Design, Simulation & Optimization of a MEMS Based Piezoelectric Energy Harvester

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Abstract— Energy harvesting is defined as a process of acquiring energy surrounding a system and converting it into electrical energy for usage. Piezoelectric energy harvesting is a very important concept in energy harvesting in microelectronics. In this report, an analysis of the cantilever type piezoelectric energy harvester is conducted using the finite element method (FEM) based software COMSOL Multiphysics. A unimorph type cantilever beam of the silicon substrate, structural steel as proof mass and support, and PZT-5A material as piezoelectric constitute the physical system. The effect of the resonance frequency is analyzed with different design parameters. It is found that a cantilever shape unimorph piezoelectric energy harvester has a great impact of length and thickness on the resonance frequency where the impact of width is negligible A specific field of application from the analysis is chosen based on the available frequency source of the environment and the design has been modified with two configurations based on the parametric dimension analysis. The electric potential has been simulated in every case and the voltage output analysis shows that modification of length is more optimum.

Index Terms— Energy harvesting, piezoelectric, PZT-5A, unimorph cantilever, COMSOL Multiphysics.

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1. INTRODUCTION

Energy harvesting means capturing minute energy from surrounding sources, accumulating them, and storing them. With recent advancements in wireless technology, energy harvesting is highlighted as an alternative for the conventional battery. [1] While there are different ways through which energy is harvested, piezoelectric devices show great promise. Piezoelectric materials have the property of producing electrical charge when strained. This is called the direct piezoelectric effect. On the other hand, these materials undergo deformation when an electric field is applied. This is called the converse piezoelectric effect. [1] This property of piezoelectric materials is used in converting vibrational energy to electrical energy which may be stored and used as an alternative power source for portable electronics. In recent advancements, energy harvesting has attracted considerable attention as an energy source for wireless sensor networks because batteries cause a series of inconveniences like limited operating life, size, and contamination issues. Solar energy provides some solutions but it is limited in dark conditions. Piezoelectric devices are proved to be the potential source for power generation. [1] Therefore they serve as a good alternative for conventional batteries.

The applications for the piezoelectric energy harvesting are-

Condition Monitoring and Structural Health Monitoring (SHM): A typical application example is the monitoring of components in complex systems such as airplane wings. Piezo transducers perform a series of functions, they measure deformations, but also supply transmitters with energy for wireless data transmission.

Data Monitoring and Data Transmission: Power supply for sensors and radio transmitters, for example in heating and air-conditioning technology for monitoring the temperature or the airflow in pipes.

Product Monitoring during Transport If vehicle vibrations are used for generating energy, products can be continuously monitored during transport without the corresponding sensors having to be connected to a power supply or equipped with batteries. This is useful if temperatures have to be recorded inside closed containers, for example, Energy Supply of Wireless ZigBee Network.

2. DIFFERENT FORMS OF ENERGY HARVESTING

Energy harvesting can be obtained from different energy sources, such as mechanical vibrations, electromagnetic sources, light, acoustic, air flow, heat, and temperature variations. Energy harvesting, in general, is the conversion of ambient energy into usable electrical energy. When compared with energy stored in common storage elements, such as batteries and capacitors, the environment represents a relatively infinite source of available energy.

Ambient energy sources

Ambient energy harvesting, also known as energy scavenging or power harvesting, is the process where energy is obtained and converted from the environment and stored for use in electronic applications. Usually, this term is applied to energy harvesting for low power and small autonomous devices, such as wireless sensor networks, and portable electronic devices. A variety of sources are available for energy scavenging, including solar power, ocean waves, piezoelectricity, thermoelectricity, and physical motions (active/passive human power).

For example, some systems convert random motions, including ocean waves, into useful electrical energy that can be used by oceanographic monitoring wireless sensor nodes for autonomous surveillance. This just shows that no single power source is sufficient for all applications, the selection of power sources must be considered according to the application. [2]

Mechanical energy harvesting

An example of electric power generation using rotational movement is the self-powered, batteryless, cordless wheel computer mouse. The system was designed uniquely to capture rotational movements with the help of the mouse ball to generate and harvest electric power. The electric generator is powered by exploiting rolling energy by dragging the mouse. The energy harvesting system was intended to power the electronic system of a mouse device, such as the ultralow-power RF transmitter and microcontroller. The experimental results of the study showed that the mouse only needed 2.2mW energy to operate. The total energy captured using an energy harvesting system was bigger than 3mW, which was enough for the wireless mouse operations in a transmit range of one meter. [3] Another example of mechanical energy harvesting is an electrostatic micro-generator. In this system, a micromachined electrostatic converter consisted of a vibration-sensitive variable capacitor polarized by an electret. A general multidomain model was built and analyzed in the same study, and it showed that power generation capabilities up to 50μW for a $0.1cm^2$ surface were attainable. [4]

Mechanical vibration

Indoor operating environments may have reliable and constant mechanical vibration sources for ambient energy scavenging. For example, indoor machinery sensors may have plentiful mechanical vibration energy that can be monitored and used reliably. Vibration energy harvesting devices can be either electromechanical or piezoelectric. Electromechanical harvesting devices, however, are more commonly researched and used. Energy withdrawal from vibrations could be based on the movement of a spring-mounted mass relative to its support frame. Mechanical acceleration is produced by vibrations that, in turn, cause the mass component to move and oscillate. This relative dislocation causes opposing frictional and damping forces to be applied against the mass, thereby reducing and eventually extinguishing the oscillations. The damping force energy can be converted into electrical energy via an electric field (electrostatic), magnetic field (electromagnetic), or strain on a piezoelectric material. These energy conversion schemes can be extended and explained under the three listed subjects because the nature of the con-version types differs even if the energy source is vibration. [5]

Electromagnetic

This technique uses a magnetic field to convert mechanical energy to electrical energy [6]. A coil attached to the oscillating mass is made to pass through a magnetic field, which is established by a stationary magnet, to produce electric energy. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law. The induced voltage is inherently small and therefore must be increased to become a viable source of energy [7]. Techniques to increase the induced voltage include using a transformer, increasing the number of turns of the coil, or increasing the permanent magnetic field [8]. However, each of these parameters are limited by the size constraints of the microchip as well as its material properties.

Piezoelectric

This method alters mechanical energy into electrical energy by straining a piezoelectric material [9]. Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field and consequently a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, which provides a higher strain for a given input force [10]. The voltage produced varies with time and strain, effectively producing an irregular AC signal on average. Piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system. Moreover, piezoelectricity has the ability of some elements, such as crystals and some types of ceramics, to generate an electric potential from mechanical stress [11]. This process takes the form of the separation of electric charge within a crystal lattice. If the piezoelectric material is not short-circuited, the applied mechanical stress induces a voltage across the material. There are many applications based on piezoelectric materials, one of which is the electric cigarette lighter. In this system, pushing the button causes a spring-loaded hammer to hit a piezoelectric crystal, and the voltage that is produced injects the gas slowly as the current jumps across a small spark gap. Following the same idea, portable sparkers used to light gas grills, gas stoves, and a variety of gas burners have built-in piezoelectric-based ignition systems.

Thermal (Thermoelectric) Energy Harvesting

Temperature changes between opposite segments of a con-ducting material result in heat flow and consequently charge flow since mobile, high-energy carriers diffuse from high to low concentration regions. Thermopiles consisting of n- and p-type materials electrically joined at the high-temperature junction are therefore constructed, allowing heat flow to carry the dominant charge carriers of each material to the low-temperature end, establishing in the process a voltage difference across the base electrodes. The generated voltage and power are relative to the temperature differential and the Seebeck coefficient of the thermoelectric materials. Large thermal gradients are essential to produce practical voltage and power levels. [12] However, temperature differences greater than 10°C are rare in a microsystem, so consequently, such systems generate low voltage and power levels.

Moreover, naturally occurring temperature variations also can provide a means by which energy can be scavenged from the environment with high temperatures. Stordeur and Stark (1997) have demonstrated a thermoelectric microdevice, which is capable of converting 15W/cm3 from 10°C temperature gradients. Although this is promising and, with the improvement of thermoelectric research, could eventually result in more than 15W/cm3, situations in which there is a static 10°C temperature difference within 1cm3 are, however, very rare, and assume no losses in the conversion of power to electricity. [13]

Pyroelectric Energy Harvesting

The "pyroelectric effect" converts temperature changes into electrical voltage or current. [14] Pyroelectricity is the capability of certain materials to generate an electrical potential when they are either heated or cooled. As a result of the temperature change, positive and negative charges move to opposite ends through migration (polarized), and thus, an electrical potential is established. Pyroelectric energy harvesting applications require inputs with time variances which results in small power outputs in energy-scavenging applications. One of the main advantages that pyroelectric energy harvesting has over thermoelectric energy harvesting is that most of the pyroelectric materials or elements are stable up to 1200°C or more. Stability allows energy harvesting even from high-temperature sources with increasing thermodynamic efficiency.

Solar Energy Harvesting

A photovoltaic cell has the capability of converting light energy into electrical energy. [15] Each cell consists of a reverse-biased pn+ junction, in which the light crosses with the heavily conservative and narrow n+ region. Photons, where the light energy exists, are absorbed within the depletion region, generating electron-hole pairs. The built-in electric field of the junction immediately separates each pair, accumulating electrons and holes in the n+ and p regions, respectively, establishing an open circuit voltage. With a load connected, accumulated electrons travel through the load and recombine with holes at the p-side, generating a photocurrent that is directly proportional to the light intensity and independent of the cell voltage. Several research efforts have been conducted so far have demonstrated that photovoltaic cells can produce sufficient power to maintain a microsystem. Moreover, a three-dimensional diode structure constructed on absorbent silicon substrate helps increase efficiency by significantly increasing the exposed internal surface area of the device. [16] Overall, photovoltaic energy conversion is a well-known integrated circuit-compatible technology that offers higher power output levels, when compared with the other energy-harvesting mechanisms. Nevertheless, its power output is strongly dependent on environmental conditions; in other words, varying light intensity.

Acoustic Noise

Acoustic noise is the result of the pressure waves produced by a vibration source. A human ear detects and translates pressure waves into electrical signals. Generally, a sinusoidal wave is referred to as a tone, a combination of several tones is called a sound, and an irregular vibration is referred to as noise. Hertz(Hz) is the unit of sound frequency; 1 Hz equals 1 cycle, or one vibration, per second. The human ear can perceive frequencies between 20 Hz and 20,000 Hz. Acoustic power and acoustic pressure are types of acoustic noise. Acoustic power is the total amount of sound energy radiated by a sound source over a given period of time, and it is usually expressed in Watts. For acoustic pressure, the reference is the hearing threshold of the human ear, which is taken as 20 microPa. The unit of measure used to express these relative sound levels is the Bel or decibel (1 Bel equals 10 decibels). The Bel and decibel are logarithmic values that are better suited to represent a wide range of measurements than linear values. [17]

Human Power

An average human body burns approximately 10.5MJ every day, which is equal to about 121W of power dissipation. Power dissipation occurs in the average human body either actively or passively in daily life motions, making the human body and motions an attractive ambient energy source. Re-searchers have proposed and conducted several studies to capture power from the human body. For example, Starner has researched and investigated some of these energy-harvesting techniques to power wearable electronics. [18] MIT researchers considered these studies and suggested that the most reliable and exploitable energy source occurs at the foot during heel strikes when running or walking. [19] This research initiated the development of piezoelectric shoe inserts capable of producing an average of 330μW/cm2 while an average person is walking. The first application of shoe inserts was to power a low-power wireless transceiver mounted to the shoe soles. The ongoing research efforts mostly focused on how to get power from the shoe, where the power is generated, to the point of interest or application. Such sources of power are considered as passive power sources in that the person is not required to put extra effort to generate power because power generation occurs while the person is doing regular daily activities, such as walking or running. Another group of power generators can be classified as active human-powered energy scavengers. These types of generators re-quire the human to perform an action that is not part of the normal human performance. For instance, Freeplay has self-powered products that are powered by a constant-force spring that the user must wind up to operate the device. [20] These types of products are very useful because of their battery-free systems.

Typical Configurations of Piezoelectric Energy Harvester

In most cases of piezoelectric energy harvesting, the vibration or mechanical energy sources either have low motion frequencies or low acceleration. A thin and flat form factor allows a piezoelectric element to readily react to the motion for the host structure. In addition, such a form factor is also beneficial in reducing the overall dimensions and weight of the energy harvesting device. Thus, the piezoelectric materials used in most of the piezoelectric energy harvester designs and configurations explored to date possess a thin-layer geometric shape.

a. Cantilever Beam

Cantilever geometry is one of the most used structures in piezoelectric energy harvesters, especially for mechanical energy harvesting from vibrations, as large mechanical strain can be produced within the piezoelectric during vibration, and construction of piezoelectric cantilevers is relatively simple. More importantly, the resonance frequency of the fundamental flexural modes of a cantilever is much lower than the other vibration modes of the piezoelectric element. [21] Therefore, a majority of the piezoelectric energy harvesting devices re-ported today involve a unimorph or bimorph cantilever design. A thin layer of piezoelectric ceramics can be built into a cantilever, bonding it with a nonpiezoelectric layer (usually a metal serving as a conductor of the generated charge), and having it's one end fixed in order to utilize the flexural mode of the structure (Figure 1.1). Such a configuration is called a “unimorph” as only one active layer (the piezoelectric layer) is used in this structure. A cantilever can also be made by bonding the two thin layers of piezoelectric ceramic onto the same metal layer to increase thpower output of the unit. This is called a “bimorph” structure as two active layers are used. Bimorph piezoelectric cantilevers are more commonly used in piezoelectric energy harvesting studies because the bimorph structure doubles the energy output of the energy harvester without a significant increase in the device volume. [22]

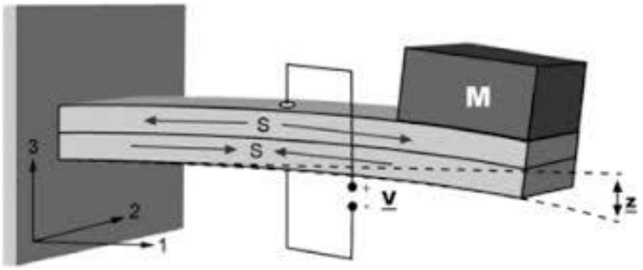

Figure 1.1: Typical piezoelectric cantilever beam.

In a piezoelectric cantilever, the poled directions of the piezoelectric layers are usually perpendicular to the planar direction of the piezoelectric layers because it is the most convenient way to polarize piezoelectric sheets when they are fabricated. Piezoelectric cantilevers operating in the above manner are said to be operating in the “31 mode”, where “3” denotes the polarization direction of the piezoelectric layer and “1” denotes the direction of the stress, which is primarily in the planar direction of the cantilever. The 31 mode utilizes the d31 piezoelectric charge constant, the induced polarization in the poled direction (direction “3”) of the piezoelectric per unit stress applied in direction “1”. For a give piezoelectric material, d31 is always smaller than d33 because in the 31 mode the stress is not applied along the polar axis of the piezoelectric material. Therefore, in order to utilize a piezoelectric sheet in the “d33”mode for higher energy output, an interdigitated electrode design can be used. In this electrode design, an array of narrow positive and negative electrodes is placed alternately on the surface of a piezoelectric sheet when it is fabricated. During poling treatment of the sheet, the interdigitated electrodes direct the electric field to apply laterally within the sheet so that the sheet is polarized in the lateral direction instead of the conventional vertical direction. This way, when the sheet is subjected to bending, the stress direction is parallel to the poled direction of the piezoelectric, enabling the utilization of the primary piezoelectric charge constant, d33. [23]

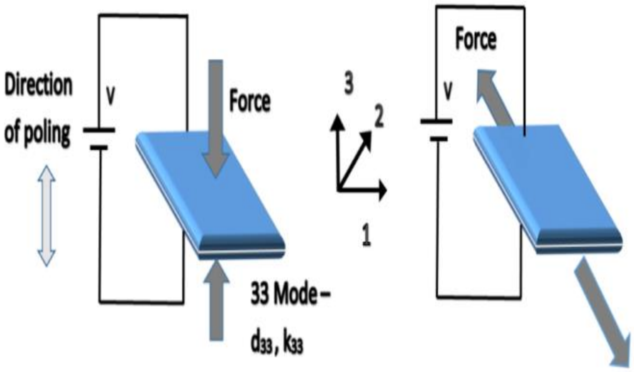

Figure 1.2: The 31mode and 33 mode

Figure 1.2: The 31mode and 33 mode

b. Cymbal Transducer

Cymbal transducers were developed for applications that have high impact forces. It typically consists of a piezoelectric ceramic disc and a metal (steel) end cap on each side. Steel is typically used because it provides higher yield strength than brass and aluminum, thus leading to higher force loading capability of the transducer. When axial stress is applied to the cymbal transducer, the steel end caps convert and amplify the axial stress to radial stress in the PZT disc. Therefore, both d33 and d31 piezoelectric charge coefficients are combined to contribute to the charge generation of the transducer. [24] Cymbal transducers can provide a higher energy output than cantilever energy harvesters because the cymbal structure withstands a higher impact than the cantilever beam. For example, a cymbal transducer with a piezoelectric ceramic disc of a diameter of 29 mm and a thickness of 1 mm showed an output power of 39 mW and 52 mW under AC force of 7.8 N and 70 N, respectively, at 100 Hz. On the other hand, however, the robust nature of the cymbal structure also limits its potential use in applications that provide high-magnitude vibration sources. They are not suitable for energy harvesting from natural ambient vibration sources, which have a low magnitude of vibrations. [25]

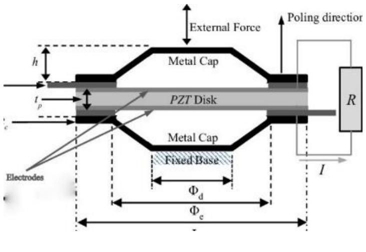

Figure 1.3: Cymbal transducers

c. Circular Diaphragms

A piezoelectric circular diaphragm transducer operates in a similar fashion to that of piezoelectric cantilevers. To construct a piezoelectric circular diaphragm transducer, a thin circular piezoelectric ceramic disc is first bonded to a metal shim and then the whole structure is clamped on the edge while piezoelectric cantilevers are only clamped at one end of the cantilever beam. In some cases, a proof mass is attached at the center of the diaphragm to provide pre-stress to the piezo-electric ceramic, as it has been found that pre-stress within the piezoelectric element can improve the low-frequency performance of the energy harvester and increase the power output. A piezoelectric ceramic layer is first sandwiched between two dissimilar metal layers, and then the composite is heated and cooled to room temperature. The difference in the thermal expansion coefficients of the two dissimilar metals causes the whole structure to warp, thus introducing pre-stress in the piezoelectric material. [26]

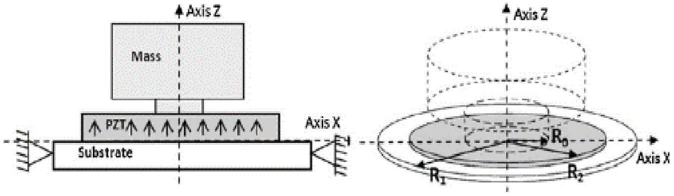

Figure1.4: Circular diaphragms type

3. NUMERICAL METHODOLOGY

3.1 THEORETICAL BACKGROUND

A cantilever-type vibration energy harvesting has a very simple structure and can produce large deformation under deformation. The cantilever model can be used in two different modes,33 modes, and 31 modes. The 33 mode (compressive mode) means the voltage is obtained in the 3 directions parallel to the direction of applied force. The 31 mode (Transverse Mode) means the voltage is obtained in 1 direction perpendicular to the direction of applied force [3]. The most useful mode in harvesting applications is 31 mode because an im-mense proof mass would be needed for 33 configurations. [1] The vibration spectrum shows that the acceleration decreases [1] for higher modes of frequency compared to the fundamental mode of frequency. Therefore, the design of the cantilever beam focuses on the fundamental mode of frequency.

The power density would be maximum when the vibration frequency matches the resonant frequency of the piezoelectric generator. It has been proved that power density decreases when resonant frequency deviates from the vibration frequency. [1]

The resonance frequency of a simply supported cantilever beam can be calculated using the following equation-

$$f = \frac{Vn^2}{2\pi L}\sqrt{\frac{EI}{mw}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

where E is the Young's modulus, I the moment of inertia, L the length, w the width of the
cantilever, m the mass per unit length of the cantilever beam, and vn =1.875 the eigenvalue for the fundamental vibration mode.

To further lower the resonance frequency of the cantilever, a proof mass can be attached to the free end of the cantilever (Figure 1d). Equation 1 can be approximated into Equation 2 to include the proof mass.

$$f = \frac{V\prime n^2}{2\pi L}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Where, $V'n^2 = Vn^2\sqrt{0.236/3}$, $me = 0.236mwL$ the effective mass of the cantilever, Δm is the proof mass and K is the effective spring constant of the cantilever

When piezoelectric materials are deformed or stressed, voltage appears across the material. The mechanical and electrical behavior can be modeled by two constitutive equations-

$$\{S\} = S_E\{T\} + d\{E\} \ldots\ldots\ldots\ldots\ldots\ldots 3$$

$$\{D\} = d\{T\} + \varepsilon_T\{E\} \ldots\ldots\ldots\ldots\ldots\ldots 4$$

Where,

$\{S\}$ = Strain, $\{T\}$ = Stress, $\{E\}$ = Electric Field, $\{D\}$ = Electric Displacement

S_E = Compliance, d = Piezoelectric Coefficient, ε_T = Permittivity

3.2 COMSOL MULTIPHYSICS

COMSOL Multiphysics is cross-platform Finite Element Method (FEM) software that uses numerical techniques to find approximate solutions to boundary value problems for differential equations. This software is popularly used for various physics and engineering applications. The main purpose of multiphysics is to make simulations that involve multiple physical models, basically, each application mode contains multiphysics which has its own laws, equations, restrictions, etc. This software can also be used to solve partial differential equations. The way it works is the user has to put various inputs. Starting with selecting the desire multiphysics, it can be both single and different multiple multiphysics. Then it involves setting desired parameters, drawing structures, then setting the subdomain and boundary conditions by giving appropriate values or selecting laws for the project. After every condition has been fulfilled by the users, now the person has to initialize the mesh according to the desire requirements and compute the results.

From the Modules MEMS module is desirable for the the piezoelectric energy harvesting.

MEMS Module

The field of MEMS evolved as engineers and scientists explored new avenues to exploit the fabrication technologies developed by the microelectronics industry. These technologies enabled complex micron and submicron structures to be integrated with electronic systems and batch fabricated at a low cost. Mechanical devices fabricated using these technologies have become known as microelectromechanical systems (MEMS) or alternatively as microsystems. A proper description of these devices usually requires multiple physical effects to be incorporated. At the microscale different physical effects become important to those dominant at macroscopic scales. Inertial forces, which scale with the volume of the system, become comparatively less important than effects that scale more favorably when the system size is reduced, such as electrostatic forces. Consequently, electrostatically actuated devices have been developed to measure acceleration and/or rotation with high accuracy in a small package. These accelerometers and gyroscopes have found widespread application in the automotive industry (where they are used to deploy airbags), in industrial applications (as sensors), and in consumer applications (where smart phones have driven rapid growth in the use of MEMS devices in recent years).

Capacitive sensing has also led to the widespread adoption of capacitive pressure sensors which have largely superseded the piezoresistive pressure sensors that were some of the first MEMS devices to come to market. Piezoelectric MEMS devices have also great importance in wireless sensor networks.

3.3 MODEL SETUP

3.3.1 GEOMETRY

Cantilever beam piezoelectric generator has three types unimorph, bimorph series, and parallel configurations. When the beam has only one piezoelectrical layer attached to the substrate, the device is known as unimorph. On the other hand, if a metal shim is sandwiched between two piezoelectric layers, the device is known as bimorph. For energy harvesting, a unimorph structure is chosen.

The geometry is simple as like a cantilever beam with a piezoelectric layer with support and a proof mass. The geometry is drawn within the COMSOL geometry tool. The model is drawn with 4 different blocks. The 3D geometry is shown in Fig.3.4.1 below.

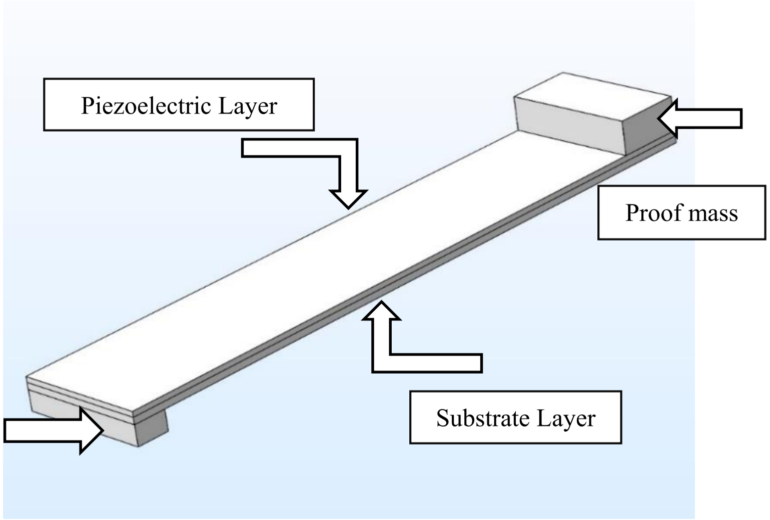

Figure 3.2 Isomeric view of Unimorph Cantilever piezoelectric beam.

Table 3.1 detail dimensions of the cantilever beam

Components	Dimensions
Substrate layer	Length of the substrate 50 mm Width of the substrate 10mm Thickness of the substrate 0.5 mm
Piezoelectric layer	Length of the Piezoelectric layer 50 mm Width of the Piezoelectric layer 10mm Thickness of the Piezoelectric layer 0.4 mm
Proof mass	Length of the tip mass 5 mm Width of the tip mass 10mm Thickness of the tip mass 2.5 mm
Support	Length of the Support 2.5 mm Width of the s Support 10mm Thickness of the Support 1.5 mm

3.3.2 MATERIAL SELECTION

For the geometry of the unimorph cantilever beam with the prof mass and support three different materials are selected. They are shown in the table 3.3.2 below

Table 3.2 Selection of material

Components	Materials
Substrate Layer	Silicon
Piezoelecric layer	Lead Zirconate Titanate (PZT-5A)
Support and Proof mass	Structural steel

The materials are in the default build-in material library the properties are given below-

Table 3.3: Property of silicon substrate

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

Table 3.4: Property of structural steel

Name	Value	Unit
Density	7850	kg/m^3
Young's modulus	200e9	Pa
Poisson's ratio	0.33	1

Table 3.5: Property of Lead Zirconate Titanate (PZT-5A

Name	Value	Unit
Density	7750	kg/m^3
Young's modulus	66e9	Pa
Poisson's ratio	.31	1

3.3.3 BOUNDARY CONDITIONS

In COMSOL Multiphysics the study of piezoelectric effect is combined with two physics: solid mechanics and electrostatics

i. Boundary Conditions for Solid Mechanics:

In the physics of solid mechanics all domains are considered as linear elastic materials. The lower surface of the support is made fixed for the analysis. The piezoelectric domain is selected for piezoelectric material. A boundary load 2 N is applied in the downward direction of y-axis in the upper surface of the mass.

ii. Boundary Conditions for electrostatics:

In the physics of electrostatics only piezoelectric domain is selected for the electrostatics study. The charge conversion is selected for the piezoelectric domain. The initial electric potential is set as 0 V. The four side boundary is selected as zero charge. The lower surface of piezoelectric layer is defined as terminal and the upper surface of the piezoelectric layer is defined as ground. For the voltage output in DC a circuit was connected with the terminal as the piezoelectric material generates AC voltage when they are stressed in two directions. A resistor 1ohm was connected parallel to the output.

3.3.4 MESHING

The finite element method requires dividing the analysis region into sub-regions. Here small regions are elements, which are connected with adjacent to their nodes. Mesh generation is a procedure of generating the geometric data of the elements and their nodes and involves computing the coordinates of nodes, defining their connectivity, and thus constructing the elements. Here, mesh designates aggregates of elements, nodes, and lines representing their connectivity, capability, and convenience of modeling and analysis domains are dominated by the mesh generation procedure. The geometric characteristics of generated elements affect the overall performance and accuracy of the finite element analysis. Therefore, mesh generation is one of the most important procedures in finite element modeling. The mesh settings determine the resolution of the finite element mesh used to discretize the model. The finite element method divides the model into small elements of geometrically simple shapes, in this case, tetrahedrons. In each tetrahedron, a set of polynomial functions is used to approximate the structural displacement field - how much the object de-forms in each of the three co-ordinates direction.

i. Default Mesh Generation

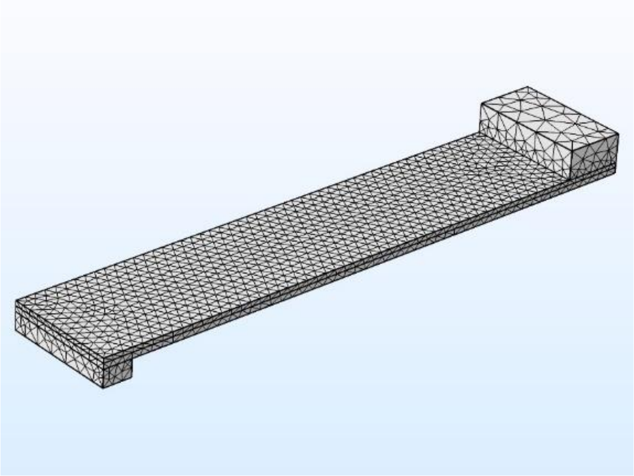

Figure3.3: Default mesh generation

Table 3.6: Sizing parameter for default mesh

Description	Value
Maximum element size	5mm
Minimum element size	0.9mm
Curvature factor	0.6
Resolution of narrow regions	0.5
Maximum element growth rate	1.5

ii. Mesh Sensitivity

For the mesh sensitivity analysis and selection of the perfect mesh for the convergence of the result a graph is plotted of the first eigenfrequency against different mesh elements. The mesh is gradually finer in the rightward direction.

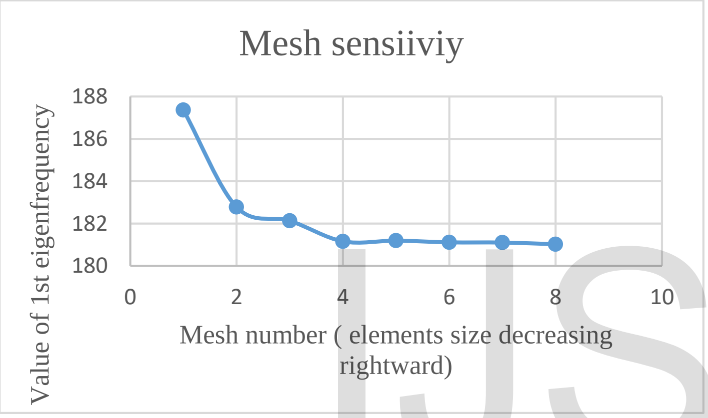

Figure 3.4 : Mesh sensitivity analysis

From the mesh sensitivity analysis we can see that after mesh-3 the value of 1st eigenfrequency is almost constant. So, mesh-4 is selected and at this point the result is converged. For the selected mesh generation the number of domain elements, boundary elements and edge elements are 9869, 5172 and 488 respectively.

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3.3.5 STUDY SETTING

After all the boundary conditions have been set and after getting the converging mesh the mode setup is done with two different study mode.

i. Eigenfrequency study

In the eigenfrequency study the number of first eigenfrequency was chosen as 6. The eigenfrequency was selected as the closest in absolute value. The study is accomplished with the two default physics -solid mechanics and electrostatics. The default plot or the study was marked and the study setting was completed.

ii. Frequency domain study

In the frequency domain study a range of frequency was set. The range is from 1Hz to 250Hz. The intermittent step was selected as 1 Hz.

i.

Table 3.7: Sizing parameter for different meshes

Description	Mesh 1	Mesh 2	Mesh 3	Mesh 4	Mesh 5	Mesh 6	Mesh 7	Mesh 8
Maximum element size	15mm	9.5mm	7.5mm	5mm	4mm	2.5mm	1.75mm	1mm
Minimum element size	2.7mm	2mm	1.4mm	0.9mm	0.9mm	0.2mm	0.075mm	0.01mm
Curvature factor	0.1	0.2	0.3	1.5	0.6	0.7	0.85	1
Resolution of narrow regions	2	1.85	1.7	1.5	0.45	1.4	1.35	1.3
Maximum element growth rate	1	0.9	0.8	0.5	0.5	0.4	0.3	0.2

3.3.6 VALIDATION

The resonance frequency analysis of the unimorph cantilever beam is validated by the eigenfrequency solution of Varadrajan and Bhanusri. [50]

Table 3.8: Dimension of present study & Varadrajan and Bhanusri

Components	Dimension	
	Present study	Varadrajan and Bhanusri
Substrate layer	Length 50 mm Width 10mm Thickness 0.5 mm	Length 60 mm Width 30 mm Thickness 1 mm
Piezoelectric layer	Length 50 mm Width 10mm Thickness 0.4 mm	Length 60 mm Width 30 mm Thickness 0.11 mm
Proof mass	Length 5 mm Width 10mm Thickness 2.5 mm	Length 12 mm Width 30 mm Thickness 3.5 mm

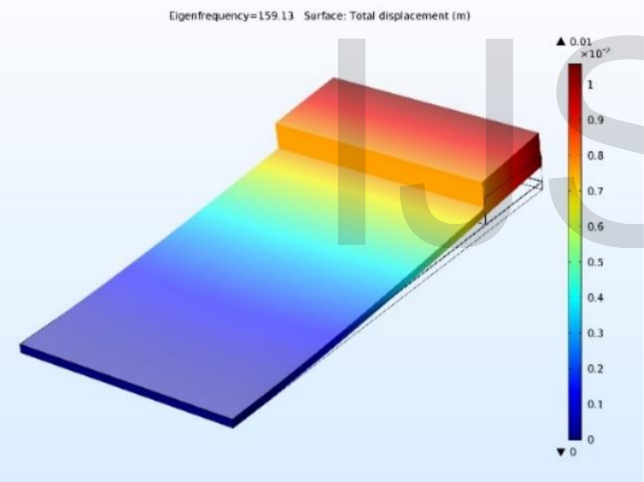

Figure 3.5: Resonance frequency for the geometry of Varadrajan and Bhanusri [50]

In the present analysis the resonance frequency is 153.13Hz where the Varadrajan and Bhanusri [50], simulated value was 153.22Hz. The deviation between these studies was found to be: 0.06% only. As such, the current simulation methods are considered appropriate. The result of this study is also compared with that of Varadrajan and Bhanusri. [50] In this case, the substrate length and thickness were varied in the range of 0.03m to 0.1m and 0.001m to 0.005m respectively. Both results were found to merge each other, indicating the simulation technique is valid.

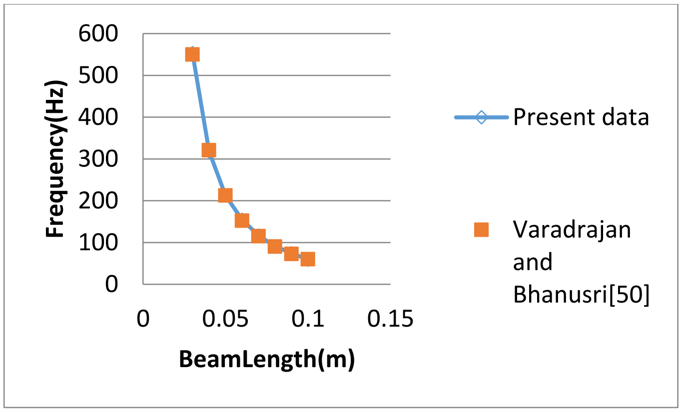

Figure 3.6 : Validation of result by Frequency convergence with respect to length.

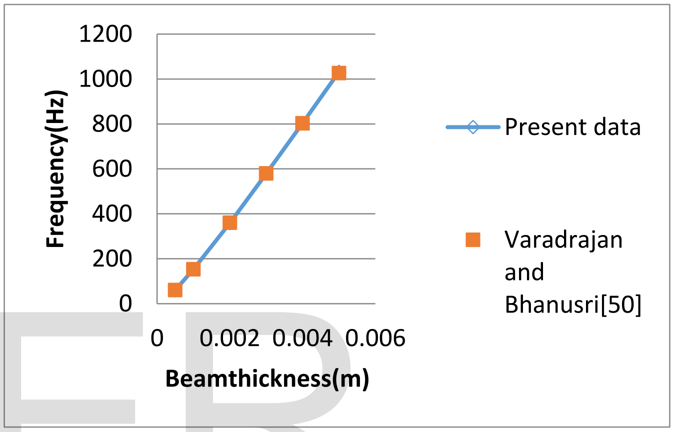

Figure 3.7 : Validation of result by Frequency convergence with respect to thickness

4. RESULT & DISCUSSION

4.1 EIGENFREQUENCY ANALYSIS OF THE PROPOSED GEOMETRY

Efficiency and power density of a piezoelectric vibrational energy harvesting device are strongly frequency dependent because the piezoelectric generates maximum power at its resonance frequency. For this reason the different resonance modes of the cantilever beam of the defined geometry was calculated using the COMSOL Multiphysics. The resonance frequencies are called eigenfrequency.

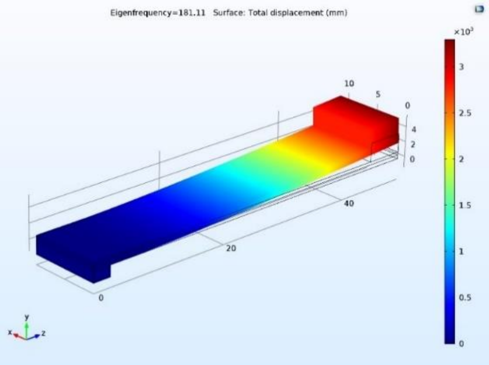

Figure 4.1: First mode of eigenfrequency of proposed geometry (eigenfrequency=181.11Hz).

From the different modes it was found that the first eigenfrequency was 181.11 Hz. The other modes are higher and hence they are not practical in general use of energy harvesting from the ambient source. So the first resonance frequency of 181.11Hz was taken into consideration for energy harvesting.

4.2 RESONANCE BEHAVIOR

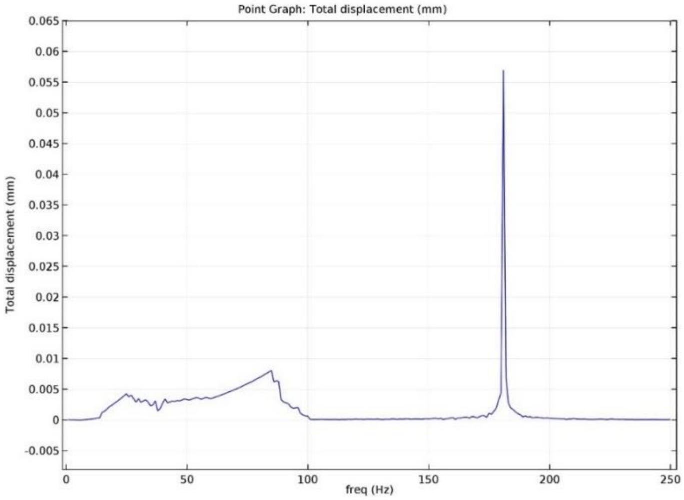

Figure 4.2: Variation of total displacement with frequency

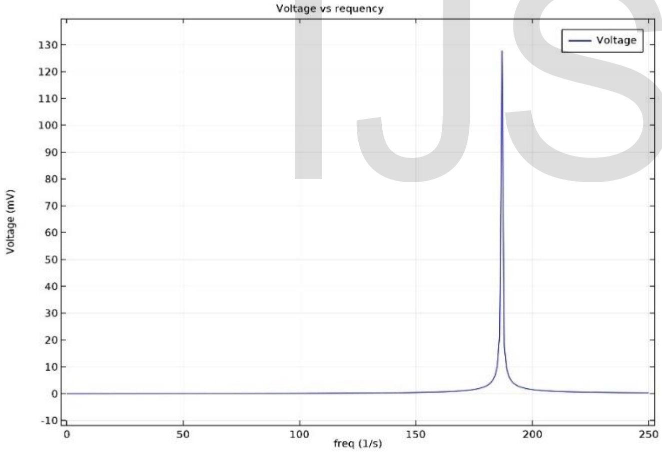

Figure 4.3: Variation of electric potential with frequency

The reason for analyzing the eigenfrequency was investigated. Figure 4.2 shows that the maximum displacement of the piezoelectric cantilever beam occurs at the frequency of 181.11Hz which is 0.0575 mm and also the Figure 4.3 shows that the output voltage is maximum at this frequency. The magnitude of the output voltage is 129.19mV.

4.3 ANALYSIS OF THE DESIGN PARAMETERS VARYING THE LENGTH, WIDTH & THICKNESS

a) Variation of Length

The resonance frequency of the cantilever beam is greatly dependent upon its design parameters. The three design parameters are the length, width and thickness. The variation of eigenfrequency was investigated varying the design parameters.

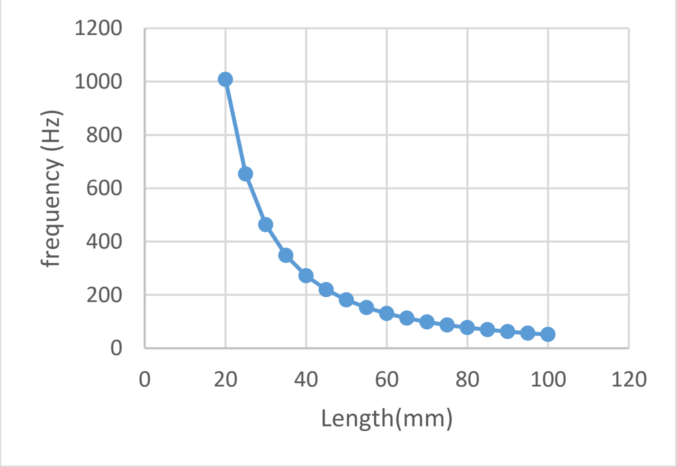

Figure 4.4 Variation of eigenfrequency with respect to length

The variation of length was changed from 20mm to 100mm having the intermittent step of 5 mm. From the figure 4.4 we can see that the length has a great importance with the resonance frequency. As the length increases the resonance frequency inversely decreases.

b) Variation of Width

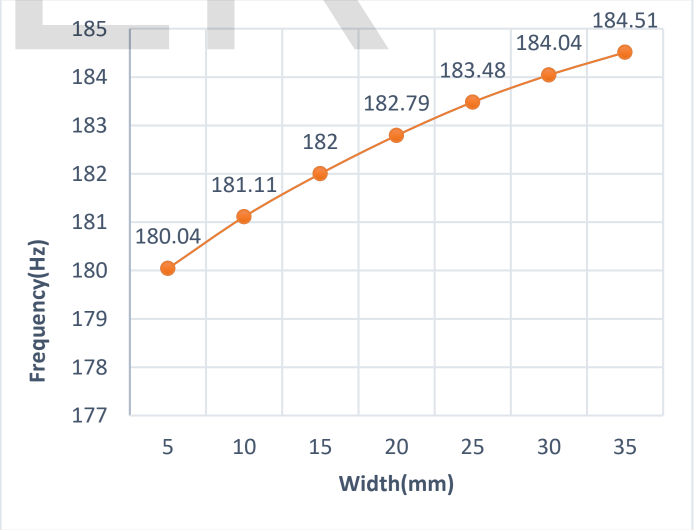

Figure 4.5 : Variation of frequency with respect to width

Similarly the width was changed from 5 mm to 35mm with the interval of 5mm. It is shown that the width has a very low effect on resonance frequency as it changes from 180.04Hz to 184.51Hz only for a vast change from 5mm to 35mm.

c) Variation of Thickness

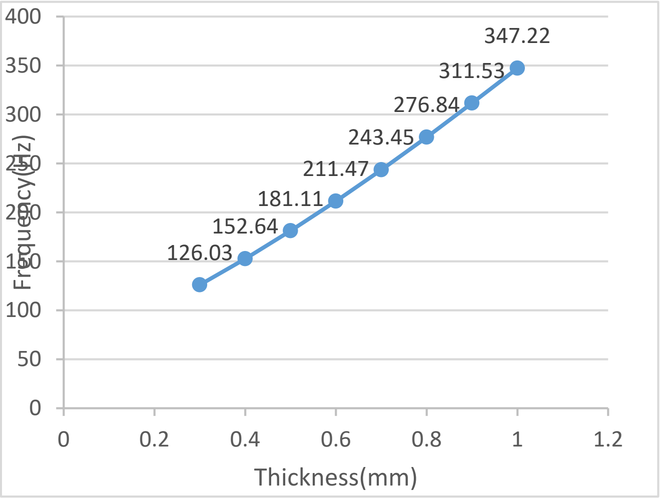

Figure 4.6 : Variation of frequency with respect to thickness

The thickness is changed from 0.3 mm to 1mm with an increment of 0.1mm. The thickness also has a great impact on resonance frequency. As the thickness increases the frequency also increases almost linearly.

It was found that the variation of length and thickness are highly influential on the eigenfrequency, and the width has a very low impact on eigenfrequency. So the width was kept constant as 10mm and the subsequent analysis was done with the length and width only.

After modification of the design it was found that both the modified model gives maximum displacement at the frequency of 200Hz which is desirable for the maximum piezoelectric effect in the chosen field of application.

From figure 4.9 and 4.10 it has been found that after modification of length the voltage output is 59.24mV on the other hand after the modification of thickness the voltage output is 49.63mV.So the modification of design is more optimum as it produces more voltage output and optimize the device dimension.

5. Conclusion and Future Work Recommendations

This chapter integrates the findings of all chapters and offers suggestions for possible future works.

5.1 Conclusions

The piezoelectric energy harvester has great impact on the resonance frequency. From the thesis work the following results are summarized:

- The proposed geometry has a resonance frequency of 181.11Hz at which it gives maximum displacement and at this point the voltage output is 129.19mV
- A cantilever shape unimorph piezoelectric energy harvester has a great impact of length and thickness on the resonance frequency where the impact of width is negligible.
- For the chosen field of 200Hz the geometry has been changed with two configurations based on the parametric dimension analysis.
- The modification of the length (47.3mm) gives an output voltage of 59.24mV and the modification o thickness) gives an output voltage of 49.63mV.
- The voltage output analysis shows that modification of length is more optimum.

5.2 Future works recommendation

i. In this study the effect of tip mass has not been investigated. The effect of tip mass on the resonance frequency can be investigated by varying dimension of the tip mass.

ii. In this study only one layer on piezoelectric material has been considered. More piezoelectric layer can be fabricated with the substrate and hence the efficiency can be improved.

iii. The effect of damping has not been considered. An investigation of damping can be done to improve the system.

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