A Piezoelectric Harvester and Its Evaluation

A Project Report

submitted by

RAHUL TRIPATHI
EE16M002

in partial fulfillment of the requirements

for the award of the degree of

MASTER OF TECHNOLOGY

in

CONTROLS AND INSTRUMENTATION ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY MADRAS.

MAY 2018

CERTIFICATE

This is to certify that the thesis titled "**A Piezoelectric Harvester and Its Evaluation"** submitted by **Rahul Tripathi** to the Indian Institute of Technology Madras for the award of the degree of **Master of Technology** in Controls and Instrumentation Engineering is a bonafide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. Boby George
Project Guide
Associate Professor
Dept. of Electrical Engineering
IIT-Madras, 600036

Date :
Place: Chennai

ACKNOWLEDGEMENTS

At the outset, I express my deep sense of gratitude to my Project Guide Dr. Boby George for his guidance, support, encouragement and help throughout the period of the project work. I am highly indebted to him for devoting his valuable time to help me complete the work in time.

I thank all the teaching and non-teaching staff, Shri. Umaithanu Pillai and Smt. Rekha of the Electrical Department for extending all the support and cooperation to me throughout.

I also avail this opportunity to express my sincere gratitude to the Indian Air Force for giving me the opportunity to be a part of this prestigious institute.

My lab mates K P Bijoy, Hari have always supported me during the work. A special mention about A S Ramkumar for spending time with me to discuss finer details of the project work.

All this wouldn’t have been possible if it was not for the unconditional support by my parents, wife Ritu, daughter Rakshita and Sunita Bua.

Last, but not the least I thank Almighty for the blessings he showered upon me during the course of the project, and indeed the entire life.

Rahul Tripathi

ABSTRACT

In an effort to eliminate the replacement of the batteries of electronic devices that are difficult or impractical to service once deployed, harvesting energy from mechanical vibrations or impacts using piezoelectric materials has been researched over the last several decades. However, a majority of these applications have very low input frequencies. This presents a challenge for the researchers to optimize the energy output of piezoelectric energy harvesters, due to the relatively high elastic moduli of piezoelectric materials used to date.

This paper reviews the current state of research on piezoelectric energy harvesting devices for low frequency (0–100 Hz) applications and the methods that have been developed to improve the power outputs of the piezoelectric energy harvesters. Various key aspects that contribute to the overall performance of a piezoelectric energy harvester are discussed, including geometries of the piezoelectric element, types of piezoelectric material used, techniques employed to match the resonance frequency of the piezoelectric element to input frequency of the host structure, and electronic circuits specifically designed for energy harvesters

First problem deals with fabrication of a cantilever system which will provide vertical shaking platform with the varying frequency from signal generator. The cantilever strip will provide the place for the piezoelectric strip to be installed and tested. The cantilever system has a suitable place for the attachment of Piezo strip and an accelerometer for measurement.

The second problem is for optimization of the energy obtained from the piezoelectric sensor and then to interface it with the energy harvesting circuit so that the generated energy can be store it in a battery/ super capacitor.

The third problem is visual interface all the setup through LabVIEW software, such that the signal generator, the oscilloscope and all the data’s can be collected digitally on a single console.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

NI	National Instruments
ELVIS	Electronic Laboratory Virtual Instrumentation Suite
LabVIEW	Laboratory Virtual Instrumentation Electronic Workbench
LED	Light Emitting Diode
LCD	Liquid Crystal Display
VI	Virtual Instrument
AI	Analog Input
DAQ	Data Acquisition

NOTATIONS

C	Capacitance
V_o	Output Voltage
V_p	Positive reference voltage
V_N	Negative reference voltage
V_R	Reference voltage

CHAPTER 1

INTRODUCTION

1.1 General

Energy harvesting is an active field of research aimed at powering low power wireless systems, self-powered sensors and micro-systems and recharging existing batteries. Renewable energy can be harvested by generating electrical energy from solar, thermal or kinetic energy present within or around the system. Solar cells are excellent energy harvester under direct sunlight, but are limited in application under dim day light condition, in the night and where light has no access, such as in embedded systems. Thermal energy can be converted into electrical energy using Seeback effect, but this approach produces energy in the range of a few μW only. Kinetic energy harvester converts kinetic energy present in the environment into electrical energy. It has already been demonstrated by several groups that the ambient kinetic energy can be easily converted into electrical energy in the μW range. Kinetic energy is typically present in the form of vibration, random displacement of forces and is typically converted into electrical energy using electromagnetic, electrostatic and piezoelectric energy transduction method.

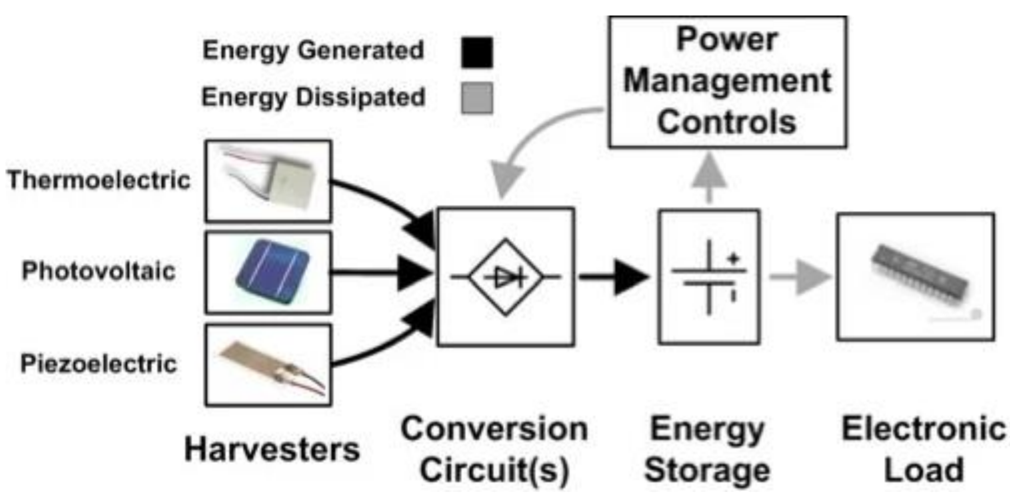

Figure 1.1: Basic components of an energy harvesting system [21]

1.2 Necessity of energy harvesting

In some applications, where the sensors are deployed at remote locations or inside the human body, the replacement of the battery at the end of its service life can be challenging or even unpractical. Therefore, the need of harvesting ambient energy to power the electronic devices in these situations arises.

There are various methods to convert mechanical energy from vibrating or moving objects into electrical energy needed by electronic devices, including electromagnetic induction, electrostatic induction, and the piezoelectric effect. Compared with electromagnetic and electrostatic methods, energy harvesting with piezoelectric materials provides higher energy density and higher flexibility of being integrated into a system, and thus has been the most widely studied

The continuous improvement of semiconductor manufacturing technologies has led to tremendous technological advancements in small electronic devices, such as portable electronics, sensors, and transmitters in the last three decades. Functionality has been largely broadened and energy efficiency has been greatly enhanced, all while reducing size by orders of magnitude. In addition, as the energy density of batteries continues to improve, many of these devices are able to operate for long periods of time solely on battery

Enable to reduce the cost of battery replacement and the cost of power line connection. The sensors located at remote location can be easily and wirelessly powered.

1.3 Source of vibrational energy harvester

Vibration energy available in a wide variety of sources can be conveniently used for potential powering of wireless sensors and low power devices. Examples of Vibrational source include escalators, bridges, rotor blades, windmill blades, pumps and one of great resources are automobiles.

1.4 Objective and scope of the work

The main objective of the work described in this thesis is of fabrication of a cantilever system wherein the piezoelectric strip can be installed and tested for different signal frequency and different **g** values. The cantilever system to accommodate a suitable actuator and an accelerometer for measurement. The second part is the Visual interface system to be made under LabVIEW so that all the data is collected directly on the computer and the full control of the system can be done from a single console.

1.5 Organization of work

A brief introduction to requirement of energy harvesting is presented in Chapter1. Chapter 2 deals with the working principle of piezoelectric transducer. Chapter 3 describes hardware set up used for the cantilever system Chapter 4 explains the working of signal conditioning circuit used in the design of Energy harvester and. Chapter 5 provides experimental results of the designed setup. The conclusion of the work carried out and its future scope is provided in Chapter 6.

CHAPTER 2

TYPICAL CONFIGURATIONS OF PIEZOELECTRIC ENERGY HARVESTERS

2.1 Introduction

A transducer is any device used to convert energy from one form to another; typically when converting input energy into output energy. For transduction to occur, a change from one form of energy must also take place, such as a conversion from mechanical to electrical energy or vice versa. The uses of transducers are widespread, impacting us in many ways. A common example is a microphone, which converts the input energy, the sound waves produced by a voice or instrument, to output energy, the electrical impulses in the form of amplified sound.

2.1 Piezoelectric transducers

The piezoelectric transducers work on the principle of piezoelectric effect. When mechanical stress or forces are applied to some materials along certain planes, they produce electric voltage. This electric voltage can be measured easily by the voltage measuring instruments, which can be used to measure the stress or force.

The physical quantities like stress and force cannot be measured directly. In such cases the material exhibiting piezoelectric transducers can be used. The stress or the force that has to be measured is applied along certain planes to these materials. The voltage output obtained from these materials due to piezoelectric effect is proportional to the applied stress or force. The output voltage can be calibrated against the applied stress or the force so that the measured value of the output voltage directly gives the value of the applied stress or force. In fact the scale can be marked directly in terms of stress or force to give the values directly.

The voltage output obtained from the materials due to piezoelectric effect is very small and it has high impedance. To measure the output some amplifiers, auxiliary circuit and the connecting cables are required.

2.2 Materials used for the piezoelectric transducers

a) There are various materials that exhibit piezoelectric effect as mentioned above. The materials used for the measurement purpose should posses desirable properties like stability, high output, insensitive to the extreme temperature and humidity and ability to be formed or machined into any shape. But none of the materials exhibiting piezoelectric effect possesses all the properties. Quartz, which is a natural crystal, is highly stable but the output obtained from it is very small. It also offers the advantage of measuring very slowly varying parameter as they have very low leakage when they are used with high input impedance amplifiers.

b) Due to its stability, quartz is used commonly in the piezoelectric transducers. It is usually cut into rectangular or square plate shape and held between two electrodes. The crystal is connected to the appropriate electronic circuit to obtain sufficient output.

c) Rochelle salt, a synthetic crystal, gives the highest output amongst all the materials exhibiting piezoelectric effect. However, it has to be protected from the moisture and cannot be used at temperature above 115 degree F. Overall the synthetic crystals are more sensitive and give greater output than the natural crystals.

2.4 Advantages of piezoelectric transducers

Every devise has certain advantages and limitations. The piezoelectric transducers offer several advantages as mentioned below:

a) **High frequency response:** They offer very high frequency response that means the parameter changing at very high speeds can be sensed easily.

b) **High transient response:** The piezoelectric transducers can detect the events of microseconds and also give the linear output.

c) **High output:** They offer high output that be measured in the electronic circuit.

d) **Small size:** The piezoelectric transducers are small in size and rugged construction.

2.5 Limitations of piezoelectric transducers

Some of the limitations of piezoelectric transducers are:

a) **Output is low:** The output obtained (closed circuit) from the piezoelectric transducers is low, so external electronic circuit has to be connected for harvesting energy.

b) **High impedance:** The piezoelectric crystals have high impedance so they have to be connected to the amplifier and the auxiliary circuit, which have the potential to cause errors in measurement. To reduce these errors amplifiers high input impedance and long cables should be used.

c) **Forming into shape:** It is very difficult to give the desired shape to the crystals with sufficient strength.

2.6 Applications of the piezoelectric transducers

a) The piezoelectric transducers are more useful for the dynamic measurements, i.e. the parameters that are changing at the fast rate. This is because the potential developed under the static conditions is not held by the instrument. Thus piezoelectric crystals are primarily used measurement of quantities like surface roughness, and also in accelerometers and vibration pickups.

b) For the same reasons they can be used for studying high speed phenomenon like explosions and blast waves. They are also used in aerodynamic shock tube work and seismograph (used for measurement of acceleration and vibration in rockets).

c) Many times the piezo sensors or transducers are used along with the strain gauges for measurement of force, stress, vibrations, etc.

d) The automotive companies used piezoelectric transducers to detect detonations in the engine blocks.

e) Piezoelectric transducers are used in medical treatment, sonochemistry and industrial processing equipments for monitoring the power.

2.7 Examples of piezoelectric material

The materials are:

1) Barium Titanate.
2) Lead zirconate titanate (PZT).
3) Rochelle salt.

2.8 Principle of operation

The way a piezoelectric material is cut produces three main operational modes:

1) Transverse
2) Longitudinal
3) Shear.

(a) Transverse effect

A force applied along a neutral axis (y) displaces charges along the (x) direction, perpendicular to the line of force. The amount of charge (Cx) depends on the geometrical dimensions of the respective piezoelectric element. When dimensions a,b,c apply,

$$Cx= dxy\ Fy\ b/a,$$

Where a is the dimension in line with the neutral axis, b is in line with the charge generating axis and d is the corresponding piezoelectric coefficient.

(b) **Longitudinal effect**

The amount of charge displaced is strictly proportional to the applied force and independent of the piezoelectric element size and shape. Putting several elements mechanically in series and electrically in parallel is the only way to increase the charge output. The resulting charge is

$$Cx = dxx\ Fx\ n,$$

where dxx is the piezoelectric coefficient for a charge in x-direction released by forces applied along x-direction (in pC/N). Fx is the applied Force in x-direction [N] and n corresponds to the number of stacked elements.

(c) **Shear effect**

The charges produced are strictly proportional to the applied forces and independent of the element size and shape. For n elements mechanically in series and electrically in parallel the charge is

$$Cx = 2\ dxx\ Fx\ n.$$

In contrast to the longitudinal and shear effects, the transverse effect make it possible to fine-tune sensitivity on the applied force and element dimension.

2.9 Piezoelectric transducer

Based on piezoelectric technology various physical quantities can be measured; the most common are pressure and acceleration. For pressure sensors, a thin membrane and a massive base is used, ensuring that an applied pressure specifically loads the elements in one direction. For accelerometers, a seismic mass is attached to the crystal elements. When the accelerometer experiences a motion, the invariant seismic mass loads the elements according to Newton's second law of motion.

The main difference in working principle between these two cases is the way they apply forces to the sensing elements. In a pressure sensor, a thin membrane transfers the force to the elements, while in accelerometers an attached seismic mass applies the forces.

Sensors often tend to be sensitive to more than one physical quantity. Pressure sensors show false signal when they are exposed to vibrations. Sophisticated pressure sensors therefore use acceleration compensation elements in addition to the pressure sensing elements. By carefully matching those elements, the acceleration signal (released from the compensation element) is subtracted from the combined signal of pressure and acceleration to derive the true pressure information.

Vibration sensors can also harvest otherwise wasted energy from mechanical vibrations. This is accomplished by using piezoelectric materials to convert mechanical strain into usable electrical energy.

The specifications of the sensor are as follows:

Electrode material	Thin Piezo polymer w/ high piezo activity
Contacts	Flexible silver ink metallization
Min. input impedance	1 MΩ,
Output voltage	mV to 100s of volts
Operating temp	-40 to 60°C
Length	20cm
Width	1.2cm

Table 2.1: Specifications of the sensor

2.10 Converting force into electricity using piezoelectric transducer:

The piezoelectric effect is used here for converting a small force into voltage signal using the piezoelectric transducer (piezo strip/ disc)**.** Then to store the energy produced by pressure application in a super capacitor/ battery.

a) Soldering the terminals:

Soldering the wire to the piezoelectric transducer is the main part of using them. Be careful not to overheat the surface since it melts off even at low temperature for a few seconds. Hence try to melt the lead in soldering iron and drop the molten solder over the surface. For this operation, terminals positive and negative will be enough and can be seen in the picture above.

b) Operation:

The Piezoelectric Transducer produces a discontinuous or alternating output on applying repeated tapping force over it. Hence it has to be rectified to make it storable or usable DC. Hence for a higher rectifying efficiency of 80% or above, we are going to use full wave rectifier.

The alternating output from the piezoelectric transducer is converted into DC and stored inside the output capacitor. The stored energy is then dissipated through an LED with controlled output switch. Hence, the dissipation of stored energy will be visible.

2.11 Piezoelectric Transducer Circuit Diagram:

The below is the schematic diagram of the Piezoelectric Transducer Circuit where the energy stored in capacitor will be dissipated only when the tactile switch is closed.

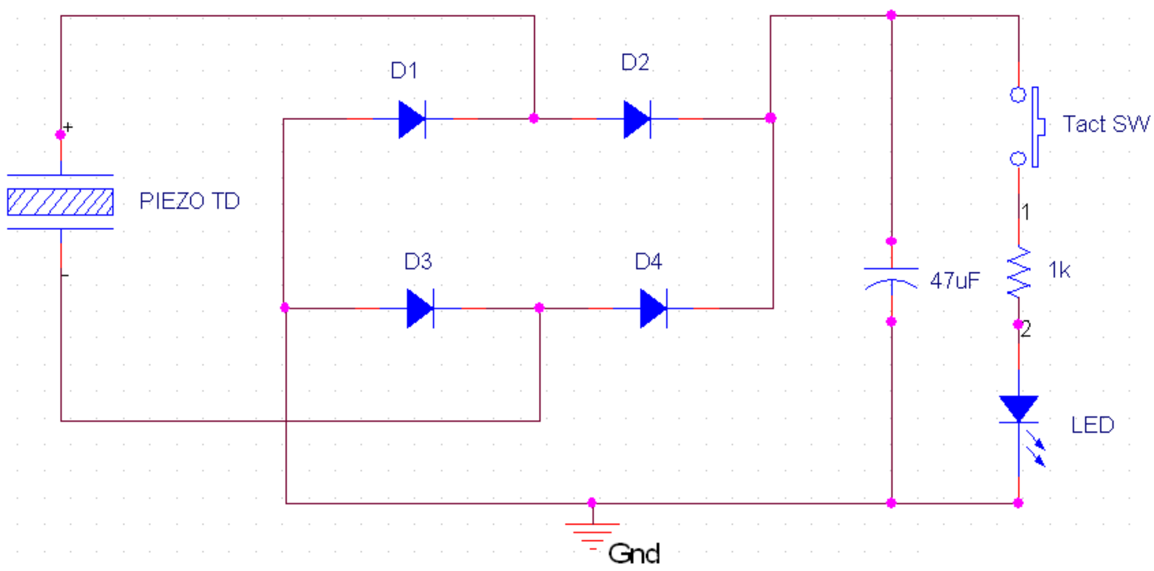

Fig.2.1: Piezoelectric Transducer Circuit Diagram [20]

The capacitor used in the output can be increased further to increase the storage capacity.

2.12 Challenges faced during harvester setup fabrication

During the fabrication of the setup many challenges were observed:

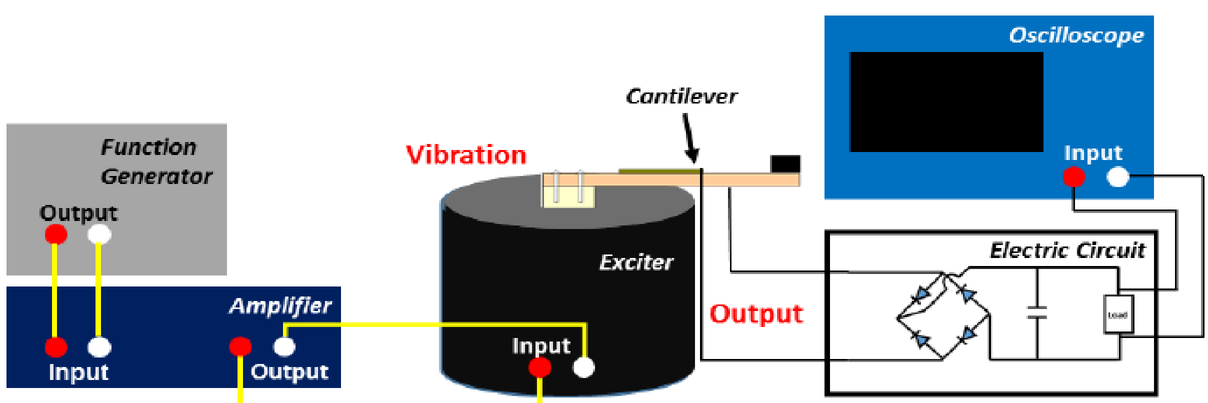

Fig2.2: System to evaluate the harvester or Piezo element [7]

a) Fabrication and design of cantilever unit:

A cantilever unit has been designed and fabricated. The length is also adjustable to install piezo strips with different dimensions on it. The cantilever unit is made up of Aluminum material so as to have less weight and therefore easy portable and corrosion resistant. The scale will accommodate the piezo electric transducer and accelerometer as well.

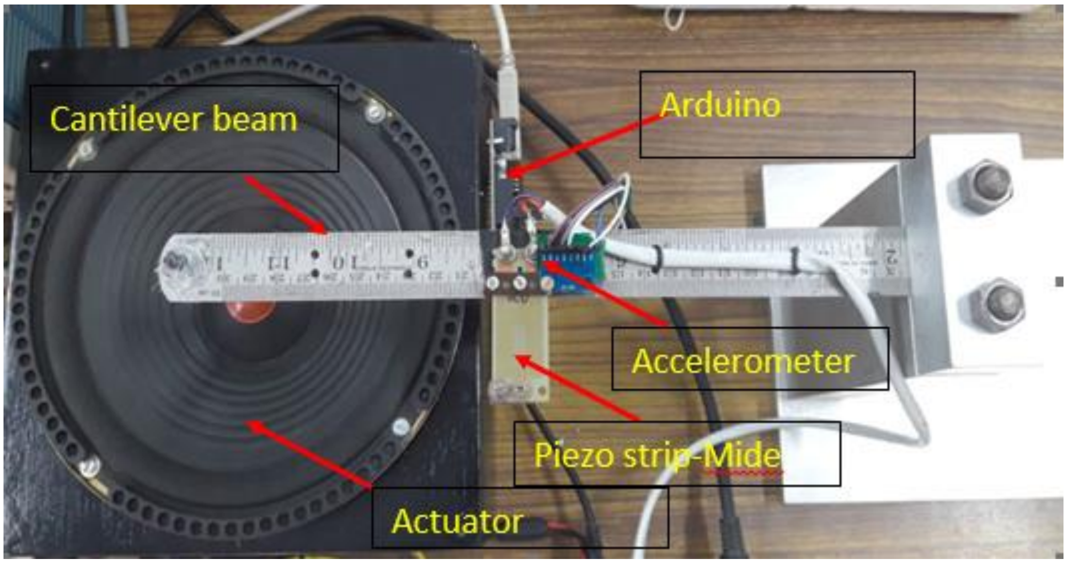

Fig. 2.3: Photograph of the set-up. The Computer, signal generator, power amplifier, signal acquisition unit, etc. are not included in the photograph, but they are present in the set-up.

b) Speaker used in place of costly Shaker

An appropriate speaker unit is used as the vibrating source for the cantilever. The input to the speaker is being given via signal generator with varying frequency and amplitude. A power amplifier is also used in between to boost up the vibration amplitude. The speaker diaphragm is been connected to the scale via a suitable plastic piece.

c) **Piezoelectric transducer to be used**.

During the discussion along with the DRDO team present here, different types of piezoelectric strips were tested and output voltages were recorded using the virtual instrument. Among the tested items, highest voltage output was noted from 2 inch long Mide Tech piezoelectric strip. The output voltage was almost 72 V (p-p). The rms value was almost 38 V. Photographs of some of the piezoelectric strips employed are shown in Fig. .

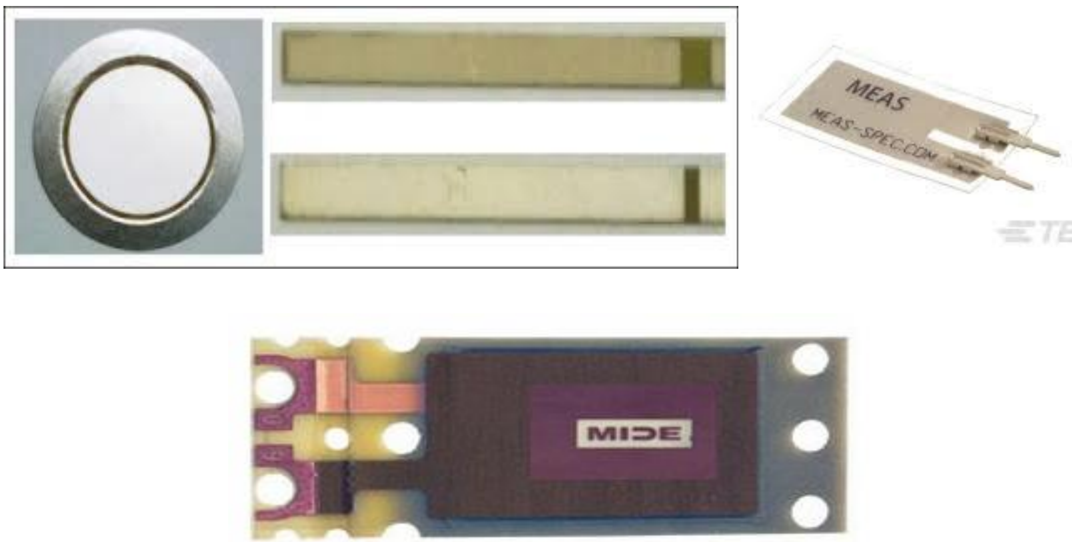

Fig.2.4: Disk type and long strip shape piezoelectric strip developed by DRDO and tested using the set-up. The picture in the right side shows a commercially available piezo electric strip used in the test system, initially. The picture at the bottom is the piezo strip purchased from Mide Tech. which was used in final result.

d) **The Visual interface of the whole setting using LabVIEW**

The visual interface of the full setup and the fully automatic control through one console is being carried out. The reading from the accelerometer, the output from the piezoelectric transducer all to be obtained on the single console. However the maximum output from the Mide Tech piezo strip was around 70 V which is beyond the parameter of Lab VIEW therefore the voltage output of Piezo and rectified output was taken on Digital Oscilloscope.

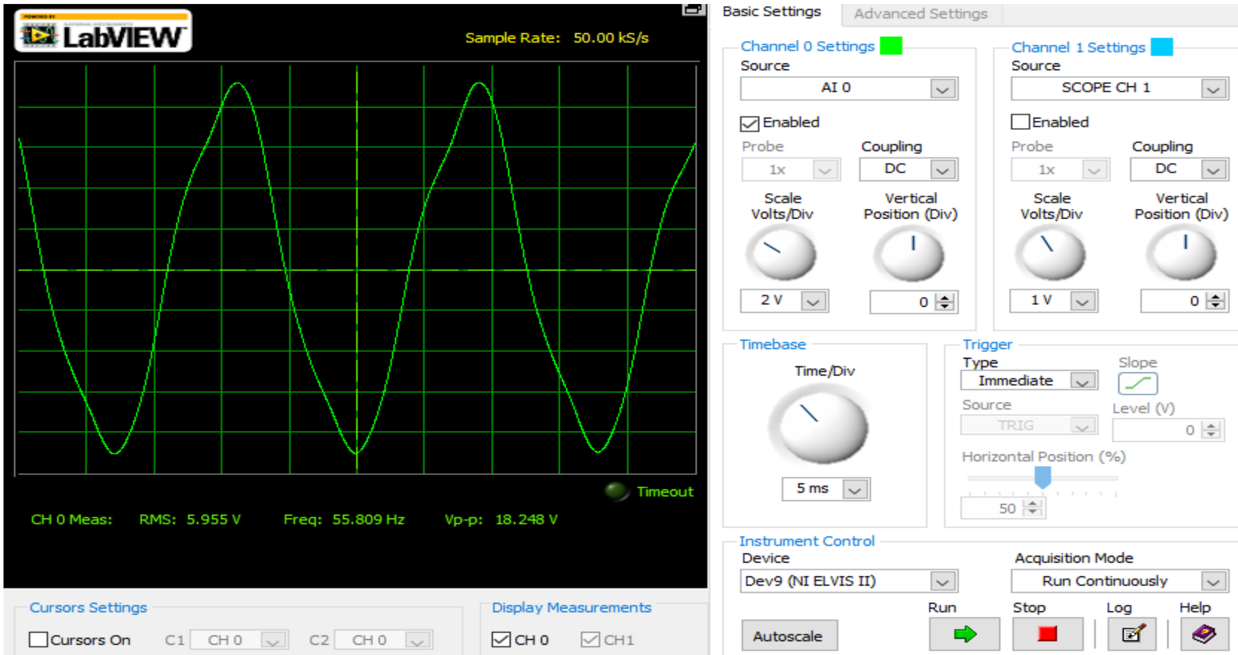

Fig. 2.5: Photograph of LabVIEW Digital oscilloscope for Normal Piezo strip

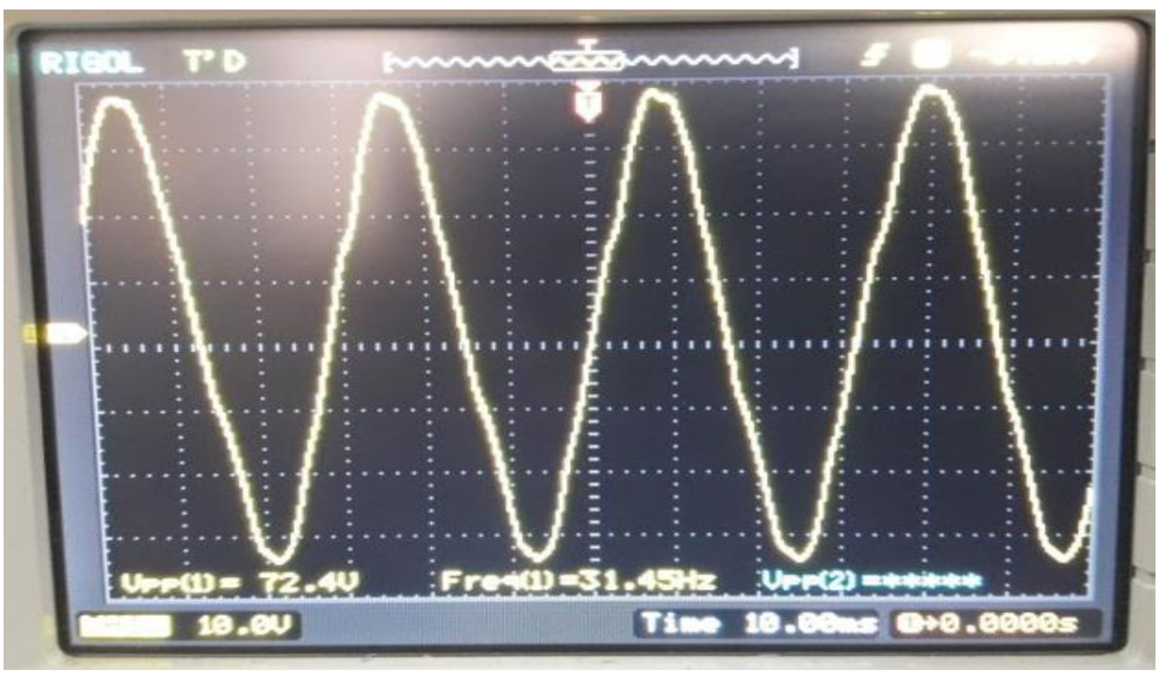

Fig. 2.6: Photograph of Full sinusoidal output from Mide piezo strip on Digital Oscilloscope

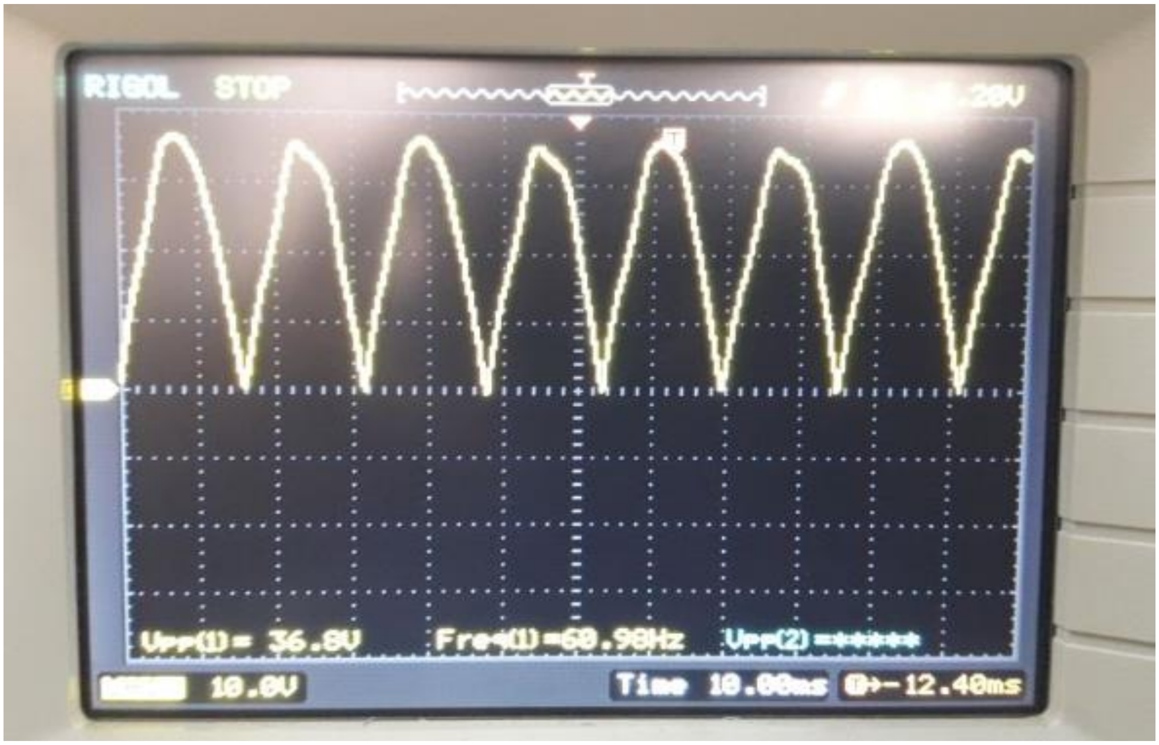

Fig. 2.7: Photograph of Half wave rectified output from Mide piezo strip on Digital Oscilloscope

CHAPTER 3

POWER CONDITIONING CIRCUIT

3.1 Introduction

The information or data generated by a basic measuring device generally require "processing" or "conditioning" ofone sort or another before they are presented to the observer as an indication or a record.

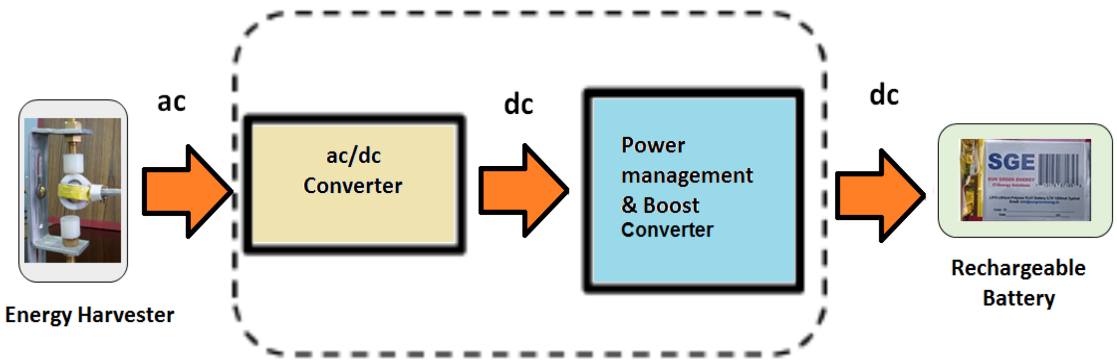

Fig. 3.1: Block diagram of a Harvester with power conditioning system [7]

3.2 Power Conditioning Circuit

Three types of signal conditioning circuits were used from initial to final stage. They are as follows:

(a) <u>LTC3588-1</u>

The power conditioning unit LTC3588-1 (Nano power Energy Harvesting Power Supply) was procured and tested at **the initial stage** of development. The LTC3588-1 integrates a low-loss full-wave bridge rectifier with a high efficiency buck converter to form a complete energy harvesting solution optimized for high output impedance energy sources such as piezoelectric. An ultralow quiescent current under voltage lockout (UVLO) mode with a wide hysteresis window allows charge to accumulate on an input capacitor until the buck converter can efficiently transfer a portion of the stored charge to the output. In regulation, the

LTC3588-1 enters a sleep state in which both input and output quiescent currents are minimal. The buck converter turns on and off as needed to maintain regulation.

Four output voltages, 1.8V, 2.5V, 3.3V and 3.6V, are pin selectable with up to 100mA of continuous output current. An input protective shunt set at 20V enables greater energy storage for a given amount of input capacitance. A photograph of the evaluation unit is shown below in Fig.3.2

Fig.3.2: EVAL board for LTC3588-1

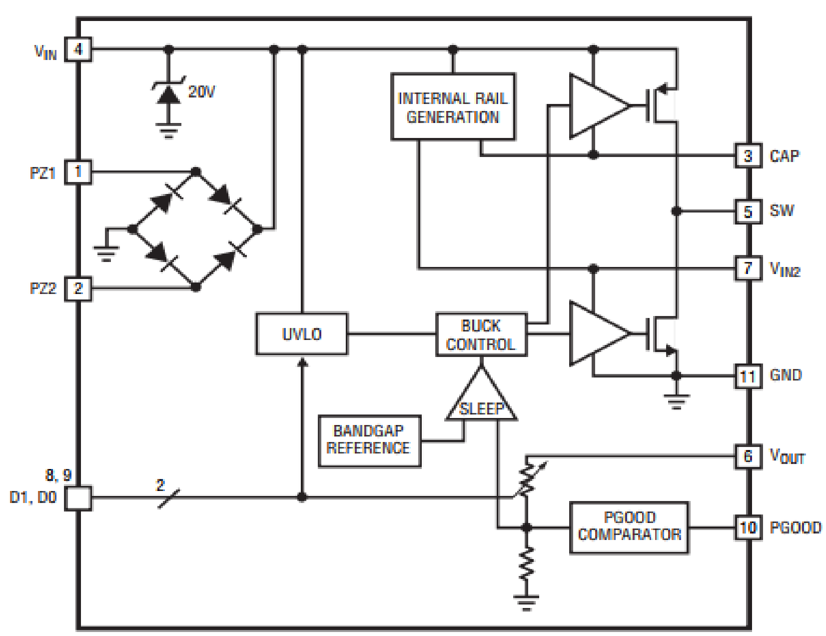

Fig.3.3: Block diagram of EVAL board of LTC3588-1 [16]

(b) BQ25570EVM-206

The bq25570 evaluation module (EVM) is a complete module for evaluating the bq25570 energy harvesting charger for storage elements like single-cell Li-Ion/Polymer batteries or super-capacitors. Intended to be powered by high impedance supplies, such as solar panels, thermo-electric generators (TEGs) or piezoelectric generators, the bq25570 regulates its input voltage so that it will not collapse its input source while charging the storage element up to a set voltage point. This signal conditioning circuit was used in **middle stage**. A power good output indicates when the charger's storage element reaches a user set voltage level. The bq25570 has an integrated buck regulator that provides a regulated output from the charger output. With minimum changes, the EVM can also be configured as an ultra-low power boost converter, regulating the output voltage from a low impedance source, while simultaneously providing a second output voltage from the buck regulator.

Fig.3.4: BQ25570EVM-206

(c) <u>EH301A</u>

EH300/EH301 Series EPAD® Energy Harvesting TM Modules can accept energy from many types of electrical energy sources and store this energy to power conventional 3.3V and 5.0V electrical circuits and systems. EH300/EH301 Series modules are completely self-powered and always in the active mode. They are intended for low power intermittent duty cycle sampled data or condition-based monitoring/ extreme lifespan applications. These modules can accept instantaneous input voltages ranging from 0.0V to +/-500V AC or DC, and input currents from 200nA to 400Ma from **energy harvesting sources** that produce electrical energy in either a steady or an intermittent and irregular manner with varying source impedances. This signal conditioning circuit was used in **final stage**. EH300/EH301 Series modules condition the stored energy to provide power at output voltage and current levels that are within the limits of a particular electronic system power supply specifications. For example, 1.8V and 3.6V is a useful voltage range for many types of IC circuits, such as microprocessors.

Fig.3.5: EH301A

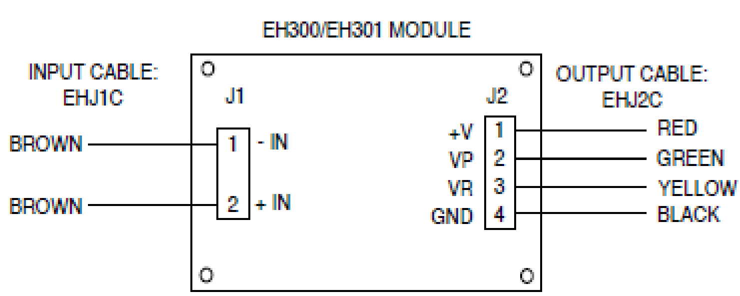

Fig.3.6: Block diagram of cable connections [14]

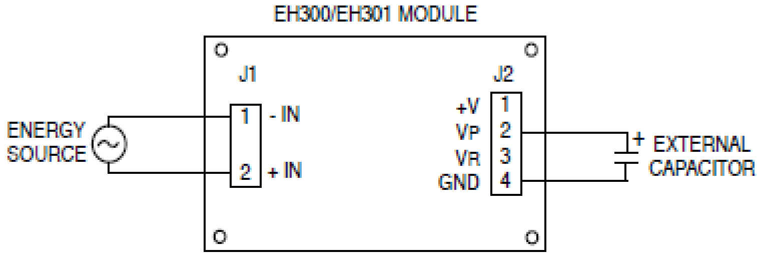

Fig.3.7: Block diagram of external capacitor connection [14]

The comparison between the three signal conditioning circuits has been made in a tabular form as shown below. The EH301A was giving the fast response and fat charging of the super capacitor in less time, there EH301A was used and finalized for energy harvesting from piezo.

Power Conditioning units and their main Technical difference	LTC 3588-1 	BQ25570EVM-206 	EH301A 
Manufacturer	Linear Technology	Texas Instruments	Advanced Linear Devices Inc.
Vin (DC) Min	2.7V	0.13V	Couple of mV
Vin (DC) Max	20V	4.0V	500V
Input Current (min)	950nA	100mA	1nA
Output Voltage Modes	1.8V,2.5V,3.3V & 3.6V	1.75V-1.85V (Nominal 1.8V)	3.1v-5.2V
Rectifier Required	No	Yes	Yes
Super Capacitor Available	No, Externally applied	No, Externally applied	Yes qty-2 of 3.3mF(6.3V)

Table 3.1: Comparison between power conditioning circuits [14], [15], [16]

3.3 Data acquisition with LabVIEW

The ability to pull in data from an outside *source*, process the data, and send signals back out to control devices is what sets LabVIEW apart from numerous other software products that can be used to analyse data. The goal of *data acquisition* is to capture data from one or more laboratory instruments on a computer so that it can be analysed, stored and displayed.

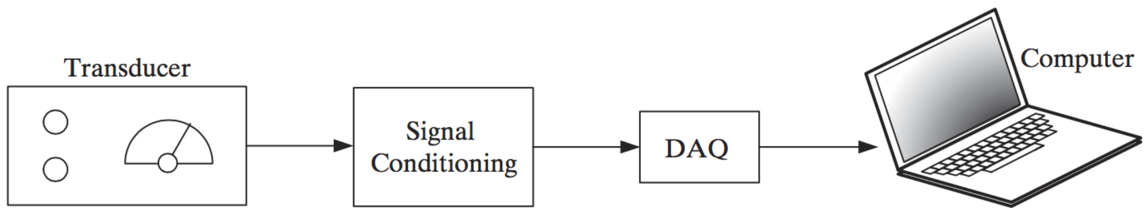

Figure 3.8: Data acquisition system with external signal conditioning [18]

After the required signal conditioning, which helps to adjust the signal type and range of the output signal to align with the requirements of the data acquisition system, data can be collected. The computer driving the data acquisition system will need to know what signal(s) to measure, how often to take readings and how many readings to collect, or how long to continue reading the signal(s)

The data acquisition process is configured by providing this required information prior to collecting data. The LabVIEW approach is to create a data acquisition *task* that contains this information. The collected data is available to the computer system and can be displayed, modified, analysed, or simply stored.

The heart of most data acquisition systems is an analog-to-digital converter (ADC) that can receive an analog signal and convert it to a digital form that can be used and stored on a computer system. The sensor's analog signals are connected to an analog input (AI. Many data acquisition systems provide several AIs (called *channels*) that share a single ADC by means of a multiplexer.

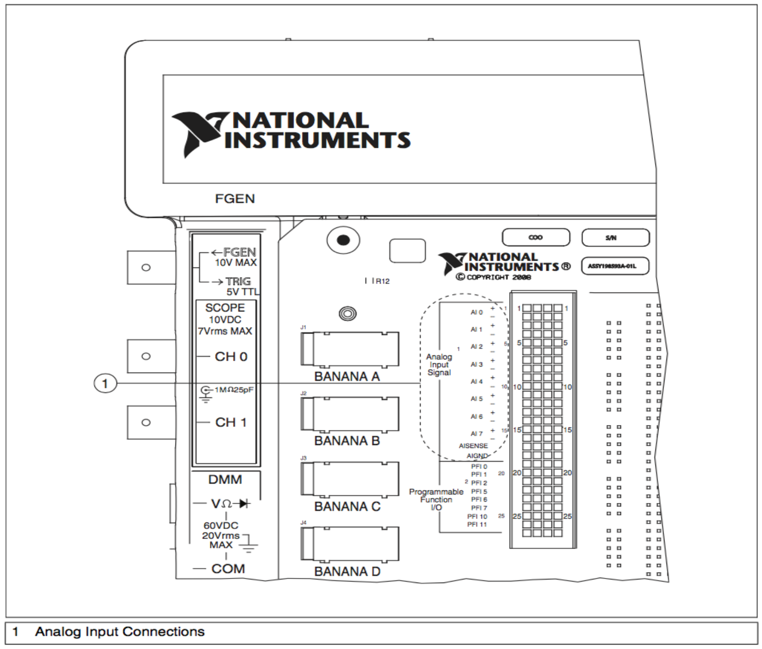

Figure 3.9: Analog Input connections on prototyping board [18]

The LabVIEW operates the data acquisition system and a request for a data acquisition device to collect one or more data values is called a *task*. The task for data acquisition has been created in LabVIEW.

CHAPTER 4

EXPERIMENTAL SETUP AND RESULTS

4.1 Introduction

In order to demonstrate the practical functioning of the proposed transducer, the cantilever setup was made. The piezoelectric strip and accelerometer was mounted on it. The output of the piezo electric strip was connected initially to full bridge Schottky diode rectifier.

A signal generator followed by a power amplifier serve as the source of signal for the speaker. The frequency can be varied for a wide range and the speaker can vibrate at different resonance frequencies, based on the need. First we have to set the required g for the experiment to take place. Here we used reading at different g values by varying the amplitude through the power amplifier.

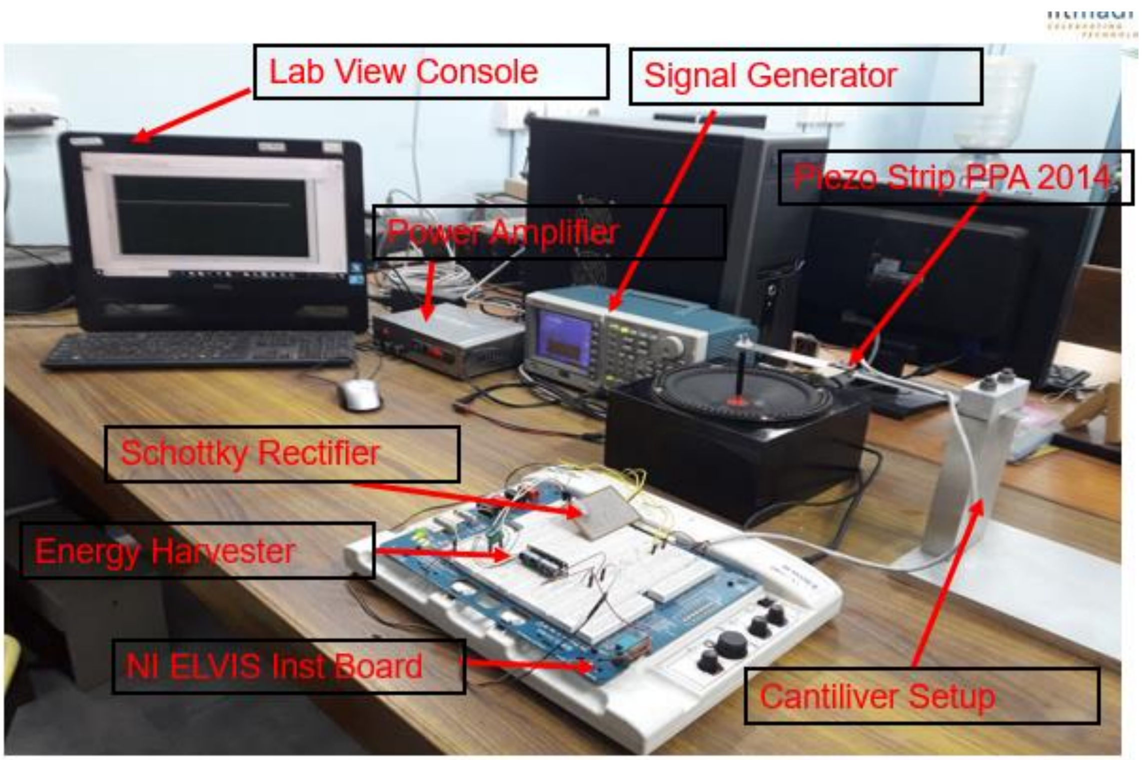

Figure 4.1: Experimental Setup to evaluate Energy Harvesting system

4.2 Accelerometer

An accelerometer was attached on the point of maximum acceleration (Middle region of the scale where it is attached to the speaker diaphragm). The accelerometer used in the system is GY-521. The codes to read from the GY-521 were burned into an Arduino board. The measured value is then communicated to a computer for recording. With the help of accelerometer we were able to monitor the g value being experienced by the piezo strip in experimental setup.

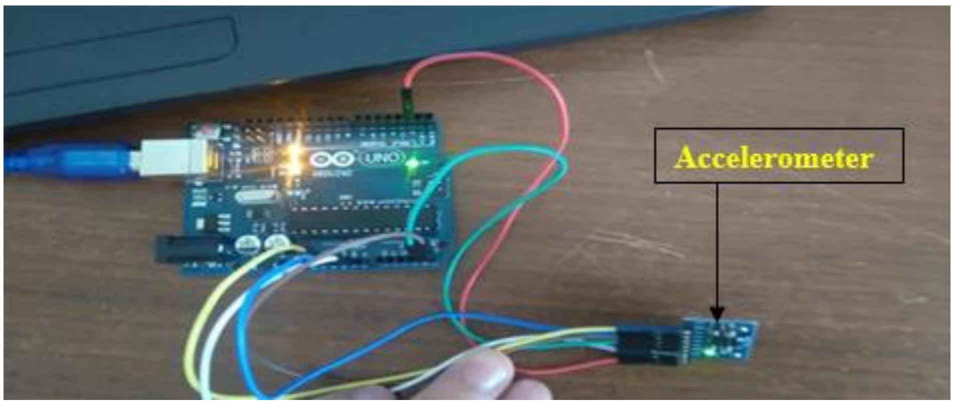

Figure 4.2: Photo of accelerometer GY-521 along with Arduino board in function

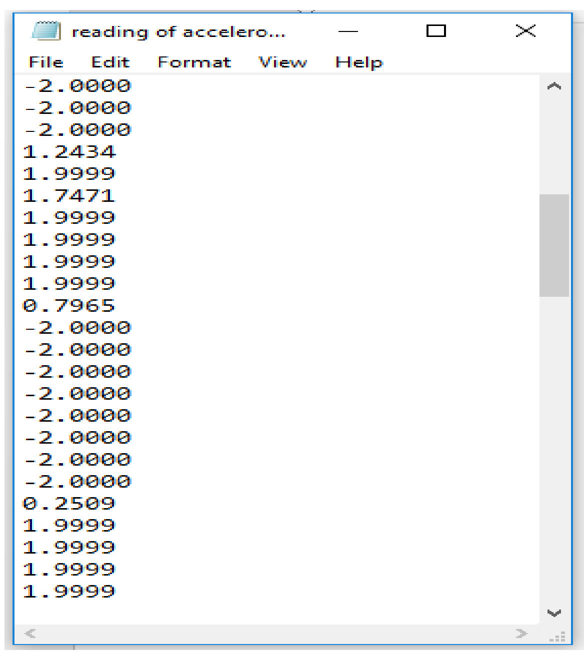

Figure 4.3: Snap shot of accelerometer GY-521 reading at 2g setting

4.3 Experimental results

The voltage output from the piezo strip (Mide Tech) was taken through Digital Oscilloscope, as the full wave sinusoidal wave form was of 72V amplitude. Therefore it cant not be taken through Lab VIEW console 9upper limit 20 V).

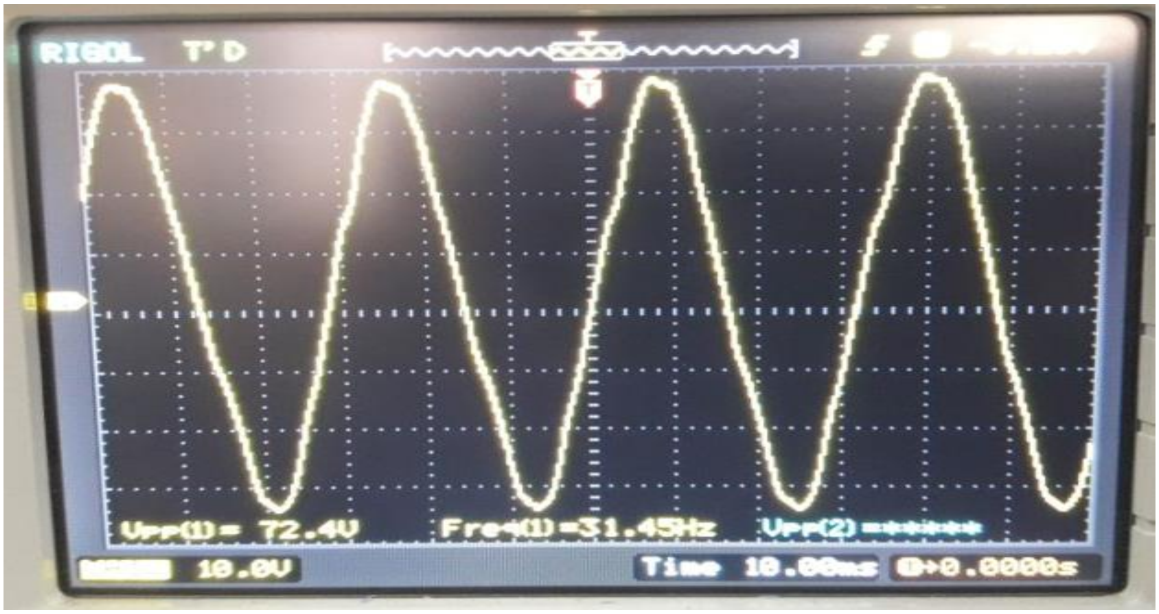

Figure 4.4: Output (Vo) from piezo strip after actuation

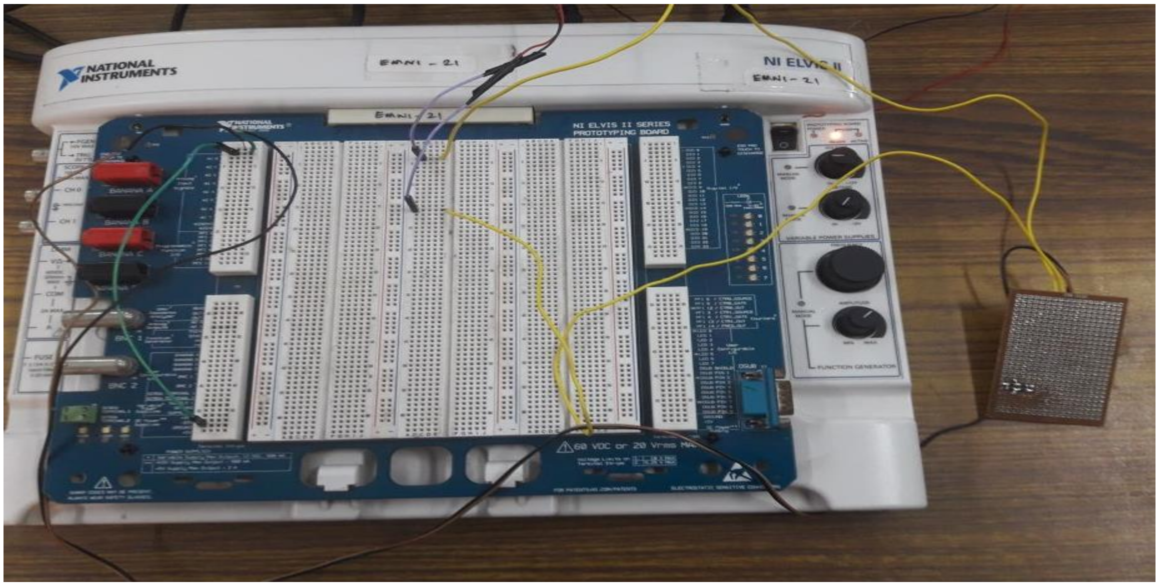

Figure 4.5: Schottky diode full bridge rectifier used to get the rectified output

The output voltage from the piezo electric strip was given across the full bridge rectifier made up of Schottky diode. The rectified output was applied across the digital oscilloscope. The rectified output from the full bridge Schottky diode was gain taken at digital oscilloscope instead of Lab VIEW, because the output rectified value was around 36V(max) which was still more than Lab VIEW output value(20 V max).

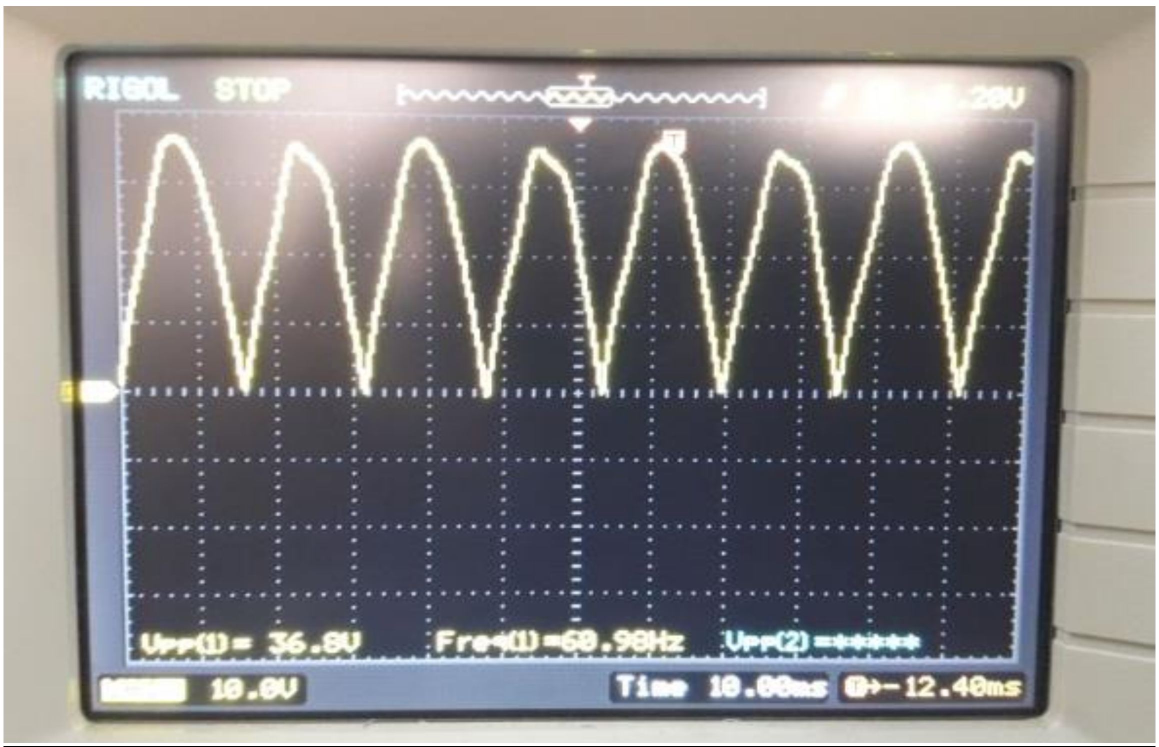

Figure 4.6: Output (Vo) from Schottky diode full bridge rectifier

The values (Vpp and applied Frequency) at 4g simulation were recorded and then it was plotted down.

S. No	Freq(Hz)	Vpp (V)	Rms(V)
1	13	3.8	1.4
2	15	6.5	1.85
3	20	7.4	2.21
4	25	5.3	1.43
5	30	4.8	1.32
6	35	4.2	1.25
7	40	5.2	1.5
8	45	6.1	2.3
9	50	9.3	3.5
10	55	15	5
11	60	21	7.8
12	65	21	8.5
13	70	20.6	7.2
14	75	15.2	5.4
15	80	11.9	4.14
16	85	10.5	3.6
17	90	9.2	3.1
18	95	8.3	2.7
19	100	7.9	2.5

Table 4.1: Value of V_{pp} and Vrms at different frequency

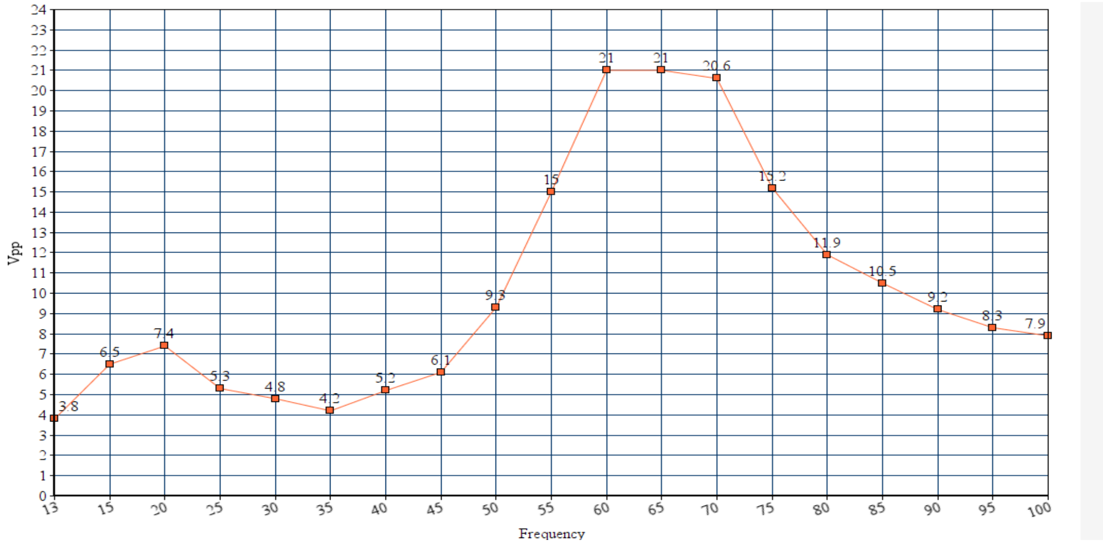

Figure 4.7: Graph of Vpp Vs Frequency

From the plot it can be inferred that the usable range of frequency for getting Vmax is between 55Hz to 75Hz. However the resonance frequency of the cantilever beam (stainless steel) without load is 25Hz, but with the addition of load (accelerometer and piezoelectric strip with tip mass) the resonance frequency tends to increase beyond 50 Hz. The maximum value is at 60 Hz frequency. The resonance frequency was varying with the value of g too. The above readings were found at 4 g value.

There was a considerable amount of voltage drop across the full wave bridge rectifier due to the high impedance of the piezo electric strip therefore energy harvesting board EH301A was used, as this is designed especially for high resistance load such as piezo strip. The output leads of piezo strips are connected to the PZ1 And pZ2 and the output is taken from Vo and ground

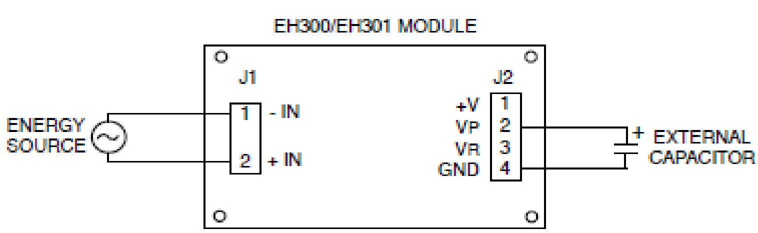

Figure 4.8: Connection of EH301A to piezoelectric strip [14]

4.4 Charging duration required with different load circuit

A photograph of the complete system with variable vibrational source, power conditioning circuit and pc based display of the results is given in Fig.4.1. The power conditioning circuit is shown in Fig.4.7.The system has been tested using three power conditioning units; one from TI, another one from Linear Technology and a relatively new unit EH 301A from Advanced Linear Devices, CA, USA. For the later one, the charging capacity was 3.3mF. The waveform recorded from the system is shown in Fig. 4.8. Later, the capacity of the unit was increased to 0.47F by introducing a super capacitor and the experiment was repeated. The results recorded are given in Fig. 4.9.

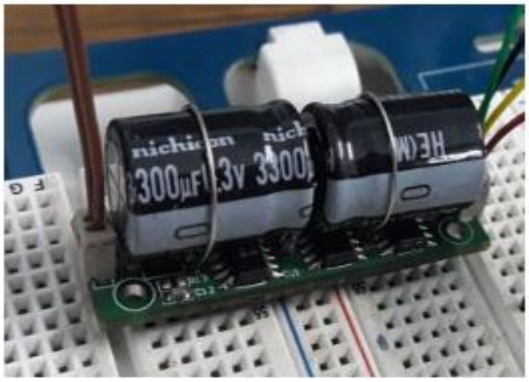

Figure 4.9: EH301A with two internal capacitor of 300µF

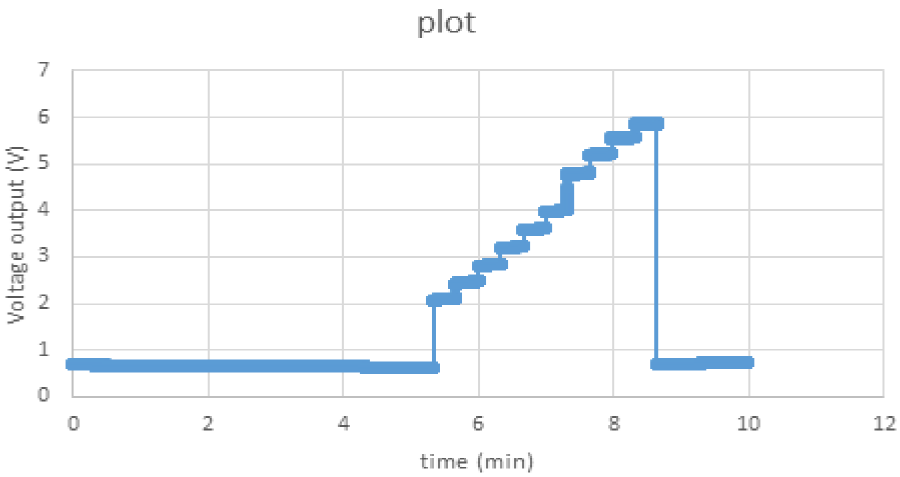

Figure 4.10: Output from 3.3mF super capacitor

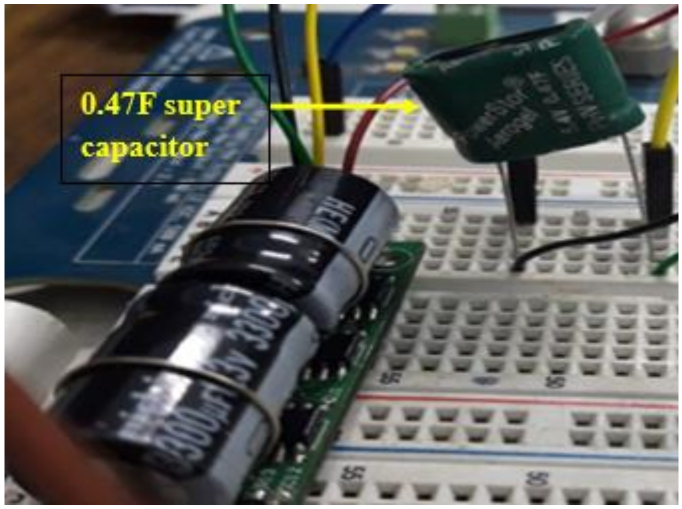

Figure 4.11: Connection of EH301A to 0.47F super capacitor

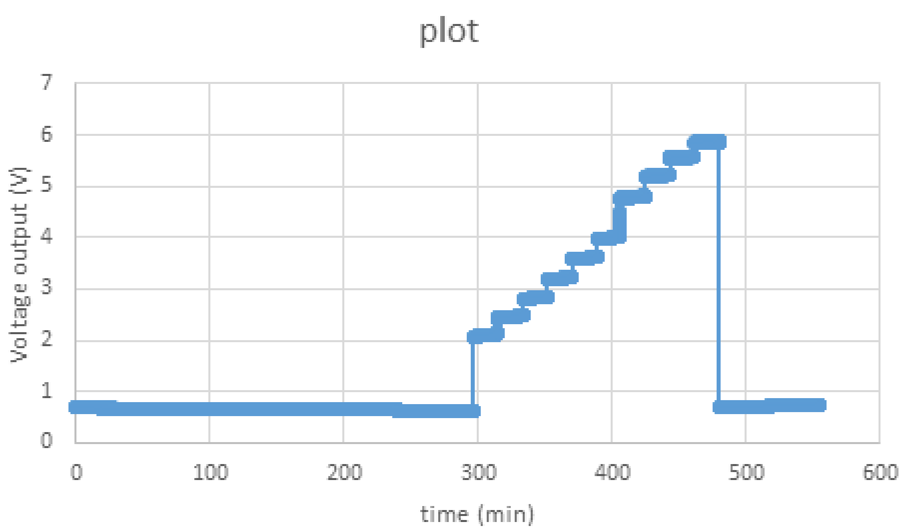

Figure 4.12: Output from 0.47F super capacitor

As can be seen from Fig. 9, the voltage build-up (0 V to 6.4V) is quite fast (5mins) with a capacitor of smaller capacity (3.3mF). While, with a capacitor of larger capacity (0.47F), the time that took for build-up (0 V to 5.4V) was 180min.

4.5 Quality factor

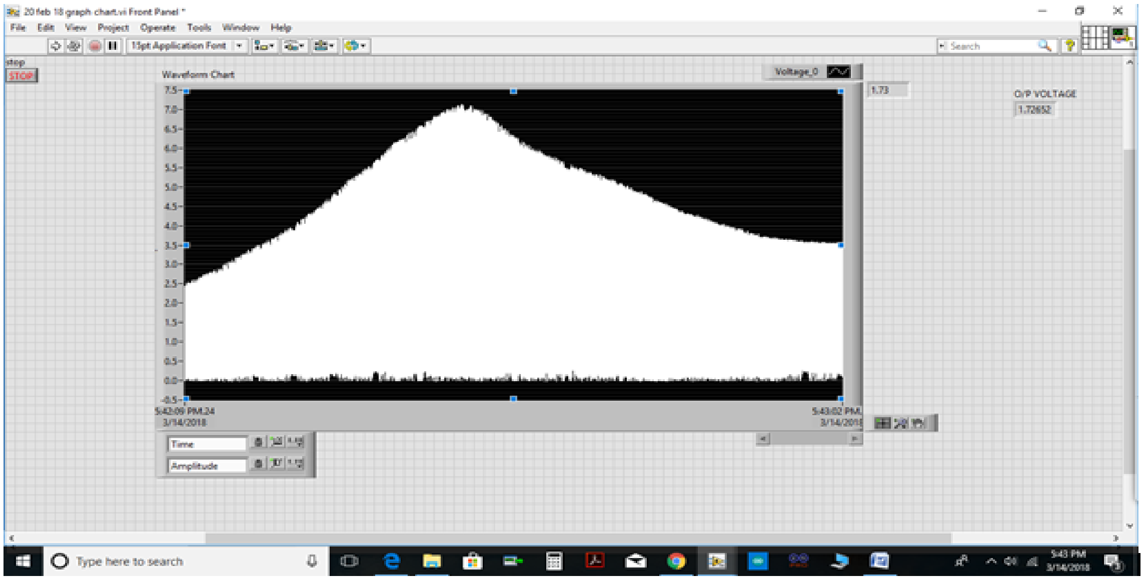

Figure 4.13: Output obtained at Sweep Mode

For finding the quality factor, the Open Circuit the signal generator was operated at sweep mode from start frequency at 20 Hz and stop frequency at 70 Hz (As the calculated resonance frequency of the setup was 52.5Hz). The resonance frequency for cantilever beam (steel ruler) is 25Hz, however with the loading effect of accelerometer and piezo strip and tip mass the resonance frequency is increased to 52.5 Hz.

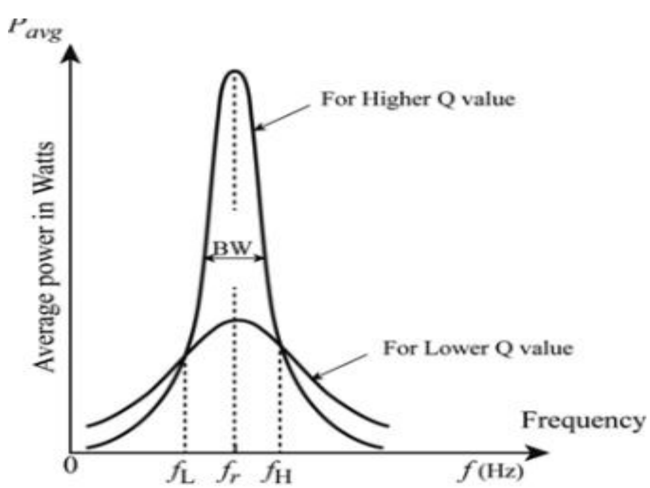

Figure 4.14: Resonance output [19,Fig.2]

f_1=49Hz, f_2=57 Hz and fr =52.5 Hz

Quality Factor (Q) = Resonance Frequency (f_r) /Band width (f_2-f_1)

$$Q= f_r / (f_2-f_1)$$

Therefore the quality factor=52.5/ (57-49) = 6.5625.

The high the value of Q the good the circuit is.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

The energy extraction from the piezoelectric strip was done successfully. The next step was to condition the signal and get the output voltage in measurable value like Volt, so that the voltage can be utilise to drive some other load. For this purpose supercapacitor was used along with the Evaluation board, the accelerometer was mounted on the scale and amount of g acting on the scale was measured. The hardware testing was carried out in which three signal conditioning circuit were used. The comparison between the three signal conditioning (energy harvesting) circuit showed that EH301A was the best among the three. The output voltage from EH301A was in mV and the charging of the super capacitor was also fast. Form the result it was clear that the piezo PVDF material from the Mide Tech was giving much higher output (open circuit) voltage than the rest of piezo material used like ceramic disk and the one PVDF supplied from DRDO team.

The same cantilever beam was subjected to different amplitude signal from signal generated to achieve different g effect on the cantilever beam and the same was recorded. It was found out that minimum of 2g value of g was achievable from the cantilever arrangement.

Even though energy harvested is small and in the order of milliwatts, it can provide enough power for wireless sensors, embedded systems, and other low-power applications.

5.2 Future scope

The future scope is to replace the independent Mide piezo strip and the Schottky diode full bridge rectifier by Schottky Diode based ac-to-dc Converter (SDC) on an SOI wafer. This wafer is to be mounted directly on the cantilever beam and the testing of the full system is to be carried out.

ANNEXURE

Codes for accelerometer (upto 16g), here the output form Z axis has been taken

```
#include <Wire.h>

long accelX, accelY, accelZ;
float gForceX, gForceY, gForceZ;

long gyroX, gyroY, gyroZ;
float rotX, rotY, rotZ;

void setup() {
  Serial.begin(9600);
  Wire.begin();
  setupMPU();
}


void loop() {
  recordAccelRegisters();
  recordGyroRegisters();
  printData();
  delay(100);
}

void setupMPU(){
  Wire.beginTransmission(0b1101000); //This is the I2C address of the MPU
(b1101000/b1101001 for AC0 low/high datasheet  of MPU sec. 9.2)
  Wire.write(0x6B); //Accessing the register 6B - Power Management (Sec. 4.28)
  Wire.write(0b00000000); //Setting SLEEP register to 0. (Required; see Note on p. 9)
  Wire.endTransmission();
  Wire.beginTransmission(0b1101000); //I2C address of the MPU
  Wire.write(0x1B); //Accessing the register 1B - Gyroscope Configuration (Sec. 4.4)
  Wire.write(0x00000000); //Setting the gyro to full scale  250deg./s
  Wire.endTransmission();
  Wire.beginTransmission(0b1101000); //I2C address of the MPU
  Wire.write(0x1C); //Accessing the register 1C - Acccelerometer Configuration (Sec. 4.5)
  Wire.write(0b00011000); //Setting the accel to  16g
  Wire.endTransmission();
}

void recordAccelRegisters() {
  Wire.beginTransmission(0b1101000); //I2C address of the MPU
  Wire.write(0x3B); //Starting register for Accel Readings
  Wire.endTransmission();
  Wire.requestFrom(0b1101000,6); //Request Accel Registers (3B - 40)
  while(Wire.available() < 6);
  accelX = Wire.read()<<8|Wire.read(); //Store first two bytes into accelX
```

```
  accelY = Wire.read()<<8|Wire.read(); //Store middle two bytes into accelY
  accelZ = Wire.read()<<8|Wire.read(); //Store last two bytes into accelZ
  processAccelData();
}

void processAccelData(){
  gForceX = accelX / 2048.0;
  gForceY = accelY / 2048.0;
  gForceZ = accelZ / 2048.0;
}

void recordGyroRegisters() {
  Wire.beginTransmission(0b1101000); //I2C address of the MPU
  Wire.write(0x43); //Starting register for Gyro Readings
  Wire.endTransmission();
  Wire.requestFrom(0b1101000,6); //Request Gyro Registers (43 - 48)
  while(Wire.available() < 6);
  gyroX = Wire.read()<<8|Wire.read(); //Store first two bytes into accelX
  gyroY = Wire.read()<<8|Wire.read(); //Store middle two bytes into accelY
  gyroZ = Wire.read()<<8|Wire.read(); //Store last two bytes into accelZ
  processGyroData();
}

void processGyroData() {
  rotX = gyroX / 131.0;
  rotY = gyroY / 131.0;
  rotZ = gyroZ / 131.0;
}

void printData() {
  /*Serial.print("Gyro (deg)");
  Serial.print(" X=");
  Serial.print(rotX);
  Serial.print(" Y=");
  Serial.print(rotY);
  Serial.print(" Z=");
  Serial.print(rotZ);*/
  Serial.print(" Accel (g)");
  /*Serial.print(" X=");
  Serial.print(gForceX);
  Serial.print(" Y=");
  Serial.print(gForceY);*/
  Serial.print(" Z=");
  Serial.println(gForceZ);
}
```

REFERENCES

[1] Doebelin E.O., *Measurement Systems – Application and Design*, McGraw-Hill Publications, Fifth Edition, 2004.

[2] Neubert, Hermann K.P., *Instrument Transducers: An Introduction to their Performance and Design*, Oxford University Press, Second Edition, 2003.

[3] Book: Mechanical and Industrial Measurements by R. K. Jain, Khanna Publishers

[4] Mechanical Measurements by Thomas G. Beckwith and N. Lewis Buck

[5] http://en.wikipedia.org/wiki/Piezoelectricity

[6] NI ELVIS II user manual *www.ni.com/pdf/manuals/374629c.pdf*

[7] Energy harvesting from low frequency applications using piezoelectric materials Huidong Li, Chuan Tian, and Z. Daniel Deng

[8] Design Study of Piezoelectric Energy- Harvesting Devices for Generation of Higher Electrical Power Using a Coupled Piezoelectric-Circuit Finite Element Method IEEE Transactions on Ultrasonic's, Ferroelectrics, and Frequency Control, vol. 57, no. 2, February 2010.

[9] Estimation of Electric Charge Output for Piezoelectric Energy Harvesting,LA-UR-04-2449, Strain Journal, 40(2), 49-58, 2004;Henry A. Sodano, Daniel J. Inman, Gyuhae Park.

[10] LTC-3588-1 Data sheet, http://cds.linear.com/docs/en/datasheet/35881fb.pdf

[11] SODERKVIST, J., 'Dynamic behaviour of a piezoelectric beam', J.Acoust. Soc. Am.. 90 (2), Pt. 1, pp.686-691, August 1991.

[12] A.K. Batra, J.R. Currie1, A.A. Alomari, M.D. Aggarwal, C.R. Bowen, A versatile and fully instrumented test station for piezoelectric energy harvesters, Measurement 114 (2018) 9–15.

[13] Haris Fazilah Hassan et.al, Acoustic Energy Harvesting Using Piezoelectric Generator for Low Frequency Sound Waves Energy Conversion

[14] EH300/EH301 Series EPAD® Energy Harvesting Modules, Advanced Linear Devices, Inc

[15] User's Guide for bq25505 Battery Charger Evaluation Module for Energy Harvesting, Texas Instruments

[16] www.linear.com/product/LTC3588-1

[17] MPU-6000/MPU-6050 Product Specification

[18] Getting Started with LabVIEW, http://www.ni.com/pdf/manuals/373427j.pdf

[19] Bandwidth and Power of Resonant Circuit, https://www.chegg.com

[20] https://circuitdigest.com/electronic-circuits/piezoelectric-transducer-circuit-diagram

[21] The How and Why of Energy Harvesting for Low-Power Applications, https://www.allaboutcircuits.com

VITAE

Name	:	Rahul Tripathi
Date of Birth	:	08 Jan 1984
Educational Qualification	:	B. Tech. (Electronics & Comm. Engg.)
		U.P. Tech University
		PG Diploma in Aeronautical Engg.
Occupation	:	Aeronautical Engg. In IAF (Defence)
Contact Address	:	House no 258. Mr AK Tripathi
		New Colony Palhani, Behind Railway Dak bunglow, Durgavati Kung
		Azamgarh-276001 (U.P.)
Phone	:	7358642063/9419015836/9419015829
E-mail	:	rahultri333@gmail.com