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Design and Simulation of Vibration Based MEMS Piezoelectric Energy Harvester

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Abstract: *A MEMS based energy harvester device is designed to convert mechanical vibration energy to electrical energy via piezoelectric effect. This paper describes vibration based MEMS piezoelectric energy harvester covering design, analysis and simulation of microcantilever structure of various shapes. The cantilever based piezoelectric energy harvester is proposed, designed and optimized using COMSOL multiphysics tool. The focus of this paper is to study the effect on resonance frequency and voltage enhancement of piezoelectric MEMS devices. To lower the resonance frequency and maximize the output voltage, a proof mass is placed on the tip of the cantilever. The output and sensitivity of cantilever structure with different shapes and materials are assessed under identical excitation conditions.*

Keywords: *Piezoelectric energy harvester, unimorph cantilever, bimorph cantilever, COMSOL Multiphysics*

I. Introduction

Due to advancements in the field of microelectronics and wireless sensor node, the need for energy harvesting from surroundings has received much attention in the last decade. Presently, most of the electronics devices are fabricated using micro and nano technologies, hence power requirement of these devices have steadily decreased. All electronics devices are powered using conventional batteries which have limited capacity and life time. So, changing and replacement respectively becomes difficult. An alternative approach is to harvest energy from renewable energy sources [1].

There are so many energy sources like solar, thermal, kinetic, vibration that can be harvested. Vibration energy is our prime concern as different amplitude and frequency vibrations are freely available in the environment [2] and power harvested from vibrations is suitable to drive a microelectronic device. Hence capturing and harvesting vibration energy can become an alternative source and provide endless energy for the electronics devices.

Piezoelectric materials, type of transducer that converts one form of energy into another form [3], have been used to convert vibration energy into electrical energy due to the piezoelectric property. The piezoelectric effect was first demonstrated by Pierre Curie and Jaques Curie in 1881.

The piezoelectric effect exists in two properties: first is the direct piezoelectric effect that describes the material’s ability to transform mechanical strain into electrical charge and the second form is the converse effect, the ability to convert an applied electrical potential into mechanical strain. This property allows the material to function as a power harvesting medium. The main focus of this paper is on direct piezoelectric effect to convert the applied mechanical vibration into electrical energy.

In this paper, unimorph and bimorph microcantilever structures with different shapes are designed and simulated with COMSOL multiphysics tool for the conversion of applied mechanical energy into electrical energy and to obtain a large voltage and large strain at lower resonance frequency.

II. Modeling of Cantilever Structure

Most of the piezoelectric energy harvester structure uses a cantilever structure [5]. Cantilever, a structure with one end fixed and other end free to vibrate, is made up of one or more layer of piezoelectric material bonded to an elastic metal, in order to increase the sensitivity of the structure and reduce the brittleness of the piezoelectric layer. Cantilever structure can be designed in the form of unimorph and bimorph. Here in this paper, unimorph and bimorph type of cantilever are designed and simulated with two different structures: rectangular and rectangular cut. Dimensions of the model of cantilever are provided in Table 1.

Table 1: Dimension of Cantilever Structure

Symbol	Description	Value
L_b	Beam length	75 mm
W_b	Beam width	36 mm
t_p	Thickness of piezoelectric material	0.4 mm
t_s	Thickness of substrate material	0.8 mm
t_m	Thickness of mass structure	5 mm
L_m	Length of mass	5 mm
ρ_s	Density of piezoelectric material	7500 kg/m3
ρ_p	Density of substrate material	7850 kg/m3
E_p	Young's modulus of piezoelectric material	64 Gpa
E_s	Young's modulus of substrate material	200 Gpa

When mechanical stress is applied on a piezoelectric material, electric charge is generated. IEEE standard on piezoelectricity has given different form of piezoelectric constitutive equations. Strain-charge form has been used for cantilever structure and the equations are:

$$S = s^E T + d\bar{E} \qquad (1)$$

$$D = dT + \varepsilon^T \bar{E} \qquad (2)$$

s : Mechanical strain.
S^E : Elastic compliance tensor (Pa^{-1})
T : Mechanical stress vector (Nm^{-2})
Ē : Electric field vector (Vm^{-1})
D : Electrical displacement (Cm^{-2})
ε^T : Dielectric permittivity tensor (Fm^{-1})
d_{ij} : Electro-mechanical coupling factor (CN^{-1}), where i be polarization direction (usually 3) and j be strain direction.

Typically, two different modes can be used in the design of a piezoelectric harvester: longitudinal and transversal mode. The former is longitudinal mode (d_{31}) where the polarization of the beam is laterally developed in the deposited film. The commonly used is transversal mode (d_{33}) where the polarization of the beam is perpendicular to the deposited film.

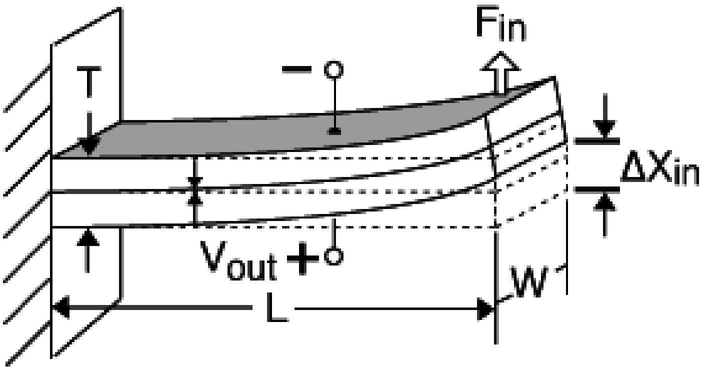

Fig.1 Cantilever structure

Most important design parameter of a vibration energy harvesting device is the resonant frequency. Resonant frequency is calculated by using the given equation [3]

$$f_n = \frac{{v_n}^2}{2\Pi}\frac{1}{L^2}\sqrt{(D_p/m)} \qquad (3)$$

where, $m = \rho_p t_p + \rho_s t_s$ (4)

v_n = 1.875 for first mode

m is the mass per unit area.

The bending modulus (D_P) is a function of Young's modulus and thickness and is expressed by

$$D_P = \frac{{E_P}^2{t_p}^4 + {E_s}^2{t_s}^4 + 2E_S E_p t_p t_s (2{t_p}^2 + 2{t_s}^2 + 3t_p t_s)}{12(E_P t_p + E_S t_s)}$$

Hence the variation of resonant frequency is

$$f_n \propto \frac{1}{L^2}\sqrt{t_p}\sqrt{t_s} \qquad (6)$$

Cantilever oscillates when placed in vibrating environment. The oscillations attain maximum peak value when vibration frequency of the environment matches the resonance frequency of the cantilever structure, and damps out dramatically for other frequencies. Most of vibration source present in the environment have frequency in the range of 50-200 Hz, the proof mass lowers the resonance frequency of the cantilever by order of few Hz, which is generally the order of frequency of vibration present in the nature. Proof mass also increases the amount of deflection, hence increasing the stress at the fixed end due to which charge is generated in the cantilever structure. Electrical output voltage is highest when stress is maximum, which is at the resonance frequency.

III. COMSOL Multiphysics Tool

Piezoelectric energy harvesters are designed with different structures and simulated using COMSOL multiphysics tool. Piezoelectric device module in 3D configuration has been selected. The goal is to study the deformation and voltage generated for different structures.

I.1 Sub Domain Setting

Each structure contains either two or three sub-domains. Piezoelectric layer (PZT 5H) gets deposited on the substrate layer in unimorph structure which is made of Aluminum while deposition is on both sides of the Aluminum layer in bimorph structure.

I.2 Boundary Condition

Cantilever structure was simulated such that fixed constraint applied at the vertical faces of the cantilever structure means one end of the cantilever fixed and other end free to vibrate. Applying floating potential at the upper face and grounding the lower face while all other faces are at zero charge constraint of piezoelectric layer implies that d_{31} mode is selected. Body load of 0.1 N is applied at the cantilever structure.

Afterwards, the model is 'meshed' where the geometry of structure is divided into group of simpler finite element bricks and presented to the finite element solver.

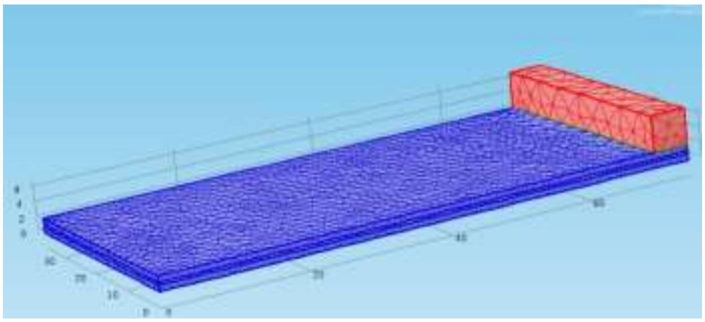

Fig.2: Meshing of cantilever beam

IV. Simulation Results

In the paper, two cantilever structures, rectangular and rectangular cut, have been simulated as unimorph, bimorph and bimorph with tip mass. In the simulation results, the sensitivity of these cantilever structures with same applied load of 0.1N is analyzed. Fig.3 and Fig.4 shown below, provides maximum displacement at the free end of cantilever.

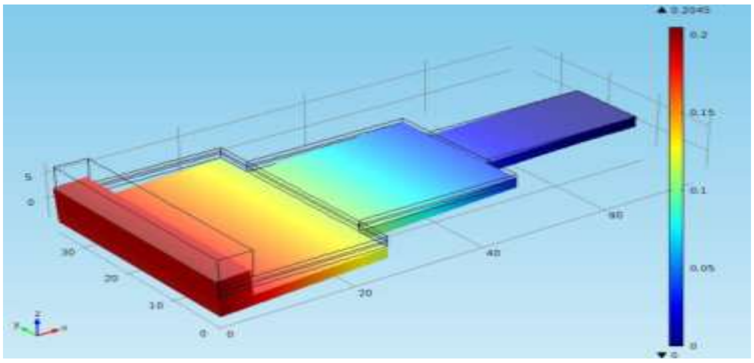

Figure 3 Displacement of rectangular cut cantilever structure with tip mass

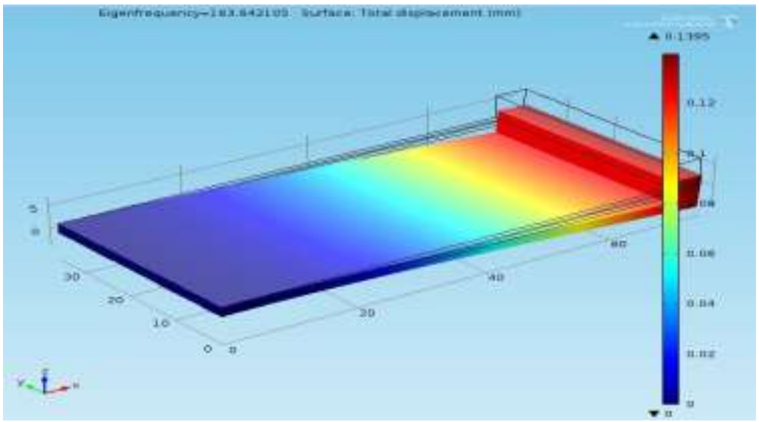

Figure 4 Displacement of rectangular cantilever structure with tip mass

4.1 Eigen Frequency Analysis

Eigen frequency analysis was conducted to obtain the resonance frequency of piezoelectric device. Knowledge of the resonance frequency is essential, since at resonance frequency, piezoelectric harvester will give optimum output with highest possible energy conversion efficiency. After the simulation, it was analyzed that the resonance frequency decreases with applied tip mass at the cantilever structure.

Table 2: Eigen frequency of cantilever structures

Rectangular cantilever structure			
	Rectangular unimorph	Rectangular bimorph	Rectangular bimorph with tip mass
Eigen frequency(Hz)	143.45	193.3069	173.63
Rectangular cut cantilever structure			
	Rectangular cut unimorph	Rectangular cut bimorph	Rectangular cut bimorph with tip mass
Eigen frequency(Hz)	86.31	111.99	99.7439

Cantilever beam can have many different modes of vibration, each with different resonance frequency. The first mode of vibration has lowest resonance frequency, provides maximum deflection and therefore maximum output voltage [7]. First four resonance frequencies of the rectangular cut structure are shown in the following figures (fig 5-8). It has been made clear that for the same length, width and thickness, rectangular cut structure with tip mass has lower resonance frequency as compared to other structures. Most of the vibration sources present in the environment vibrates at the frequency of 50-200 Hz, hence to match these frequencies, reduce the Eigen frequency of cantilever structure to obtained maximum output voltage.

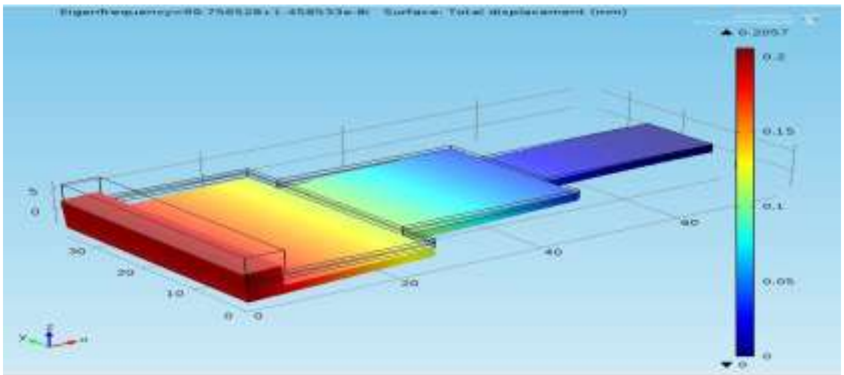

Figure 5 Eigen frequency at 99.74 Hz

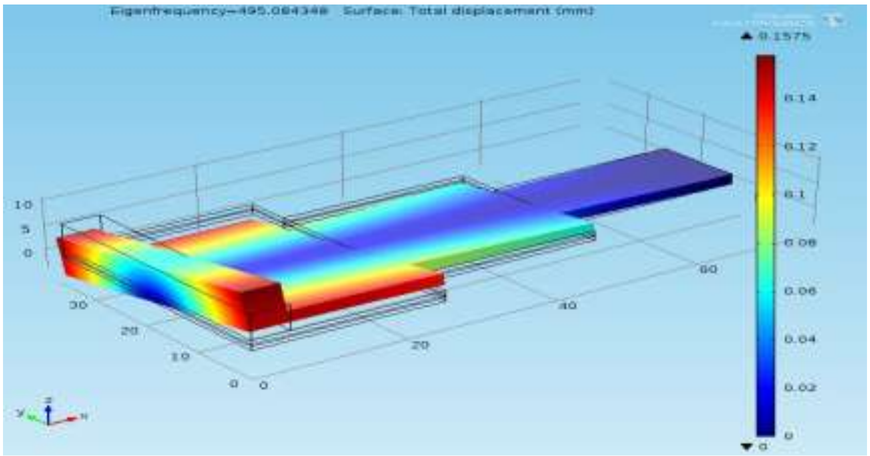

Figure 6 Eigen frequency at 495.08 Hz

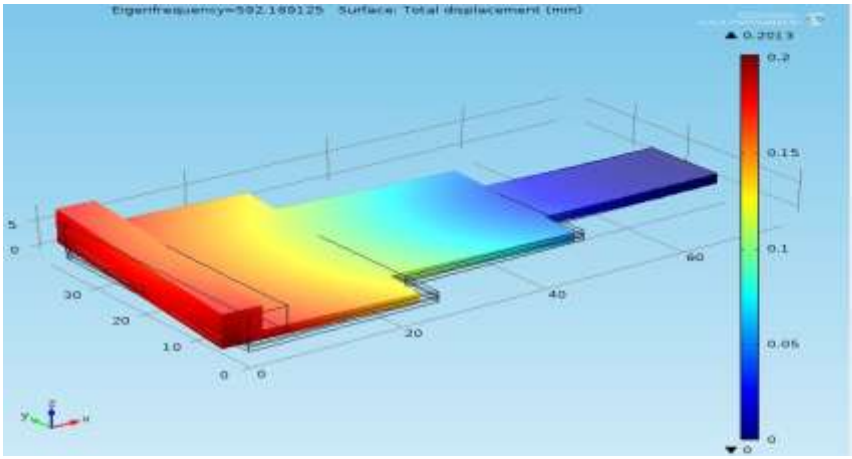

Figure 7 Eigen frequency at 592.16 Hz

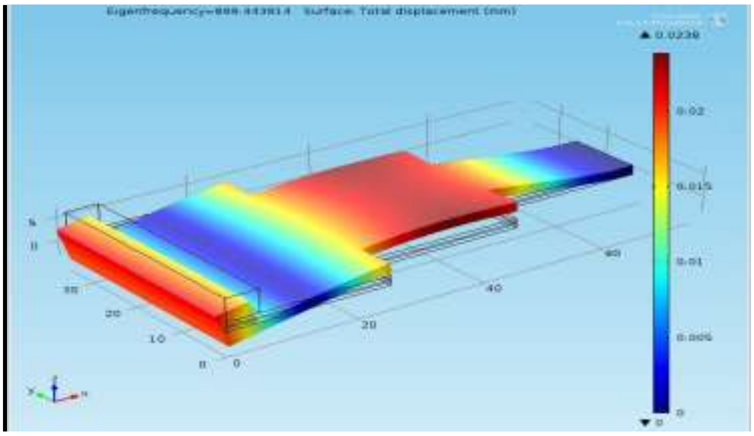

Figure 8 Eigen frequency at 899.44 Hz

4.2 Voltage Analysis

Potential differences among various cantilever structures are summarized in the Table below.

Table 3 Voltage of Cantilever Structures

Rectangular Cantilever Structure			
	Rectangular Unimorph	Rectangular Bimorph	Rectangular Bimorph with Tip Mass
Voltage(v)	3.67	4.1454	4.2335
Rectangular cut cantilever structure			
	Rectangular Cut Unimorph	Rectangular Cut Bimorph	Rectangular Cut Bimorph with Tip mass
Voltage(v)	3.6352	8.5648	8.568

Generated potential differences of rectangular cut bimorph with tip mass are shown in Fig.9. From the figure, it is analyzed that stress is maximum at the fixed end of the cantilever and minimum at the free end, therefore generated voltage is maximum at the fixed end. After the simulation of various structures, it is reported that voltage of rectangular cut with tip mass is maximum.

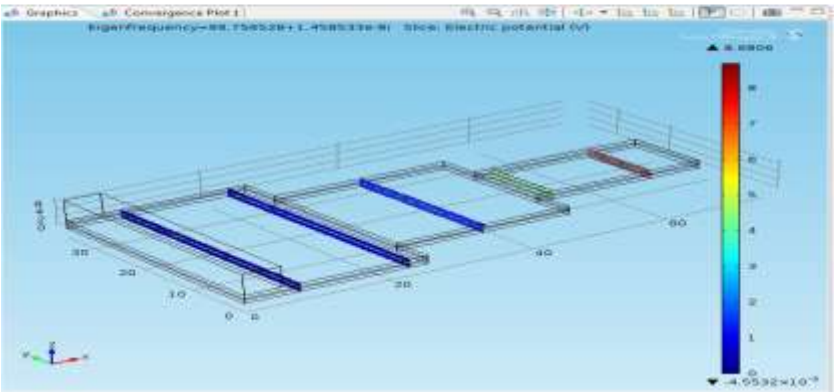

Fig. 9 Potential Difference of Rectangular Cut Cantilever at 99.74Hz.

4.3 Performance of Different Material on Piezoelectric Energy Harvesting

In this paper, five important piezoelectric materials are considered which consist of lead-based and newly developed lead-free piezoelectric materials. Ferroelectric lead zirconate titanate is most frequently used piezoelectric ceramic for sensor applications due to its superior electromechanical coupling factor [8]. A number of lead free ferroelectric and piezoelectric materials have been recently explored and will be examined in this study [9]. In addition, researchers have reported promising properties for polyvinylidene fluoride (PVDF), a ferroelectric polymer, for energy harvesting applications due to its low density, toughness and mechanical flexibility. The properties of Young's modulus (*E*), piezoelectric constant (e_{31}), dielectric constant (ε) and Poisson's ratio(*v*) are important material properties for energy harvesting application and multiple physical properties of a material have an impact on the performance.

The simulations are carried out to predict the output voltage, V across the piezoelectric layers and resonance frequency for different piezoelectric materials using FEM since rectangular cut cantilever can operate in voltage sensitivity mode. It is to be noted that to perform all the necessary numerical simulations, the geometric properties, boundary conditions (for mechanical boundary condition one edge is fixed and rest are free; for electrical boundary condition floating potential and ground are applied on piezoelectric layer), different base materials (Aluminum, Nickel, Silicon, Titanium, Steel) and loading conditions are held constant while different piezoelectric materials are substituted. A summary of the materials examined and their output voltage and resonance frequency are shown in Table 4.

Table 4 Summary of Piezoelectric Materials Examined

Substrate material	Piezoelectric layer	Eigen frequency(Hz)	Voltage(v)
Aluminum	PVDF	157.7	8.46
	PZT 4	114.724	8.44
	PZT -5A	98.72	8.51
	PZT -5H	99.74	8.56
	ZNO	157.7	8.47
Nickel	PVDF	37.36	8.38
	PZT 4	117.59	8.37
	PZT -5A	78.55	8.43
	PZT -5H	81.622	8.48
	ZNO	119.56	8.40
Silicon	PVDF	37.36	8.39
	PZT 4	117.59	8.46
	PZT -5A	101.30	8.52
	PZT -5H	102.39	8.56
	ZNO	8.49	162.19
Titanium	PVDF	8.4	28.22
	PZT 4	8.42	105.78
	PZT -5A	8.48	91.254
	PZT -5H	8.53	92.033
	ZNO	8.44	143.02
Steel	PVDF	8.36	37.36
	PZT 4	8.38	93.699
	PZT -5A	8.44	81.11
	PZT -5H	8.44	81.11
	ZNO	8.42	124.117

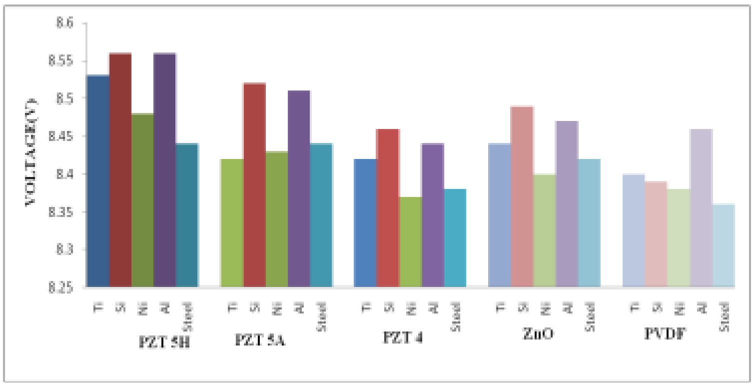

Figure 10. Output Voltage of Different Piezoelectric Materials

Fig. 10 shows the performance of different piezoelectric materials with different substrate materials. Piezoelectric materials (PZT 5H, PZT 5A, PZT 4, PVDF, ZnO) show the maximum output voltage with base material Silicon and Aluminum but for lower resonance frequency, Aluminum gives maximum output voltage.

It is observed that PZT 5H piezoelectric material shows the best performance for maximum voltage output and low resonance frequency with Aluminum substrate because of its large piezoelectric coefficient and dielectric constant, allowing it to produce more power for a given input acceleration [10].

V. Conclusion

In this paper piezoelectric cantilever energy harvester with dimensions 75 mm x 36 mm x 0.4 mm is designed and simulated using COMSOL Multiphysics. The simulation results such as Eigen frequency and voltage sensitivity are analyzed for different cantilever structures. It is analyzed that all cantilever structure have operated at resonance frequency between 80 to 200Hz and rectangular cut structure with tip mass have lower resonance frequency such as 88.31 Hz. Rectangular cut structure with tip mass give maximum output voltage 8.568V with applied force of 0.1N at resonance frequency of 88.31 Hz. The simulations are carried out to predict the output voltage (V) across the piezoelectric layers for different piezoelectric materials and substrate materials. The PZT 5H with Aluminum substrate demonstrates best performance in context of voltage output and resonance frequency compared to other piezoelectric materials under study. Hence for energy harvesting rectangular cut cantilever structure with tip mass by using PZT (5H) as piezoelectric layer and Aluminum as a substrate layer is best design.

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