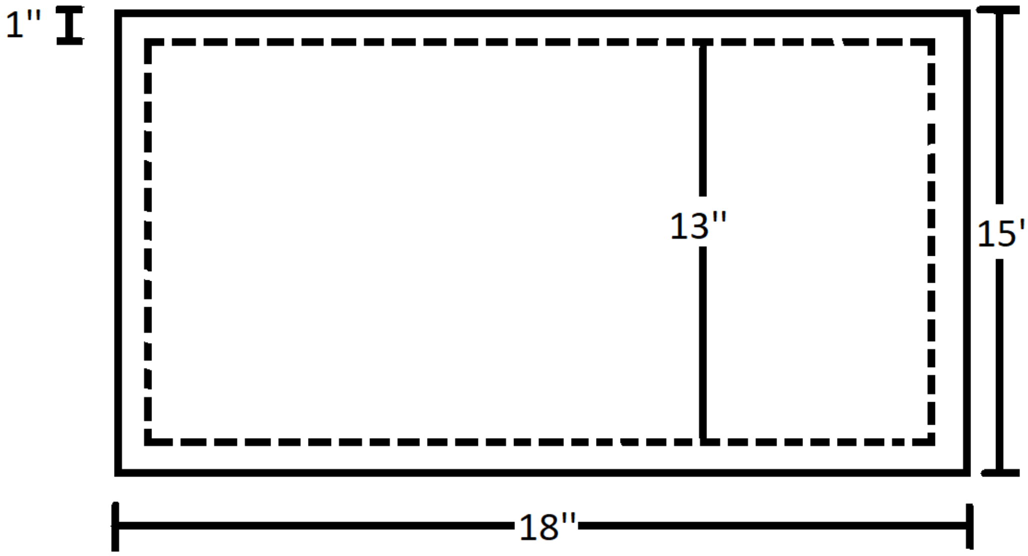

Figure 34 Top View

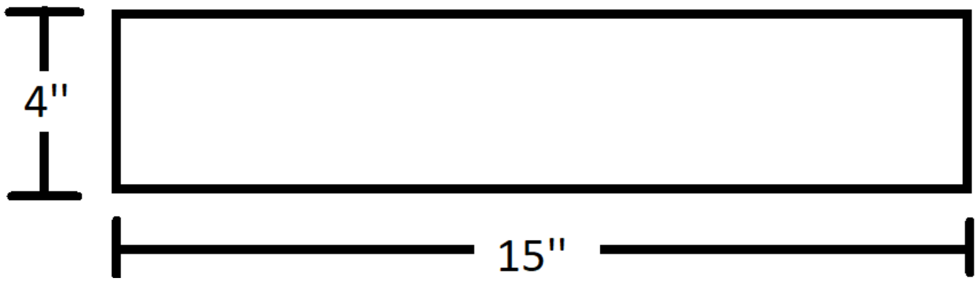

Figure 35 Front View

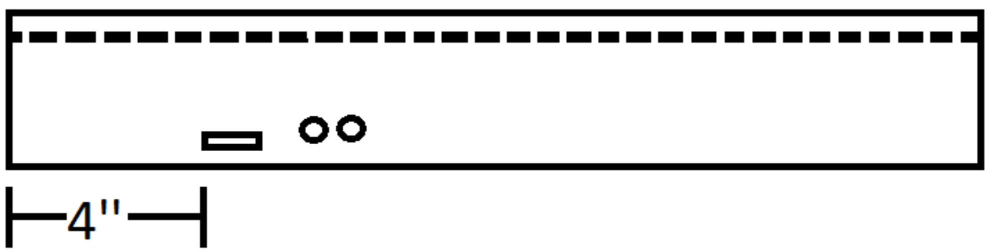

Figure 36 Rear View