# ANALYSIS OF BIMORPH PIEZOELECTRIC ENERGY HARVESTER ATTACHED WITH A CANTILEVER BEAM UNDER EXCITATION

**A Thesis Presented to**
**The Faculty of Mechanical and Production Engineering Department**

**In Partial Fulfillment**
**Of the Requirements for The Degree of**
**Bachelor of Engineering**

**By,**
**Syed Sifat Alam (160011043)**
**Ahnaf Sharaf Rhythm (160011044)**

**Supervisor,**
**Prof. Dr. Md. Zahid Hossain**

**Department of Mechanical and Production Engineering,**
**Islamic University of Technology, OIC**
**Gazipur, Bangladesh**

**Acknowledgement**

First and foremost, we are extremely grateful to our supervisor, Prof. Dr. Md. Zahid Hossain for his invaluable advice, continuous support, and patience during our Bachelor of Engineering study. His immense knowledge and plentiful experience have encouraged us in all the time of our academic research and daily life. We would also like to thank Lecturer Nagib Mehfuz for his support on our study. We would like to thank all the members in the Department of Mechanical and Production Engineering. It is their kind help and support that have made our study and life in the IUT a wonderful time. Finally, we would like to express our gratitude to our parents. Without their tremendous understanding and encouragement in the past few years, it would be impossible for us to complete our study.

**Abstract**

In this thesis work a cantilever structure based bimorph piezoelectric energy harvester have been designed and analyzed using lead zirconium titanate (PZT 5A) as piezoelectric material and steel as the elastic substrate layer. This energy harvester has one of its end clamped to a vibrating source from where vibration is being induced into the cantilever beam and a proof mass is mounted on top of the other end. The energy harvester model is designed and finite element model (FEM) simulation is done in COMSOL Multiphysics for the conversion of mechanical vibrations to electrical energy. Different structural parameters, including piezoelectric layer thickness, proof mass volume and proof mass material has been changed to increase the output electrical energy while keeping the same resonant frequency. First the frequency response of the device is performed which shows that the resonant frequency occurs at 71 Hz at a peak output voltage of 5.16V for a mechanical input power of 1.25mW resulting in an electrical output power of 1.2mW. Then, with the increase of both the top and bottom piezoelectric layer thickness, it was found that the peak voltage decreases with the increase of resonant frequency. Again with the increase of proof mass volume, it was found that the peak voltage increases with the decrease of resonant frequency. Finally, by increasing both the piezo electric layer thickness 1.33 times of initial value 0.6 mm and proof mass volume 2 times of initial value 95.2mm$^3$, voltage increases to 7.675V from initial value of 5.16V at a fixed resonant frequency of 71hz. Similar results are found at other data points by keeping increment ratio same. A load response analysis for different piezoelectric layer thicknesses was also done. At last after observing the simulation results for different proof mass materials and volume, it was found that it has negligible effect on performance if the mass remains same.

**Keywords**: Bimorph, Unimorph, Piezoelectric Energy Harvester, PZT 5A, Piezo Layer, Elastic Substrate Layer, Cantilever Beam, Structural Parameters, Proof Mass (PM), COMSOL Multiphysics.

# Table of Contents

## List of Figures

## List of Tables

**Chapter 1**

## 1.1 Introduction

Energy that is theoretically available to harness for the service of electronics is found in solar, thermal, and mechanical environmental sources. Technologies for energy harvesting that produce electrical power from mechanical vibration or motion for low-power electronic devices are of particular interest in the absence of solar energy[1]. A possible alternative to mechanical harvesting is thus minimizing battery replacement for embedded sensors in remote areas[2].The mechanism of integrating natural and human-made vibrations into usable electrical energy is vibration energy harvesting. The harvesting of resources is a technology that can be used to derive electrical energy from waste energy sources, which is the essence of waste energy. It is very attractive because of its renewable energy potential and production without any environmental concerns[3]. The variations in temperatures, wind, mechanical vibrations are the common renewable energy sources of sunlight that are easy to produce. Mechanical vibrations, among these sources, are omnipresent, and therefore promising, to power the electronic devices that are autonomous[4]. As principles of vibration energy conversion to electrical energy goes, the use of piezoelectric materials to generate power has been promising, due to its high density of energy/power, scalability and simplicity. The simplicity associated with the piezoelectric micro-generators makes it very attractive for MEMS applications, especially for remote systems. MEMS mainly knows as Micro-Electro-Mechanical Systems, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of microfabrication. Energy harvesters based on MEMS have a broad range of applications because of wind energy, devices, foot motion and many others, such as extracting energy from vibrations. To harvest energy from vibrations, electromagnetic effect, capacitive effect and piezoelectric effect, three types of mechanism are used [5]. The piezoelectric shape is well balanced because of MEMSEngineering compatibility. The cantilever beam is commonly used for the positioning of the piezoelectric materials as it has a high average strain for a given force than any other configuration. Cantilever structured PEH is thus most actively used for research focused on piezoelectric energy harvesters (PEH) and also investigated due to simple manufacturing processes and facilitate fabrications. Cantilever organized PEH usually consists of many critical components: piezoelectric material, elastic backing, and proof mass. Cantilever organized PEH during operation normally functions in resonant mode, so the energy can be effectively harvested by modification of the resonant frequency. The selection of PEH components is important for harvesting the energy along with high power density. Piezoelectric material with isotropic piezoelectric characteristics, for example, demonstrated poor performance due to its low efficiency of electromechanical energy conversion[6]. Single crystal piezoelectric materials with high anisotropic piezoelectric properties have been employed to overcome these structural drawbacks and also to improve harvesting performance. For example, The piezoelectric single crystals based on Rhombohedral structured Pb(Mg1/3Nb2/3) O3-PbTiO3 and Pb(Zn1/3Nb2/3)O3-PbTiO3 exhibit strong anisotropy and enhanced piezoelectric properties along the polarization directions (001) (d31 mode) and (011) (d32 mode) compared to the (111) direction. It is plausible to expect good energy conversion efficiency from the cantilever structured PEH by using this anisotropic existence of piezoelectric materials. Piezoelectric material placement has a great impact on the energy harvester's efficiency. The proof mass is used to reduce the vibrating frequency and increase the energy harvester's strength. For this study Piezoelectric bimorph is used, which is a cantilever that is used for actuation or sensing and consists of two active layers. The piezoelectric bimorph can also have a passive layer between the two active layers. In actuator applications, if voltage is applied, the bimorph will bend causing one active layer to contract and the other to expand. Thin films of lead zirconate titanate (PZT), which have a high piezoelectric response, are good candidates for energy harvesters of piezoelectric microelectromechanical (MEMS) used to scavenge energy from continuous mechanical vibrations. For MEMS energy harvesters, however, high resonant frequencies (typically more than 1 kHz) and poor output power are the key challenges. Low power is often the result of a tiny piezoelectric area combined with a rigid, low fracture support sheet[7]. In this research work, FEM study of duration effects and effects of thickness has been done on the piezoelectric layer. The outcomes of FEM have been recorded for varying the thickness of the piezoelectric layer from 0.2 mm to 0.8mm with two distinct 21mm length. The length and thickness variance of the piezoelectric layer has been observed. It has an effect on the overall cantilever displacement, which affects the produced net potential. FEM simulator COMSOL Multiphysics has been used in the FEM analysis, Structural Mechanics and Piezoelectric device study.

### 1.2 Related Literature review

The positioning of piezoelectric material along the length of the beam, proof mass material, form and placement of proof mass on the beam requires attention by studying the problems in energy harvesting. The necessity and novelty of this work can be completely justified by a literature survey of the published research works.

Baker et. al uses analytical methods to research alternative geometries for energy harvesting and finds that the triangular cantilever beam generates 50 percent more strain than the rectangular cantilever beam[8]. Zhang et. al theoretically and experimentally investigated that 167 percent more power than the rectangular cantilever beam is provided by the trapezoidal piezoelectric energy harvester with proof mass [9]. Mohammed Arefi and Ashraf M Zenkour have worked on the application of piezoelectric materials in beam geometries as sensors and actuators. Mechanical, thermal, electrical and magnetic loads were exposed to the assumed structure. The authors found from the theoretical and numerical findings that applied electric potential increases the structure's deflection [10]. The first-order shear deformation theory and strain gradient theory were used to describe the structure bending analysis[11]. The wave propagation, free vibration and bending study of a functionally graded rectangular cross-section of micro and nanobeams on the base of Visco-Pasternak was also studied by Mohammed Arefi and Ashraf M Zenkour[12]. The bending study of the three-layered piezomagnetic nanobeams with and without curvature was studied using the Timoshenko model and the theory of Hamilton[13]. The authors also analyzed the response under electro-magneto-elastic analysis of a three-layered curved beam[14]. Hong goo and Susan Troiler in their research work found out that to determine the relationship between output power efficiency, PZT thickness, and piezoelectric response, piezoelectric energy harvesters using focused PZT films grown either by sputtering or CSD were successfully manufactured with similar dimensions. The volume of the PZT layer was found to strongly rely on the devices' power output under the same conditions. All the instruments worked at 68 Hz or so. An average power density of 1036 $\mu W/cm^2 * G^2$was achieved by piezoelectric energy harvesters with 3 µm thick sputtered 1 percent Nb doped PZT film on Ni. The harvester's improved power density ($582 \mu W/cm^2 * G^2$) With 1 percent Mn doped sol-gel PZT films on Ni foil, achieved using an elevated temperature poling procedure, compared to room temperature poling. This result promises high power density energy extraction from ambient vibration for use in devices that consume energy in microwatt ranges[1]. In shanky saxenas research work the effect of length and thickness variation on the displacement, von-Mises stress and induced electrical potential have been investigated. From the above study, it has been found that the displacement of the cantilever increases when the piezoelectric layer length increases and the displacement decreases as the layer thickness increases. The von-Mises stress on the piezoelectric layer increases as the length of the piezoelectric layer increases and the von-Mises stress on the piezoelectric layer decreases as the thickness of the piezoelectric layer is increased[15]. A resonant tunable cantilever beam electromechanical model was developed by Senthilkumar and Vasundraa using shape memory alloy with and without tip mass alloy[16]. By adjusting the thickness of the cantilever beam, Paquin and St-Amant improved the efficiency of the piezoelectric energy harvester; the authors found that their optimum thickness varied beam has the potential to generate 72 percent more power than the classical beam[17]. On different beam geometries, Pradeesh investigated the stress, strain, frequency response, voltage and power of various types of piezoelectric energy harvester. With theoretical and experimental works, the authors confirm their numerical model[18]. COMSOL Multiphysics 5.3a's numerical findings are well correlated with theoretical and experimental work. Matova explores the effects of the tapered piezoelectric energy harvester's length and width ratio[19]. The authors infer from the experimental work that the beam with more length has an effect on the piezoelectric power output, but there is no noticeable output on power for the short-length beam. By introducing the cavity in a rectangular cantilever beam, Rami Reddy increased the power of piezoelectric energy harvesters by 75 percent[20]. Usharani designed and developed a double tapered cavity beam analytical approach and found that their beam has a broad operating frequency range[21]. By finding the optimum placement of piezoelectric materials, Liao and Sodano explore the effect of piezoelectric placement on the loss factor[22]. In order to measure the multimode vibration frequency of the beam, Botta suggested an analytical solution which is regulated by optimal placement of piezoelectric materials[23]. Using an integral equation technique, Spier discussed the optimum placement of multi piezoelectric material[24]. Piezoelectric materials are optimally positioned based on the particular frequency of the energy harvester, which has also been validated using numerical methods. In order to analyze the impact of proof mass on the energy harvester efficiency, Kim developed an analytical model and the results were verified experimentally[25]. Piezoelectric materials are optimally positioned based on the particular frequency of the energy harvester, which has also been validated using numerical methods. In order to analyze the impact of proof mass on the energy harvester efficiency, Kim developed an analytical model and the results were verified experimentally[26]. A new type of piezoelectric energy harvester has been introduced by Damya in which the structure is fixed at both ends and proof mass is put in the center and their model generates more power than the classical one[18]. Damya et. al developed a new proof-mass structure to power biosensing applications by tuning the device's natural frequency[27]. By altering the center of gravity of the roller style test mass, Somkuwar et. al tuned the natural frequency of the energy harvester[28]. Using seismic mass, Saxena created and manufactured guided two and four beam cantilever style piezoelectric energy harvesters [29]. Their model generates the same energy from the experiment with 32.14 percent less displacement compared to the traditional process. In order to boost the energy harvester efficiency by putting different types of proof mass, Sunithamani conducted experimental and simulation research; Disc-shaped proof mass produces more power of 443.65 nW than ring-shaped proof mass mass[30]. Using COMSOL Multiphysics, Alamesh optimized the effect of the test mass on the piezoelectric energy harvesters. The authors found from the experimental work that the T-shaped proof mass fixed to the free end decreases the resonant frequency of the energy harvester compared to the rectangular proof mass mass[31]. The design and simulation of the piezo-resistor barometer to measure the displacement of the Afm probe is discussed in the reasearch paper of Seyed Esmaeil Kazemipoor and Abbas Kamali. It should be noted that all the results obtained from this article, analyzed and simulated in various voltage-ohmic frames and obtained from this structure, are merely due to the strain on this structure and the disruption of the Afm probe [32]. They found out that voltage changes in piezo structures are low. Thus, it is required to use amplifiers. These modifications take place in various directions, such as pressure measurement, vibration, temperature and production of audio, etc. Ohmic changes of piezo have non-uniform Impedance matching in various load conditions. In the paper of Sathya et. al, they have optimized the dimensions of the proof mass and the bimorph piezoelectric layer to maximize the output voltage of the piezoelectric energy harvester by keeping the resonant frequency low[33]. Guizetti et. al in their work, tried to obtain the maximum output of a piezoelectric energy harvester by changing the piezoelectric layer thickness at a smaller scale such that the stiffness of the beam remains unchanged[34].

From the literature review, it was found that there were also minimal investigations into the placement of piezoelectric materials, proof mass content, different placement and form of proof mass on the beam. The efficiency of the positioning of piezoelectric material along the beam length was analyzed in this analysis. The effect of different test mass materials on the free end of the beam was analyzed. The effect of the proof mass over the vibrating frequency, open circuit voltage, optimum load, closed circuit voltage and power on the beam at different positions and shape was also analyzed.

### 1.3 Uniqueness of this work

In our work we will be changing the piezo electric layer thickness in a bimorph shaped cantilever beam structure and we will be changing it at a much larger scale than the work done in the paper of Guizetti where the stiffness of the beam remained unchanged but in our case the stiffness of the beam will change. We will also be changing the proof mass volume along with piezo layer thickness simultaneously and try to obtain the maximum possible power output by keeping the same resonant frequency. We will also be changing the proof mass material of our bimorph piezoelectric energy harvester and observe the changes in output due to that but we will change the dimensions of the proof mass so that the input mass remains the same.

## Chapter 2

### 2.1 Overview of Piezoelectric energy harvester

For developing next generation self-powered microsystems, piezoelectric microelectromechanical systems (PiezoMEMS) are attractive. PiezoMEMS promises to remove the expensive microsensor/microsystem assembly and include different battery recharging mechanisms, taking us closer to battery less wireless sensor systems and networks. This section discusses the state-of-the-art in microscale piezoelectric energy harvesting, summarizing key metrics such as power density and bandwidth of reported structures at low frequency input providing an overall idea of basic structure of piezo electric energy harvester and also its working principle.

#### 2.1.1 Piezoelectricity, Piezoelectric effect and Inverse piezoelectric effect

Piezoelectricity is the electric charge that accumulates in certain solid materials when they are subjected to mechanical stress. In crystalline materials with no inversion symmetry, the piezoelectric effect is caused by a linear electromechanical interaction between the mechanical and electrical states. The piezoelectric effect is a reversible phenomenon, meaning that materials that exhibit the piezoelectric effect (the internal generation of electrical charge as a result of an applied mechanical force) may also exhibit the reverse piezoelectric effect (the internal generation of mechanical strain as a result of an applied electrical field).

When the static structure of lead zirconate titanate crystals is deformed by about 0.1 percent of its original dimension, measurable piezoelectricity is produced. When an external electric field is applied to the material, those same crystals will change about 0.1 percent of their static dimension. Ultrasonic sound waves are generated using the inverse piezoelectric effect.

#### 2.1.2 Piezoelectric Materials

Some materials which naturally exhibit electrical charge when they are being subjected to mechanical stress are commonly known as piezo electric materials. They come in several types and they are being discussed below:

**Crystalline materials**

It is one such group of materials which shows piezoelectric effect. **Langasite** which is a quartz (analogous crystal) is one such example of crystalline materials, **Gallium Orthophosphate** is also an analogous crystal showing piezo electricity. Other examples include **lithium niobate and lithium tantalate**, **Berlinite** is also a rare phosphate mineral that is identical to quartz on a structural level showing piezoelectricity

**Topaz** is also a material showing piezoelectricity and it shows it due to its ordering. It has a centrosymmetric lattice which is of orthorhombic bipyramidal shape. The unusual properties that Topaz possess is due to its ordering which is also the reason for its piezoelectric properties.

**Tourmaline** which are a group of minerals also has piezoelectric properties.

**Lead titanate** which can be found in nature as mineral macedonite also shows piezoelectric properties and is used for research applications.

**Ceramics**

Ceramics need to ferroelectric for it to show piezoelectricity, so their grains should be oriented in a way such that it shows ferroelectric effects, doing that will enable it show piezoelectricity. However, the occurrence of irregular size of grains or its growth has unfavorable effects on the electric charge it is going to produce or in other words piezoelectric effect, these are mainly observable in polycrystalline piezoelectric ceramics and they should not be selected for any work. Also its microstructure has an orientation of finer grains which is undesirable. Some non ferroelectric ceramics like ZnO will show piezoelectricity but their effect is minimal compared to ferroelectric ones.

The most commonly used piezoelectric material is **Lead zirconium** titanate or more commonly known as **PZT 5A**

**Potassium niobate** is also a piezoelectric material which falls under the ceramics section.

**Sodium tungstate** is also ceramic which shows piezoelectric properties but only under some specific conditions**.** ZnO exhibit piezoelectric properties but only when their grains are not randomly oriented because in this case they will be polycrystalline and polycrystalline structures cannot be poled like ferroelectric structures. Single crystals of ZnO however has no problems exhibiting piezoelectricity. Only in this type of structure the ordered grains will show both piezoelectricity and pyroelectricity given that they do not cancel each other due to being polar opposite and this type of configuration is much difficult to achieve in polycrystalline structures.

**Lead-free piezoceramics** are the ones which show piezoelectricity replacing lead in their ceramic structure. Lead free ceramics enables the risk imposed by the toxicity levels in lead and thus from an environmental point of view it is much appreciated. The production and fabrication of such ceramics will ensure safe mining conditions which is not harmful to the environment and the human body.

**Sodium potassium niobate** is a promising replacement for lead included ceramics, Its properties are close to PZT5A and it has been experimented upon to find out that it has high mechanical factor even in high vibration levels. Even PZT5A loses some of its potential in this conditions. This is why it is a great alternative to PZT5A and makes it a much easier choice for power based application in need of vibrational energy transformers such as in piezoelectric transformers.

**Barium titanate** was the first of its kind to replace lead in ceramics. **Bismuth ferrite** is also a fine example of lead free ceramics to exhibit piezoelectricity.

**Sodium bismuth titanate** is also one such ferroelectric lead free ceramics which possess piezoelectric effect when they are being subjected to stress and they are being mainly used in piezoelectric actuators, capacitors and generators.

### 2.2 Mechanism

The occurrence of electric dipole moments in solids is closely related to the nature of the piezoelectric effect. The latter can be carried directly by molecular groups or induced for ions on crystal lattice sites with asymmetric charge surroundings (as in $BaTiO3$ and PZTs) (as in cane sugar). The dipole density P is a vector field since any dipole is a vector. Weiss domains are regions where dipoles near each other appear to coincide. The domains are normally oriented randomly, but they can be aligned using the poling (not to be confused with magnetic poling) technique, which involves applying a strong electric field across the material at high temperatures. It is not possible to pole all piezoelectric materials.

There are two types of piezoelectric effects that are widely observed: direct and reverse piezoelectric effects. An electric charge proportional to the applied stress is generated when mechanical stress is applied to a piezoelectric material. The direct piezoelectric effect is what this term refers to. When an electric field is applied to the same material, strain or displacement is proportional to the electric field magnitude. The converse piezoelectric effect is what it's called.

The direct piezoelectric effect is responsible for the conversion of mechanical to electrical energy. A rectifier can be used to condition the produced energy for further applications and works in energy generating sector.

There are mainly three basic steps in power generation which is being shown below:

(a) Mechanical stress is being induced in the structure from an available vibrational source

(b) Using of piezoelectric effect to convert the mechanical stress to electric charges produced due to it being mechanically actuated.

(c) Storing the electrical energy produced and also conditioning it for further application. A piezoelectric transducer can be made depending upon the resonant frequency of the structure and also the max displacement of the mechanical stress induced.

Thus the required piezoelectric transducer and its sizes and the operational vibrational mode that it works on can be designed based on the resonant frequency and max amplitude of the mechanical stress that is induced. The efficiencies of a energy harvesting system is mainly calculated by the way the mechanical stress is being induced in each phase minimizing the losses generated. The losses in this case are the ones which provides hindrance to mechanical power generation and also the electromechanical loss which is being based on the coupling factor and its magnitude.

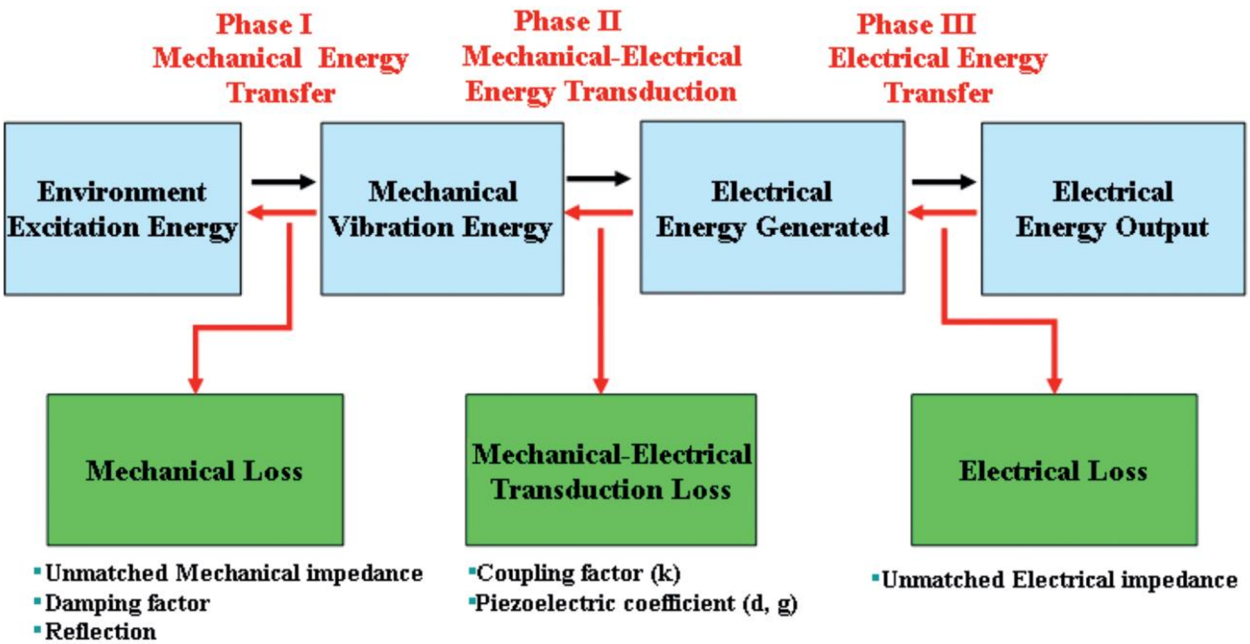


***Figure 1**: Piezoelectric energy Harvester Mechanism* [35]

From the above diagram we can see the energy flow between different domains starting from phase 1 to phase 3, the basic concept of a cantilever based piezoelectric energy harvester includes utilizing ambient vibration to induce mechanical power in the cantilever beam from where we can get electrical energy. Thus at every cycle seismic activity is present which delivers energy into the whole system. This mechanical energy is thus converted to kinetic energy of the proof mass and stored in the cantilever beam as potential energy by help of mechanical strain. Some of the energy due to strain is stored in the cantilever beam from where to piezoelectric effect electric charge is produced in the piezoelectric layer of the beam, if a stable electrical connection is made using electrodes and utilizing the piezoelectric layer, electrical energy can be obtained from such configuration. Losses are present in three phases of the above figure starting from mechanical loss when the beam is actuated by a source vibration. Damping factor and some mechanical impedance is taken into account in this loss. In phase 2 we will have mechanical-electrical transduction loss where we will take coupling factor and piezoelectric co-efficient into account. Lastly in Phase 3 we will have some minor amount of electrical loss.

Mainly two types of cantilever based piezo electric energy harvester are present, one being unimorph and the other being bimorph. Although bimorph piezoelectric energy harvester are less favorable for MEMS based application as it does not have the microfabrication that MEMS need. Unimorph piezoelectric energy harvesters are thus prioritized for MEMS application. A proof mass is normally mounted on top pf the structure to adjust the resonant frequency of the cantilever beam for optimization procedures.

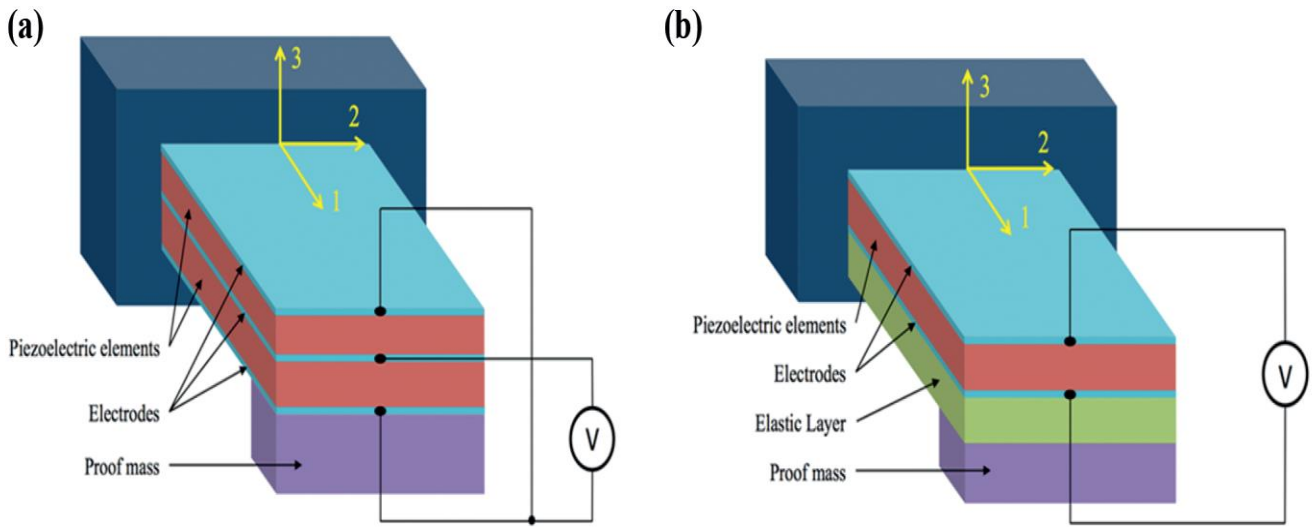


***Figure 2: Cantilever Based Piezoelectric Energy Harvester*** [35]

### 2.3 Key Piezoelectric Properties

- Piezoelectric co-efficient mainly measures the mechanical strain that is produced by the voltage which is applied and they are d33, d31, d15 etc. Higher values of dxy of coefficients mean that they larger body displacements and these are essential for controlling the piezoelectric transducer devices.

- The piezoelectric co-efficient d33 is used to measure the deformation of the cantilever beam in the direction of the polarization axis or the mechanically induced axis

- The piezoelectric co-efficient d31 is used to describe the effect when an external force is applied perpendicular to the axis of polarization or the mechanically induced axis.
- The piezoelectric co-efficient d15 is used to measure the effect when the mechanical stress induced in the cantilever beam is due to the shear deformation.

**2.4 Application of Piezoelectric materials in MEMSEngineering**

- Micro electro mechanical systems are a technology that is most commonly defined as a small miniaturized mechanical and electro-mechanical device made of elements like devices and structures. This element is made by microfabrication.
- This energy harvesters which are based on MEMS have a wide range of applications including wind energy, devices, linear foot motion and other stuff such as extracting energy from source vibrations
- The use of piezoelectric materials to generate power has been promising, due to its high density of energy/power, scalability and simplicity.
- The simplicity associated with the piezoelectric energy harvesters makes it very attractive for MEMS applications, especially for remote systems.

**2.5 Piezoelectric Cantilever Beam Structures**

Piezoelectric energy harvesters generally have bimorph or unimorph cantilever beam structures.

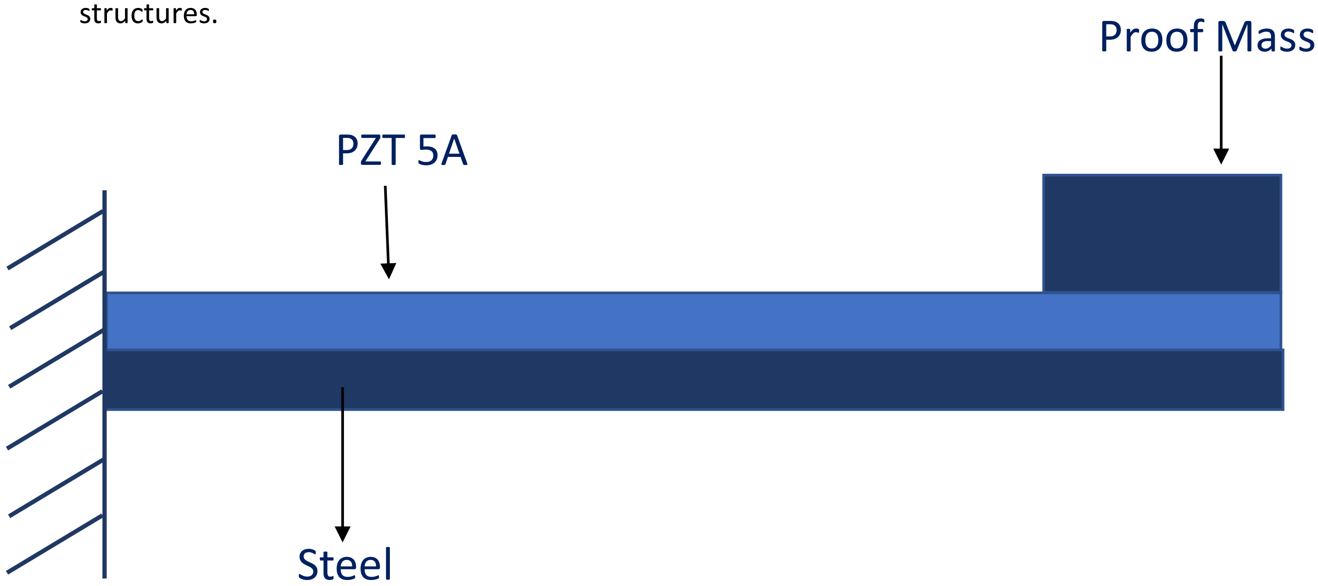


***Figure 3: Unimorph Piezoelectric Energy Harvester***

A unimorph or monomorph is a cantilever that consists of one active layer and one inactive layer. In the case where active layer is piezoelectric, deformation in that layer may be induced by the application of an electric field. This deformation induces a bending displacement in the cantilever. The inactive layer may be fabricated from a non-piezoelectric material. Unimorph structure has one piezoelectric layer and an elastic substrate layer. M is considered as proof mass. Bimorph cantilever are less manufacturable with existing microfabrication processes. As a result, MEMS cantilevers mostly have a unimorph configuration.

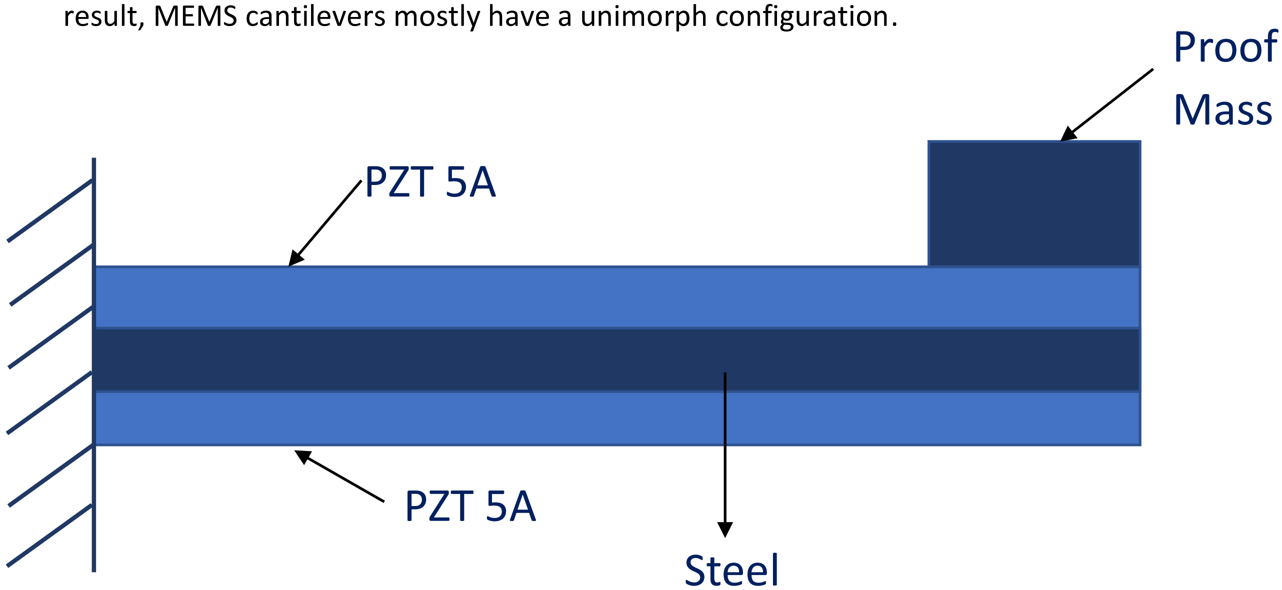


***Figure 4: Bimorph Piezoelectric energy harvester***

A bimorph is a cantilever used for actuation or sensing which consists of two active layers. It can also have a passive layer between the two active layer.

Bimorph structure that has two independently polarized piezoelectric layers. A bimorph is constructed with a substrate in center sandwiched between two piezoelectric layers as shown in below figure. Thickness of piezoelectric layer is tp while that for substrate layer is ts. The piezoelectric layers are electrically shorted in series with layers being poled towards the substructure. In order to tune cantilever a proof mass Mt is placed at tip of cantilever.

**Chapter 3**

## 3.1 Design Of Bimorph Piezoelectric Energy Harvester

### 3.1.1 Structural design

The design of our bimorph piezoelectric energy harvester comprises of one layer of steel and two layers of piezoelectric material. The steel cantilever plane fills in as a substrate and two layers of piezoelectric materials are put on the either sides of the substrate. The piezoelectric layers are bonded with thin surface electrodes. A reference (ground) electrode is installed inside the design. This is designed in such a way so that similar voltage is induced on the surface electrodes despite the fact that stress above and under the neutral layer is of opposite sign. The energy harvester is clamped at one end and a proof mass is mounted on the other end. The clamp is attached to a vibrating machinery. For this reason, the piezo electric energy harvester is analyzed in a vibrating reference frame.

In the setup, one side is connected to the vibrating source and proof mass is placed at the other

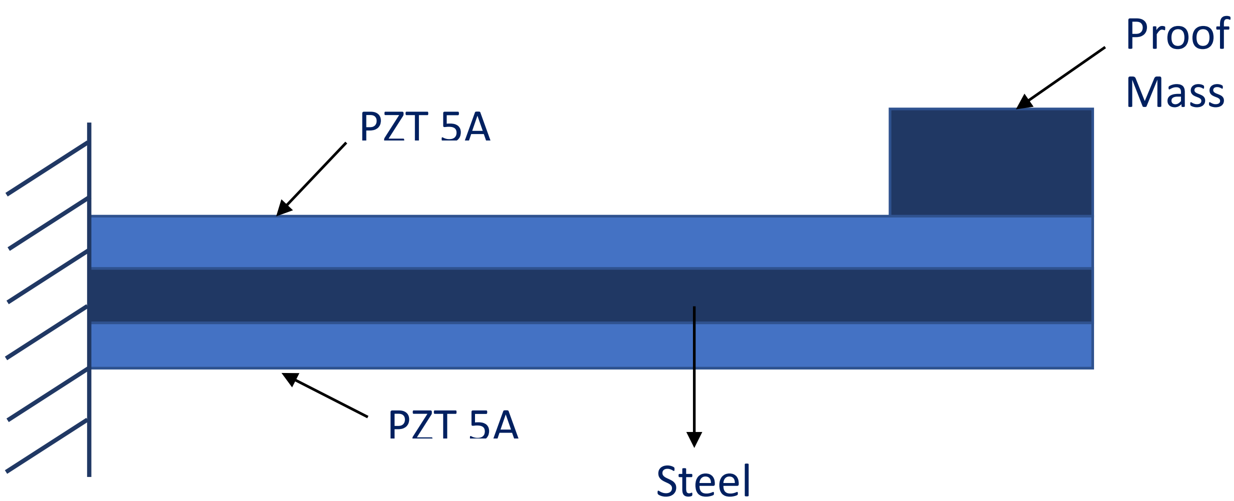


*Figure 5: Schematic Diagram of Bimorph Piezo electric energy harvester*

side. The system vibrates on one end. This vibration is induced in the cantilever plane. Then this induced vibration of plane consequently is converted into electricity. This is possible due to piezoelectric effect and as a result an alternating voltage is produced on the surface of the electrodes. A resistive load is connected to the electrodes to complete the outer circuit. Thus an electric output power is dissipated in the circuit.

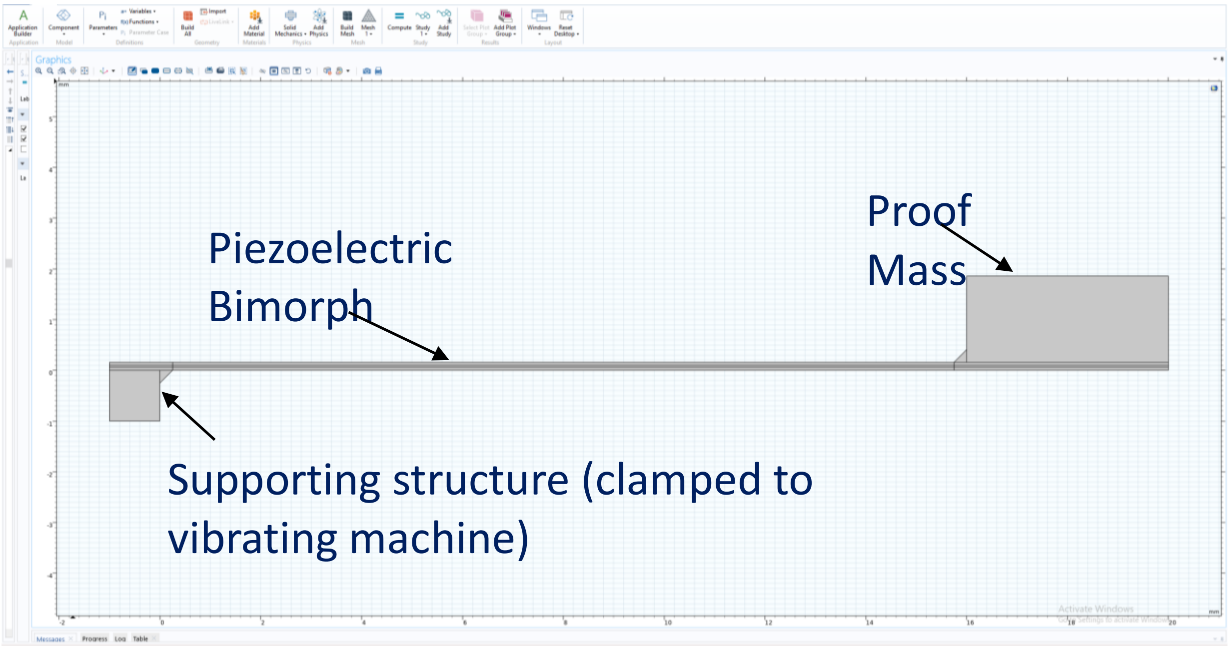


***Figure 6: 2D model depicting the major components of the energy harvester*.**[36]

Two dimensional model of our device can be seen in the picture above. Our analysis comprises of changing the piezo electric layer thickness and the proof mass volume. For initial validation purpose, we take the dimension of the beam as length: 21 mm, height: 0.16 mm and depth: 14 mm. The thickness of the piezoelectric films is taken as .06 mm each and the thickness of the elastic layer (structural steel) is taken as .04 mm. The proof mass(PM) dimensions are length: 4 mm, height: 0.17 mm and depth: 14 mm. The PM material is taken as structural steel. Lastly the support structure dimension is taken as length: 1 mm, height: 1 mm and depth: 14 mm. The material is taken as steel. Then at first we change the beam dimension according to the parameters given in table 1.

***Table 1: Dimensions Of Piezoelectric energy Harvester for different thickness***

| *Piezo Material* | *Piezo layer thickness (mm)* | *Steel layer thickness (mm)* | *Beam dimension (mm)* | | | *PM material* | *density (kg/m^3)* | *Number of PM* | *PM dimension (mm)* | | | *PM volume (mm^3)* | *PM mass (kg)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Length | Height | Depth | | | | Length | Height | Depth | | |
| PZT-5A | 0.02 | 0.04 | 21 | 0.08 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 |
| PZT-5A | 0.04 | 0.04 | 21 | 0.12 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Steel | 7850 | 2 | 4 | 1.7 | 14 | 190.4 | 0.00149464 |
| PZT-5A | 0.08 | 0.04 | 21 | 0.2 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 |
| PZT-5A | 0.08 | 0.04 | 21 | 0.2 | 14 | Steel | 7850 | 2 | 4 | 1.7 | 14 | 190.4 | 0.00149464 |

***Table 2: Dimensions Of Piezoelectric energy Harvester for different thickness and proof mass volume***

| *Piezo layer thickness (mm)* | *Steel layer thickness (mm)* | *Beam dimension (mm)* | | | *PM material* | *density (kg/m^3)* | *Number of PM* | *PM dimension (mm)* | | | *PM volume (mm^3)* | *PM mass (kg)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Length | Height | Depth | | | | Length | Height | Depth | | |
| 0.0451 | 0.04 | 21 | 0.1302 | 14 | Steel | 7850 | 1 | 4 | 0.85 | 14 | 47.6 | 0.00037366 |
| 0.06 | 0.04 | 21 | 0.16 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 |
| 0.08 | 0.04 | 21 | 0.2 | 14 | Steel | 7850 | 2 | 4 | 1.7 | 14 | 190.4 | 0.00149464 |
| 0.1064 | 0.04 | 21 | 0.2528 | 14 | Steel | 7850 | 2 | 4 | 3.4 | 14 | 380.8 | 0.00298928 |
| 0.141512 | 0.04 | 21 | 0.323024 | 14 | Steel | 7850 | 2 | 4 | 6.8 | 14 | 761.6 | 0.00597856 |

For two piezo layer thickness .06 mm and .08 mm we also use two proof mass. All the other properties remain the same. We run simulation for each case. and see how changing the piezo layer thickness and volume of proof mass influence the result.

After that we change both the piezo layer thickness and proof mass volume according to the values from table 2.

Lastly for we perform simulation for different proof mass materials that is steel, aluminum, copper, lead and platinum. And for each case we change the volume of the proof mass. For first two cases we change the height and for next two cases we change the length of the proof mass. Dimensions for different proof mass material is given in the table 3.

A load of 12 K$\Omega$ is connected to the electrodes to complete the outer circuit for determining the output power. Our simulations indicate the specific frequencies at which the cantilever beam resonates which results in bending. This consequently distributes the strain along the whole length. This in turns is then converted into electrical energy by the piezoelectric effect through transverse (d31) mode. D31 indicates that the electric field (polarization direction "3") sits perpendicular to the direction of applied stress "1". We ran the simulation to find the peak voltage, mechanical power input and electric power output at the resonant frequency.

***Table 3: Dimensions Of Piezoelectric energy Harvester for different proof mass material***

| *Piezo Material* | *Piezo layer thickness (mm)* | *Steel layer thickness (mm)* | *Beam dimension (mm)* | | | *PM material* | *density (kg/m^3)* | *No of PM* | *PM dimension (mm)* | | | *PM volume (mm^3)* | *PM mass (kg)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Length | Height | Depth | | | | Length | Height | Depth | | |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Aluminum | 2700 | 1 | 4 | 4.9426 | 14 | 276.785185 | 0.00074732 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Copper | 8960 | 1 | 4 | 1.4894 | 14 | 83.40625 | 0.00074732 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Lead | 11340 | 1 | 2.769 | 1.7 | 14 | 65.9012346 | 0.00074732 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Platinum | 21450 | 1 | 1.4639 | 1.7 | 14 | 34.8400932 | 0.00074732 |

**Table 4: Property Table**

| **Property** | **Symbol** | **Value** |
|---|---|---|
| Density of PZT-5A | $\rho_{pzt}$ | 7750 kg/m^3 |
| Relative permittivity of PZT-5A | $\varepsilon_r$ | 919.1, 919.1,826 |
| Density of Steel | $\rho_s$ | 7850 kg/m^3 |
| Relative permittivity of steel | $\varepsilon_r$ | 1 |
| Young's modulus of steel | E | 200*10^9 Pa |
| Poisson's ratio of steel | ν | .33 |
| Density of Aluminum | $\rho_a$ | 2700 |
| Density of Copper | $\rho_c$ | 8960 |
| Density of Lead | $\rho_l$ | 11340 |
| Density of Platinum | $\rho_{pt}$ | 21450 |

### 3.1.2 Numerical modeling and Equations governing FEM Simulation

Piezoelectric effect is the basis of piezoelectric energy collector. The equations provided below governs this effect and connects mechanical domain with electric domain.[33] Stress(T) and strain (S) is present in mechanical domain. On the other hand, electric field (E) and charge density (D) is present in the electrical domain.

$$\begin{bmatrix} Converse \\ Direct \end{bmatrix} = \begin{bmatrix} S \\ \mathrm{D} \end{bmatrix} = \begin{bmatrix} S^E & d^{\mathrm{t}} \\ d & \varepsilon^T \end{bmatrix} = \begin{bmatrix} T \\ E \end{bmatrix}$$

Here,

$S^E$- Compliance under a constant electrical field

$\varepsilon^T$- Dielectric permittivity under a constant stress

$d$, $d^{\mathrm{t}}$- direct and converse piezoelectric effect matrices

We model the substrate steel cantilever plane as solid elastic material. This goes through mechanical damping with and isotropic loss factor of .001. Equations related to our modeling in solid mechanics are given below,

*Solid Mechanics:*

$$-\rho\omega^2 u = \nabla . S + F_V e^{j\phi}$$

$$S = S_{ad} + C : \varepsilon_{el}, \epsilon_{el} = \varepsilon - \varepsilon_{inel}$$

$$S_{\mathrm{ad}} = S_0 + S_{ext} + S_q$$

$$\varepsilon_{inel} = \varepsilon_0 + \varepsilon_{th} + \varepsilon_{hs} + \varepsilon_{pl} + \varepsilon_{cr}$$

$$\varepsilon = \frac{1}{2}[(\nabla u)^T + \nabla u]$$

*Piezoelectric materials:*

$$-\rho\omega^2 u = \nabla . S + F_V e^{j\phi}$$

$$\nabla . D = \rho_v$$

$$S = S_{ad} + C_E : \varepsilon_{el} - e^T E, \epsilon_{el} = \varepsilon - \varepsilon_{inel}$$

$$S_{\mathrm{ad}} = S_0 + S_{ext} + S_q$$

$$\varepsilon_{inel} = \varepsilon_0 + \varepsilon_{th} + \varepsilon_{hs} + \varepsilon_{pl} + \varepsilon_{cr}$$

$$\varepsilon = \frac{1}{2}[(\nabla u)^T + \nabla u]$$

$$D = D_r + e\varepsilon_{el} + \varepsilon_{0,vac}\varepsilon_{rS}E$$

*Damping:*

$$S = S_{ad} + C_E : \varepsilon_{el}$$

$$C \rightarrow (1 + i\eta_s)C$$

*Mechanical Damping:*

$$S = S_{ad} + C_E : \varepsilon_{el} - e^T E$$

$$C_E \rightarrow (1 + i\eta_s)C_E$$

*Body Load:*

$$-\rho\omega^2 u = \nabla . S + F_V e^{j\phi}$$

*Fixed constraint:*

$$u = 0$$

Equations corresponding to the electrostatic modeling are:

*Electrostatics:*

$$\nabla . D = \rho_v$$

$$E = -\nabla V$$

*Charge Conservation:*

$$E = -\nabla V$$

$$\nabla.(\varepsilon_0 \varepsilon_r E) = \rho_v$$

*Zero Charge:*

$$n.D = 0$$

*Charge Conversion in piezoelectric:*

$$E = -\nabla V$$

$$\nabla.D = \rho_v$$

*Ground:*

$$V = 0$$

*Terminal:*

$$\int_{\partial\Omega}^{\cdot} DndS = Q_0$$

$$\frac{\partial Q_0}{\partial t} = I_{cir}$$

Here

$D$ - Electric displacement vector

$\varepsilon$ - Strain vector

$E$ – Electric field vector

$u$ – Displacement

$F_V$ – Force vector

**Chapter 4**

## 4.1 Simulation and Result Analysis:

The design and simulation of the bimorph cantilever PEH is done using finite element modeling in COMSOL. A free triangular mesh is applied on the whole structure. The picture of mesh of the beam is shown below.

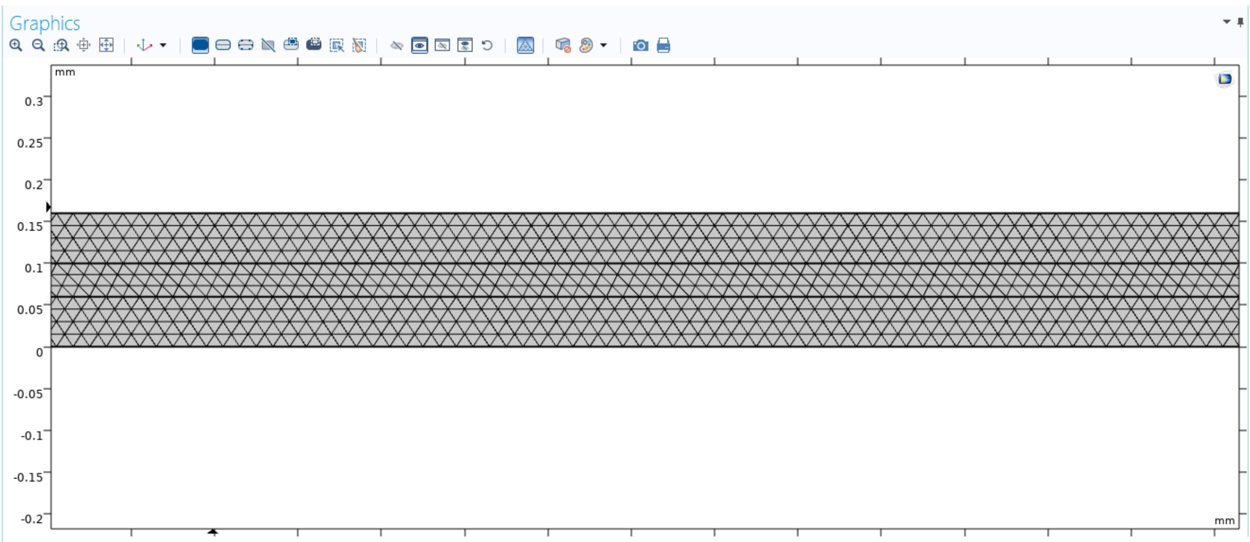


*Figure 7: Model displaying the mesh of the beam.*

The mechanism of the simulation occurs as follows:

- The system vibrates on the host end as it is clamped to the vibrating source.
- As a result, a sinusoidal body load is applied at the host end and the device is analyzed in vibrating reference frame.
- This vibration is induced in the cantilever plane.
- If the induced vibration matches the natural frequency of the beam, then the cantilever beam resonates which generates mechanical energy.
- This energy induces stress which is distributed along the length resulting in bending at resonant frequency.
- The piezo electric layer at the upper and lower surface of cantilever plane experience the stress and develop electrical potential through piezoelectric effect using transverse (d31) mode.
- As a result, an alternating voltage is produced on the surface of the electrodes and electric output power is dissipated in the circuit.

- The whole structure is designed in such a way so that similar voltage is induced on the surface electrodes despite the fact that stress above and under the neutral layer is of opposite sign.

We perform our analysis to find following things.

1. For the initial structure:
   (i) Frequency response at a constant load and acceleration.
   (ii) Load response at a constant frequency and fixed acceleration.
2. For different piezoelectric layer thickness again frequency response and load response.
3. Frequency response with changing the proof mass volume.
4. Optimization by changing both proof mass and piezo layer thickness.
5. Performance for different proof mass material with different volume.

### 4.2 Result Analysis of Initial Structure:

#### 4.2.1 Frequency response Vs Voltage, Power and displacement

A frequency response analysis is performed by varying the frequency of the source from 62 Hz to 80 Hz with an input acceleration of 1g (9.8). The load resistance is kept at 12 KΩ. Electric potential generated, mechanical power input and electric power output are plotted as a function of frequency.

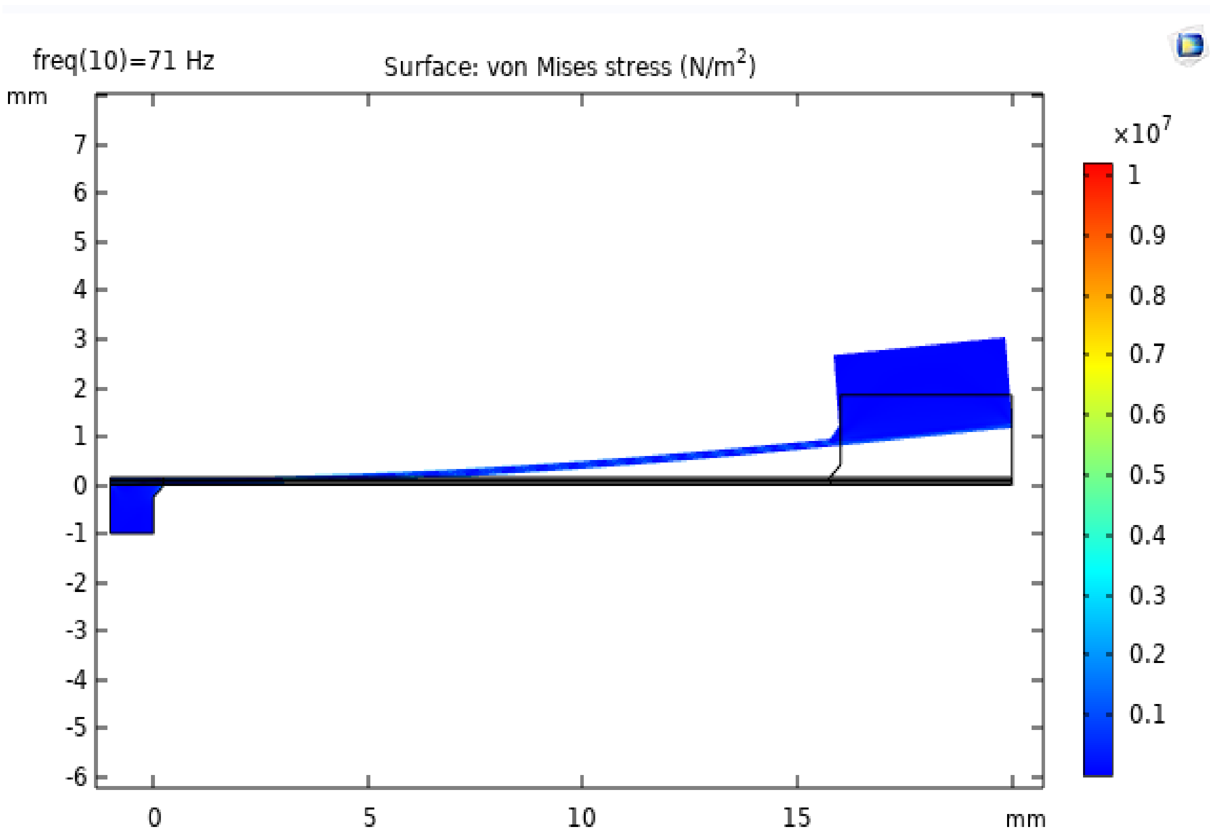


*Figure 8: Stress induced on the cantilever plane at resonant frequency of 71 Hz*.

In our analysis the base excitation results in induced vibration in the cantilever beam. This vibration energy is considered as the mechanical power input in the system. The induced vibration causes stress in the piezoelectric layer as shown in figure 8. This results in a electrical potential. With the help of embedded electrodes and the load resistance, external circuit is completed and current flow is achieved. This is the electrical power output from the device. Our device is fairly ideal. That's why the mechanical power input and the electrical power output is almost similar. But know system can produce power exact same of the input. It can be seen if we look closely at the result of the electrical power and mechanical power graph.

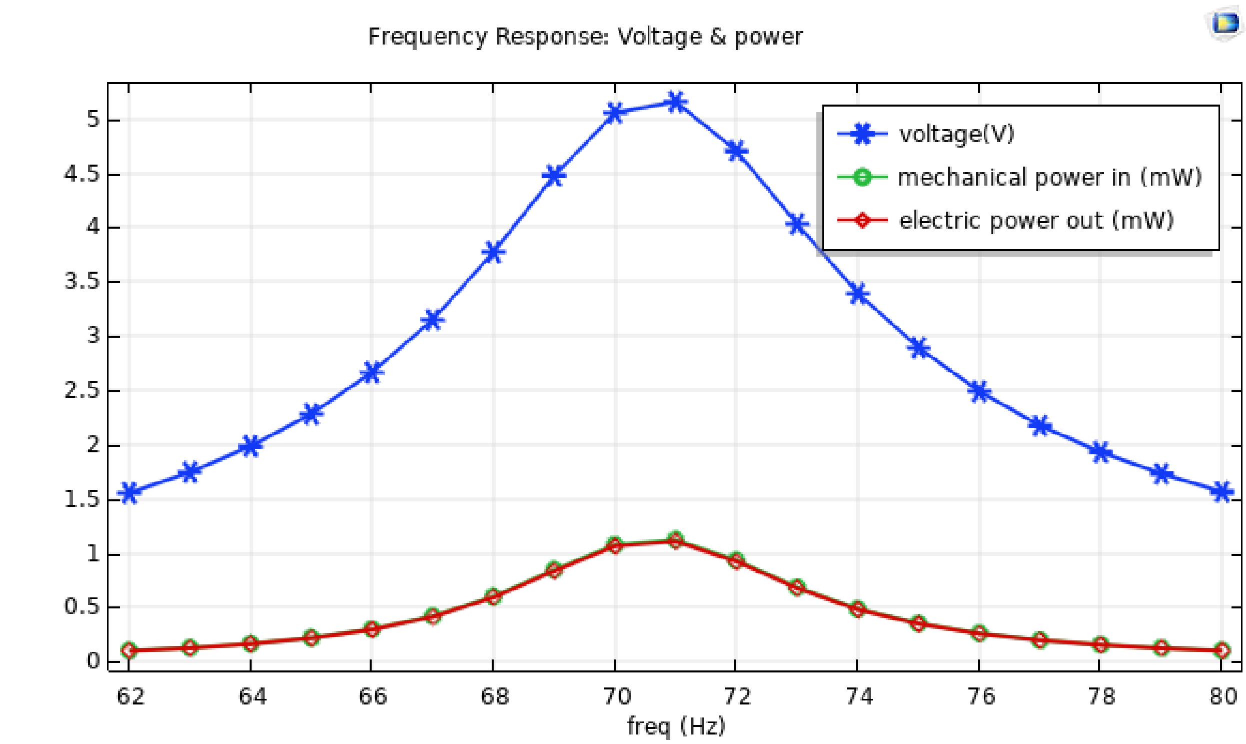


*Figure 9: Voltage and power as a function of frequency*

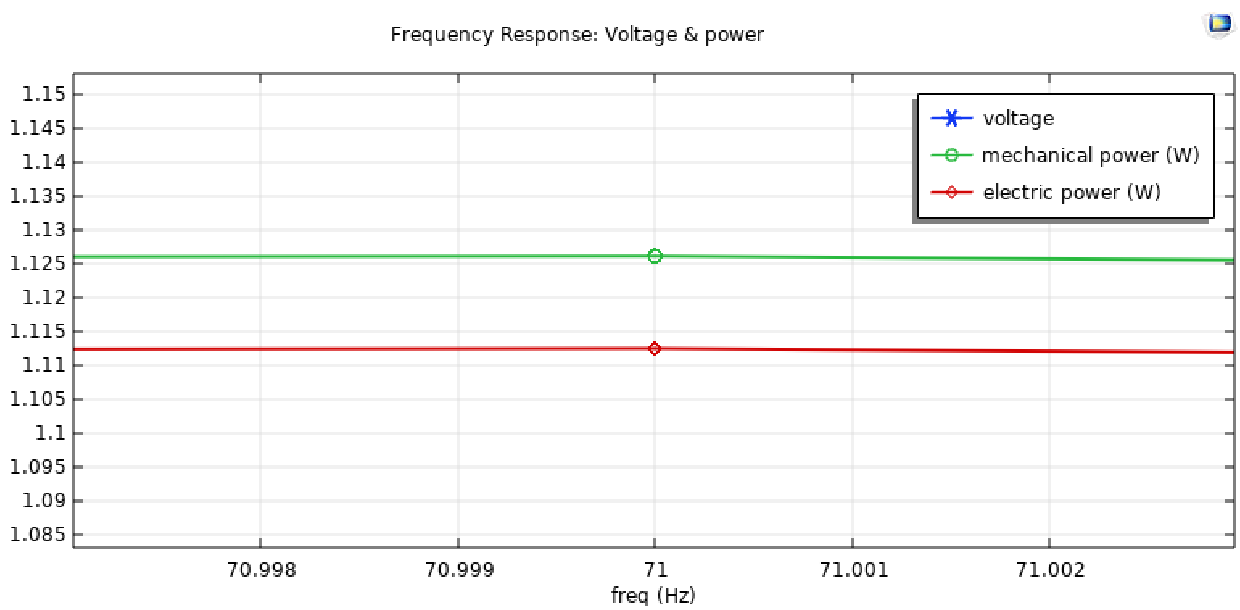


*Figure 10: Voltage and power as a function of frequency*

The results are shown in the graph of figure 9. In the graph along the x axis the frequency of

base excitation was plotted. And the blue line represents the voltage generated due to the piezoelectric effect. The green and the blue line represents mechanical power input and electric power output respectively.

The graph shows that the peak voltage of 5.16 V and mechanical power input of 1.25 and electric power output of 1.11 occurs at the resonant frequency of 71 Hz. Because this is the natural frequency, thus maximum bending occurs at this frequency.

Graph below shows the displacement amplitude graph for the frequency range. This graph shows the amplitude of vibration of the top point of the proof mass. It shows that the highest

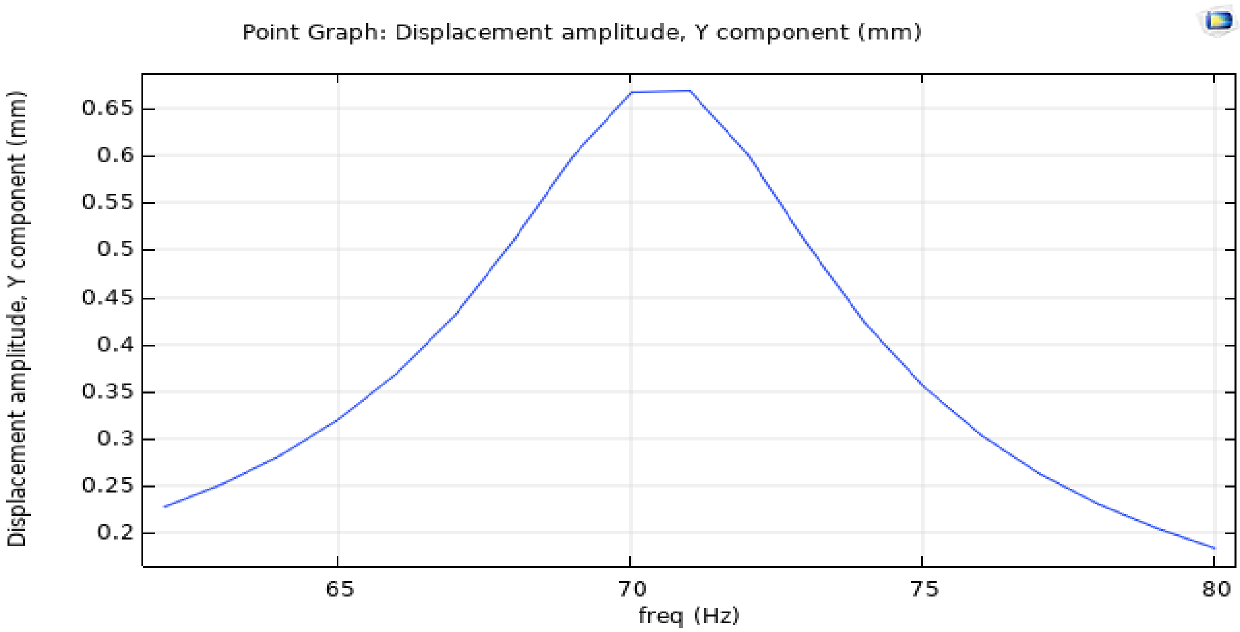


*Figure 11: Displacement amplitude as a function of frequency*

displacement along the Y axis occurs at the resonant frequency of 71. Thus maximum bending occurs at this point which generates maximum strain energy.

### 4.2.2 Load response Vs Voltage and Power

The performance of the energy harvester on varying load resistance is analyzed for an acceleration of 1g at resonant frequency of 70.5 Hz. In the graph below, voltage generated, input mechanical power and output electrical power as a function of load is plotted.

The graph shows that at 70.5 Hz frequency of base excitation, highest voltage output can be obtained at 5420 Ω. It also shows that mechanical and electric power increases with increase in load up to a certain value but then starts to decrease. But for voltage, it increases with increase in the load until a point, then becomes constant.

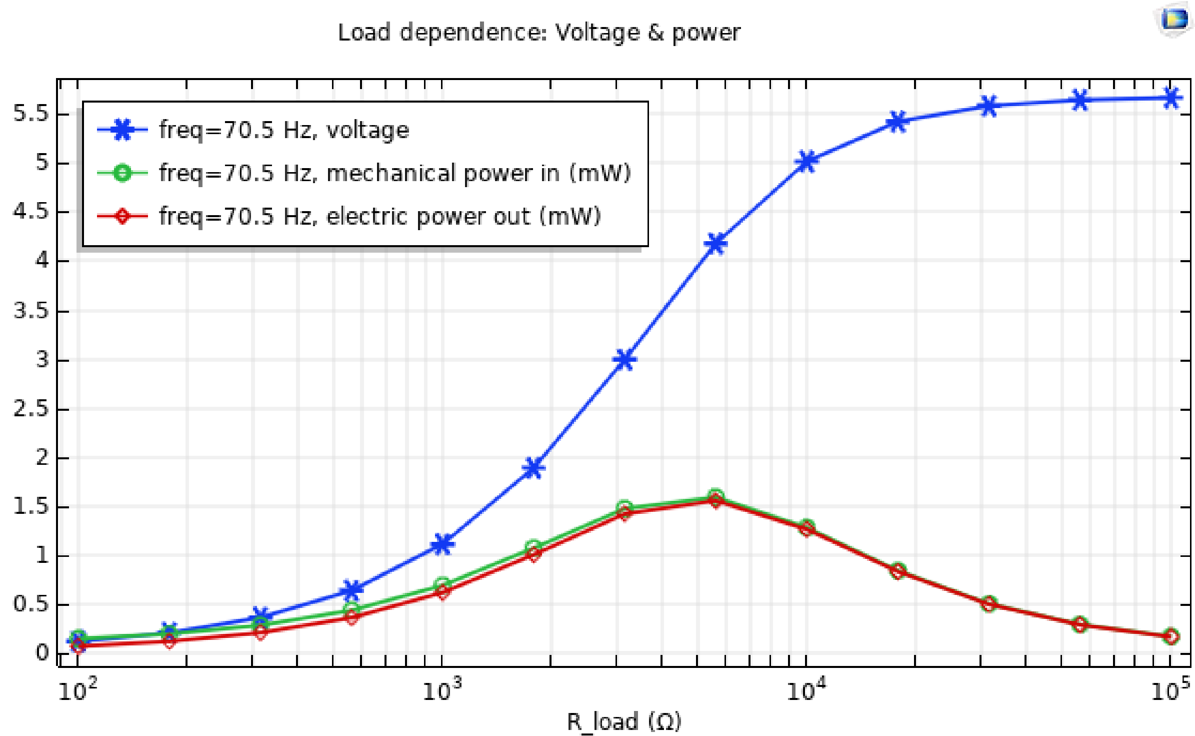


*Figure 12: Voltage, mechanical and electric power as a function of load.*

**4.3 Analysis for different piezoelectric layer thickness:**

**4.3.1 Frequency response Vs Voltage and Power.**

Now for changing piezoelectric layer thickness, we perform the Frequency Response Vs Voltage and Power analysis by decreasing and increasing the thickness by .02 mm for both the top and bottom layer and kept all other parameters constants. We took 4 thickness values of .02 mm, .04 mm, .06 mm and .08 mm. We find out how the resonant frequency as well as peak voltage and power changes due to the change in thickness.

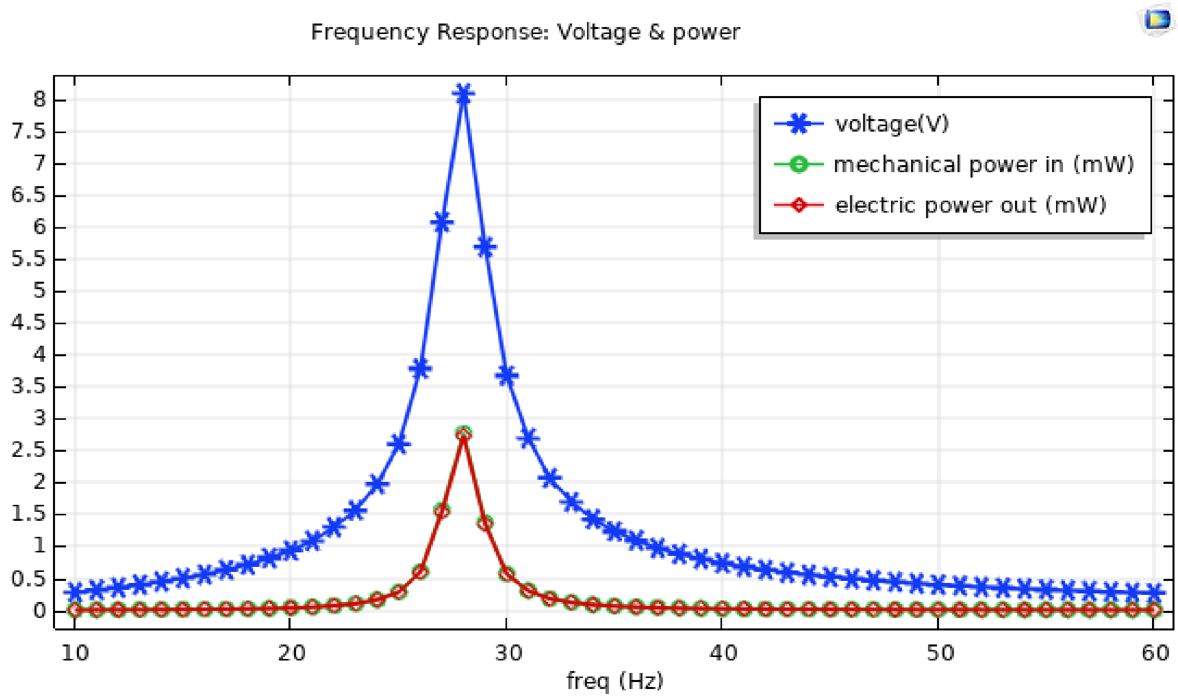


*Figure 13: Voltage and power as a function of frequency for .02 mm piezo electric layer thickness*

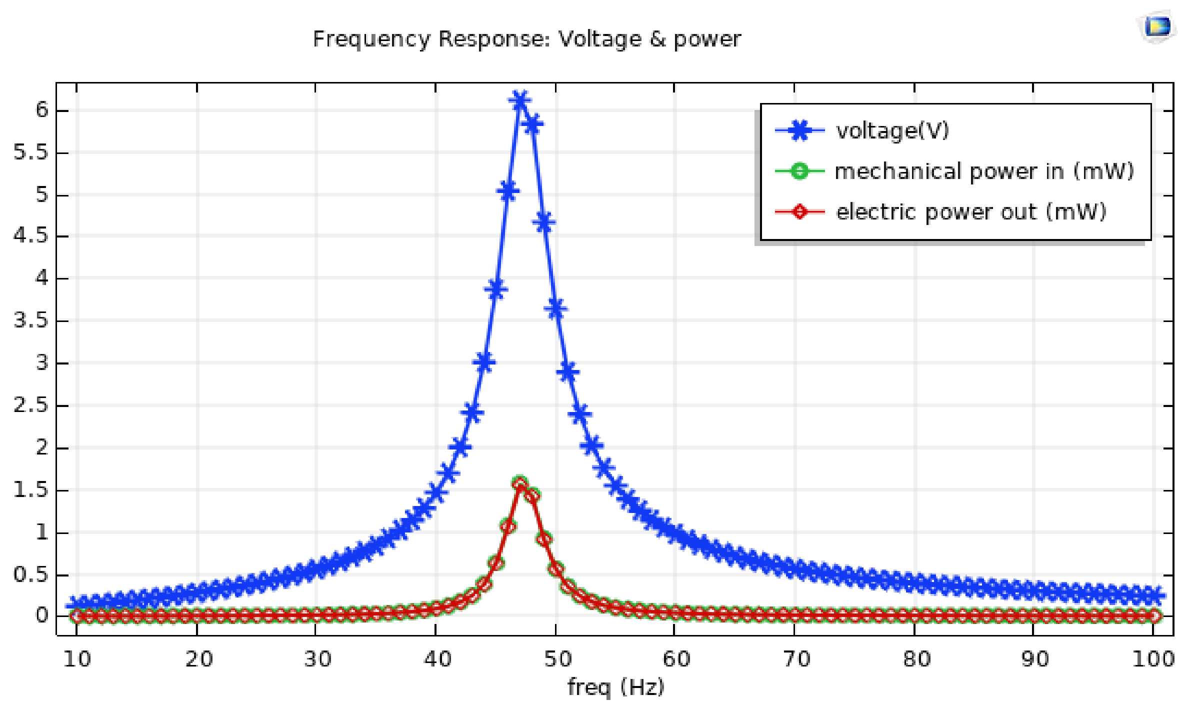


*Figure 14: Voltage and power as a function of frequency for .04 mm piezo electric layer thickness*

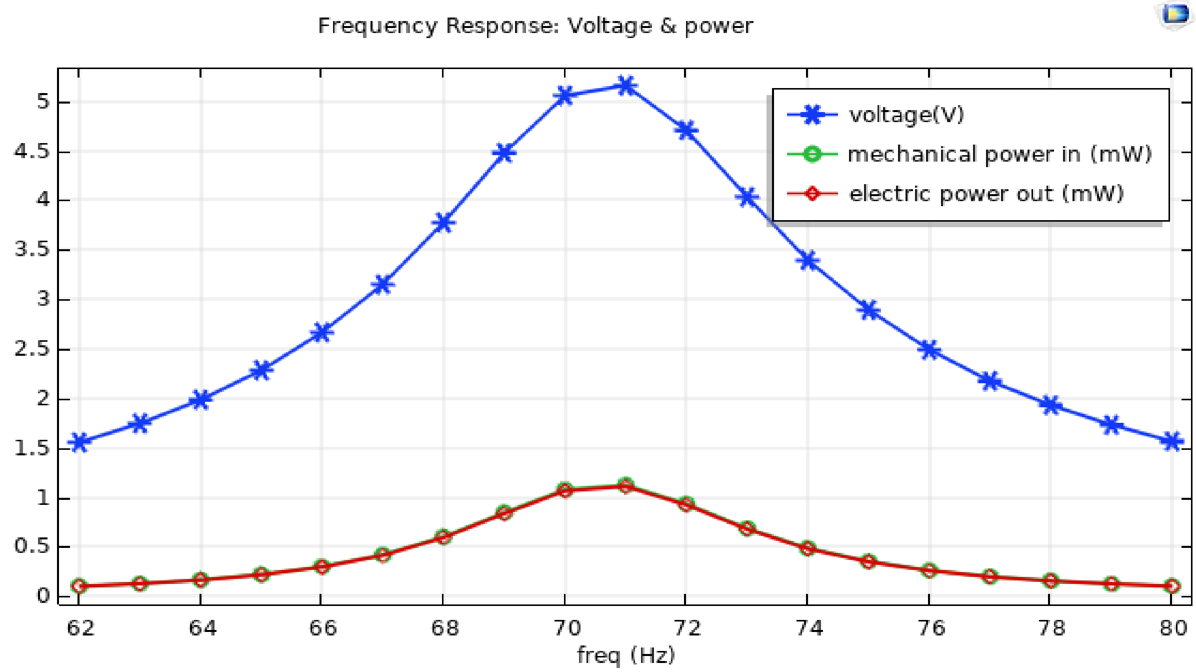


*Figure 15: Voltage and power as a function of frequency for .06 mm piezo electric layer thickness*

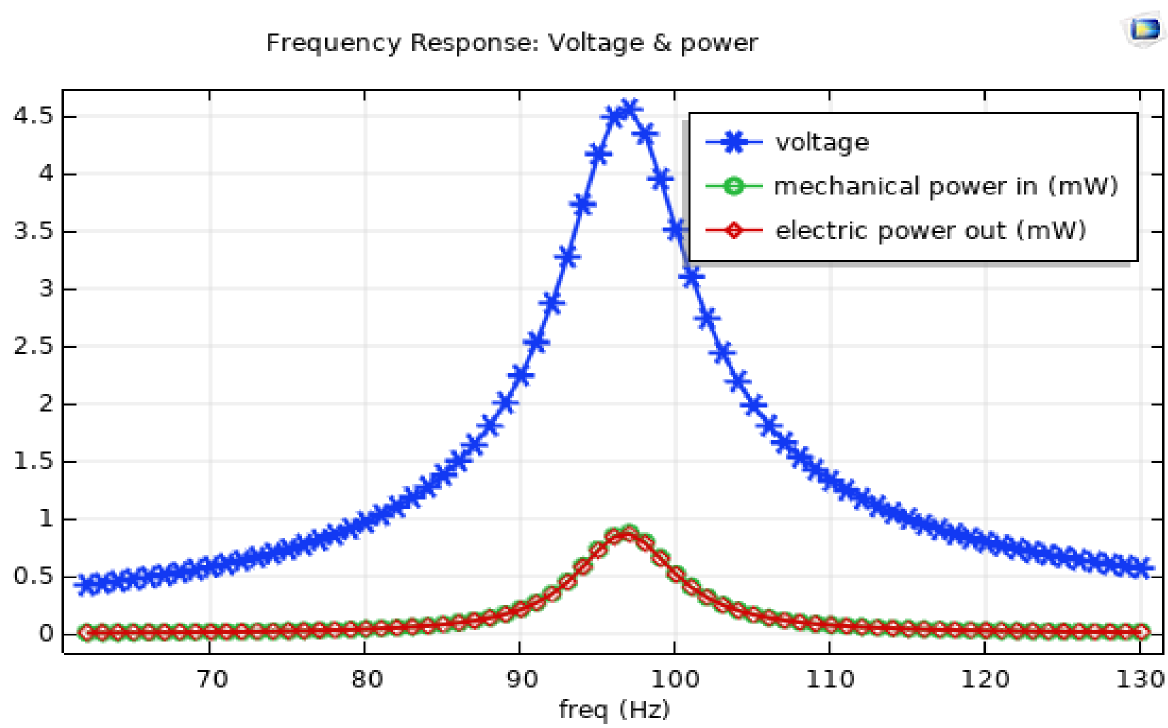


*Figure 16: Voltage and power as a function of frequency for .08 mm piezo electric layer thickness*

From the graph it can be seen that with the increase in piezo layer thickness, the resonant frequency at which peak voltage and power is obtained increases. The value of peak voltage and power also changes; it decreases with increase in piezo layer thickness.

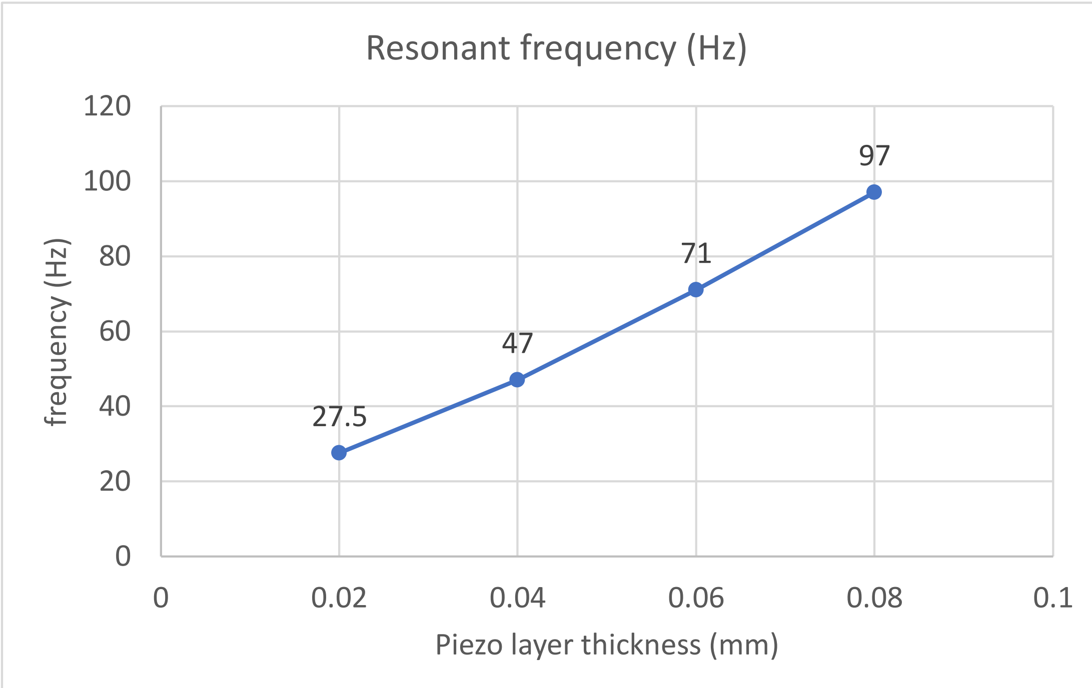


***Figure 17: Change of resonant frequency with the change in piezo layer thickness.***

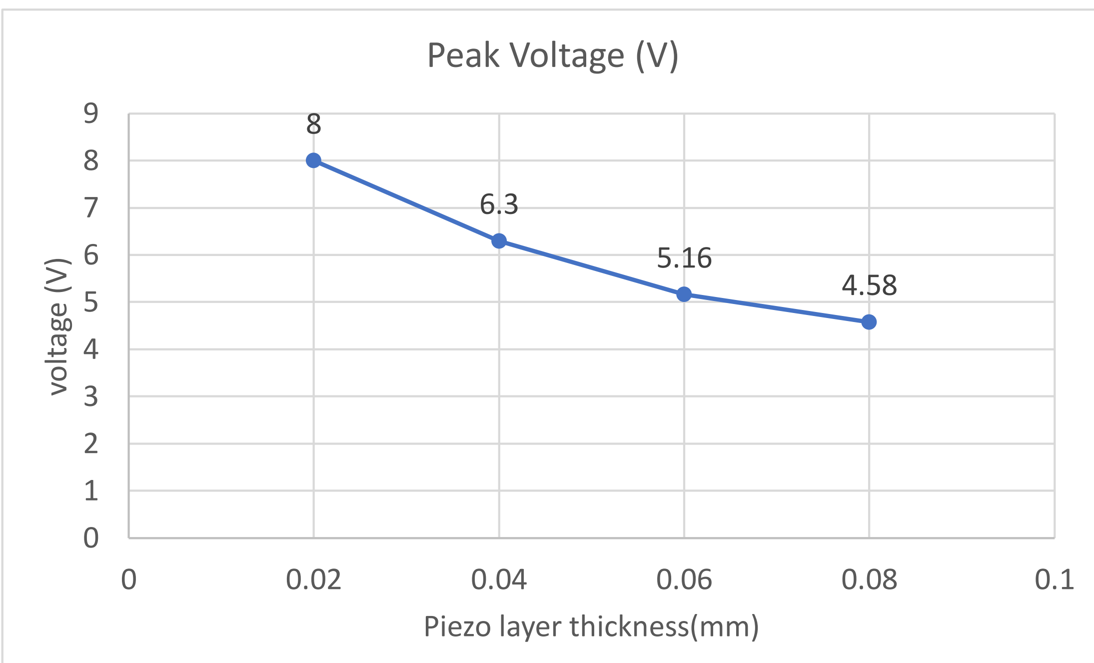


***Figure 18: Change of resonant frequency with the change in piezo layer thickness***.

This two graphs shows the values of resonant frequency and peak voltage at different thickness. At .02 thickness the value is 27.5 HZ, 47 HZ at .04 mm, 71 HZ at .06mm and 97 HZ at .08mm. Thus upward trend is clearly visible. But for peak voltage it is 8 at .02mm and decreases at each step of increment of thickness. Our results show these trends because with only increase in piezo layer thickness, the stiffness of the beam increases. As the proof mass volume remains constant and due to the fact that most of the input force comes from proof mass higher frequency is needed to reach the resonant frequency for beam with increased thickness; that is high stiffness.

#### 4.3.2 Load response Vs Voltage and Power

The performance of the energy harvester on varying load resistance is analyzed for an acceleration of 1g at resonant frequencies for different thickness of piezo layer.

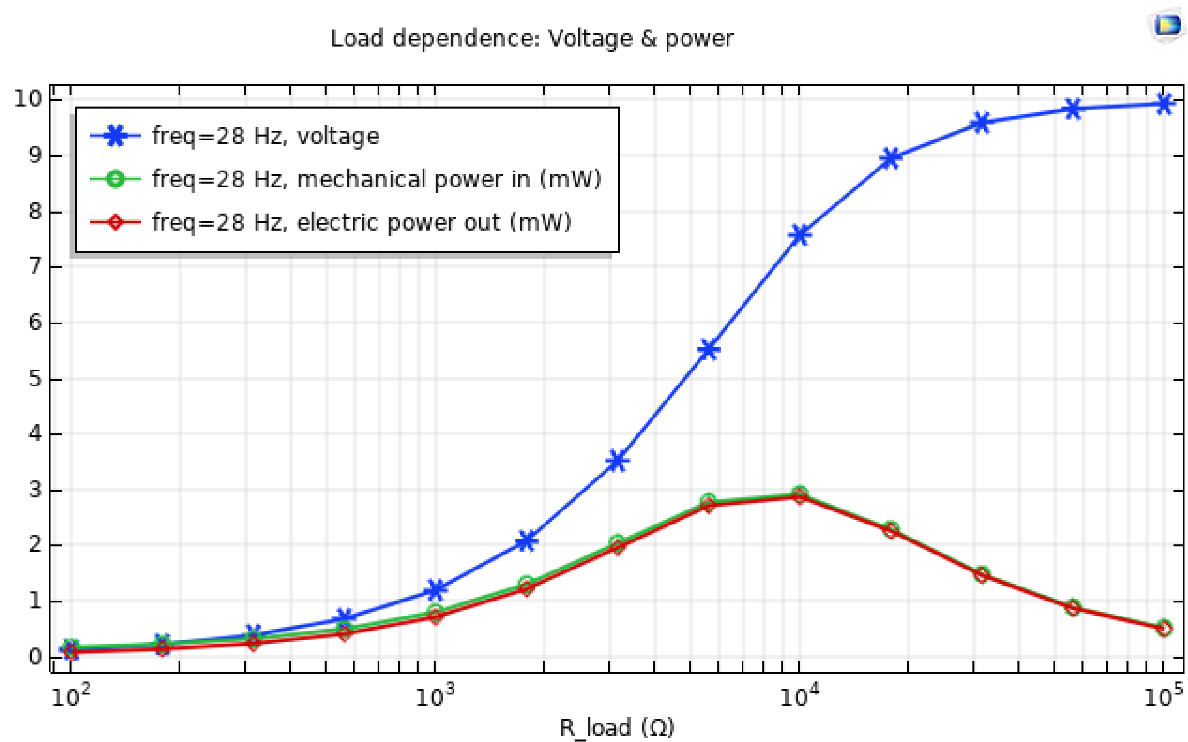


*Figure 19: Voltage and power as a function of load resistance for .02 mm piezo electric layer thickness*

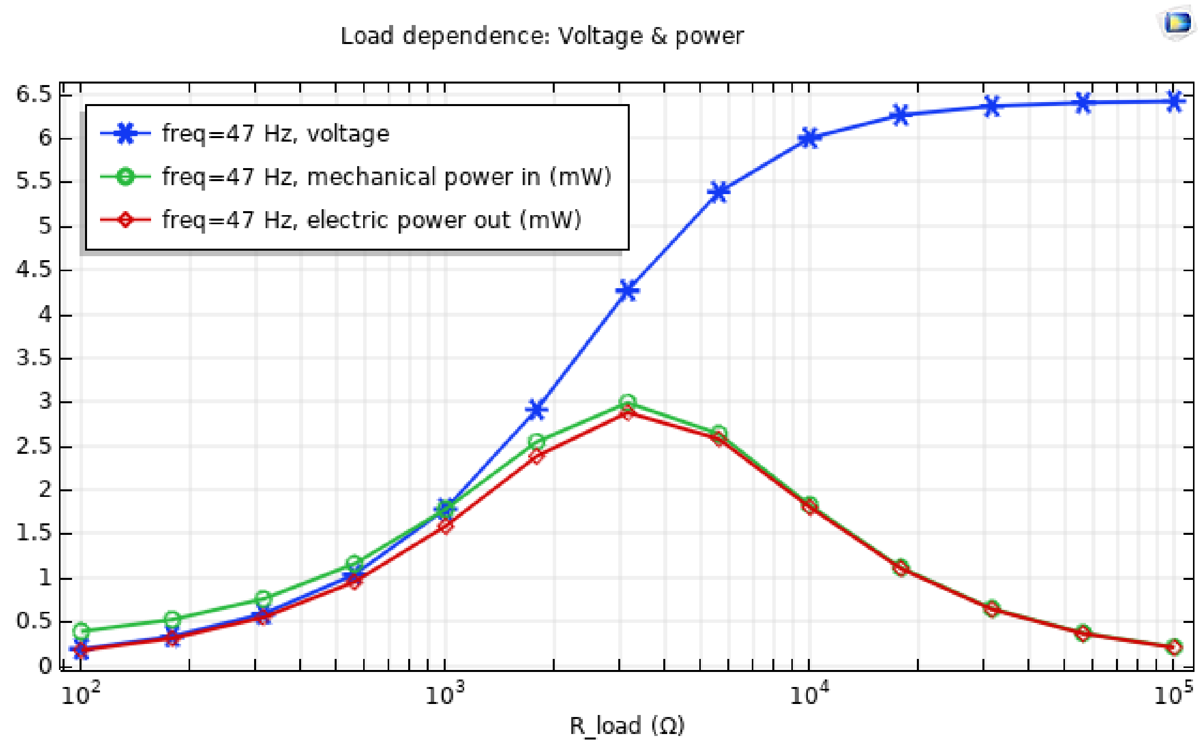


*Figure 20: Voltage and power as a function of load resistance for .04 mm piezo electric layer thickness*

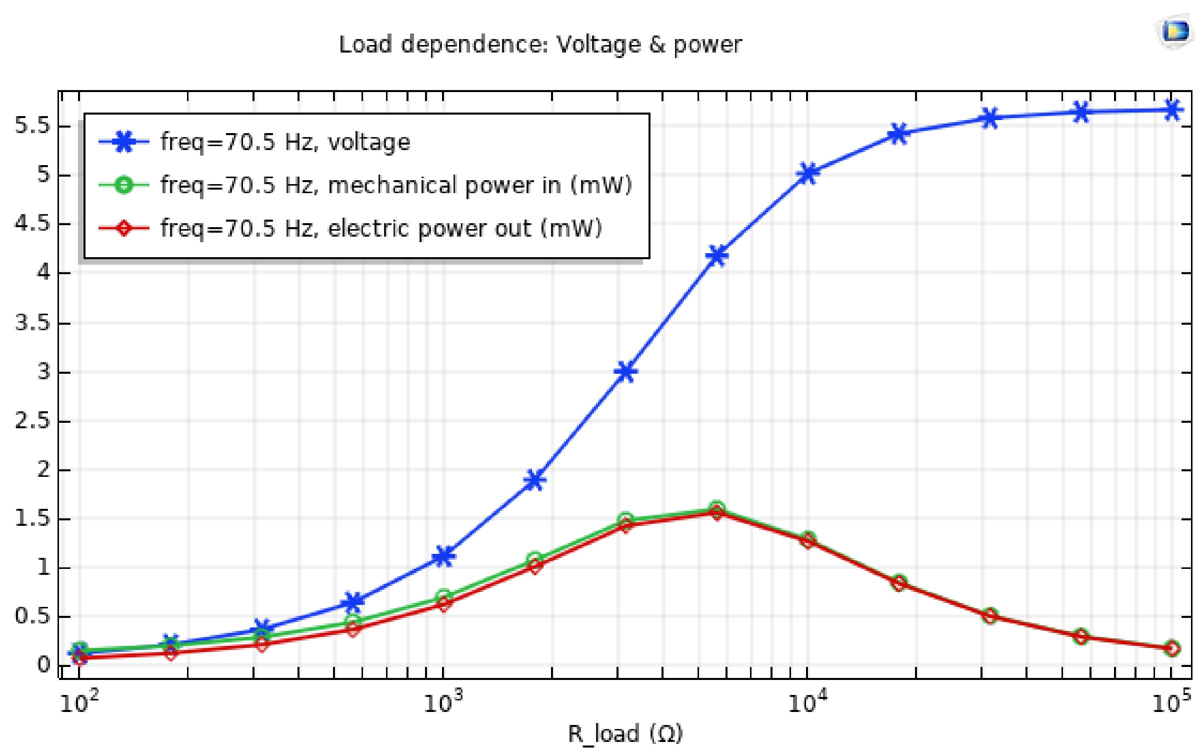


*Figure 21: Voltage, mechanical and electric power as a function of load for .06 mm piezo electric layer thickness.*

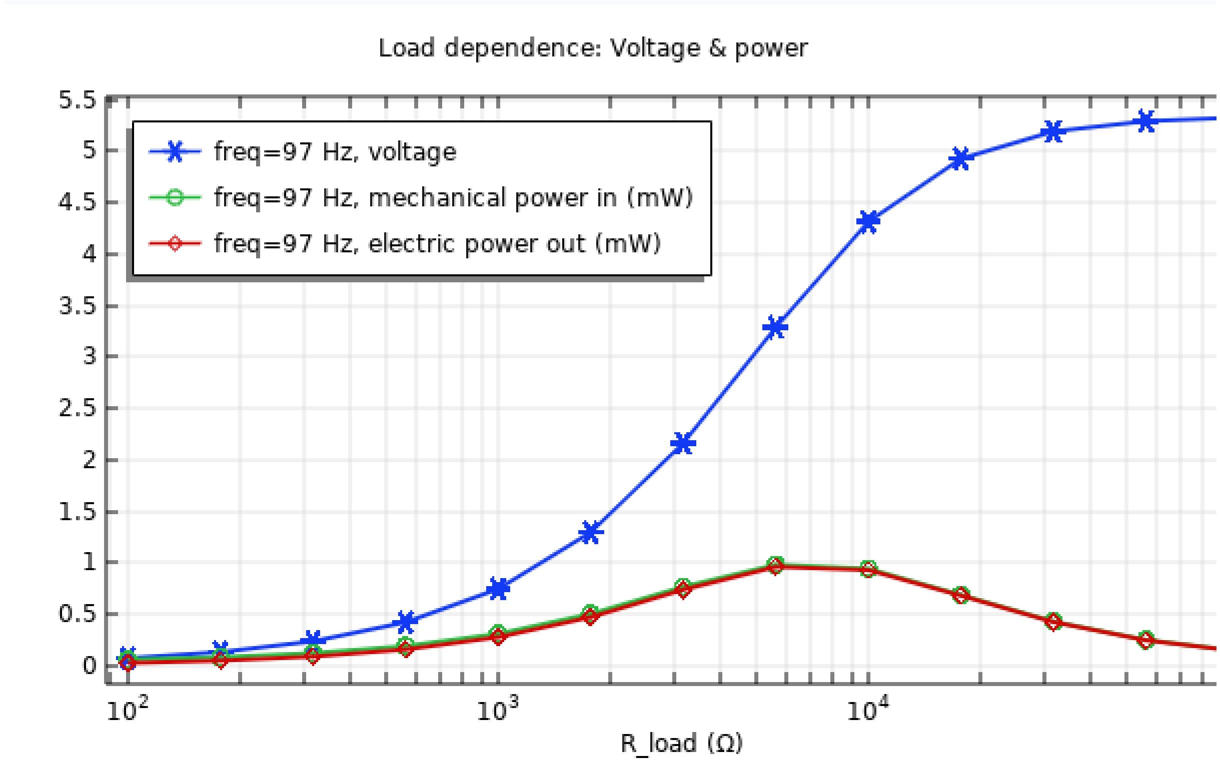


*Figure 22: Voltage, mechanical and electric power as a function of load for .08 mm piezo electric layer thickness.*

**4.4 Frequency response with changing the proof mass volume:**

For next analysis we keep all the beam parameters same to the initial structure, thus the stiffness remains same, only change the proof mass volume by doubling. For our experiment we can increase the proof mass volume by changing the volume dimension.

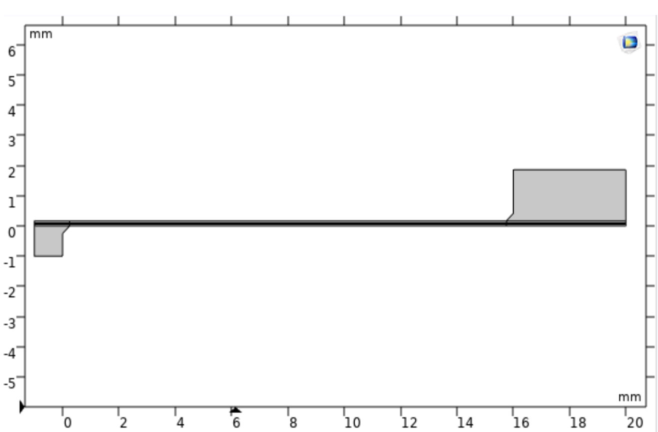

*Figure 23: Structure with single proof mass*

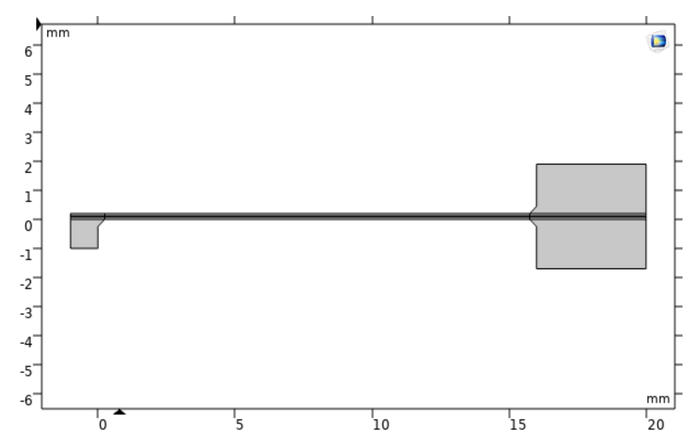

*Figure 24: Structure with single proof mass*

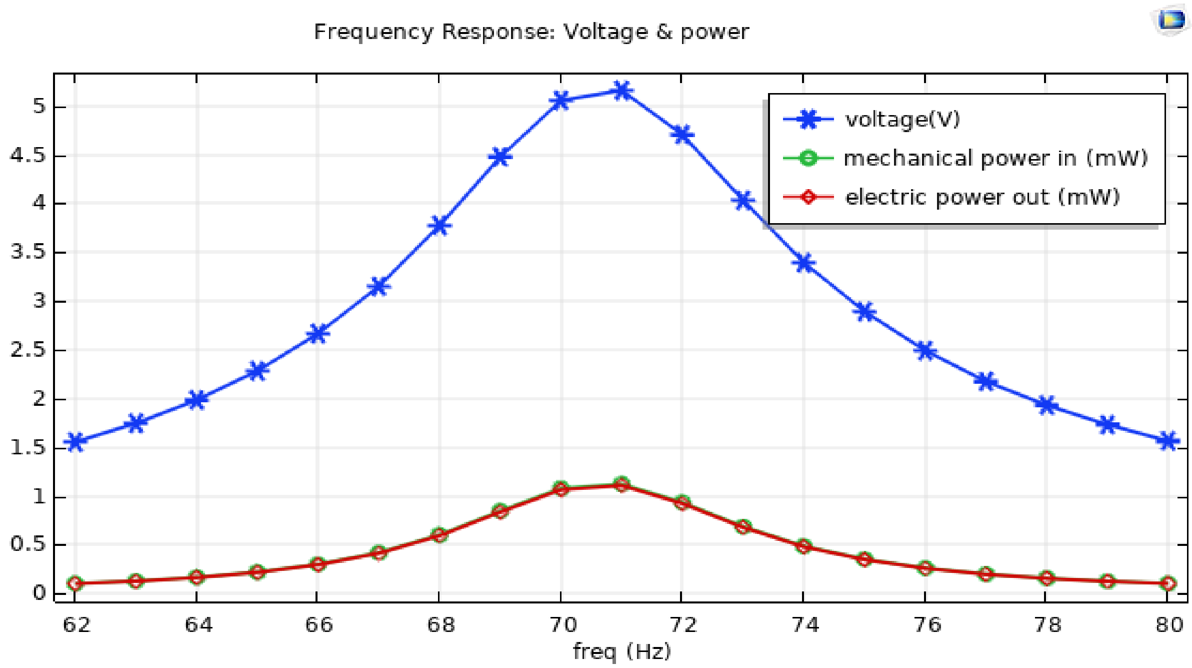


*Figure 25: Frequency response with single proof mass.*

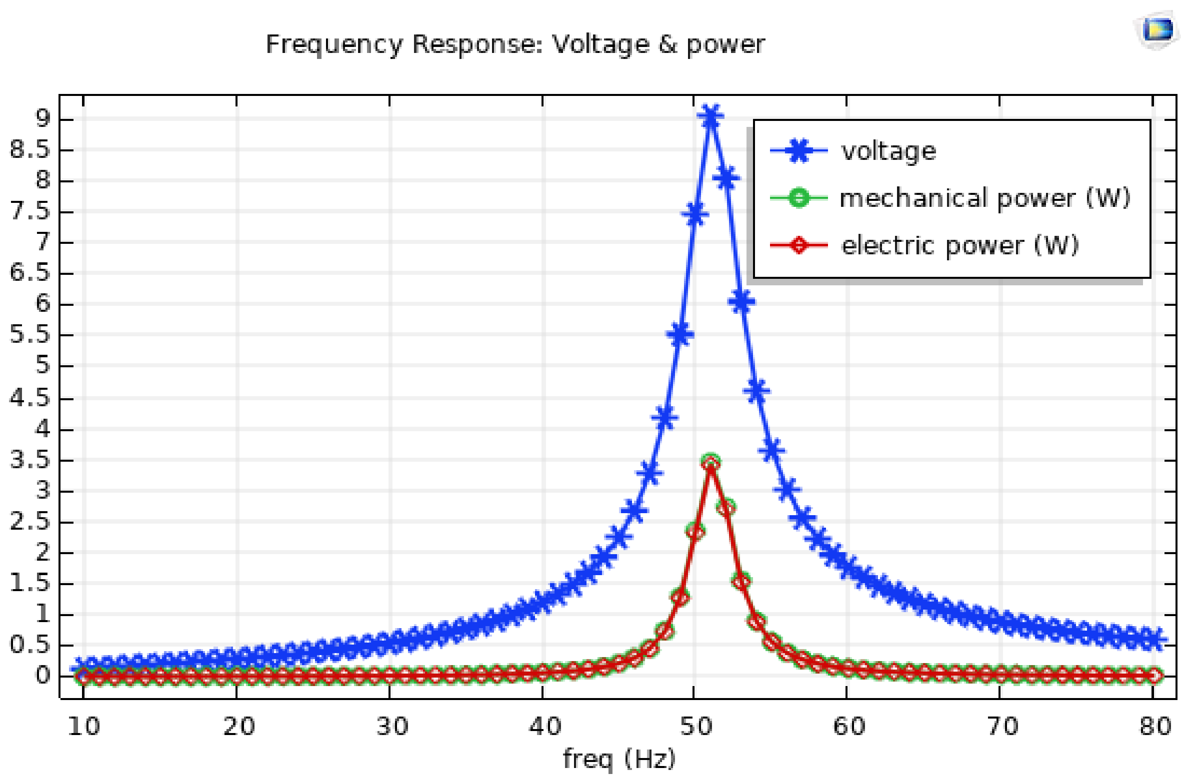


*Figure 26: Frequency response with single proof mass.*

Or we can increase the number of PM by attaching two proof mass above and below the beam. These two changes show similar result. The effect of changing proof mass can be seen that resonance was reached at a lower frequency of around 50HZ from initial frequency of 71 HZ. And the maximum voltage rises from around 5V to around 9V. This happens due to the fact that as input force from the proof mass increased but as the stiffness was constant, resonance was reached easily at a lower frequency. And high voltage was from higher bending due to higher input force.

## Chapter 5

### 5.1 Optimization by changing both proof mass and piezo layer thickness.

We can see that in both cases of increasing the piezo layer thickness and proof mass volume the frequency at which maximum voltage can be obtained, that is the resonant frequency changes. But the vibration frequency of the source, that is the available frequency due to the vibrating machine to which we have clamped our device and from which we are trying to extract the energy remains constant. Moreover, we see increase in piezo layer actually decreases the peak voltage value at the higher resonant frequency due to increase in thickness. And for proof mass volume, the voltage produced increases with the increase in proof mass but resonant frequency decreases. But we want to get higher voltage and power output at the available frequency which is always constant. So we aim to increase voltage output at the constant resonant frequency of the initial structure. We see that increase in thickness increases the frequency and increase in PM decreases the frequency. Now if we increase both the thickness and proof mass volume simultaneously, we find that the frequency remains relatively same as the effects neutralize each other but the output voltage increases. So we perform trial and error to find the best thickness ratio and PM volume ratio by which we can increase their initial dimension to get the desired result. Thus we try to optimize our initial structure to get higher voltage at the same frequency range by increasing both the thickness and proof mass volume simultaneously.

Our simulation results show that if we increase the thickness from initial .06 mm to .08 and also double the proof mass volume, the resonant frequency remains same at 71 HZ but the peak voltage increases from 5.16 to 7.675. .08 is 1.33 times .06. So we again increase the thickness by 1.33 times and double the proof mass and see that the voltage and power again increased but the frequency remains the same at 71. We repeat the process one more time and get similar result. We take another data point by decreasing thickness 1.33 times and halving the proof mass volume and see that voltage and power reduced but frequency remains same as expected.

The table below shows how we change the structural parameters from the initial values so that the desired result can be achieved. And the voltage output, mechanical power input and electrical power output for each values are given. Then a graph is plotted to show how the peak voltage value increases with the increase in the thickness given that we double the PM volume in each case. This is very different from the graph shown before where we can see that with only increase in the thickness decreased the peak voltage

.

***Table 5: Simulation result for both piezo layer thickness and proof mass changes.***

| *Piezo layer thickness (mm)* | *Steel layer thickness (mm)* | *Beam dimension (mm)* | | | *Number of PM* | *PM dimension (mm)* | | | *PM volume (mm^3)* | *Peak Voltage (V)* | *Resonant frequency (Hz)* | *Mechanical power input (mW)* | *Wlectric power output (mW)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Length | Height | Depth | | Length | Height | Depth | | | | | |
| 0.045 | 0.04 | 21 | 0.130 | 14 | 1 | 4 | 0.85 | 14 | 47.6 | 3.68 | 72 | 0.57 | 0.565 |
| 0.06 | 0.04 | 21 | 0.16 | 14 | 1 | 4 | 1.7 | 14 | 95.2 | 5.16 | 71 | 1.25 | 1.11 |
| 0.08 | 0.04 | 21 | 0.2 | 14 | 2 | 4 | 1.7 | 14 | 190.4 | 7.675 | 71 | 2.49 | 2.45 |
| 0.106 | 0.04 | 21 | 0.252 | 14 | 2 | 4 | 3.4 | 14 | 380.8 | 11.8 | 71 | 5.92 | 5.81 |
| 0.141512 | 0.04 | 21 | 0.323 | 14 | 2 | 4 | 6.8 | 14 | 761.6 | 17.9 | 70 | 13.64 | 13.32 |

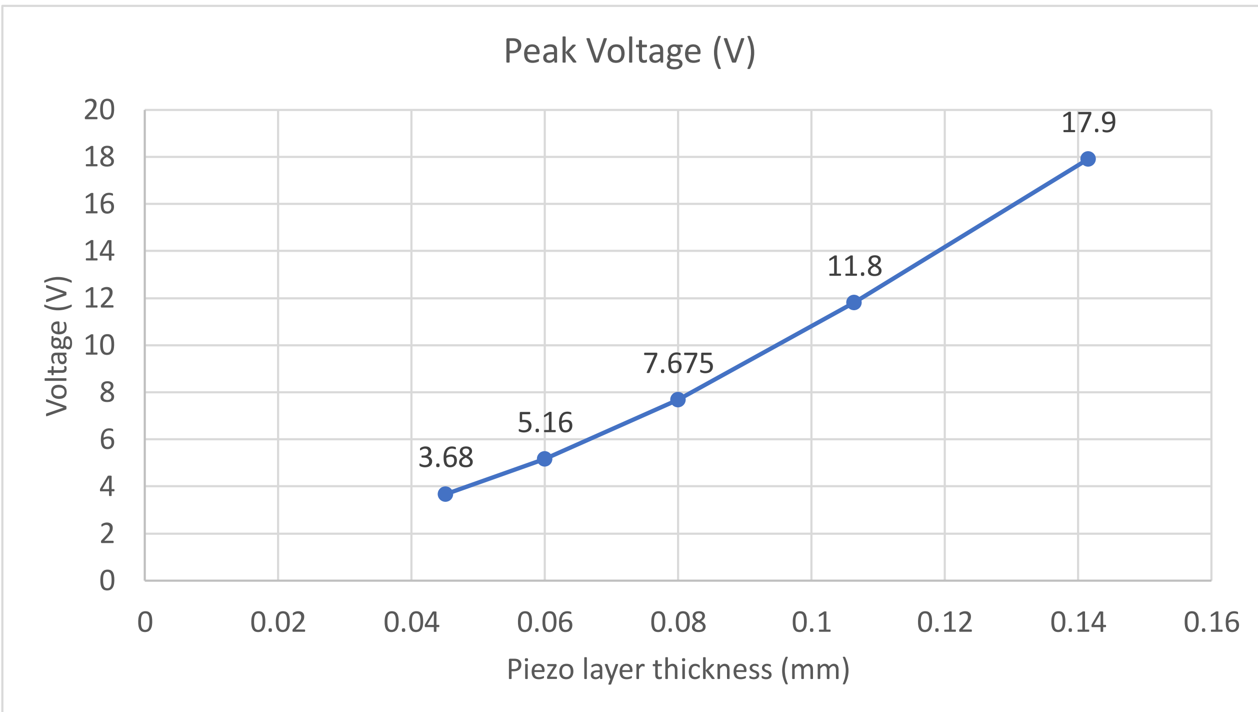


***Figure 27: Peak voltage for both piezo layer thickness and proof mass changes.***

One thing is needed to keep in mind that our device is very small compared to the vibrating machine with which it is attached to and produce a small voltage at mW range. So we assume that increasing the dimension of our device does not hinder the ability of the source to vibrate at a particular frequency. That is, we cannot increase the size of our device to the extent that it becomes difficult for the vibrating machine to operate at its normal operating condition.

### 5.2 Performance for different proof mass material with different volume.

Lastly we do frequency response study for different proof mass material with changed volume and see the result. For each case we take the initial structure dimension for the piezoelectric layer and elastic substrate layer. Only the proof mass properties are changed. With change in the proof mass material, the density also changes. So we change the volume accordingly so that the mass remains same. We do this to keep the input force same and find out the impact of changing the PM material and volume on the performance of the energy harvester. Besides the initial material steel, we take aluminum(Al), copper(Cu), lead (Pb) and platinum (Pt). For the first two material change, we change the height of the proof mass to adjust the volume, and for the last two materials, we change the length of the PM to adjust the volume. The result shows that volume change does not have much effect. We can see that the output voltage almost around 5 V and output electric power is around 1.1 mW. But length change has larger effect than the height change. This is due to the fact that as the mass is same for all the different PM materials, higher concentrated mass is available at the free end for decrease in length of the PM with higher density material. The higher the density of the material, the shorter the proof mass length will be for similar mass. As a result, the resonant frequency for platinum PM changes to 65 HZ from 71 HZ of the steel PM. But overall the effect of PM volume and material change is negligible on the performance of the device.

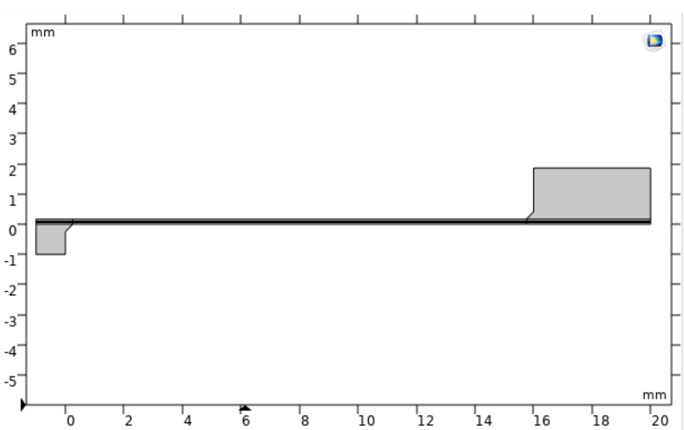


*Figure 28: Structure with steel proof mass*

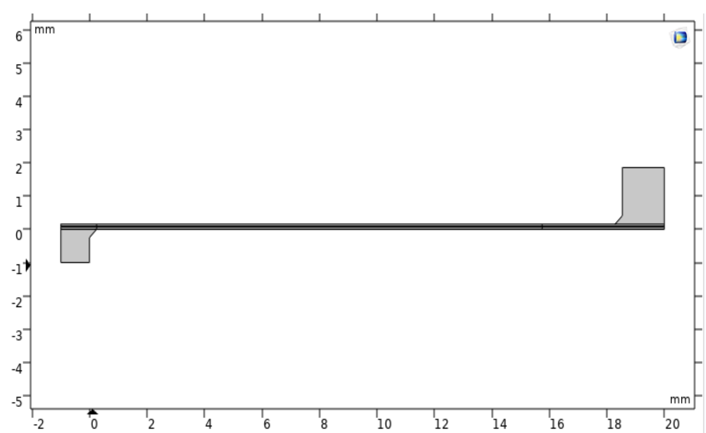


*Figure 29: Structure with platinum proof mass*

***Table 6*: *Values for different proof mass material***

| *PM material* | *density (kg/m^3)* | *No of PM* | *PM dimension (mm)* | | | *PM volume (mm^3)* | *PM mass (kg)* | *Peak Voltage (V)* | *Resonant frequency (Hz)* | *Mechanical power input (mW)* | *Electric power output (mW)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Length | Height | Depth | | | | | | |
| Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 | 5.16 | 71 | 1.25 | 1.11 |
| Aluminum | 2700 | 1 | 4 | 4.94 | 14 | 276.78 | 0.00074732 | 5.12 | 69 | 1.104 | 1.09 |
| Copper | 8960 | 1 | 4 | 1.48 | 14 | 83.40 | 0.00074732 | 5.2 | 71 | 1.135 | 1.12 |
| Pb | 11340 | 1 | 2.769 | 1.7 | 14 | 65.90 | 0.00074732 | 5.28 | 68 | 1.178 | 1.165 |
| Pt | 21450 | 1 | 1.463 | 1.7 | 14 | 34.84 | 0.00074732 | 5.4 | 65 | 1.23 | 1.21 |

## Chapter 6

### 6.1 Discussion

Below is the table with data of our all our simulations. It can be seen that at first we increased thickness gradually by .02 mm from .02 mm to .08 mm and ran simulation. Then for .06 mm thickness we increased proof mass by doubling the PM volume from 95.2 $mm^3$ to 190.4 $mm^3$ , and kept all other parameter same and ran simulation. Lastly we increased thickness from .06 mm to .08 mm and PM volume from 95.2 $mm^3$ to 190.4 $mm^3$ simultaneously and found increased voltage at similar frequency range. From this we calculated the ratio by which the dimensions were increased. Then with the obtained thickness and proof mass ratio we reproduced the result for different data points. For our last analysis, we tried to find out the effect of proof mass volume change by keeping all other parameters constant. So we changed the proof mass material and volume accordingly to keep the PM mass constant.

Our work comprises of change of two parameters of the piezoelectric energy harvester. piezo layer thickness and proof mass volume. We did two kinds of analysis of proof mass. For first one we increased the volume of the proof mass for the same material. This basically increased the input force of the device as the mass of proof mass is changing. For the next analysis of the proof mass, we kept the mass constant and saw what kind of effect the volume change has on the performance of the energy harvester. Both of these analysis has importance. For increase in mass, we see later when we increased PM together with increase in thickness, we achieved higher voltage output at same frequency which was available initially. Now we always have to consider the fact that we will attach this device to a vibrating machine. So we can take any of the beam and proof mass dimension from the obtained combinations as suitable for using with the vibrating machine to get the maximum voltage output without disrupting the operating condition of the machine. We cannot increase the weight of the device a large amount as at some point it will become a burden to the main vibrating body and thus hinder the process. It can also effect the available frequency. Another thing is the size of the device. The size should be manageable so that it fits in the space where the vibrating machine is operating. For our last data point in the analysis where we changed both the piezo layer thickness and PM volume simultaneously, we took the height of the proof mass as 6.8 mm. It is greater than PM length and creates an abnormal shape. It may not be suitable for using in practice. But we saw from our second analysis with proof mass that, if we change the PM material and volume accordingly, keeping the mass constant, it doesn’t have much effect on the performance. So we can use a material with higher density for proof mass like platinum, thus require less volume for same mass and achieve the same result. So we can reduce the 6.8 mm height as height change has less effect than length change which we found from our analysis.

For piezo layer thickness, we did frequency response analysis for change in thickness. This analysis is by itself important as if available frequency at source is different from initial

### *Table 7: Simulation result for all the experiments*

| *Piezo Material* | *Piezo layer thickness (mm)* | *Steel layer thickness (mm)* | *Beam dimension (mm)* | | | *PM material* | *density (kg/m^3)* | *No of PM* | *PM dimension (mm)* | | | *PM volume (mm^3)* | *PM mass (kg)* | *Total volume (mm^3)* | *Peak Voltage (V)* | *Resonant frequency (Hz)* | *Mechanical power input (mW)* | *Electric power output (mW)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Length | Height | Depth | | | | Length | Height | Depth | | | | | | | |
| PZT-5A | 0.02 | 0.04 | 21 | 0.08 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 | 118.72 | 8 | 27.5 | 2.8 | 2.8 |
| PZT-5A | 0.04 | 0.04 | 21 | 0.12 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 | 130.48 | 6.3 | 47 | 1.5 | 1.48 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 | 142.24 | 5.16 | 71 | 1.25 | 1.11 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Steel | 7850 | 2 | 4 | 1.7 | 14 | 190.4 | 0.00149464 | 237.44 | 9 | 52 | 3.5 | 3.48 |
| PZT-5A | 0.08 | 0.04 | 21 | 0.2 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 | 154 | 4.58 | 97 | 0.9 | 0.88 |
| PZT-5A | 0.08 | 0.04 | 21 | 0.2 | 14 | Steel | 7850 | 2 | 4 | 1.7 | 14 | 190.4 | 0.00149464 | 249.2 | 7.675 | 71 | 2.49 | 2.45 |
| | | | | | | | | | | | | | | | | | | |
| PZT-5A | 0.045 | 0.04 | 21 | 0.130 | 14 | Steel | 7850 | 1 | 4 | 0.85 | 14 | 47.6 | 0.00037366 | 85.878 | 3.68 | 72 | 0.57 | 0.565 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 | 142.24 | 5.16 | 71 | 1.25 | 1.11 |
| PZT-5A | 0.08 | 0.04 | 21 | 0.2 | 14 | Steel | 7850 | 2 | 4 | 1.7 | 14 | 190.4 | 0.00149464 | 249.2 | 7.675 | 71 | 2.49 | 2.45 |
| PZT-5A | 0.106 | 0.04 | 21 | 0.252 | 14 | Steel | 7850 | 2 | 4 | 3.4 | 14 | 380.8 | 0.00298928 | 455.123 | 11.8 | 71 | 5.92 | 5.81 |
| PZT-5A | 0.141 | 0.04 | 21 | 0.323 | 14 | Steel | 7850 | 2 | 4 | 6.8 | 14 | 761.6 | 0.00597856 | 856.569 | 17.9 | 70 | 13.64 | 13.32 |
| | | | | | | | | | | | | | | | | | | |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Steel | 7850 | 1 | 4 | 1.7 | 14 | 95.2 | 0.00074732 | 142.24 | 5.16 | 71 | 1.25 | 1.11 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Aluminum | 2700 | 1 | 4 | 4.942 | 14 | 276.785 | 0.00074732 | 323.825 | 5.12 | 69 | 1.104 | 1.09 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Copper | 8960 | 1 | 4 | 1.489 | 14 | 83.406 | 0.00074732 | 130.446 | 5.2 | 71 | 1.135 | 1.12 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Pb | 11340 | 1 | 2.769 | 1.7 | 14 | 65.901 | 0.00074732 | 112.941 | 5.28 | 68 | 1.178 | 1.165 |
| PZT-5A | 0.06 | 0.04 | 21 | 0.16 | 14 | Pt | 21450 | 1 | 1.463 | 1.7 | 14 | 34.840 | 0.00074732 | 81.880 | 5.4 | 65 | 1.23 | 1.21 |

frequency of 71 HZ we can choose piezo layer thickness accordingly to get maximum voltage output. We also saw how our analysis helped later to optimize our initial structure by finding the thickness ratio and a proof mass volume ratio by which if we increase the thickness and PM, we get desired increased voltage at the source frequency. We have also done load response analysis for different piezo layer thickness. It helped us to determine the optimum load at which highest voltage output and the power output can be achieved at the resonant frequency.

### 6.2 Scope of This Study

In our study we did the dimensional analysis to find the suitable structural dimension for maximum power output at a fixed frequency of 71 HZ. But the available frequency at the source can be higher or lower. So for different available frequencies, further studies can be done following the similar trend as seen in our study to obtain different piezoelectric layer ratios and proof mass volume ratios for increasing the output voltage at the fixed available frequency. Some real world study can be done by observing the available space for attaching the device and taking data and calculating value accordingly to find the suitable dimension.

For all our cases we kept the thickness of elastic layer that is the steel layer of the beam constant. But analysis can be done to find out elastic layer to piezo layer ratio and its effect on the performance of the device.

In our design, we used a bimorph structure. That is, we covered the whole upper and lower part of the steel layer with piezo layer. But we know that maximum bending occurs, that is strain energy is generated at the area closer to the fixed end of the vibrating beam. So study can be done to find out the impact of different lengths of piezo layer and the percent increase in the output voltage for covering different percent of the steel beam. This study can show whether it will be more cost effective to cover only the portion of the beam with higher bending and save money on piezo electric materials.

### 6.3 Conclusion

From our study we came to conclusion of the following points

- Increase in the piezoelectric layer thickness increases the resonant frequency and decreases the voltage output.
- Increasing the proof mass volume decreases the resonant frequency and increases the voltage output.
- By increasing both piezo layer thickness and proof mass higher voltage at similar frequency can be obtained.

- By changing the piezo layer thickness and proof mass volume following a fixed ratio, different voltage and power can be obtained at fixed frequency.
- Proof mass volume change has negligible effect on performance if mass is same, although length change has more effect than height change on resonant frequency.

## References


[1] H. G. Yeo and S. Trolier-McKinstry, "Effect of piezoelectric layer thickness and poling conditions on the performance of cantilever piezoelectric energy harvesters on Ni foils," *Sensors and Actuators, A: Physical*, vol. 273, pp. 90–97, Apr. 2018, doi: 10.1016/j.sna.2018.02.019.

[2] C. R. Bowen, H. A. Kim, P. M. Weaver, and S. Dunn, "Piezoelectric and ferroelectric materials and structures for energy harvesting applications," *Energy and Environmental Science*, vol. 7, no. 1. Royal Society of Chemistry, pp. 25–44, 2014, doi: 10.1039/c3ee42454e.

[3] I. Jafer, P. Stack, and K. MacNamee, "Design of new power management circuit for light energy harvesting system," *Sensors (Switzerland)*, vol. 16, no. 3, Feb. 2016, doi: 10.3390/s16030270.

[4] J. Siang, M. H. Lim, and M. Salman Leong, "Review of vibration-based energy harvesting technology: Mechanism and architectural approach," *International Journal of Energy Research*, vol. 42, no. 5. John Wiley and Sons Ltd, pp. 1866–1893, Apr. 01, 2018, doi: 10.1002/er.3986.

[5] J. W. Yi, W. Y. Shih, and W. H. Shih, "Effect of length, width, and mode on the mass detection sensitivity of piezoelectric unimorph cantilevers," *Journal of Applied Physics*, vol. 91, no. 3, pp. 1680–1686, Feb. 2002, doi: 10.1063/1.1427403.

[6] L. Jin, S. Gao, and X. Zhang, "The effect of the beam shapes on the doubly-clamped piezoelectric energy harvester," *Applied Mathematics and Mechanics*, vol. 40, no. 9, pp. 1361–1374, Sep. 2019, doi: 10.1007/s10483-019-2513-7.

[7] K. Morimoto, I. Kanno, K. Wasa, and H. Kotera, "High-efficiency piezoelectric energy harvesters of c-axis-oriented epitaxial PZT films transferred onto stainless steel cantilevers," *Sensors and Actuators, A: Physical*, vol. 163, no. 1, pp. 428–432, Sep. 2010, doi: 10.1016/j.sna.2010.06.028.

[8] J. Baker, S. Roundy, and P. P. Wright, "Alternative Geometries for Increasing Power Density in Vibration Energy Scavenging for Wireless Sensor Networks."

[9] G. Zhang, S. Gao, H. Liu, and S. Niu, "A low frequency piezoelectric energy harvester with trapezoidal cantilever beam: theory and experiment," *Microsystem Technologies*, vol. 23, no. 8, pp. 3457–3466, Aug. 2017, doi: 10.1007/s00542-016-3224-5.

[10] M. Arefi and A. M. Zenkour, "A simplified shear and normal deformations nonlocal theory for bending of functionally graded piezomagnetic sandwich nanobeams in magneto-thermo-electric environment," *Journal of Sandwich Structures and Materials*, vol. 18, no. 5, pp. 624–651, Sep. 2016, doi: 10.1177/1099636216652581.

[11] M. Arefi and A. M. Zenkour, "Vibration and bending analysis of a sandwich microbeam with two integrated piezo-magnetic face-sheets," *Composite Structures*, vol. 159, pp. 479–490, Jan. 2017, doi: 10.1016/j.compstruct.2016.09.088.

[12] M. Arefi and A. M. Zenkour, "Wave propagation analysis of a functionally graded magneto-electro-elastic nanobeam rest on Visco-Pasternak foundation," *Mechanics Research Communications*, vol. 79, pp. 51–62, Jan. 2017, doi: 10.1016/j.mechrescom.2017.01.004.

[13] M. Arefi and A. M. Zenkour, “Size-dependent vibration and bending analyses of the piezomagnetic three-layer nanobeams,” *Applied Physics A: Materials Science and Processing*, vol. 123, no. 3, Mar. 2017, doi: 10.1007/s00339-017-0801-0.

[14] Mohammad Arefi, “Mohammad Arefi / A complete set of equations for piezo-magneto-elastic analysis of a functionally graded thick shell of revolution,” 2014.

[15] S. Saxena, R. Sharma, and B. D. Pant, “Piezoelectric layer length and thickness variation effects on displacement, von-Mises stress and electric potential generated by cantilever type piezoelectric energy harvester,” in *Materials Today: Proceedings*, 2020, vol. 30, pp. 23–27, doi: 10.1016/j.matpr.2020.03.747.

[16] M. G. Vasundhara, M. Senthilkumar, and G. K. Kalavathi, “A distributed parametric model of shape memory alloy-based resonant frequency tunable cantilevered PZT energy harvester with tip mass,” *ISSS Journal of Micro and Smart Systems*, vol. 8, no. 1, pp. 13–24, Jun. 2019, doi: 10.1007/s41683-019-00034-0.

[17] S. Paquin and Y. St-Amant, “Improving the performance of a piezoelectric energy harvester using a variable thickness beam,” *Smart Materials and Structures*, vol. 19, no. 10, Oct. 2010, doi: 10.1088/0964-1726/19/10/105020.

[18] A. Damya, E. Abbaspour Sani, and G. Rezazadeh, “An innovative piezoelectric energy harvester using clamped–clamped beam with proof mass for WSN applications,” *Microsystem Technologies*, vol. 26, no. 10, pp. 3203–3211, Oct. 2020, doi: 10.1007/s00542-018-3890-6.

[19] S. P. Matova, M. Renaud, M. Jambunathan, M. Goedbloed, and R. van Schaijk, “Effect of length/width ratio of tapered beams on the performance of piezoelectric energy harvesters,” *Smart Materials and Structures*, vol. 22, no. 7, Jul. 2013, doi: 10.1088/0964-1726/22/7/075015.

[20] A. R. Reddy, M. Umapathy, D. Ezhilarasi, and U. Gandhi, “Improved energy harvesting from vibration by introducing cavity in a cantilever beam,” *JVC/Journal of Vibration and Control*, vol. 22, no. 13, pp. 3057–3066, Jul. 2016, doi: 10.1177/1077546314558498.

[21] R. Usharani, G. Uma, and M. Umapathy, “Design of high output broadband piezoelectric energy harvester with double tapered cavity beam,” *International Journal of Precision Engineering and Manufacturing - Green Technology*, vol. 3, no. 4, pp. 343–351, Oct. 2016, doi: 10.1007/s40684-016-0043-1.

[22] Y. Liao and H. A. Sodano, “Optimal placement of piezoelectric material on a cantilever beam for maximum piezoelectric damping and power harvesting efficiency,” *Smart Materials and Structures*, vol. 21, no. 10, Oct. 2012, doi: 10.1088/0964-1726/21/10/105014.

[23] F. Botta, D. Dini, C. Schwingshackl, L. di Mare, and G. Cerri, “Optimal placement of piezoelectric plates to control multimode vibrations of a beam,” *Advances in Acoustics and Vibration*, 2013, doi: 10.1155/2013/905160.

[24] C. Spier, J. C. Bruch, J. M. Sloss, S. Adali, and I. S. Sadek, “Placement of multiple piezo patch sensors and actuators for a cantilever beam to maximize frequencies and frequency gaps,”

*JVC/Journal of Vibration and Control*, vol. 15, no. 5, pp. 643–670, May 2009, doi: 10.1177/1077546308094247.

[25] M. Kim, M. Hoegen, J. Dugundji, and B. L. Wardle, “Modeling and experimental verification of proof mass effects on vibration energy harvester performance,” *Smart Materials and Structures*, vol. 19, no. 4, 2010, doi: 10.1088/0964-1726/19/4/045023.

[26] L. Tang and J. Wang, “Size effect of tip mass on performance of cantilevered piezoelectric energy harvester with a dynamic magnifier,” *Acta Mechanica*, vol. 228, no. 11, pp. 3997–4015, Nov. 2017, doi: 10.1007/s00707-017-1910-8.

[27] R. Somkuwar, J. Chandwani, and R. Deshmukh, “Wideband auto-tunable vibration energy harvester using change in centre of gravity,” *Microsystem Technologies*, vol. 24, no. 7, pp. 3033–3044, Jul. 2018, doi: 10.1007/s00542-018-3846-x.

[28] S. P. Beeby, M. J. Tudor, and N. M. White, “Energy harvesting vibration sources for microsystems applications,” *Measurement Science and Technology*, vol. 17, no. 12, Dec. 2006, doi: 10.1088/0957-0233/17/12/R01.

[29] S. Saxena, R. Sharma, and B. D. Pant, “Design and development of guided four beam cantilever type MEMS based piezoelectric energy harvester,” *Microsystem Technologies*, vol. 23, no. 6, pp. 1751–1759, Jun. 2017, doi: 10.1007/s00542-016-2940-1.

[30] S. Sunithamani and P. Lakshmi, “Experimental study and analysis of unimorph piezoelectric energy harvester with different substrate thickness and different proof mass shapes,” *Microsystem Technologies*, vol. 23, no. 7, pp. 2421–2430, Jul. 2017, doi: 10.1007/s00542-016-2917-0.

[31] A. H. Alameh, M. Gratuze, M. Y. Elsayed, and F. Nabki, “Effects of proof mass geometry on piezoelectric vibration energy harvesters,” *Sensors (Switzerland)*, vol. 18, no. 5, May 2018, doi: 10.3390/s18051584.

[32] Z. D. O. S. Wong Chin Chye, *Electromagnetic Micro Power Generator - A Comprehensive Survey*. .

[33] P. S. Sathya, “Bimorph Piezoelectric Energy Harvester at Low Frequency,” Feb. 2020, doi: 10.1109/ic-ETITE47903.2020.202.

[34] M. Guizzetti, V. Ferrari, D. Marioli, and T. Zawada, “Thickness Optimization of a Piezoelectric Converter for Energy Harvesting.”

[35] S. Priya *et al.*, “A Review on Piezoelectric Energy Harvesting: Materials, Methods, and Circuits,” *Energy Harvesting and Systems*, vol. 4, no. 1, pp. 3–39, Feb. 2017, doi: 10.1515/ehs-2016-0028.

[36] Comsol, “Piezoelectric Energy Harvester.” [Online]. Available: www.comsol.com/trademarks.