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RESEARCH ARTICLE

Design of Piezoelectric MEMS Sensor for Energy Harvesting from Low Frequency Applications

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Abstract— This paper presents a design of a Piezo-electric sensor model which acts as an energy harvester based on vibrations. The ample vibration-based micro electromechanical systems (MEMS) piezoelectric harvester has become an important subject in most research publications. It provides a green and practically infinite alternative power source to conventional energy sources, this harvester will significantly explore the applications of wireless sensor networks, biomedical implants etc., which may generate mW or µW level of power. Vibration energy harvesting has been employed for converting ample amount of kinetic energy into electric energy by several different transduction methods. Amongst many transducing harvesters, the piezoelectric energy harvester (PEH) is compatible with MEMS technology and has a high electromechanical coupling effect and requires no external voltage sources and accordingly has been in most of recent research. The simplicity associated with piezoelectric micro-generators make them very attractive for MEMS applications in which ambient vibrations are harvested and converted into electric energy. These micro shaped-generators can become an alternative to the battery-based solutions in the future. In this paper, we propose a model and present the simulation of a MEMS-based energy harvester under ambient vibration excitation using the COMSOL 4.3b approaches.

Keywords— Piezoelectric energy harvesting system (PEHS), Piezoelectric materials; Energy conversion; cantilever; MEMS

I. INTRODUCTION

The ability associated with piezoelectric materials makes them very efficient for power harvesting. The captivating property of piezoelectric materials is that it possesses a large amount of mechanical energy that can be converted into electrical energy, and they can defy large strain magnitude applied to it. The ambient energy used in a PEHS is the kinetic energy of vibration that is substantially affected by amplitude and frequency of vibration in time domain [1]. This vibration can be resulted in movement of live creatures such as humans or mobile artifacts like vehicles.

Many methods have been found out to improve the harvested power of micro electromechanical systems (MEMS). One of the methods to improve harvested power is by changing the device configuration, accomplished by adding multiple piezoelectric materials to the harvester. Johnson et al. [2] demonstrated that, a highest power could be generated using the configuration under lower excitation frequencies and load resistance, as the charging and discharging will be slow and hence the voltage generated will be maximum.

The other method is the selection of a proper coupling mode of operation. It involves two modes in which the first mode which is called 31mode, conceives the excited vibration force being applied perpendicular to the poling direction. The second mode is the 33mode in which the force is applied on the same side as the poling direction. Between these two modes, the 31mode is the most commonly used, which produces a lower coupling coefficient "k" than the 33mode.

Similarly, Anderson and Sexton [6] found that varying the length and width of the proof mass affected the output of the harvested power

There are two kinds of structures that can be designed viz., the unimorph structure and the bimorph structure. A cantilever with one piezoelectric layer is called as unimorph while the structure with two piezoelectric layers is called as bimorph .Several researchers have carried out studies to improve the efficiency of bimorph structure. Jiang et al. [5] found that when a bimorph cantilever is attached with a proof mass to its tip. Their results showed that by reducing the bimorph thickness and increasing the attached proof mass decreased the harvester resonant frequency and produced a maximum harvested power.

Again two types of bimorph structure can be designed, namely, the series and the parallel types. Series and parallel triple-layer bimorph structures were presented by Ng and Liao [3,4].

The series triple-layer bimorph designed as metallic layer sandwiched between two piezoelectric materials and the piezoelectric layers were electrically connected in series. In the parallel triple-layer bimorph structure, which was also sandwiched between two piezoelectric layer bimorph and the piezoelectric materials were connected in parallel.

Ng and Liao investigated that in the parallel triple-layer bimorph highest power can be generated under medium excited frequencies and load resistance; while the series triple-layer bimorph generates the highest power when excited under higher frequencies and load resistance. At higher loads, the series connection method will increase the device impedance as well as it increases the output power generated. Fig.1 below depicts the types of structures.

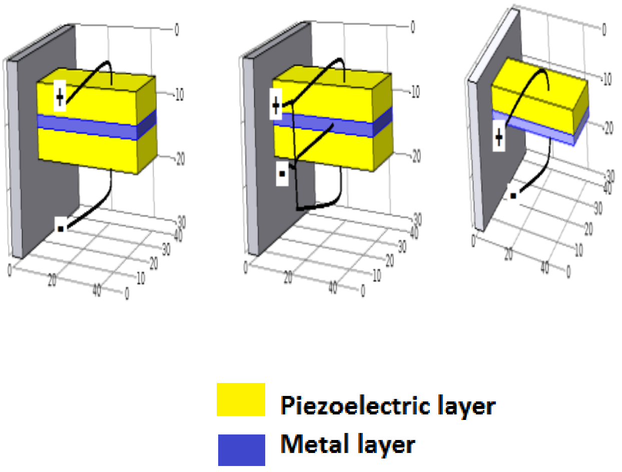


Fig 1- Piezoelectric cantilevers used in PEHS; (a) Bimorph-Series (b) Bimorph-Parallel (c) Unimorph

For improving the harvester's efficiency, the cantilever geometrical structure also plays an important role. In MEMS-based piezoelectric harvesters rectangular-shaped cantilever structures are most commonly used in. They are easy to implement and effective in harvesting energy from ambient vibrations, as stated in the review paper by Salem and Sidek [8]. Going forward the study conducted by Mateu and Moll [9] depicted that a triangular-shaped cantilever beam with a small free end can withstand higher strains and allows maximum deformation which gives higher power output in comparison with the rectangular beam by keeping parameters same as corresponding to triangular cantilever beam. Thus by changing the device shape there can be chances of getting more output than the present structures. This paper also suggests that the change in device structure changes the amount of output.

. Similarly Salem and Sidek [7] proposed that by increasing the cantilever branches one can get more harvested power out of a PEH system. Similar kind of work had been carried out by Roundy et al. [10]. They discovered that the strain on a trapezoidal-shaped cantilever beam can be more distributed throughout its structure. At the same they also observed that, for the same volume of lead zircon ate titan ate (PZT), the trapezoidal cantilever beam can deliver more than twice the energy than the rectangular-shaped beam can. They found that 30% more power could be achieved using the trapezoidal beam than that using the rectangular one.

Another way of increasing the efficiency of a PEHS is by tuning the device according to vibrations generated. If the frequency matches with vibrating frequency, the device produces resonating device with ambient vibrations. Shahruz [11, 12] designed a power harvester that can be resonated at various frequency ranges without the need for any adjustment. This device consisted of different cantilever beams with different lengths and different tip masses attached to its common base frame such that each cantilever has its own resonant frequency. But as the size and cost of the device increases, it is not practical to implement it. Rastegar et al.[12] designed a passive tuning system that had a two-stage system in which a very low frequency (0.2 Hz to 0.5 Hz) can be converted into potential energy and then transferred to the system at a higher natural frequency. Similar works on the modeling, design, fabrication, and simulations of shaped cantilevered structure MEMS based piezoelectric power harvesters were conducted by other authors [13–29].

II. **CANTILEVERED-BASED TYPICAL MEMS HARVESTER**

To achieve a maximum output power out of the cantilever beam based energy harvester, the resonant frequency should be taken into account. The device geometrical parameters of the cantilever beam and the mass attach to its tip decides the desirable resonant frequency of the harvester. Any slight deviation from the resonant frequency will cause a large reduction in the output power of such harvester. Thus, the main aim of this paper is to match the excitation frequency which is vibration frequency of the harvester and meet the optimal conditions for its output harvested power. This resonant frequency should be calculated carefully. To determine the value of resonant frequency of any cantilevered piezoelectric energy harvester, important parameters should be defined from its structure as denoted on figure 2.

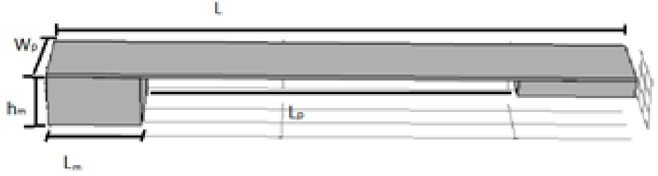


Fig 2- Typical MEMS based cantilevered piezoelectric energy harvester

Usually, the resonant frequency of a piezoelectric cantilever expressed by following equation 1 [30]

$$f_n = \frac{\upsilon_n^2}{2\pi l^2}\sqrt{\frac{EI}{m'}} \qquad (1)$$

Where f_n and n are the resonant frequency and the eigen value respectively of the nth mode, the cantilever length is *l* while E
is the Young's modulus which is nothing but modulus of elasticity, I is the moment of inertia about the neutral axis and *m'* is the mass per unit length of the cantilever. Equation 1 can be modified in terms of the bending modulus per unit width (Dp) as follows:

$$f_n = \frac{\upsilon_n^2}{2\pi l^2}\sqrt{\frac{D_p}{m}} \qquad (2)$$

A cantilever consists of two different material layers viz., PZT and Aluminium. Thus, the mass per unit area (m) is calculated by the sum of the products of the density and thickness of each layer. Eptp is the product of the density and thickness of the piezoelectric layer, whereas Ests is the product of the density and thickness of the support layer. As expressed by 3 [30], the bending modulus Dp is a function of Young’s modulus and the thicknesses of the both the given two layers, which is given by;

$$D_p = \frac{E_p^2 t_p^4 + E_s^2 t_s^4 + 2E_p E_s t_p t_s \left(2t_p^2 + 2t_s^2 + 3t_p t_s\right)}{12\left(E_p t_p + E_s t_s\right)} \tag{3}$$

Where tp and ts are the thicknesses while Ep, Es are the Young’s modulus of the two materials. The purpose of attaching a proof mass at the tip of the cantilever is to lower its resonant frequency and to provide a large displacement at the cantilever tip. The resonant frequency in this case is calculated by Equation (4) [30]

$$f_r = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K}{m_e}} \tag{4}$$

Where, $m_{e,}$ *w* and *K* are the effective mass of the cantilever angular frequency and the spring constant at the tip, respectively. When the size of the attached proof mass is smaller than the cantilever length, the resonant frequency approximation is expressed in [31] as,

$$f_n = \frac{\upsilon'^2_n}{2\pi}\sqrt{\frac{K}{m_e + \Delta m}}$$
$$\text{Where } \upsilon_n^2 = \upsilon'^2_n \sqrt{3/0.236} \tag{5}$$

Whereas the effective mass *me=0.236mwl by* considering the axial velocity that acts on the length or the width (w<<l). The spring constant K can be written as,

$$K = \frac{3D_p w_p}{l^3} \tag{6}$$

When the center of the proof mass has a concentrated load, its distance is lm/2 from the tip, and the effective spring constant at this point is expressed in Equation (7) [32]

$$K' = K\left(\frac{l}{l - l_m/2}\right)^3 \tag{7}$$

Therefore, by substituting the spring constant (K) in Equation (6) with the effective spring constant (K’), the resonant frequency of the cantilever with a proof mass is expressed by Equation (8)

$$f_n = \frac{\upsilon_n^2}{2\pi}\sqrt{\frac{0.236 w_p D_p \left(l - l_m/2\right)^3}{0.236 m w_p l^7 + \Delta m l^3 \left(l - l_m/2\right)^3}}$$
$$\Delta m = \rho_m l_m w_m h_m \tag{8}$$

Thus, the low resonant frequency of the cantilever beam can be determined either by increasing the cantilever length or by attaching a larger proof mass at its tip. Based on the previously mentioned equations, the design of a cantilever-based piezoelectric harvester demands a beam with high mechanical strength against vibration, as well as a higher mass density to meet the high efficiency requirement.

III. MODELING OF CANTILEVER-BASED MEMS ENERGY HARVESTER

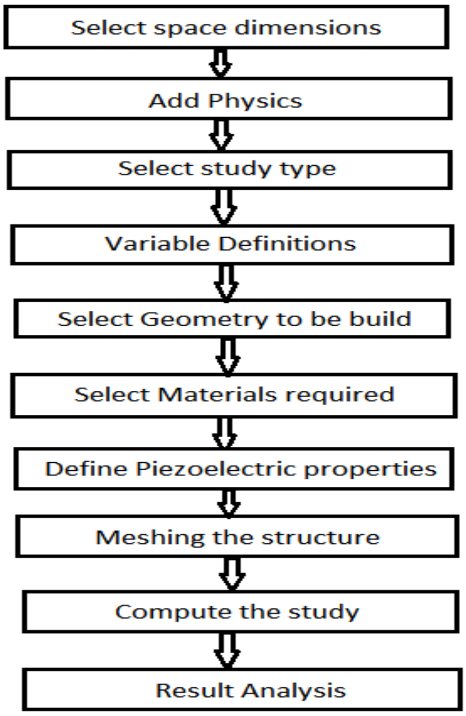


Fig 3-Modelling process steps of energy harvester

Fig 3 gives the flowchart of the steps carried out while designing of the model. All the steps mentioned above will be explicated in details throughout the design and simulation steps in the coming sections.

A. MATERIALS DECLARATION

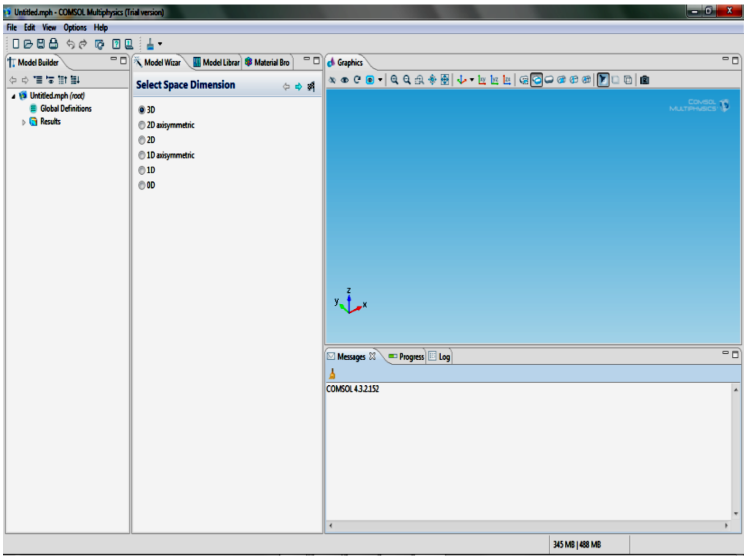
Four materials have been used in this design, such as Lead zircon ate titan ate (PZT), Silicon, Aluminium and Silicon dioxide (SiO_2). The supported anchor layer and the mass are of the same material (Si) due to the higher density of silicon, and a high electromechanical coupling of PZT compared to other piezoelectric materials. Four main materials have been used throughout the design, namely, PZT and silicon, Aluminium and Silicon Dioxide; their important properties are presented in Table 1.

TABLE1. MATERIAL PROPERTIES

Materials	**Density (kg/um^3)**	**Young's modulus (MPa)**	**Poisson's ratio**
PZT	7.55e-15	8.9e+4	0.25
Silicon	2.5e-15	1.69e+5	0.3
Aluminium	2.7e-15	7.3e+4	0.33
Silicon dioxide	2.27e-15	7.0e+4	0.17

B. MODELING PROCESSES

At the starting one has to open Model Wizard window and select the space dimensions. In that the user has to select from 3D, 2D, 1D, 2D axissymetric or 1D axissymetric.



Select Space Dimension

● 3D
○ 2D axisymmetric
○ 2D
○ 1D axisymmetric
○ 1D
○ 0D

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COMSOL 4.3.2.152
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Fig 4- Starting window of Comsol 4.3b

If the dimensions are not defined in Comsol4.3b, one can go for 1D or 2D dimensions and then transform it into 3D form. There after by selecting physics and the type of study, the user can proceed to design it actually. Specifying dimensions in Geometry, materials and their properties along with related specifications moving ahead towards computing the made structure.

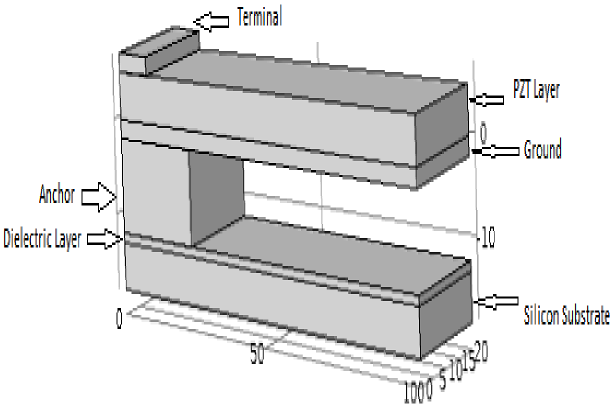

Fig 5- Geometrical structure of piezoelectric sensor

The mask layers are arranged from down to top according to the process modeling shown in figure 3. The purpose of the anchor fixed at the substrate surface to support all the cantilever layers of the system. Whereas each layer properties were defined previously at the material section and their lengths and widths can be reading in microns in geometry section.

This structure of the harvester is similar to the cantilever based structure of the previously discussed structures of several researchers, but in fact, here the proposed structure is different as the given single structure is without mass and the acceleration considered here is the gravitational acceleration which is 9.81 m/s^2.But the actual structure is different and it will be shown in coming sections. The result of single structure is given as shown in fig 7 below.

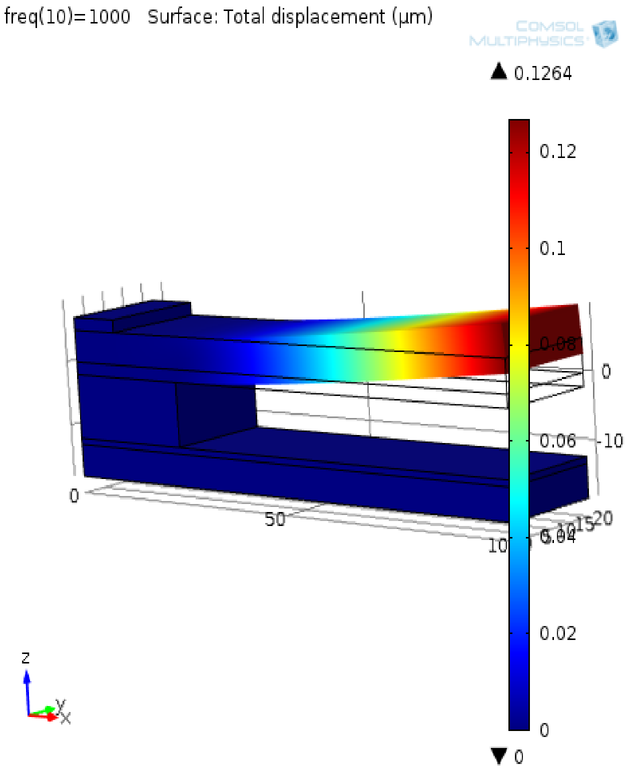

Fig 6- Result of single structure showing displacement at particular frequency

E. Boundary conditions

The applied force and acceleration as boundary conditions that affect the deflection magnitude of the cantilever depends upon the proof mass size connected to the tip end and the base acceleration of the harvester in the actual structure but in single structure without tip mass the output is taken. The acceleration in this case adjusted to 9.81 m/s2 as a base acceleration.

The measured value of pressure can be applied to the device by specifying it into the piezoelectric devices properties. By adding the mass at the tip the device is made to bend more so that more displacement will cause more deformation and hence more output voltage can be harvested.

Again the array of the single structure can be designed to get even better output than the single one. As the main objective is to design a device which could be practically implemented, hence for using it in bridge over which many types of vehicles go through; we can make an array of the given composition. According to the weight of vehicle and pressure that it exerts on the device the output voltage is harvested, which is the main objective.

The array structured device can be implemented where generation of vibrations is variable. They can work like a single beam with output generated more than it and when used as an array; it can be configured as a combination of these single structures. The Fig 8 shows the arrayed structure again with no load.

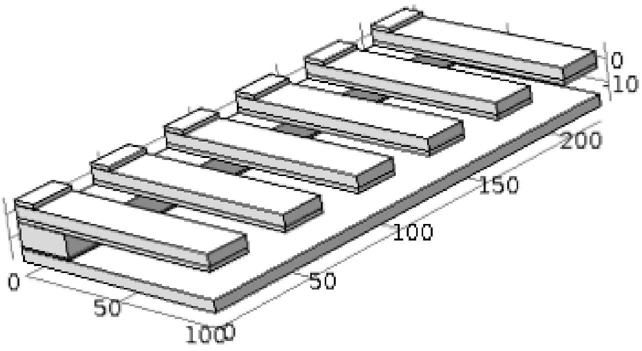

Fig 7(a)- Geometrical array structure

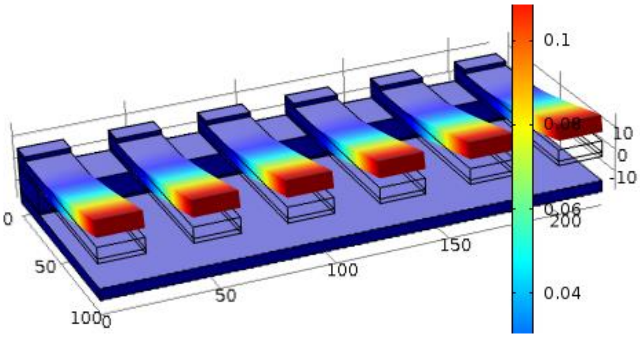

Fig 7(b)- Array structure displacement

Output voltage and displacement

The output from a single cantilever structure has comes out to be 0.1268 um displacement for 100Hz frequency and the output voltage comes out to be 0.273Volts.(This is the maximum voltage harvested out of above structure.)

The output from the above arrayed cantilever structure has comes out to be 0.3475 Volts at frequency of vibration equals to 3000Hz and the displacement is 0.127 um.

CONCLUSIONS

The above model designed in Comsol 4.3b depicts that the energy harvesting through vibrations can be made and the harvested voltage can be increased if used the proper material and the layers of PZT material along with the supporting materials in the structure.

The maximum output voltage seen in this structure is 0.273Volts for single cantilever beam and 0.3475 volts for the arrayed structure of the same.

Hence the conclusions can be made that by increasing the cantilever branches the harvested power can be increased as well as if the cantilever attached with masses at their tips also increases the output, but causes more difficulties in MEMS fabrication process.

ACKNOWLEDGMENT

As this work has been done in COMSOL4.3b, the mentioned software trail version was made available in the COMSOL workshop conducted by COMSOL-India in Nagpur by Mr. Siddharth Gadkari, dated July 11 2013. Conveying regards hereby for giving platform.

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