DESIGN OPTIMIZATION OF MEMS BASED PIEZOELECTRIC ENERGY HARVESTER FOR LOW-FREQUENCY APPLICATIONS

A Thesis Submitted in Partial Fulfilment of the Requirement for the Award of the Degree of

MASTER OF TECHNOLOGY

in VLSI Design

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DECLARATION

I, Roohi Singh hereby declare that the work presented in this thesis entitled " **Design Optimization of MEMS based piezoelectric energy harvester for low-frequency applications"** in partial fulfillment of the requirement for the award of degree of Master of Technology (VLSI Design) submitted at Electronics and Communication Engineering Department, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala is an authentic record of work carried out under supervision of **Dr. Anil Arora (Assistant Professor, ECED)** from June 2017 to June 2018. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.

Date:...09/08/2018.......

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It is certified that the above statement made by the student is correct to best of my knowledge and belief.

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The study has indeed helped me to explore knowledge and I am sure it will help me in my future

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ABSTRACT

In recent years, piezoelectric based energy harvester had become major research topic. Piezoelectric materials are excellent transducers in converting vibrational energy into electrical energy, and vibration based piezoelectric generators are seen as an enabling technology for wireless sensor networks, especially in self powered devices**.** These are mostly made of thin film technology and different configurations as unimorph and bimorph for sensor and actuator applications. In this thesis work, analysis and comparison of two widely used cantilever design in MEMS energy harvesting devices i.e. wide beam structure and narrow beam structure have been done. Aluminum Nitride (AIN) is chosen as a piezoelectric material due to its CMOS and biocompatibility. To study the output of the design, Finite Element Modelling was used. The power density obtained based on the volume of the structure was 14.8 $\mu W/\text{cm}^3$ for the wide beam structure and 0.10 $\mu W/\text{cm}^3$ for narrow beam structure individually. In selecting a device, bandwidth is also a vital parameter. An array of cantilever structure resulted in a bandwidth of 4 Hz for the wide beam structure and 8.1 Hz for narrow beam structure respectively. The conclusion of the results are wide beam structure is preferred to increase power density and a narrow beam for the wide bandwidth. High power density also has a disadvantage which is likely to fail where acceleration is high, as due to increasing stress which they experience.

LIST OF PUBLICATIONS

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LIST OF ABBREVIATIONS

MEMS	:	Micro Electro-Mechanical System
NEMS	:	Nano Electro-Mechanical System
EH	:	Energy harvester
FOM	:	Figure of Merit
PIE	:	Piezoelectric Effect
FEM	:	Finite Element Modeling
Si	:	Silicon
PZT	:	Lead zirconate titanate
PVDF	:	Polyvinylidene fluoride
AIN	:	Aluminum Nitride
ZnO	:	Zinc oxide
Al	:	Aluminium
Pt	:	Platinum
CMOS	:	Complimentary metal-oxide semiconductor

CHAPTER 1

INTRODUCTION

1.1 Motivation and overview of the problem

With recent progress in Micro-Electro-Mechanical System (MEMS) and wireless networks portable electronic devices have been prevailing because of the benefits over wired devices like the flexibility of placement in any area, minute size, implementation in any area without any costly expenditure, cable trouble and with low consumption of power etc.[1]. These benefits of wireless devices conclude that the advancement and progression in electronics technology are light in weight, lowering in cost, response time is shortened, immense reliability [2].

Nevertheless, the miniaturization of devices is restricted by the conventional batteries, which are the main power source of the portable electronic devices and wireless sensor networks, nowadays. For instance, a wireless sensor network consists of control electronics, wireless element for communication, sensor and a battery for power source as shown in Figure 1.1. The wireless sensor network is scaling down as the size of sensors, communication element and control unit is scaled down due to advancement in MEMS but on the other side, the battery size is still the same.

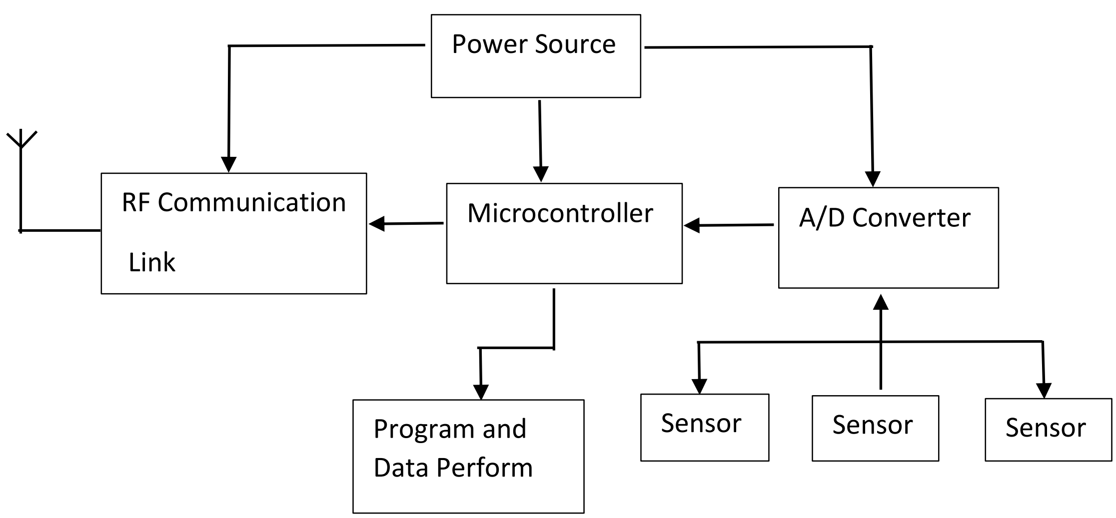


Figure 1.1 Architecture of a sensor node

Mostly the wireless networks use AA batteries as a power source [3], thus it restricts further scaling of the wireless network. Moreover, it has another disadvantage too as a short operational time span, immense maintenance of battery, have dangerous chemicals.

The short operational period of battery makes it not much reliable, as it may stop working any time without giving any warning. Then exhausted battery has to be replaced which is very expensive work if it has to be placed in the remote area. The battery has dangerous chemicals which will affect the environment when it is not disposed of correctly or recycled. In addition to it if battery explodes due to malfunction or misusage may result in a vital loss. Therefore, the battery has to be replaced in wireless electronic devices.

Thus the renewable power source is required to replace the battery in order to increase the operational timespan and dependability on the wireless electronic device and self-power devices.

1.2 Solution-Energy harvester

1.2.1 Energy Harvesting

For harvesting of ambient energy from environment there exists various technologies like solar energy harvesting [4], thermal energy harvesting [5] and vibrational energy harvesting [6]. Highest power density is offered by the solar energy harvesting as it is obtained in direct sunlight which is $-$ 15 μm/mm^3 and if same harvesting device is monitored on a cloudy day then 0.15 μm/mm^3 power density can be obtained. Whereas its performance is further reduced if the device is monitored indoor. A piezoelectric based device which harvest energy from vibrations gives power density of 0.25 μm/mm^3 [7]. Comparison between solar and the vibrational energy harvesting, compared in terms of batteries in lifespan and the power density. As shown in Figure 1.2, for long term applications, battery power is not sufficient.

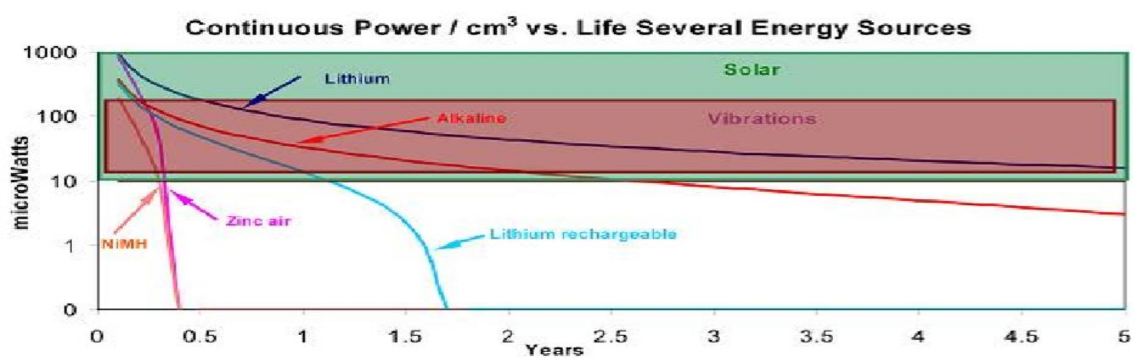
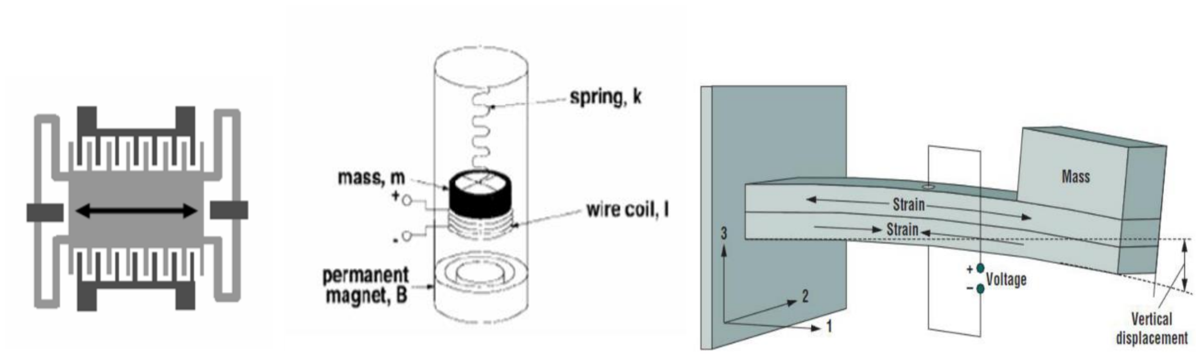


Figure 1.2 Comparison of power density and lifespan among batteries, solar energy, and vibrational energy harvesting.[7]

Solar energy has the highest power density but its application area is limited, whereas vibrations are accessible.

Electromechanical transducers are the device for converting mechanical (motion) into variations of an electric current or voltage (electric signals) and vice versa.

There are three types of electromechanical transducers which are electrostatic, electromagnetic and piezoelectric as shown in Figure 1.3.



(a) **(b** **(c)**

Figure 1.3 Schematic diagrams of the three types of electromechanical transducers: (a) electrostatic; (b) electromagnetic; (c) piezoelectric

Amirtharajah et al. used a MEMS capacitive transducer to convert the vibrational energy to power a small device in 2000 [8]. Meninger et al. proposed a variable capacitor to convert the mechanical vibration into electrical energy and power density simulated was 3.8 μW/cm^3 in 2001 [9]. Roundy et al. designed a MEMS electrostatic to convert the vibration to the electricity, the power density obtained is 116 μW/cm^3 from the input vibration of 2.25 m/s^2 at 120 Hz in 2002 [10]. Miyazaki et al. made variable resonating capacitor to convert vibrational energy in electrical energy in 2003 [11]. Beeby et al. made an electromagnetic transducer to release a vibration based electromechanical power generator in 2006 [12].

Piezoelectric energy harvesting devices have been studied and experimented intensively, as a result, it possesses various advantages over the other two transducers like in terms of configuration, efficiency and control. The comparison between the three transducers is depicted in Table 1.1. The piezoelectric transducer generates a higher power output, simple configuration and miniaturization. Therefore it is chosen as the study objective of the dissertation.

Table 1.1 Comparison of electrostatic, electromagnetic and piezoelectric transducer

	Electrostatic	**Electromagnetic**	**Piezoelectric**
Advantages	It can be easily integrated into the microsystems, there is	In this, there is no requirement of the voltage source, and	In this no voltage source is required, it has high voltage as an output,

	slightly control of mechanical resonance	have a high power output	size is small, it is highly efficient
Disadvantages	It requires separate voltage source and needs high frequency than the piezoelectric	Design of this device is very complex and very difficult to integrate on the microsystem	Very difficult to integrate on the microsystem, need frequency and high stress, limited selection of material
Equation	U = $\frac{1}{2}\varepsilon E^2$	U = $\frac{B^2}{2\mu_o}$	U = $\frac{\sigma_y^2\, k^2}{2Y}$
Maximum energy density (practical)	4	25	35

Where U is energy density, ε is vacuum permittivity, E is an electric field, B is the magnetic field, μ_o is magnetic permeability of free space, σ_y is stress yield, k is the coupling coefficient and Y is young modulus.

1.3 Scope

The scope of piezoelectric energy harvester is

- It will be working under low-frequency as to power the low power devices and wireless sensor networks.
- It will be able to generate more power output or voltage
- Low cost and environment-friendly harvester

1.4 Research objective and Dissertation structure

1.4.1 Research objective

The objective of the research is to achieve a device which is applicable in terms of both power density and bandwidth. Piezoelectric harvesting device which is applied to low frequency (1-200 Hz) and high amplitude vibrations.

The objective is achieved in three steps

1. To optimally design a device and evaluate piezoelectric energy harvester which demonstrates the practicality of the device in terms of environment and necessity of study of this device.

The optimization is obtained through the theoretical analysis of power density and resonance frequency.

2. The main focus of device optimization of energy harvester is on increasing power and bandwidth. It is necessary to increase the amount of power to accurately power the wireless sensor networks. One technique to increase the efficiency of power is to optimize the circuitry of energy harvester. The other technique is by energy harvesting device physical dimensions. Optimizing the power from piezoelectric energy harvesting device is met by augmenting the structure dimension of the cantilever and optimizing the properties of piezoelectric material.

3. The other key aspect desired from energy harvester is wide bandwidth. The Silicon based energy harvesting devices gain large quality factor, which in turn limits it's applications in real life. Various efforts have been done in order to increase bandwidth [9-10], most of the efforts are on the basis of damping factor. Even though if there is an increase in the damping, it results in higher bandwidth. In fact, it also has the negative impact of lowering the quality factor which in turn decrease the power generated by the device. Another method is to make an array of the cantilever structure with varying resonance frequency. Size and shape of the structure affect the bandwidth. When there is an increase in number of the cantilever structure in a given area it results in the increase in bandwidth.

1.4.2 Dissertation structure

Chapter 1 states the motivation and an overview of the problem of power sources in wireless technology and the concept of energy harvesting. The piezoelectric energy harvesting device has been found a smart choice to convert mechanical vibration energy into electricity and accordingly the focus of this research.

Chapter 2 presents the literature survey of the piezoelectric energy harvester.

Chapter 3 describes the background of piezoelectric energy harvester which is piezoelectricity, the figure of merit (FOM) i.e. parameters necessary for energy harvesters study, building blocks of energy harvesters, micro cantilever resonators, piezoelectric materials, modeling of the piezoelectric device.

Chapter 4 presents methodology for the research work is mentioned in this chapter and the approach to obtain the results as selecting physics, selecting study, geometric modeling and piezoelectric material properties, boundary conditions, an electrical circuit for the device, meshing.

Chapter 5 is about the results obtained in the analysis of the piezoelectric energy harvester for low-frequency applications.

Chapter 6 concludes the achievements and proposes the future work to improve power output and safety factor.

CHAPTER 2

LITERATURE SURVEY

2.1 Overview

The following is the survey of the research which has been carried out in recent years which illustrates the usage of ambient energy to generate the power as battery limits the operational lifespan of devices. Vibrational cantilever structure using piezoelectric material can be used to generate power enough for powering low power devices and wireless sensor networks.

- **Henry A,** ***et al.*** [13] Many research has been going on in power harvesting, this paper tells the usage of piezoelectric material to be used to generate the power as piezoelectric material has crystalline structure which allows the ability to convert mechanical strain into the electrical charge and this is possible in the reverse order too, as electrical charge into strain. This property allows the material to absorb mechanical energy as vibration and converting it into the electrical energy which can be used to power the other device. Thus, with recent progress in Micro-Electro-Mechanical System (MEMS) based piezoelectric energy harvesting device have been prevailing for portable electronics and wireless sensor networks.
- **C.B. Williams,** ***et al.*** [14] To power microsystem which has no connection with the outside environment is really difficult by batteries, this device in this paper is able to generate 1 μW power from 70 Hz frequency which is coming from vibrating medium and moreover 0.1mW at 330 Hz. Whole analysis concludes that the power which is generated in the paper is a cube of the frequency. More the deflection more is the power generated. So, by the results, it is clear that the device is not suited for the low vibration frequency applications.
- **Geffrey K.Ottman,** ***et al.*** [15] In this paper, the energy harvesting from a vibration piezoelectric element is described in which there is capacitive instead of inductive power source impendence. A circuit approach is described which will achieve an optimal power from the piezoelectric element. The circuit has various components in it as AC-DC rectifier with the output capacitance, electrochemical battery, and DC-DC converter. Experimental results proved that using DC-DC converter increases the power transfer by 400% when compared to not using a DC-DC converter. Moreover, this rate is assumed to further continue to improve at the higher excitation levels too.
- **Joseph A. Paradiso,** ***et al.*** [16] Energy harvesting has been the major research topic and in this paper the energy from human activity or ambient energy sources like light, vibration, heat is been mentioned and compared. The approach to power sensor networks and low power devices from the power generated by these is mentioned. These can be used as battery charge limits the operational lifespan of devices and this approach will be very advantageous to use the ambient source to power the devices.

- **Shad Roundy, *et al.*** [17] In this paper, devices made from the piezoelectric element is used to harvest power from the low ambient environment sources and then used to power the low power devices and wireless sensor networks. In the paper, PZT (Lead Zirconate Titanate) is used and volume power density 80μW/cm^2 is obtained.
- **S. P. Beeby, *et al.*** [1] In this paper, the comparison between the piezoelectric, electrostatic and electromagnetic transduction mechanism is concluded. Piezo material is an active material which generates a charge when mechanically strained. On the other side, the electromagnetic generators generated electromagnetic induction from the relative motion between the flux gradient and the conductor. And the electrostatic generator uses the motion between the isolated charge capacitive plate to generate the energy. Among the three transduction mechanism's the energy harvesting from the vibrational piezoelectric material is able to generate the power of about μW to mW.
- **Tang, *et al.*** [18] The main focus of device optimization of energy harvester is on increasing power and bandwidth It is necessary to increase the amount of power for accurately power the wireless sensor networks. One technique to increase the efficiency of power is to optimize the circuitry of energy harvester. The various techniques for this are resonance tuning, multimodal energy harvesting, frequency up conversion, nonlinear techniques are been mentioned.
- **Guo – Hua Feng, *et al***. [19] In this paper, four optimized designs are been analyzed according to the systematic figure-of-merit (FOM) analysis. In this paper, the device for a wide range of frequency is been developed and two main design rule and fabrication characteristics are been mentioned. The power output of tens of pW to hundreds of nW over a range of frequency (300-900 Hz) at 1g acceleration is been calculated. The results in this paper are valid for the low power applications.
- **Nathan Jackson, *et al.*** [20] In this paper three structures (narrow, wide, trapezoidal) have been analyzed and experimented to obtain power density and bandwidth. Aluminum Nitride was chosen in this paper because of the CMOS compatibility and its deposition on Si-based cantilever beam is quite easy. FEM is been used in this to obtain the results. Power density obtained by the three structures are 2.5, 0.78, 0.65 mW/cm^3/g^2 and bandwidth of 4.8, 9, 26.4 The wide cantilever beam obtained the high power density which is among the three structures but this structure is quite large and thus has low bandwidth. On the other side narrow beam structure has the high bandwidth but low power density among the three structures. The trapezoidal structure can be used when compromising both power density and bandwidth.
- **Robert Andosca, *et al.*** [21] In this paper, a piezoelectric EH is been analyzed with one edge of the cantilever is fixed and the other side is free to move as have a proof mass on it. Power, Voltage and resonance frequency is been calculated. Fundamental resonance frequency and optimal load have

a difference of 4%. A device of 58 $\pm$ 2Hz under 0.7 g excitation, 63 μW power peak with 85 kohm. The conclusion of the paper is aluminium nitride based piezoelectric energy harvester device generate enough power and voltage to power low power electronic devices and wireless sensor networks.

- **M. Defosseux, *et al.*** [22] This paper states improved result of fabrication and characterization of piezoelectric micro-harvesters for a frequency of 200Hz and low acceleration.AIN was used and design was CMOS compatible. The device in the paper works efficiently for low acceleration. This device allows us to harvest power of 0.62μW at frequency of 214 Hz for acceleration of 0.17g. Power gets doubled when harvested in vacuum.
- **Q. C. Tang, *et al.*** [23] This paper demonstrate a vibration based EH that can generate power more than 1.5μW at the range of 9 Hz to 19 Hz under 1g of acceleration. The harvester uses frequency up-conversion method to excite two stages of generators. The result is the wide band capability on low frequency with the miniature size. The EH was mounted on a moving bus in order to test its performance in a real-life situation and as a result it generated 1.11 V of voltage and 123nW of power.
- **D. F. Berdy, *et al*.** [24] This paper demonstrates how a distributed proof mass can be used to get an increased operational bandwidth in a low-frequency from piezoelectric EH device. The EH device features two closely spaced resonant modes at frequency of 33 Hz and 43.3 Hz , the RMS output powers from EH device obtained is 107.3 μW and 74.9 μW, respectively, at acceleration of 0.2 g. The output power of this EH remains above 25 μW in the frequency band from 32.3 Hz up to 45 Hz. The increased bandwidth is enabled by the unique frequency response characteristics of the coupled system.
- **Kirubaveni S, *et al.*** [25] In this paper the EH device performance at low frequency results in efficiently working at strained vibration. Interdigitated electrode (IDE) based piezoelectric bi-Layer EH is designed and optimized for better outputs to power the wireless sensor networks, low power and the MEMS devices. The energy generated does not depend on the length of the bilayer and the proof mass. Therefore, the proposed design is the solution which offers the increase in the operational timespan when compared with the conventional batteries. The proposed EH gives a power of 12.5f.1W at frequency of 744 Hz.
- **Pengwei Li, *et al.*** [26] In this paper, the interdigital-shaped cantilever beam structure has been investigated, the calculated frequency responses of the device shows a 460% rise in the bandwidth below 80 Hz. The EH attains maximum voltage of about 65V and maximum output power around 4.5mW at acceleration of 1g.

2.2 Aim of work

Survey concludes that the main focus for generating the power from the vibrational based piezoelectric energy harvester is on device optimization of energy harvester to increase power and bandwidth. It is necessary to increase the amount of power for accurately power the wireless sensor networks and bandwidth for operational time span thus the work is done on increasing the power and bandwidth in energy harvester device.

CHAPTER 3

BACKGROUND OF PIEZOELECTRIC ENERGY HARVESTER

3.1 Piezoelectricity

Piezoelectricity is otherwise called piezoelectric impact, is the capacity to produce power indicated as AC voltage when subjected to mechanical pressure or vibration or to vibrate when subjected to AC voltage. The crystal when experiences a vibration or any type of mechanical stress is converted to feeble AC signal [27]. Piezoelectric coefficients develop an interlinkage between electrical stimulus and mechanical retort or vice versa. It determines the change in volume when the piezoelectric material is applied to an electric field or delivers an indication of the direction of polarization of piezoelectric material [28]. The direction of the positive polarization is made to coincide with the z-axis of a rectangular system of x, y, and z axes (Figure 3.1). Direction x, y, or z is represented by the subscript 1, 2, or 3, respectively, and shear about one of these axes is represented by the subscript 4, 5, or 6, respectively.

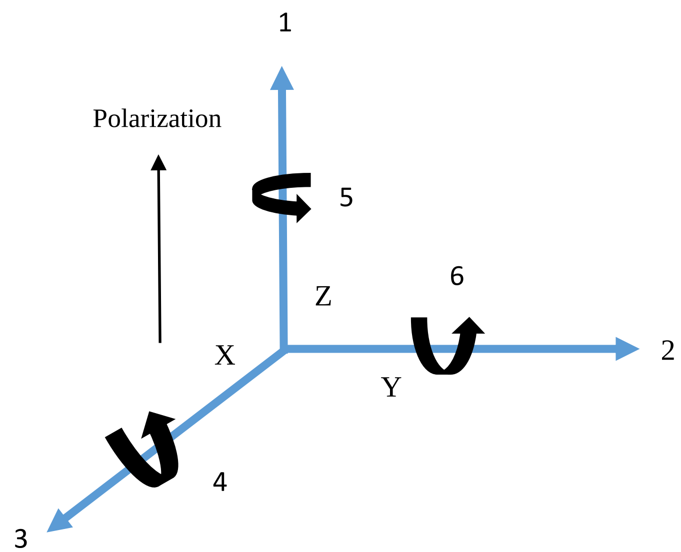


Figure 3.1. Directions of forces affecting a piezoelectric element

The piezoelectric charge constant *d*, is the polarization developed per unit of mechanical stress (T) applied to a piezoelectric material or, alternatively, is the mechanical strain (S) experienced by a piezoelectric material per unit of the electric field applied.

$$d = \frac{\text{Strain Developed}}{\text{Applied electric field}} \tag{3.1}$$

The first subscript to d indicates the direction of polarization generated in the material when the electric field, E, is zero or, alternatively, is the direction of the applied field strength. The second subscript is the direction of the applied stress or the induced strain, respectively. Because the strain induced in a piezoelectric material by an applied electric field is the product of the value for the electric field and the value for d, d is an important indicator of a material's suitability for strain-dependent (actuator) applications

Various piezoelectric charge coefficient is illustrated in Table 3.1.

Table 3.1 Piezoelectric charge coefficient

d constant	Description
d_{33}	Induced polarization along z-axis per unit stress applied along the z-axis Or Induced strain in the direction of z-axis per unit electric field applied in the direction of the z-axis
d_{31}	Induced polarization along z-axis per unit stress applied along the x-axis Or Induced strain in the direction of x-axis per unit electric field applied in the direction of the z-axis
d_{15}	Induced polarization along x-axis per unit shear stress applied along the y-axis Or Induced shear strain in the direction of y-axis per unit electric field applied in the direction of the x-axis

Figure 3.2 illustrating the d modes which can be used to model cantilever beam is as shown

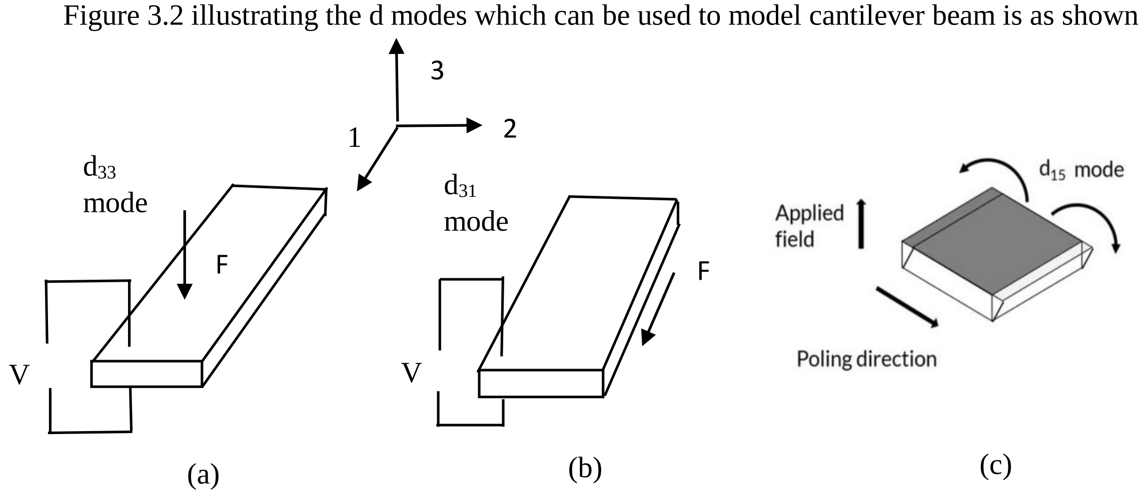


Figure 3.2 Mode d_{33}, d_{31} and d_{15}

Equations that governs the piezoelectric phenomena are as follows:

$$S_i = s_{ij}^{E} T_j + d_{li} E_l \tag{3.2}$$

$$D_m = \varepsilon_{mn}^{T} E_n + d_{mk} T_k \tag{3.3}$$

For i, j, k = 1, 2, 3, 4, 5, 6 and l, m, n = 1, 2, 3 (3.4)

Where T is applied mechanical stress, E is applied an electric field, d is a piezoelectric strain, D is electric displacement, S is a mechanical strain, ε_{mn}^{T} is permittivity under constant stress, S is a mechanical strain, s_{ij}^{E} is compliance tensor under the constant electric field.

To study the accuracy of cantilever beam Euler Bernoulli model has been adopted. No assumption has been taken into account that the piezo-plate twists on its neutral axis. In this way, higher order beam hypothesis i.e Euler Bernoulli's conventions are utilized for analysis. Therefore, higher order beam theory i.e Euler Bernoulli's conventions are used for analysis [27] [29].

3.2 Energy Harvesters

Energy harvesters are the energy storing device from unused or wasted energy resources. Generally, there are three mechanisms can be used for energy harvesting from the vibration, for example, electrostatic, electromagnetic and piezoelectric techniques. Piezoelectric materials are the best appropriate ones for harvesting energy from encompassing vibration sources, in light of the fact that they can perform transformation of mechanical strain to an electric charge with no external power and have the least complex structure [30], [31]. Piezoelectric sensors are also known as piezoelectric resonators. It has the potential to compensate the energy deficit as well as to produce feasible power sources from our environment. Energy harvesting plays a promising role as it facilitates alternative scope to the scarcity of fossil fuel. Nowadays, smart grids acquire a great influence in energy sectors and for the enhancement of energy efficiency in the smart grid harvesters has its major contribution. Piezoelectric collector converts direct energy from vibrations and mechanical disfigurements to helpful electrical energy. The phenomenon behind this energy conversion is the direct piezoelectric phenomena and as a result, piezoelectric detection technique is used. In this technique energy generated by external forces and mechanical vibrations [28] [32]. Energy harvesters can both work as a sensor and also in energy storage too. Quality of a piezoelectric material can be determined from the figures of merit (FOM) of a material. Great piezoelectric materials indicate high piezoelectric charge cofficient (d), voltage steady (g), electromechanical coupling factor (k), and mechanical quality factor (Qm), which are the FOM of the piezoelectric material necessary for energy harvesting.

Various parameters are described as follows :

1. **Piezoelectric strain (unit : pm/V) and charge (unit : pC/N) constant**

$$x = dE \text{ (d = piezoelectric strain and charge constant)} \tag{3.4}$$

where x and E are a strain and external electric field.

2. **Piezoelectric voltage constant (unit : Vm/N)**

$$E = gX\left(g = \frac{\varepsilon_0}{\varepsilon_r}\right) \tag{3.5}$$

Where ε_0 and ε_r are dielectric constant in a vacuum and relative dielectric constant

3. **Electromechanical coupling factor**

$$K^2 = \frac{Stored\ mechanical\ energy}{Input\ electrical\ energy} \tag{3.6}$$

or

$$K^2 = \frac{Stored\ electrical\ energy}{Input\ mechanical\ energy} \tag{3.7}$$

Since the input electrical energy is $\frac{1}{2}\varepsilon_0\varepsilon_r E^2$ per unit volume and stored by mechanical energy per unit volume under zero external stress is given

$$\frac{\frac{1}{2}x^2}{s} = \frac{\frac{1}{2}(dE)^2}{s} \tag{3.8}$$

where s is the stress and k^2 can be calculated as

$$K^2 = \frac{d^2}{\varepsilon_0\varepsilon_r} \tag{3.9}$$

4. **Mechanical quality factor**

$$Q_m = \frac{\omega_0}{2\Delta\omega_0} \tag{3.10}$$

Where ω_0 is the resonance frequency

The energy flow in an energy harvester system is shown in Figure 3.3. In this there is three phases of energy transfer in a system. In first phase there is mechanical energy transfer in which energy is absorbed from the environment and fed to mechanical vibrational device. In the second phase there is mechanical-electrical energy transduction which means energy is converting from one from to the other (mechanical to electrical). Third phase is electrical energy transfer which is fed to the load. Moreover, there is various losses in between the transfer of energy like mechanical loss, mechanical electrical transduction loss and electrical loss.

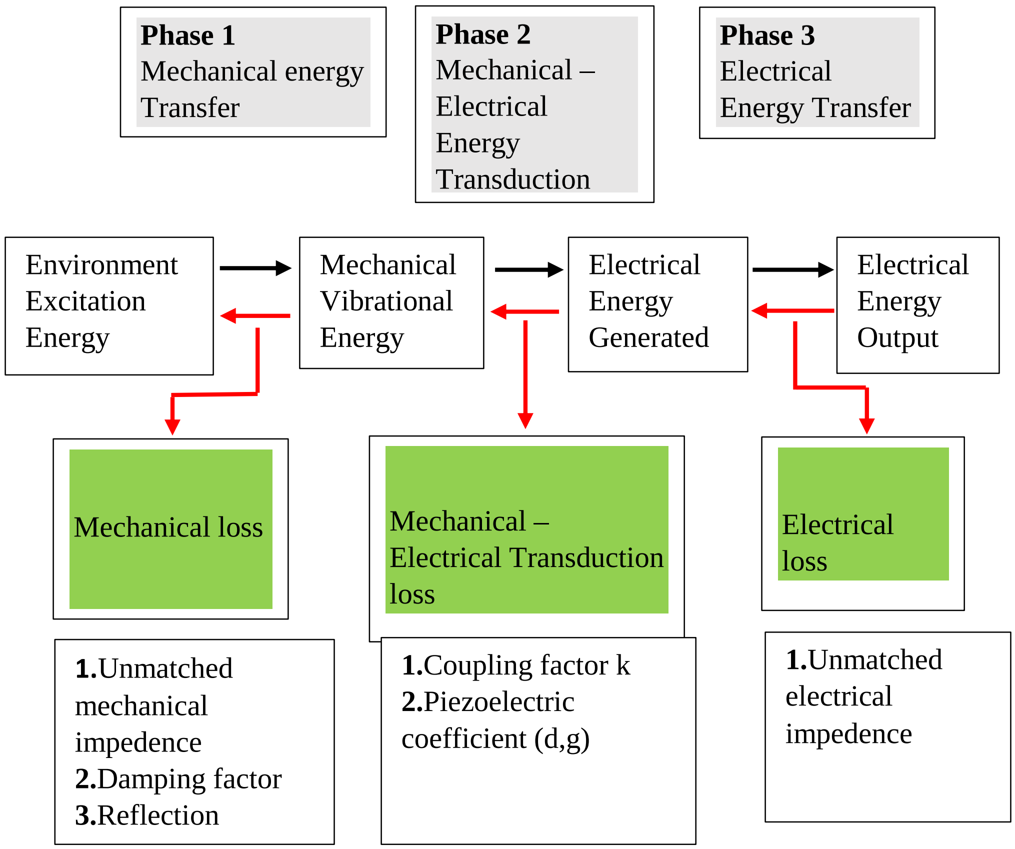


Figure 3.3 Energy flow diagram of an energy harvester

3.3 The Building Blocks of an Energy Harvesting System

The procedure of energy harvesting takes diverse structures based on the source, amount, and kind of energy being changed over to electrical energy. In its simplest form, the energy collector system requires a wellspring of energy, for example, heat, light, or vibration, and the accompanying three key parts.

As shown in Figure 3.4,

Transducer/harvester: Typical transducers incorporate photovoltaic for light, thermoelectric for heat, inductive for magnetic, RF for radio recurrence, and piezoelectric for vibrations/kinetic energy.

Power conversion circuit: converts AC to DC, voltage regulation, the voltage step up

Energy storage: Like battery or supercapacitor.

Power management: This condition the electrical energy into an appropriate form for its application. Typical conditioners incorporate regulators and complex control circuits that can deal with the power management, based on energy demand and the accessible power.

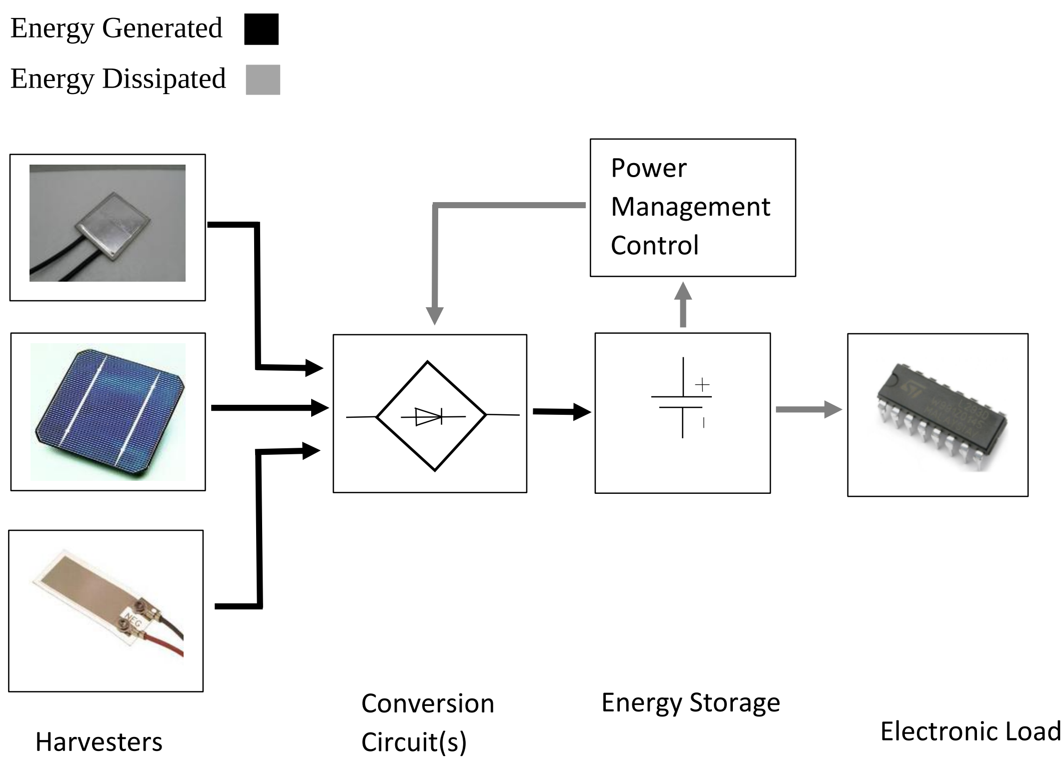


Figure 3.4 Basic Components of Energy Harvesting

3.4 MEMS resonators

Piezoelectric sensors are also known as piezoelectric resonators. It has the potent to compensate the energy deficit as well as to produce feasible power sources from our environment.

3.4.1 Microcantilever Beam Resonator

Microcantilever is a MEMS-based device which can also function as a physical, chemical, or biological sensors as well as energy harvesters by sensing the variation in the bending of the cantilever or vibrational frequency. The cantilever is a long mechanical projecting beam which one edge is fixed and the other edge is free to move. These cantilevers achieve high sensitivity in various sensing applications. A pressure sensor, a chemical sensor, and mass sensor are some few examples uses static as well as dynamic mode so as to measure variation or change in physical environment.

3.4.2 Modes of operation

Working of microcantilever sensor are based on two commonly used approaches i.e dynamic mode or static mode. The shift in the resonance frequency is the prime concern when the sensor is operating in dynamic mode. This change in resonance frequency forwarded the scope for measurement of the mass absorbed on the surface of the mass sensor which is purely based on the microcantilever. Normally cantilever is excited near to its resonance frequency.

Deviation in resonance frequency occurs when additional mass is bonded to the surface of the cantilever. As the adsorbed mass increases the frequency of the cantilever also get lowered. Equation 3.11 depicts the relation between frequency change and the adsorbed mass Δm [33, 34].

$$\Delta F_{res} \approx -f_0 \frac{\Delta m}{2m_0} \tag{3.11}$$

where f_0 is natural frequency and m_0 is an initial mass of the cantilever

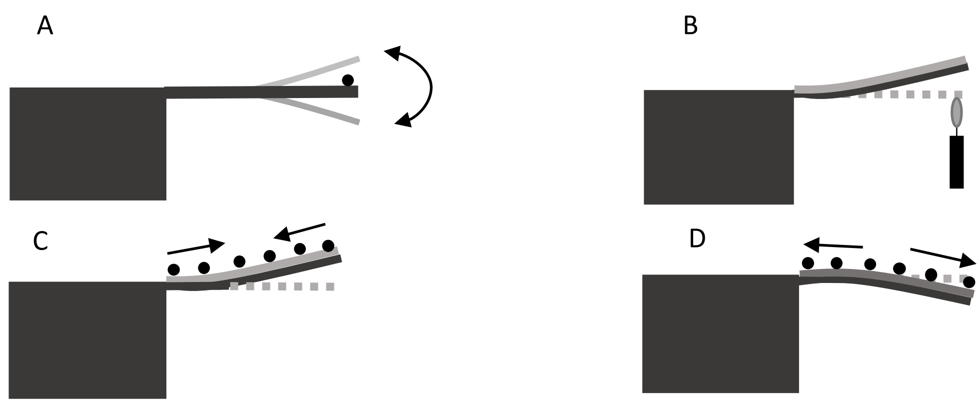


Figure 3.5 Cantilever sensor modes of operation

Methods of operation for cantilever sensors as shown in Figure 3.5 :

(A) Dynamic mode distinguishing mass changes on the cantilever by changes in resonance frequency
(B) Bimetallic mode distinguishing temperature changes by a static bending because of various thermal expansion of the metal layer and silicon cantilever
(C) Static mode is where asymmetrical molecule retention cause elastic pressure, brings about bowing the cantilever upwards
(D) Static mode where asymmetrical molecule absorption cause compressive stress, results in bending the cantilever downwards

In static mode, by observing the bending moment of the cantilever the variation in the external measurands can be sensed. Surface stress, pressure or temperature can be the main cause behind the deflection of the cantilever. In most of the biosensors, sensing is conducted with the involvement of static mode, dynamic mode is not considered as an efficient approach as because of some demerits observed when the biosensor is operated in a fluid environment. Quality factor gets drastically reduced due to the viscous damping of the fluid [35]. Bending moment of the cantilever is entirely dependent on the type of stress applied. Tensile stress causes upward movement and the downward movement due to compressive stress. Equation 3.12 shows Stoney's formula governs the relationship between the beam deflection, surface stresses, and beam dimensions.

$$\Delta\sigma = \frac{Et^2}{3\,(\,1 - v\,)L^2}\;\Delta z \tag{3.12}$$

Where equal change in surface stress amongst top and base surface of the cantilever, z is the cantilever deflection, E is Young's modulus, is Poisson proportion, L is the length of the beam and t is the thickness separately.

3.4.3 Commonly used excitation principles and detection principles

The resonant sensor consists of the mechanical resonant part as well as the excitation source for which is responsible for the vibration of the mechanical part. Basic components of this sensors are shown in below Figure 3.6. In order to achieve the desired output from the sensor a feedback control circuitry is connected back to the excitation source to ensure the resonator maintains the desired resonance mode in spite of deviation or shift in resonant frequency. Change in the measurand is always responsible for the frequency shift [12]

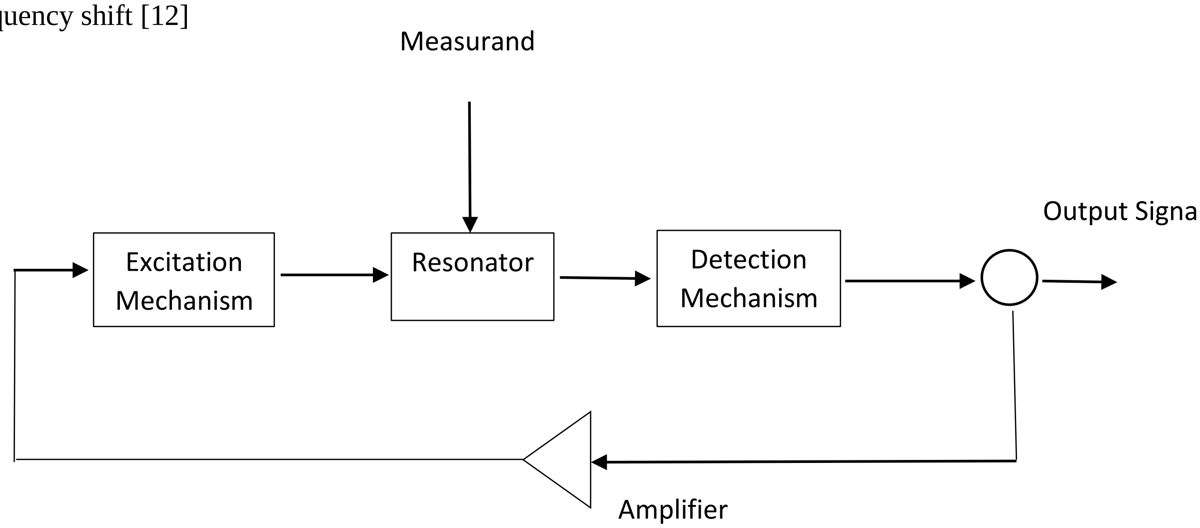


Figure 3.6 Block diagram of a resonant sensor

The six most commonly used excitation techniques and also their respective excitation method are as follows:

i) Electrostatic excitation and capacitive detection
ii) Resistive heating excitation and piezoresistive excitation
iii) Dielectric excitation and capacitive detection
iv) Piezoelectric excitation and detection
v) Magnetic excitation and detection
vi) Optical heating and detection

As the work in this thesis is based on the piezoelectric excitation principle so detail explanation is given in the methodology part

Piezoelectric excitation :

PZT materials, AIN or ZnO have excellent piezoelectric properties and have its wide application in the phenomenon of piezoelectricity. These materials are used in the excitation and detection of beam vibrations. Piezoelectric materials consist of two unique properties which contradict among them. Properties are

a) direct PIE,
b) inverse PIE effect.

The inverse piezoelectric property has its application in the excitation technique where a piezoelectric material experiences an electric potential undergoes a deformation in the lattice structure of the crystal as a result excitation of resonators occurs. Fabrication of the beam is done in such a way that the top surface of it is embedded with a pair of electrodes on which the AC voltage is applied. And in the detection principle, direct piezoelectricity is used. Vibrations in the beam cause physical alternation of the piezoelectric layer consequences generation of electricity. By measuring the intensity of the electric field, the magnitude of vibration is measured [13].

3.5 Piezoelectric materials

There are three basic category of piezoelectric materials used in micro fabrication:

- natural piezoelectric substrates, such as quartz single crystals
- piezoelectric ceramics, such as lithium niobate, gallium arsenide, zinc oxide (ZnO), aluminum nitride (AIN) and lead-zirconate-titanate (PZT).

- polymer-film piezoelectrics, such as polyvinylidene fluoride (PVDF).

Table 3.2 Various Piezoelectric Materials

Materials	**ZnO**	**AIN**	**PZT**	**PVDF**
Density (10^3 kg/m^3)	5.61-5.72	3.25-3.3	7.57	1.78
Modulus (GPa)	110-140	300-350	61	2.5
Poisson's ratio	0.36	0.22-0.29	0.27-0.3	0.33-0.4
Refractive index	1.9-2.0	1.96	2.40	1.42
Piezo-constant d33 (pC/N)	12	4.5, 6.4	289-380, 117	-35
Dielectric Constant	8.66	8.5-10	380	6-8
Effective coupling coefficient, k^2 (%)	1.5-1.7	3.1-8	20-35	2.9

Table 3.2 shows the various property values of piezoelectric materials. In research work, Aluminium nitride (AIN) is used over other piezoelectric materials which are PZT, ZnO, PVDF. In spite of having low piezoelectric coefficient and dielectric constant, AIN was chosen because of its advantages in material deposition and in compatibility with the standard CMOS processes used for fabrication of integrated circuits [7]. This makes the possibility of an integrated "power chip" realizable. AIN compatibility is high with Si semiconductor technology and this material has high resistivity. Moreover, AIN is biocompatible. The quality of AIN can be determined by dielectric constant and piezoelectric properties, which influence the material ability to convert the mechanical strain in electrical power.

3.6 Modelling of Piezoelectric device

The most convenient way of modeling the piezoelectric elements is by modeling both the mechanical and electrical parts of the piezoelectric system as the basic circuit elements. The transformer is for the electromechanical coupling [15]. In Figure 3.7, Inductor and capacitor plays a kind of role in the exchange of electrical, potential and kinetic energy, bounce back and forth energy and the currents in the device. Resistor governs the losses. Resistor, capacitor, and inductor together form the mechanical part of the device. L_m represents the mass of inertia, R_p represents the mechanical damping and C_p represents mechanical stiffness, AC source is stress generator, V is the voltage across the device.

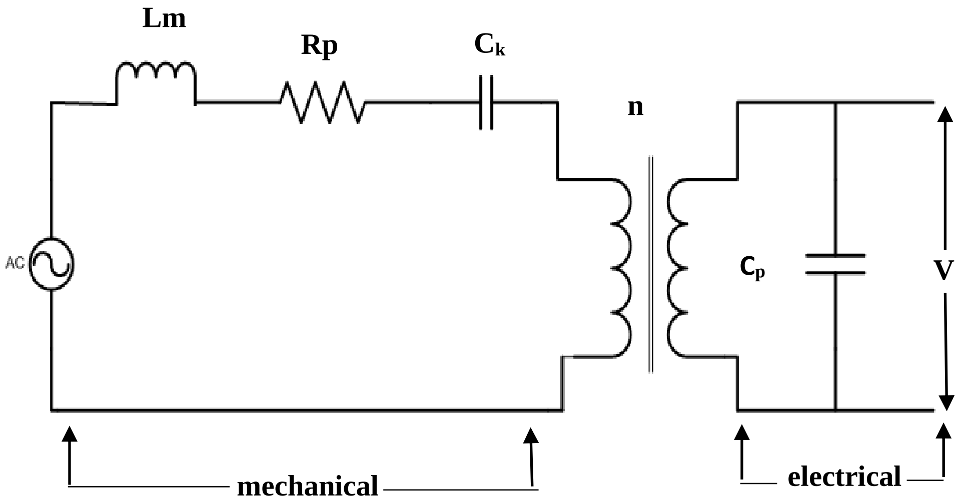


Figure 3.7 Circuit representation of piezoelectric energy harvester generator

A load (resistor) is required to measure the amount of power which is been delivered to the load (device) as shown in Figure 3.8.

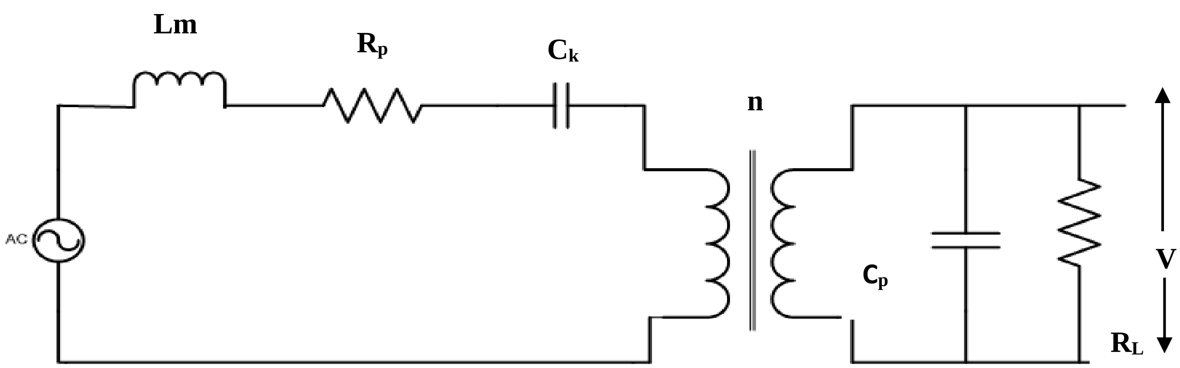


Figure 3.8 Circuit representation of piezoelectric energy harvester generator with resistive load

Resistive load is necessary so as to measure the power which is generated by the EH device.

3.6.1 Modeling of the static deflection of the cantilever

The following derivation for calculating the deflection in terms of applied voltage was done based on the model that was developed using energy density to calculate the deflection of piezoelectric cantilever bimorph [36].

The curvature of the beam can be expressed as

$$\delta" = \frac{3\, d_{31} V}{2 t_p} \tag{3.13}$$

where d_{31} is the piezoelectric strain coupling coefficient, V is the voltage, and t_p is the thickness of the piezoelectric layer.

Integrating once more with respect to (L) yields the deflection of the beam at its end as

$$\delta" = \frac{3\, d_{31} V L^2}{4 t_p} \tag{3.14}$$

The curvature of the bender can now be written as

$$\delta = \frac{2\delta_t}{L^2} = \frac{M}{EI} \tag{3.15}$$

3.6.2 Estimation of the resonant frequency

The equation of the resonance frequency f_o for the cantilever beam based on Euler-Bernoulli beam theory is [37]

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{3.16}$$

The stiffness coefficient k is

$$k = \frac{8EI}{l_2} \tag{3.17}$$

where m is mass, E is a moment of inertia and I is an area of moment of inertia of cantilever and the piezoelectric layer.

or resonance frequency f_0 is also given by

$$f_0 = \frac{1}{2\pi}\frac{t}{L^2}\sqrt{\frac{Y}{\rho}} \tag{3.18}$$

Where Y is Young's modulus, t is thickness and L is the length of the cantilever beam and ρ is the mass density.

3.6.3 Output Power

The energy harvester is integrated across an electrical circuit with the resistive load. The power can be calculated across the load resistor as [37]

$$P = V_{rect} \left(\frac{2\alpha}{\frac{\pi}{2} + RC_p\omega_r} + \frac{\frac{\pi}{2} + RC_p\omega_r}{\alpha R} \right) \tag{3.19}$$

Where C_p is the piezoelectric output capacitance, V_{rect} is the rectified voltage, ω_r is the resonance angular frequency, R is the resistance, α tells the electrical and mechanical coupling properties of the piezoelectric material.

which results in

$$P = \frac{V^2}{R} = \frac{\left(\frac{0.5V}{\sqrt{2}}\right)^2}{R} \tag{3.20}$$

Where V is the root mean square voltage at the load resistor.

In this chapter we have seen the various piezoelectric materials, figure of merits which describes the quality of material, modes of operation of cantilever beam, modeling of piezoelectric device, resonant frequency and output power formula. It concludes that for optimizing the piezoelectric layer the main things to remember are when the piezo plate width increase which results in high resonance frequency, as width increases result in an increase in frequency, whereas when the length of piezo plate increases results in a decrease in resonance frequency as length is inversely proportional to the resonance frequency. When width or height of mass is increased it results in a decrease in frequency.

CHAPTER 4

DESIGN METHODOLOGY

4.1 Overview

The methodology includes the modeling and simulation of bimorph piezoelectric based MEMS/NEMS cantilever in which maximization of electrical output will be taken care of and moreover it can be operated under low ambient frequency. Also, development of prototype has been further considered in this work.

4.2 Simulation procedure

4.2.1 Modelling and Simulation of the unimorph MEMS cantilever

The proposed bimorph cantilever beam is designed using COMSOL Multiphysics 5.2a software as shown in Figure 4.1. Steps involved in the flowchart will be well explained throughout the modeling and simulation steps in the upcoming sections.

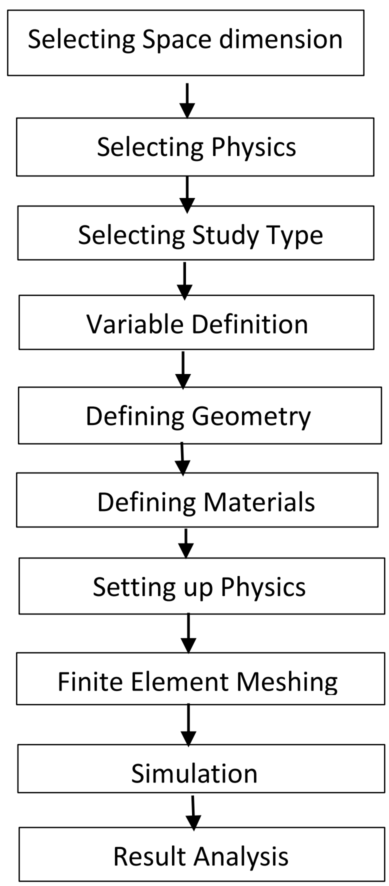


Figure 4.1 Flow chart of developing Piezo unimorph MEMS cantilever in COMSOL

Modeling of vibration based piezoelectric energy harvester is performed using COMSOL 5.2a, MEMS MODULE is used to simulate the model for the values of resonant frequency and output power. The cantilever structure used in this thesis work cover a wide beam EH and narrow rectangular beam EH.

Selecting Physics and study type

Finite element modeling of our MEMS/NEMS energy harvester was conducted in COMSOL 5.2a using structural mechanics module associated with piezoelectric devices application mode which has been selected from PHYSICS tree and electrical circuits (cir) from AC/DC from PHYSICS tree. Also selecting Frequency Domain from STUDIES

Geometric Modelling and Material defining

Three dimensional (3-D) microcantilever is successfully built using COMSOL Multiphysics 5.2a drawing tools. All layers used in the formation of piezoelectric energy harvester design had a thickness of 0.1 μm for Pt, 0.5 μm for AIN and 1 μm for Al respectively. Proof mass is made up of silicon. The wide beam had an overall area which is 8.4 × 7mm whereas the narrow beam structure had 7.5 × 0.5mm.

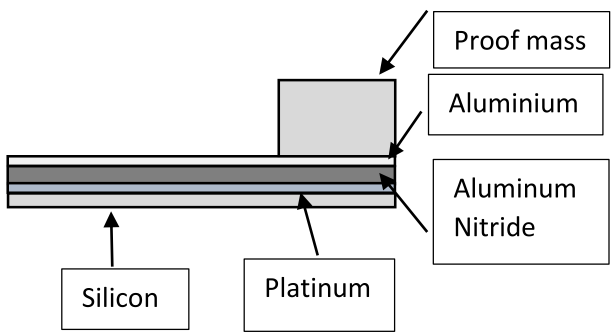
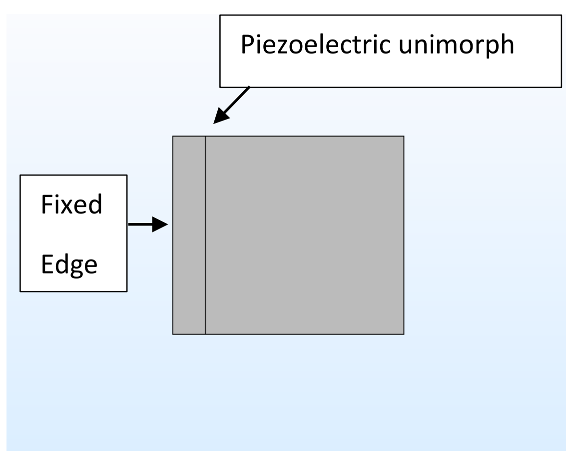
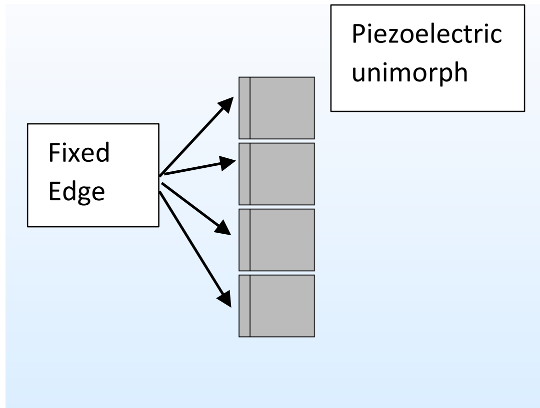


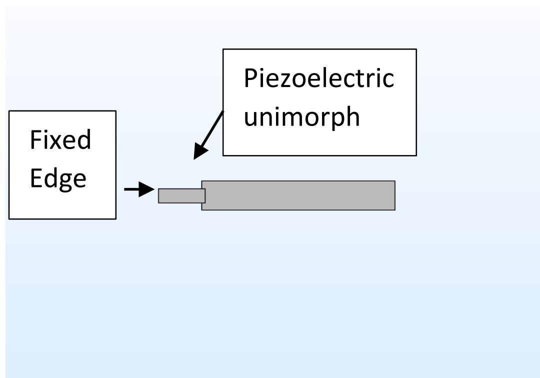
Figure 4.2 Structure of piezoelectric layer of the cantilever beam



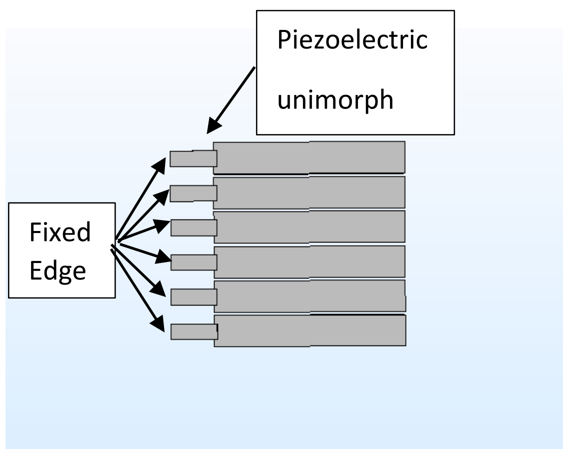
(a) Schematic of the wide single cantilever beam



(b) Schematic of the wide array cantilever beam



(c) Schematic of the single narrow cantilever beam



(d) Schematic of narrow array cantilever beam

Figure.4.3 (a), (b), (c), (d) Schematic of wide and narrow cantilever beam structure

Table 4.1. Material used in simulation and Parameters

Silicon parameters (Si)

Name	Value	Unit
Density	2329[kg/m^3]	kg/m^3
Young's modulus	170e9[Pa]	Pa
Poisson's ratio	0.28	1

Platinum parameters (Pt)

Name	Value	Unit
Density	21450[kg/m^3]	kg/m^3
Young's modulus	168e9[Pa]	Pa
Poisson's ratio	0.38	1

Aluminium parameters (Al)

Name	Value	Unit
Density	2700[kg/m^3]	kg/m^3
Young's modulus	70.0e9[Pa]	Pa
Poisson's ratio	0.35	1

Aluminum Nitride (AIN)

Property	Value	
Density[kg/m^3]	3300	
Coupling matrix (C/m^3) $e_0 = \begin{bmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{bmatrix}$	e_{31}	-0.58
	e_{33}	1.55
	e_{15}	-0.48
Relative permittivity constant matrix (F/m) $\begin{bmatrix} \varepsilon_{11}^T & 0 & 0 \\ 0 & \varepsilon_{11}^T & 0 \\ 0 & 0 & \varepsilon_{33}^T \end{bmatrix}$	ε_{11}^T	$9.20817 \times 8.85 \times 10^{-12}$
	ε_{33}^T	$10.2566 \times 8.85 \times 10^{-12}$

Elasticity matrix (GPa)	c_{11}	410
	c_{12}	149
$c_0 = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{15} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix}$	c_{13}	99
	c_{33}	389
	c_{44}	125
	c_{66}	125
Relative permittivity	9	

Boundary Conditions

It is always very necessary to provide boundary conditions to the profound model so as to obtain the desired results. Boundary conditions provided to this micro cantilever model is one edge is fixed and other edge is free to move as have a proof mass of 1g on it.

Electrostatics

In this the ground and terminal is mentioned for the electrical circuit, in which the bottom plate electrode is made ground (negative) and upper plate electrode is made terminal (positive) and this is later on attached to the resistor.

Electrical Circuit

The electrical circuit is made in the model builder to join two models element, one is piezoelectric device and second is a resistor which will help in calculating power and voltage.

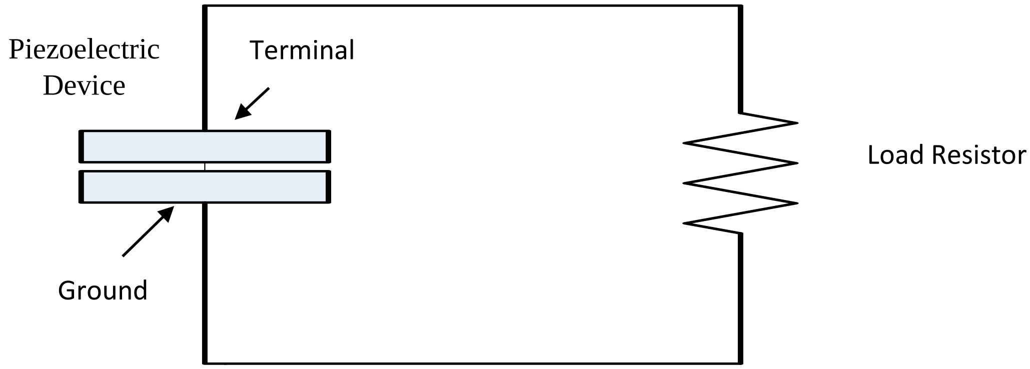
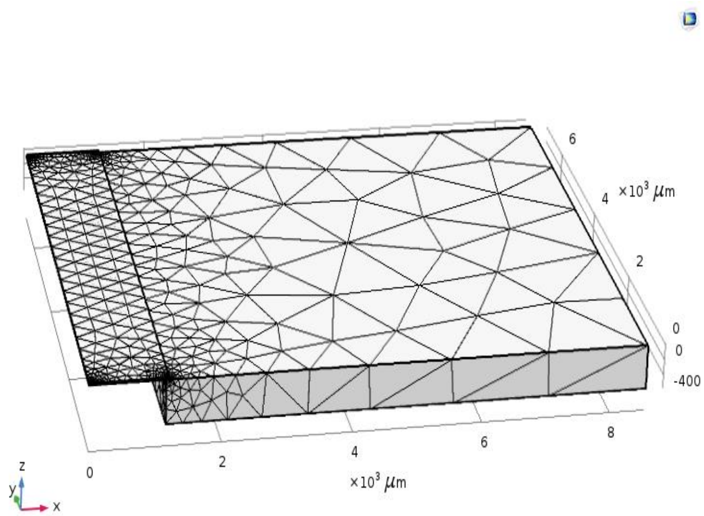


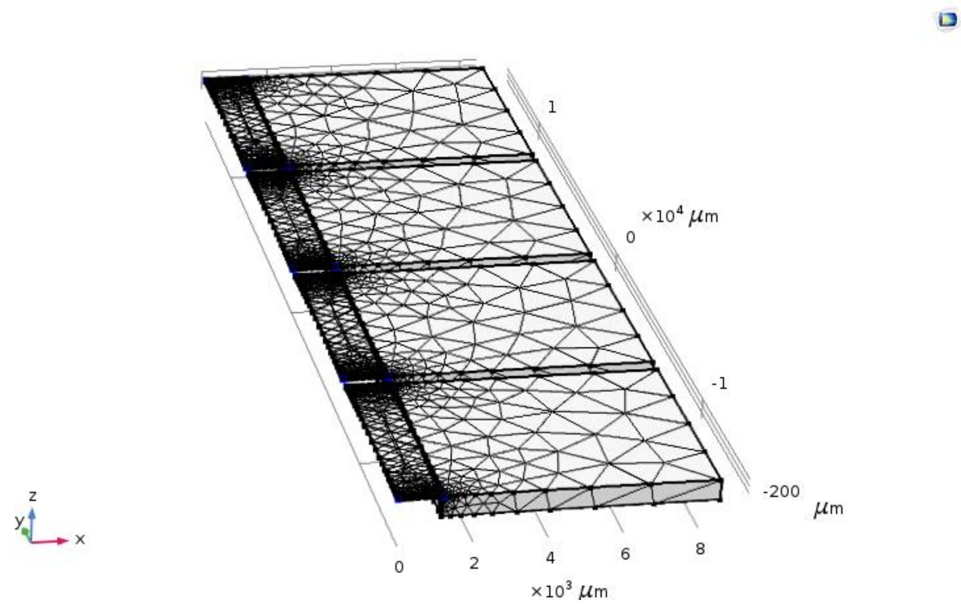
Figure 4.4 Circuit Diagram of the Piezoelectric device in COMSOL

Meshing

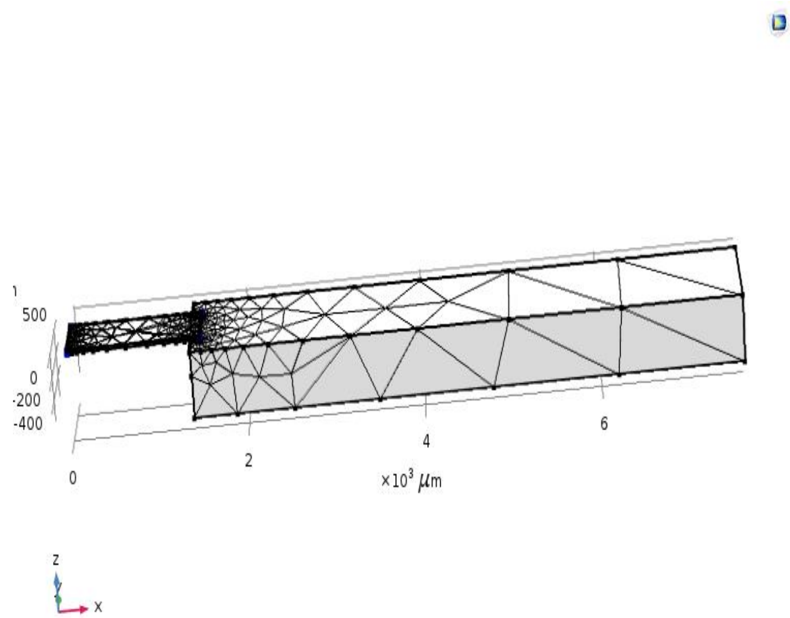
The application of meshing defines the correlation between the 3-D structure and reference structure, involves solving of mesh smoothing equations inside the COMSOL to define the coordinate transformations of the beam. Free tetrahedral meshing is used for meshing the model



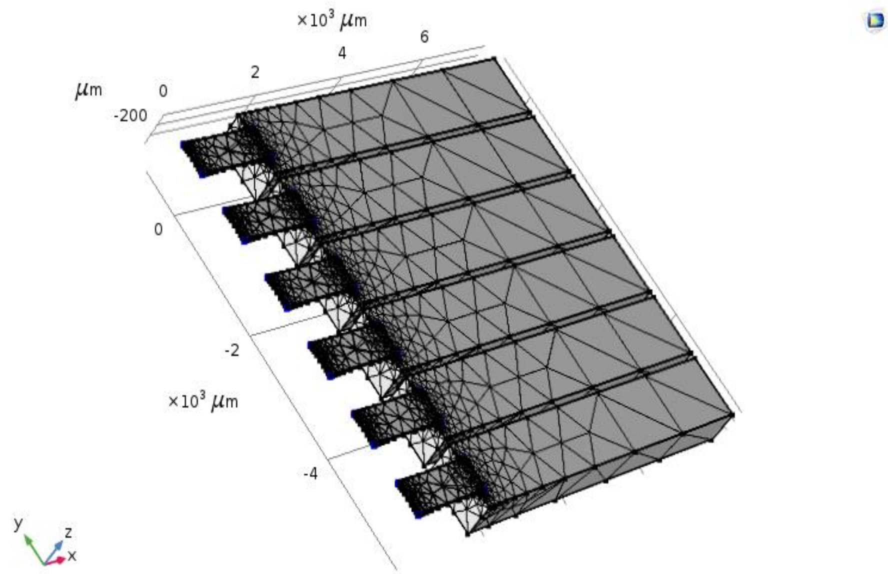
(a) Single wide cantilever beam mesh



(b) Wide cantilever beam mesh (array)



(c) Single narrow cantilever beam mesh



(d) Narrow cantilever beam mesh

Figure 4.5 (a) (b) (c) (d) Mesh model in COMSOL 5.2a

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Approach Work

Eigen frequency:

Eigen frequency is the frequency at which the system vibrate in the absence of any force. It is necessary to know the Eigen frequency as it provides the shape of the operational mode. The actual size of deformation is determined only if the actual excitation is known with the damping properties.

Simple cantilever structure is shown in Figure 5.1 and eigen frequency has been calculated.

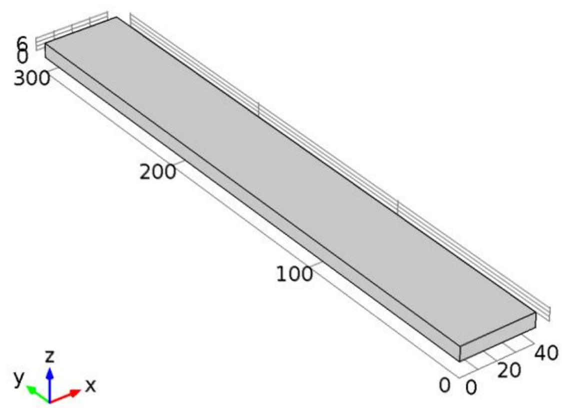


Figure 5.1 Cantilever structure

Table 5.1 illustrates the parameters of the simple cantilever structure which is in μm.

Table 5.1 Parameters of Simple Cantilever Structure

Parameter	Value (μm)
Length	300
Width	40
Height	7

Meshing is done so that it divides into different multiple elements and then calculate as a whole for final result. This is Finite Element Modeling. Free tetrahedral meshing is used for meshing the model Meshing of simple cantilever is shown in Figure 5.2.

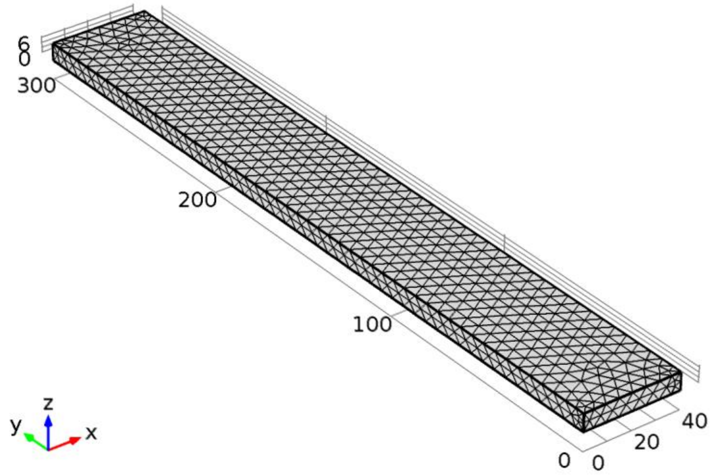
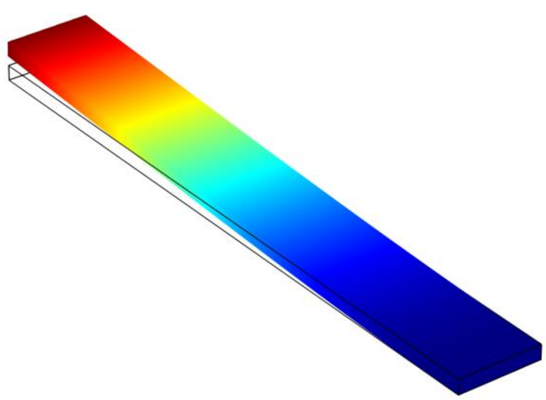
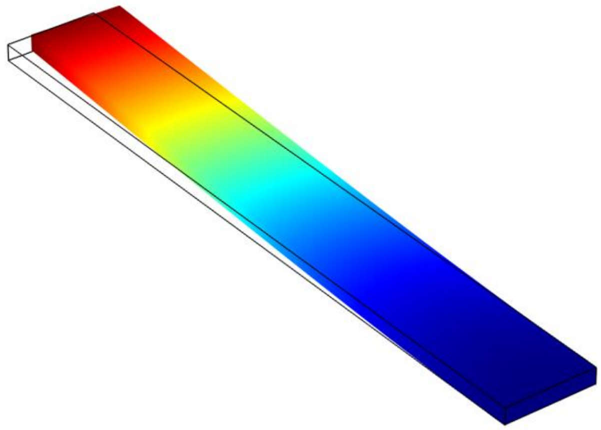


Figure 5.2 Meshing of Cantilever structure

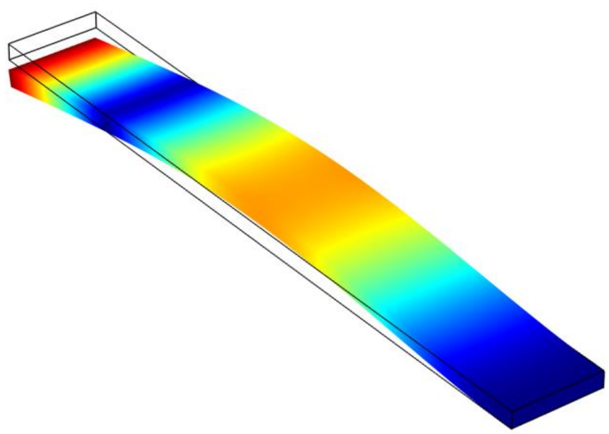
Eigen frequencies obtained are 1.0804E5, 6.0647E5, 6.7529E5, 1.4979E6, 1.885E6, 3.5312E6 as shown in Figure 5.3.



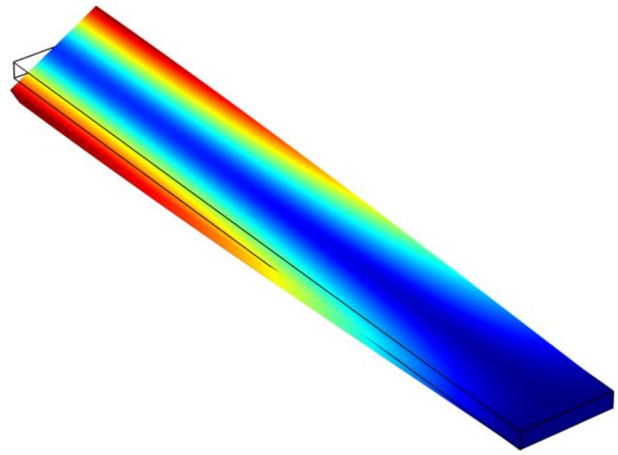
(a) 1.0804E5 Eigen frequency



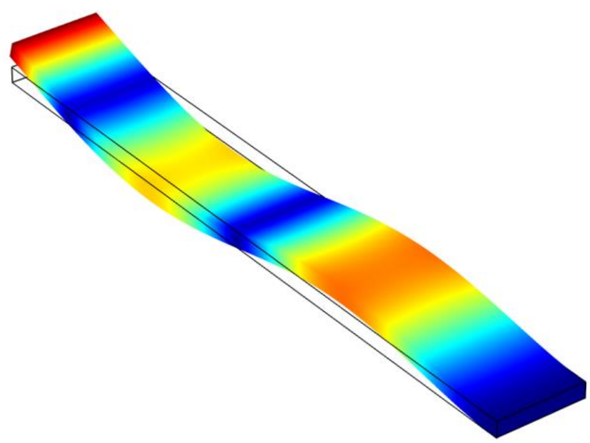
(b) Eigen frequency 6.0647E5



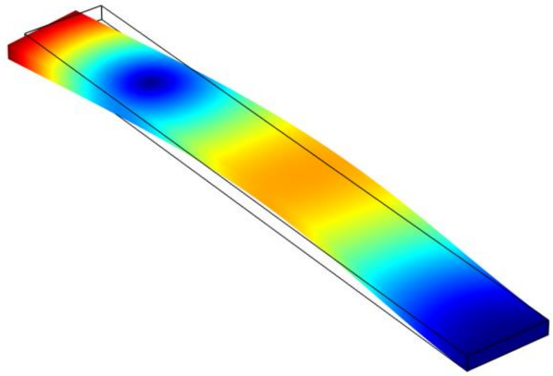
(c) Eigen frequency 6.7529E5



(d)Eigen frequency 1.4979E6



(e) Eigen frequency 1.885E6



(f)Eigen frequency 3.5312E6

Figure 5.3 (a), (b), (c), (d), (e) and (f) Eigen Frequencies

The eigen frequency 1.08×10^5 Hz as in Figure 5.4 is relevant because it is the desired deformation of the cantilever structure and operational mode. Moreover other eigen frequencies deformation is not appropriate for the device modeling.

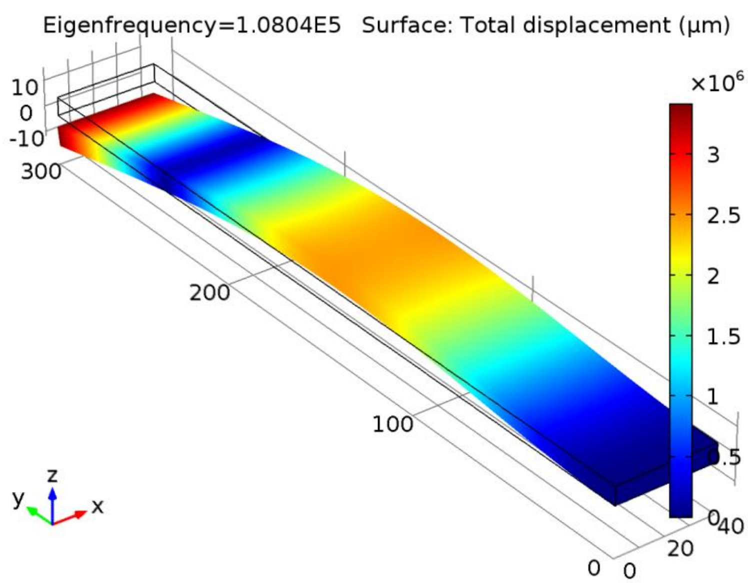


Figure 5.4 Desired Eigen frequency

2D structure

The analysis of simple cantilever structure which is fixed at one edge and free on the other is designed to generate the electrical energy from acceleration. The parameters of the cantilever structure is shown in Table 5.2. Silicon is used for proof mass and piezoelectric material used was Lead Zirconate Titanate (PZT- 5A).

Table 5.2 Parameters of simple cantilever structure

Parameters	**Value**
Acceleration (g)	1
Load resistance	12 Kohm
Width	14mm
Height	0.16mm
Length	21mm
Proof mass dimension	4mm x 1.7mm

The 2D model geometry of the cantilever structure including notable components of the energy harvester supporting element, proof mass and bimorph piezoelectric layer was shown in Figure 5.5.

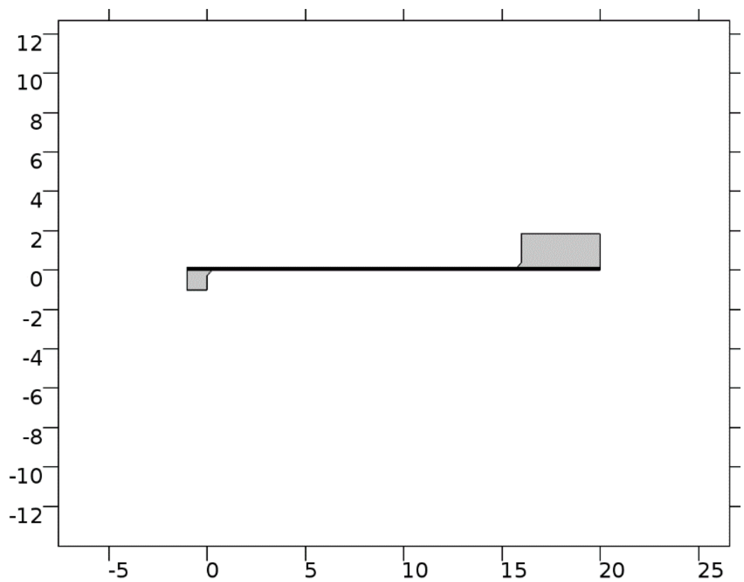


Figure 5.5 2D geometry of bimorph piezoelectric energy harvester

The meshing of the bimorph piezoelectric cantilever structure was shown in Figure 5.6 where free tetrahedral was used for solving the results.

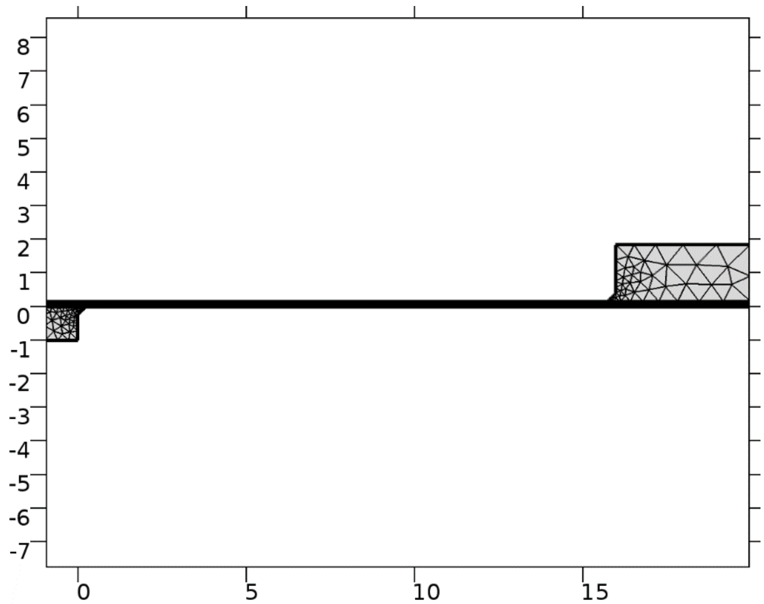


Figure 5.6 Meshing of bimorph piezoelectric energy harvester

The stress formed because of the proof mass and acceleration of 1g is shown in Figure 5.7 where the mode of operation is first mode.

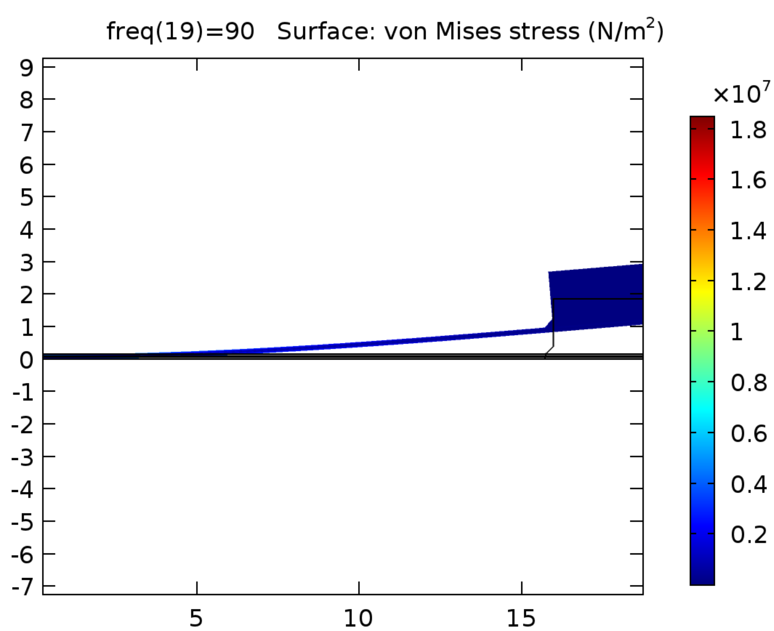


Figure 5.7 Stress generated on bimorph piezoelectric energy harvester

The response of the bimorph piezoelectric EH shows a peak at 76Hz, close to the computed resonant frequency of the cantilever at 73Hz. The electrical power obtained is 1.35mW at 76 Hz is shown in Figure 5.8.

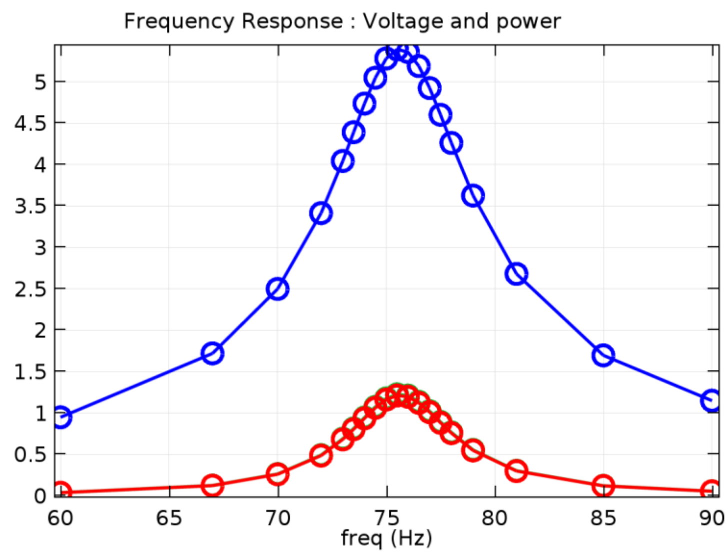


Figure 5.8 Frequency response: voltage and power of bimorph piezoelectric energy harvester

Optimization is done in order to get the desired 100 Hz (target) frequency to learn the optimization of EH. The result obtained is shown in Figure where the peak of voltage is at 100 Hz having 3.6 V and the electrical power peak is at 100 Hz having 0.6mW power shown in Figure 5.9.

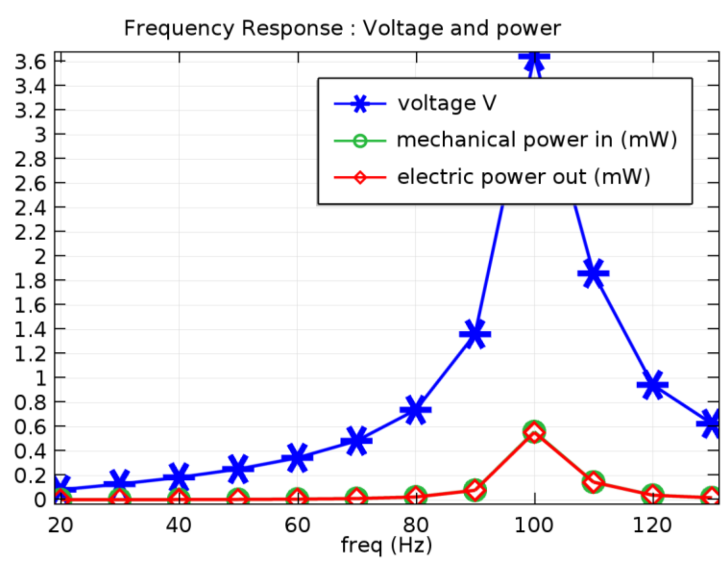


Figure 5.9 Frequency response of energy harvester: voltage and power

Further optimization is done to get the desired frequency which is low frequency operation of design at 50 Hz. Therefor the peak is at 50 Hz with 6.52 V and electrical power of 1.75 mW shown in Figure 5.10.

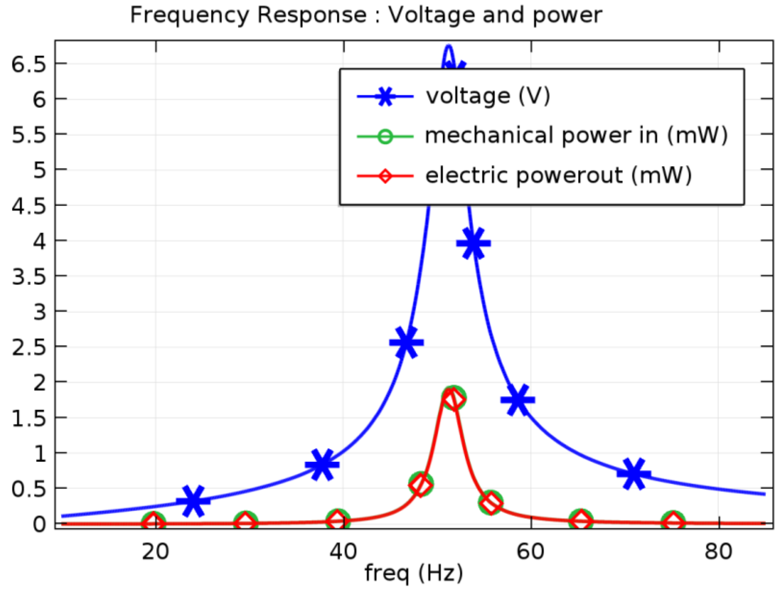


Figure 5.10 Frequency response of energy harvester

From the analysis done by bimorph piezoelectric energy harvester concludes that for optimizing the piezoelectric energy harvester the main things to remember are when the piezo layer width increase which results in high resonance frequency, as width increases result in an increase in frequency, whereas when the length of piezo layer increases results in a decrease in resonance frequency as length is inversely proportional to the resonance frequency. When width or height of mass is increased it results in a decrease in frequency.

Bimorph energy harvester are commonly used where two layers of piezoelectric material are attached together. When there is deformation in structure in the upward direction the surface layers where electrodes are exits gets stretched and compressed, vice versa is seen in downward direction.

Parallel connection of Piezoelectric layer

When the layers are poled in the same direction, it is the parallel connection of piezoelectric layer. The geometry of the simple cantilever in parallel connection is shown in Figure 5.11 fixed at one end and proof mass on the other end. PZT-5A was used as piezoelectric layer and silicon as proof mass material. The parameters of the bimorph piezoelectric EH is shown in Table 5.3

Table 5.3 Parameters of the simple energy harvester of parallel connection of piezoelectric layers

Parameter	Value
Width	15mm
Depth	1mm
Height	0.3mm
Acceleration	1g
Resistance	1200 ohm

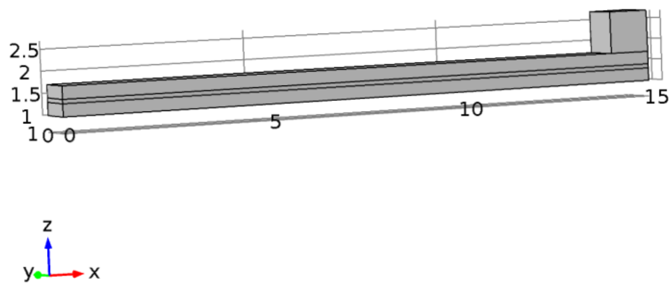


Figure 5.11 Geometry of simple energy harvester of parallel connection of piezoelectric layers

The stress generated on the cantilever structure is shown in Figure 5.12.

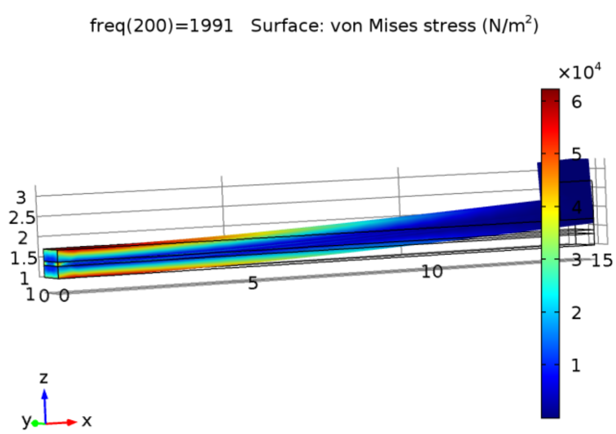


Figure 5.12 Stress generated on simple energy harvester of parallel connection of piezoelectric layers

The peak is at 1425 Hz having 0.68V and power 0.02mW as shown in Figure 5.13

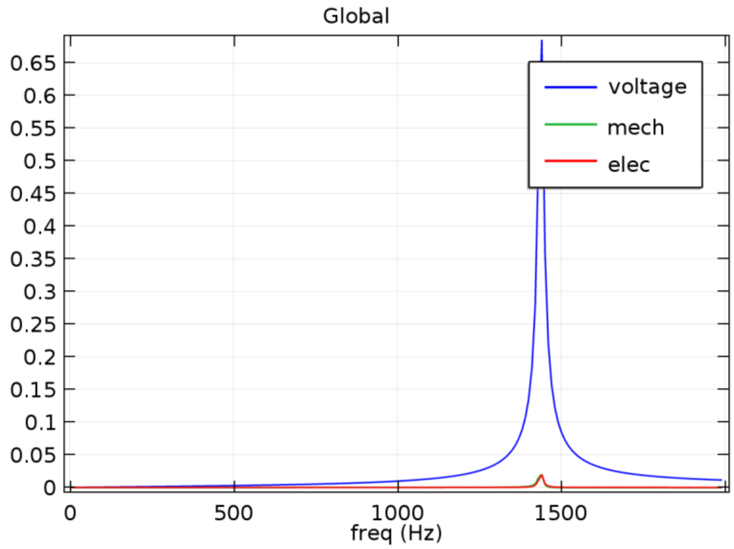


Figure 5.13 Frequency response of energy harvester having two piezoelectric layer in parallel connection

Series

When the layers are poled in the opposite direction, it is the series connection of piezoelectric layer. The geometry of the simple cantilever in series connection is shown in Figure 5.14 fixed at one edge and proof mass on the other edge. PZT-5A was used as piezoelectric layer, silicon as proof mass material and structural steel as middle layer. The parameters of the bimorph piezoelectric EH is shown in Table 5.3.

Table 5.4 Parameters of the simple energy harvester of series connection of piezoelectric layers

Parameter	**Value**
Width	15mm
Depth	1mm
Height	0.1mm
Acceleration	1g
Resistance	1200 ohm

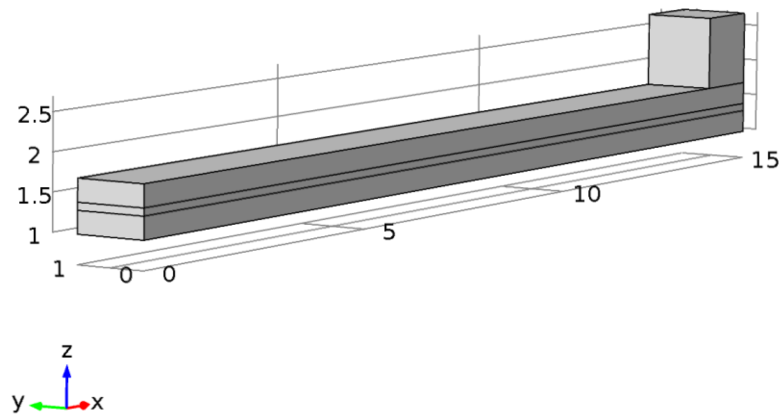


Figure 5.14 Geometry of simple energy harvester of series connection of piezoelectric layers

The stress generated on the simple EH of series connection of piezoelectric layers is shown in Figure 5.15

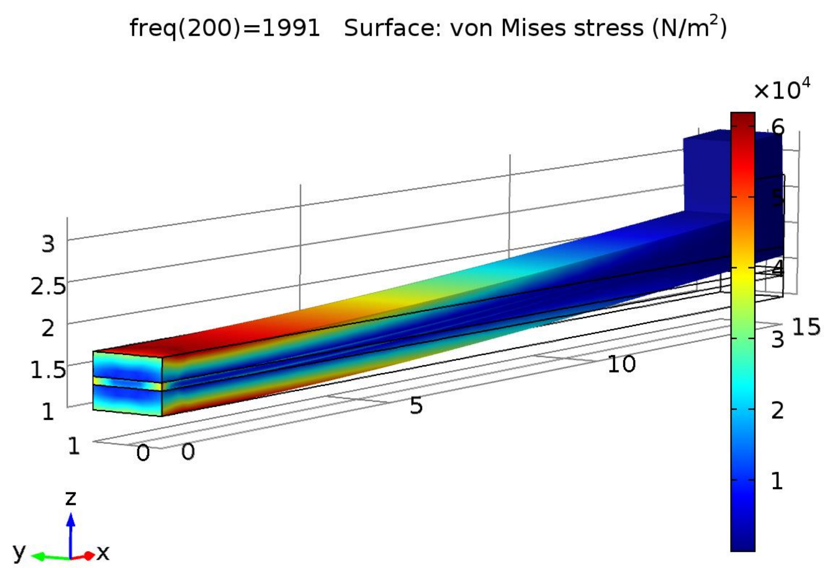


Figure 5.15 Stress generated on simple energy harvester of series connection of piezoelectric layers

The peak is at 1425 Hz having 0.125mV and electrical power $6.2 \times 10^{-4}\ nW$ as shown in Figure 5.16

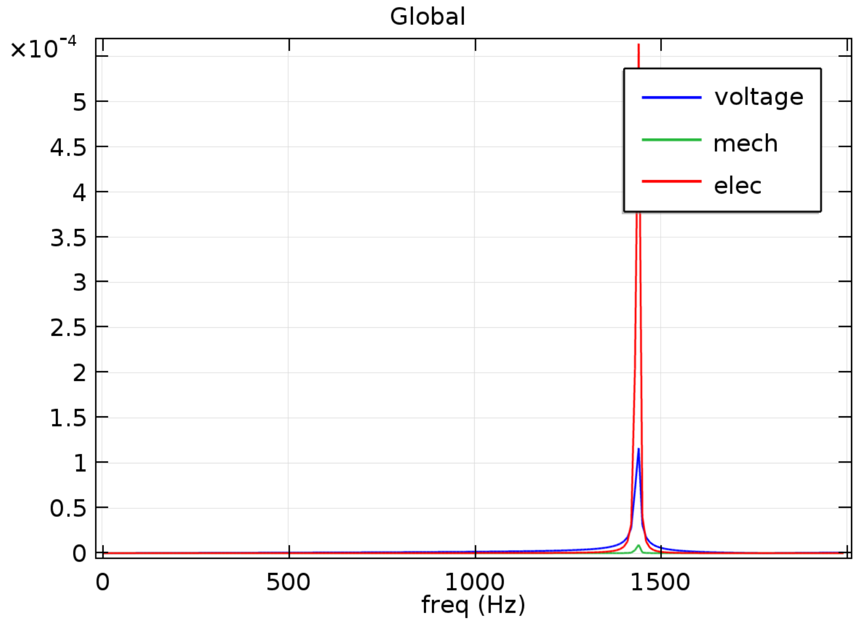


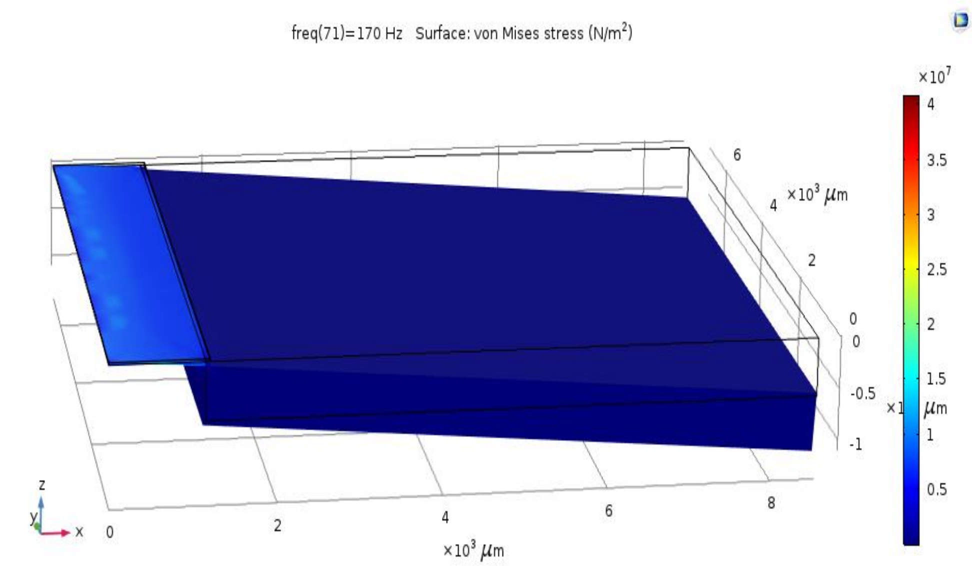
Figure 5.16 Frequency response of energy harvester having two piezoelectric layer in series connection

From series and parallel connection concludes that, in parallel the current and the capacitance gets doubled but voltage remains the same, whereas in series connection the voltage gets doubled, the capacitance gets half but current remains the same.

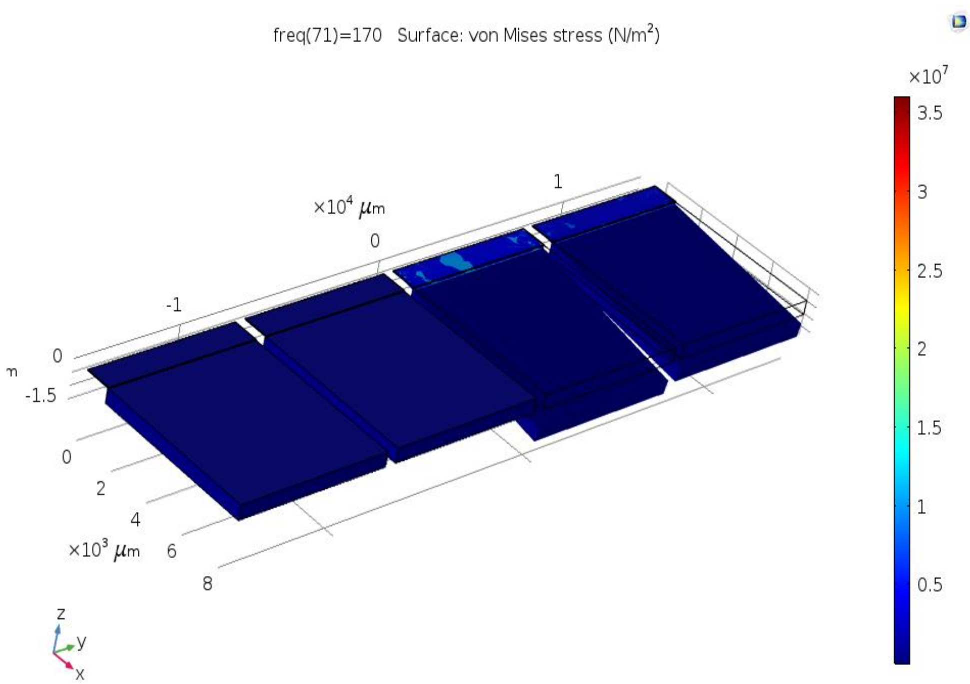
5.2 Thesis Work

Simulation and modeling of vibrational based piezoelectric energy harvester are conducted in COMSOL 5.2a. The two (wide cantilever beam and narrow cantilever beam) piezoelectric cantilever beam EH structure has been analyzed, one edge of the EH device is fixed and the other edge of EH is free to move as it has a proof mass on it. Frequency, Voltage, Power and Power density has been calculated using COMSOL 5.2a.

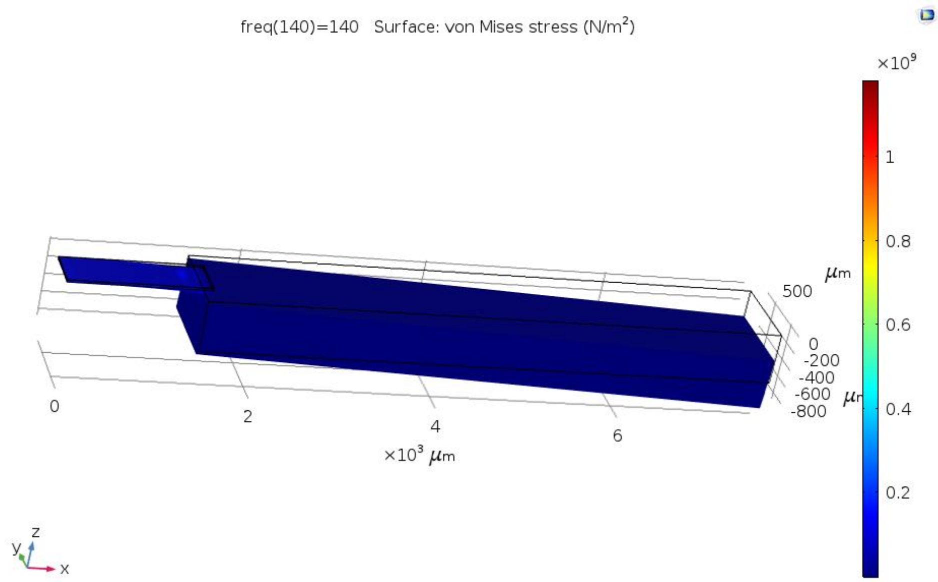
The acceleration of the device is customary as 0.2 g for a wide beam and 0.4 g for narrow beam rectangular structure [38]. The stress developed on the layers of Piezoelectric energy harvester due to proof mass and acceleration can be seen in Figure 5.17 (a) for single wide beam structure, Figure 5.17 (b) for array of wide beam structure, Figure 5.17 (c) for single narrow beam structure and Figure 5.17 (d) for array of narrow beam structure. Deflection can also be seen in Figure 5.17 (a) (b) (c) (d).



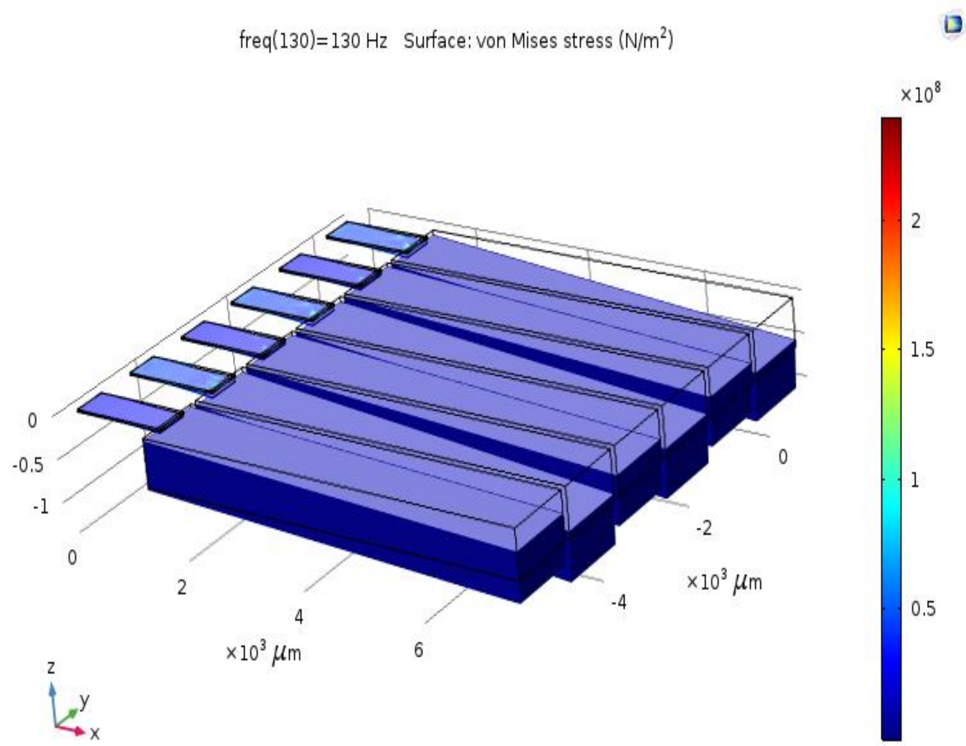
(a) Stress on the single wide cantilever beam



(b) Stress on the wide array cantilever beam

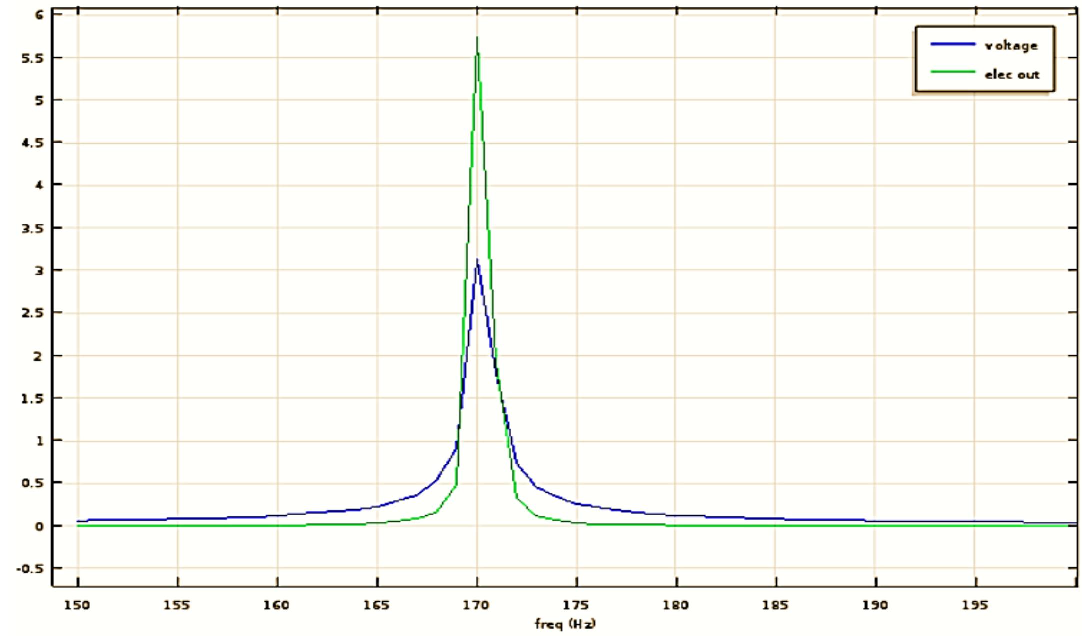


(c) Stress on the single narrow beam

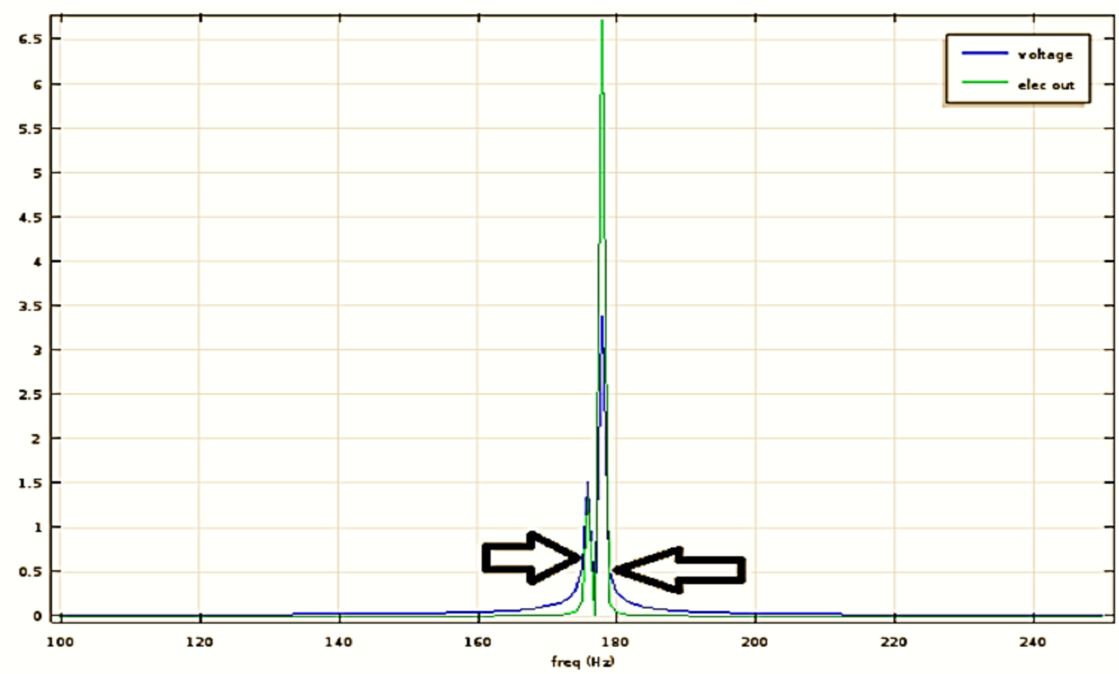


(d) Stress on narrow array cantilever beam

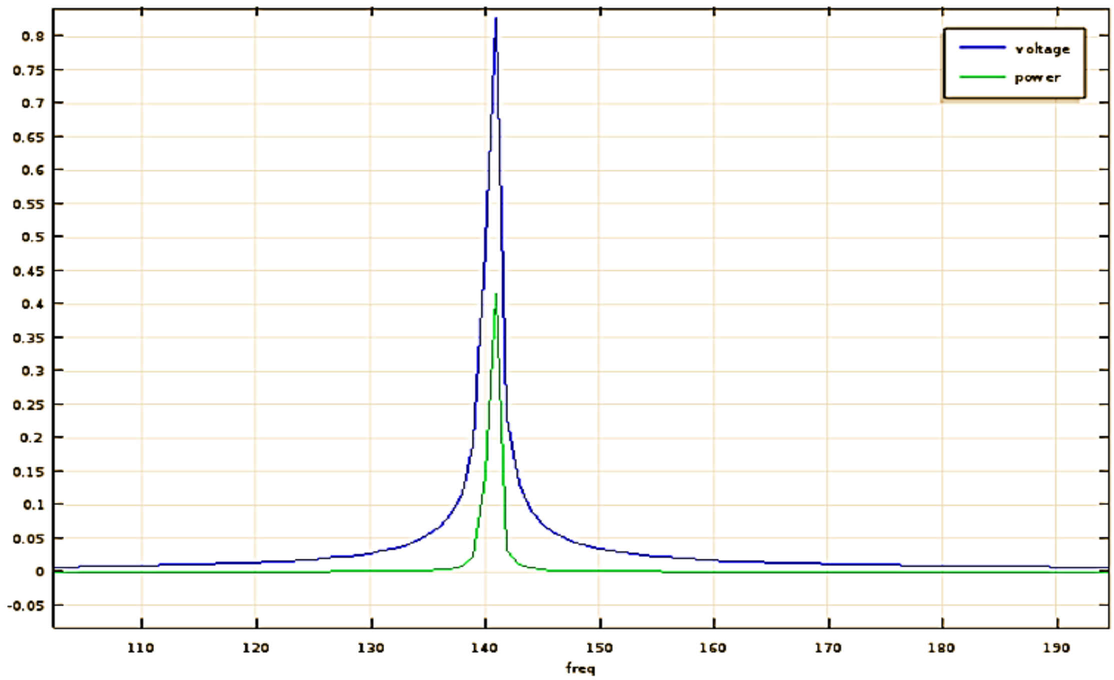
Figure 5.17 (a), (b), (c) ,(d) Stress on single and array cantilever beams



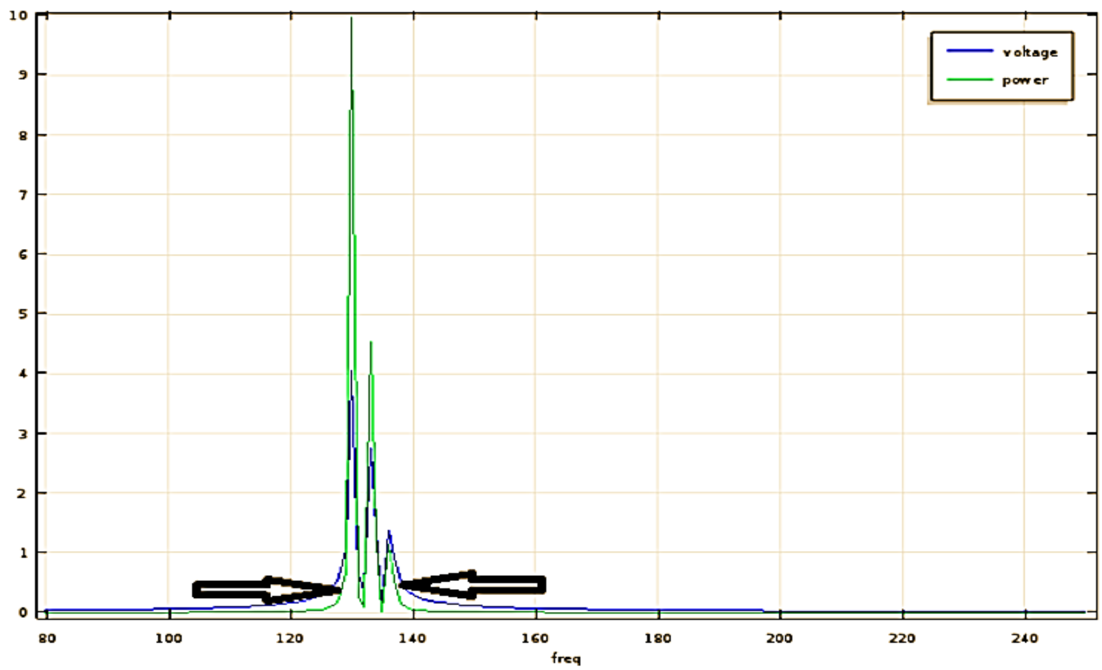
(a) Simulation result of single wide cantilever beam



(b) Simulation result of array of wide cantilever beam



(c) Simulation result of narrow cantilever beam



(d) Simulation result of array of narrow cantilever beam

Figure 5.18 (a), (b), (c), (d) Simulation results showing the voltage and power vs frequency

Figure 5.18 (a) and Figure 5.18 (c) shows the graph between frequency and voltage, frequency and power for single cantilever structure, Figure 5.18 (b) for the wide cantilever beam array and Figure 5.18 (d) for the narrow cantilever beam array structure.

Table 5.5 Voltage and Power obtained from the cantilever structures

Architecture	Voltage (V)	Electric Power (μW)	Frequency (Hz)
Wide beam cantilever structure	3.1	5.55	170
Narrow beam cantilever structure	0.85	0.42	142

The power generated was 5.55 μW for the wide EH cantilever structure and 0.42 μW for narrow EH cantilever structure which is close to the theoretical calculated power which is 5.652 μW and 0.425 μW respectively.

Figure 5.18 (b) shows the graph of voltage and power with respect to frequency for the array of the wide beam and Figure 5.18 (d) the narrow beam cantilever design. It is clearly seen that there is an increase in bandwidth and amplitude which is due to the combined result of all the wide beam and the narrow beam design in the array. As every cantilever beam have its resonance frequency and when the array is formed it gives results in combination which increases the bandwidth of the EH device as each beam is contributing in the results. Thus size and shape of the structure affect the bandwidth. As the number of cantilever structure in wide cantilever beam is four and in narrow cantilever beam is six, there is quite increase in the bandwidth when compared to the single beam structure of wide and narrow cantilever beam respectively. To get the wide bandwidth the number of cantilevers should be increased in future research.
The first aspect of energy harvesting device is the power density [21]

$$\text{Power Density} = \frac{Pp}{V} \tag{5.1}$$

Where P_p is peak electric power and v is volume.

Table 5.6 Power density of the structures

Architecture	Power density (μW/cm^3)
Wide cantilever beam structure	14.8
Narrow cantilever beam structure	0.10

From Table 5.6 can be seen the power density of single wide cantilever beam and narrow cantilever beam is 14.8 μW/cm^3 and 0.10 μW/cm^3. It is clearly seen in results that the wide beam piezoelectric cantilever structure had the highest power density than the narrow beam cantilever piezoelectric structure.

The other feature of EH device is the bandwidth. In order to increase the bandwidth, various cantilever structures are used to form an array by varying the length which in return alters the resonant frequency between each cantilever structure. The results obtained from the array structure is shown in Figure 5.18 (b) and Figure 5.18 (d). It is clearly seen in the graph of Figure 5.18 (b) and Figure 5.18 (d), there is a low bandwidth of 4 Hz in wide beam and 8.1 Hz in narrow beam cantilever structure. For increasing bandwidth narrow structure EH devices are the best kind of cantilever structures over the wide structure EH devices, however, generate low power.

The results demonstrate that the wide cantilever beam EH design delivers high power density and bandwidth is low in it, on the other hand, the narrow cantilever beam structure delivers high bandwidth and low power density. Thus optimum shape is depended on the utilization.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Modeling and simulation of the proposed energy harvester are carried out successfully. This research examines the simulation outcome of the two aspects which are power density and bandwidth of MEMS-based energy harvesting device. Simulation using Finite Element Modeling (FEM) is validated by the results and further experiments can be done using the model in future. Various cantilever designs were tested to operate on low frequency and on low acceleration.

The power generated was 5.55 μW for the wide EH device and 0.42 μW for the narrow EH device which is close to the theoretical calculated power which is 5.652 μW and 0.425 μW respectively for single cantilever beams and Power density of single wide cantilever beam and narrow cantilever beam is 14.8 $\mu W/cm^3$ and 0.10 $\mu W/cm^3$.

By forming an array of the cantilever beam structure of wide beam and narrow beam, low bandwidth is obtained are 4 Hz in wide beam and 8.1 Hz in narrow beam cantilever structure. A prototype of EH has been developed in order to demonstrate the concept behind energy harvesting from low vibrational source using the piezoelectric material.

Moreover, for optimizing the piezoelectric layer the main things to remember are when the piezo plate width increase which results in high resonance frequency, as width increases result in an increase in frequency, whereas when the length of piezo plate increases results in a decrease in resonance frequency as length is inversely proportional to the resonance frequency. When width or height of mass is increased it results in a decrease in frequency as the frequency is $1/\sqrt{\rho}$.

Each cantilever design of energy harvester type has its pro's and con's, and the conclusion of the results are wide beam structure is preferred to increase power density and a narrow beam for the wide bandwidth. High power density also has a disadvantage which is likely to fail where acceleration is high, as due to increasing stress which they experience.

6.2 Future Work

- Future work will be to optimize the two structure using finite element modeling described in this paper to widen the bandwidth and to obtain high power from the device.
- The requirement of a smart interfacing circuit for maximizing the voltage level as well overall power management between the source and the load.

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