

Simulation and Optimization of MEMS Piezoelectric Energy Harvester with a Non-traditional Geometry

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Abstract: Piezoelectric energy harvester converts mechanical vibration into electrical energy via piezoelectric effect. In this paper a MEMS based energy harvester with a non-traditional geometry is designed. The design of the energy harvester consists of a T-shaped cantilever structure with triangular shape at the tip. Simulation results demonstrated that the new cantilever structure can improve the strain distribution and generate more voltage than the triangular and rectangular structures at the resonance frequency. The proposed structure is simulated using the software COMSOL Multiphysics and the results are compared with other geometries such as rectangular and triangular.

Keywords: Energy harvesting, unimorph cantilever, non-traditional geometry, piezoelectric energy harvester.

1. Introduction

The energy harvesting devices converting ambient energy into electrical energy have attracted much interest within academic community and industry. Ambient energy is available in the form of vibration, light, temperature gradient etc. Among these energy, mechanical vibration is the most widespread and wasted energy in the environment. This mechanical vibration can be converted into electrical energy by three kinds of generators such as electromagnetic, electrostatic and piezoelectric. Piezoelectric generators are mostly used because piezoelectric materials have the advantage of large power and ease of application.

The most studied energy harvesters are based on the piezoelectric effect and are made with MEMS technology. The geometry of piezoelectric cantilever beam greatly affects its vibration energy harvesting ability [1]. In this paper MEMS based energy harvester with a non-traditional geometry is designed and simulated

with COMSOL for the conversion of mechanical into electrical energy.

2. Modelling in COMSOL Multiphysics:

Piezoelectric application mode is used to model and simulate the non-traditional geometry and moving mesh application mode is used to optimize the thickness of piezoelectric layer that maximize the output electrical energy.

2.1 Geometry

A 3 dimensional geometry is considered for the simulation. The MEMS piezoelectric energy harvester has a unimorph T-shaped cantilever with triangular shape at the tip, as shown in figure1. The device is made by a stainless steel substrate with a piezoelectric layer on the top, poled along the thickness direction. The total length of the substrate is $27000\mu\text{m}$ and total width is $3000\mu\text{m}$. The thickness of the substrate $T_0 = 200\mu\text{m}$ and that of piezoelectric layer T_1 is set initially as $60\mu\text{m}$ and then varied from $10\mu\text{m}$ to $400\mu\text{m}$ with the moving mesh application.

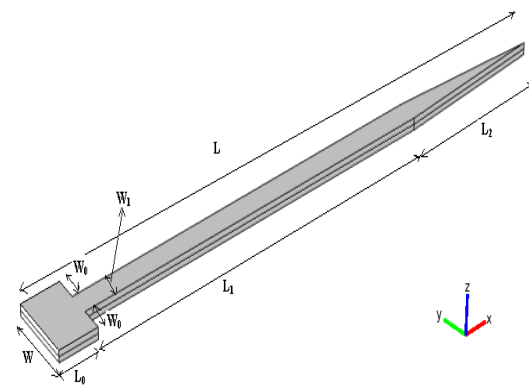


Figure 1. Structure of piezoelectric energy harvester with non-traditional geometry. $L=27000\mu\text{m}$, $L_0=2000\mu\text{m}$, $L_1=18000\mu\text{m}$, $L_2=7000\mu\text{m}$, $W=3000\mu\text{m}$, $W_0=W_1=1000\mu\text{m}$, $T_0=200\mu\text{m}$, $T_1=210\mu\text{m}$.

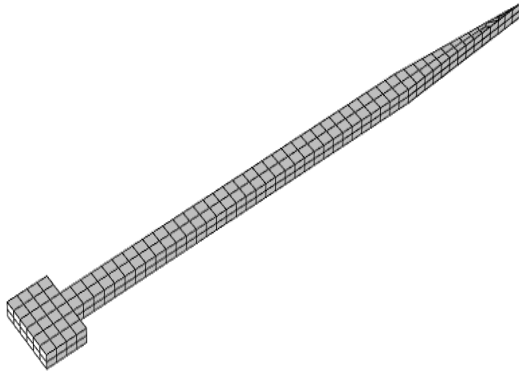


Figure 2. Piezoelectric Energy Harvester mesh.

2.2. Meshing

Figure 2 shows the meshing of piezoelectric energy harvester. The mesh consists of 238 quad elements for a total number of degrees of freedom 10639. The swept mesh tool is used to create mesh using opposite vertical surfaces of each layer as a source face and target face.

2.3. Piezoelectric Equations

Piezoelectric materials produce electrical charge when it is mechanically deformed. The piezoelectric energy harvester is governed by the following equations written in the strain-charge format

$$\begin{aligned} S &= s^E T + d E \\ D &= \varepsilon^T E + d T \end{aligned} \quad (1)$$

Where S is the mechanical strain vector, s^E elastic compliance tensor (Pa^{-1}), T mechanical stress vector (Nm^{-2}), D the elastic displacement vector (Cm^{-2}), ε^T the dielectric permittivity tensor (Fm^{-1}), E the electric field vector (Vm^{-1}) and d the transverse piezoelectric coefficient tensor (CN^{-1}). For the substrate layer only mechanical behaviour is considered using stress-strain relationship

$$S = sT \quad (2)$$

Where s is the compliance of stainless steel substrate.

2.4 Subdomain settings

The geometry consists of two subdomains, one for the substrate layer and another for the

piezoelectric layer. The substrate is made of stainless steel using the decoupled isotropic material available in the COMSOL material library. The material parameters of the substrate are as follows: its density $\rho=7850 \text{ kg/m}^3$, young's modulus $E=200 \times 10^9 \text{ Pa}$, its Poisson's ratio $\mu=0.33$.

The active layer of unimorph is made up of ultra low-temperature piezoelectric material (0-3 composite) [2] and it is modelled using the following set of properties

-Elastic compliance tensor

$$S^E = \begin{bmatrix} 50 & -20 & -20 & 0 & 0 & 0 \\ -20 & 50 & -20 & 0 & 0 & 0 \\ -20 & -20 & 50 & 0 & 0 & 0 \\ 0 & 0 & 0 & 70 & 0 & 0 \\ 0 & 0 & 0 & 0 & 70 & 0 \\ 0 & 0 & 0 & 0 & 0 & 70 \end{bmatrix} \times 10^{-12} \text{ Pa}^{-1}$$

-Piezoelectric tensor

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & 11 & 0 \\ 0 & 0 & 0 & 11 & 0 & 0 \\ -2.5 & -2.5 & 5 & 0 & 0 & 0 \end{bmatrix} \times 10^{-12} \text{ CN}^{-1}$$

-Relative permittivity matrix

$$\varepsilon^T = \begin{bmatrix} 50 & 0 & 0 \\ 0 & 50 & 0 \\ 0 & 0 & 50 \end{bmatrix} \times \varepsilon^0$$

-Density $\rho = 3000 \text{ kg m}^{-3}$

The vertical acceleration is applied using body load F_z equal to $a\rho$ in each subdomain, where $a = 0.1g$ represents the acceleration magnitude and ρ is the density of the material [2].

3. Boundary conditions

3.1 Piezo solid model

One end of the unimorph cantilever is fixed while other is free for vibration. Therefore the fixed constraint condition is applied for the vertical faces of both the layers, while all other faces are free of displacement. In order to pole piezoelectric layer along thickness direction, the electrical behaviour of PZT must be considered and it is modelled with the electrostatic boundary conditions. The upper and lower face of PZT layer are selected as floating and ground potentials respectively, while all other faces of piezoelectric layer are kept as zero charge [3].

3.2 Moving mesh ALE

Moving mesh application mode is used to optimize the thickness of the PZT layer. The bottom face of the piezoelectric subdomain is constrained as clamped while the vertical faces were clamped along thickness and left unconstrained along tangential direction allowing them to stretch freely. The upper face of the piezoelectric layer was tangentially constrained and displaced in the normal direction to the surface by a given displacement, using a parameter *deltaThickness*. The parameter *deltaThickness* is changed from 10µm to 400µm obtaining parameterized moving mesh.

4. Modelling and Optimization

4.1. FEM modelling of piezoelectric energy harvester with three different geometries

A finite element model is the basis of simulation analysis, so at first piezoelectric energy harvester in figure 1 is modelled by using the software COMSOL Multiphysics and then the model is used to study the deformation, strain and generated voltage distribution of a piezoelectric energy harvester.

Material properties are applied as described in 2.3 and 2.4 and boundary conditions are applied as explained in section 3. The FEM modelling of rectangular, triangular and non-traditional geometries are obtained as in figure 3.

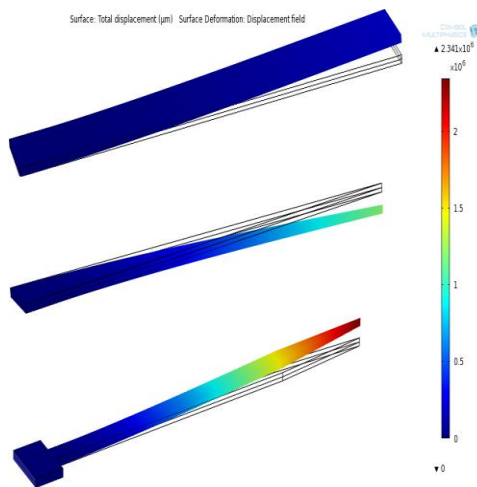


Figure 3 FEM modelling of rectangular, triangular and non-traditional geometries.

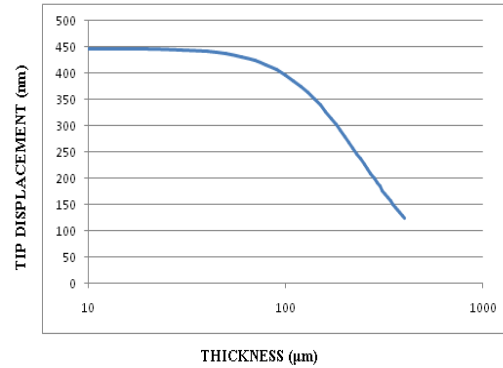


Figure 4 Tip displacement (nm) Vs Thickness(µm).

4.2. Thickness optimization of piezoelectric layer for three different geometries

Moving mesh Arbitrary Lagrangian Eulerian (ALE) method is used to compute the new piezoelectric layer dimensions. The displacement at the free tip of the piezoelectric energy harvester, the open circuit voltage and the generated charge collected on the electrodes were computed for piezoelectric layer thickness varying from 10µm to 400µm. The obtained tip displacement is shown in figure 4 in log-log scale. The tip displacement decreases with the increase in PZT layer thickness.

Figure 5 shows open circuit voltage and the charge generated on the piezoelectric energy harvester electrodes when the piezoelectric layer thickness is varied. The charge reaches maximum for the low piezoelectric layer thickness, decreasing then when the rigidity of the piezoelectric layer becomes significant and it influences the whole converter rigidity. On the other hand, the converter capacitance C monotonically decreases with thickness with an inverse proportionality. For this reason, being the output voltage V the ratio between charge Q and capacitance C , the voltage increases for a constant charge level Q , and it remains instead constant when both Q and C decrease.

The electrical energy converted from mechanical vibrations are stored in the piezoelectric material was computed with the following equation and it is plotted in figure 6 as a function of the piezoelectric layer thickness

$$E = \frac{1}{2} QV \quad (3)$$

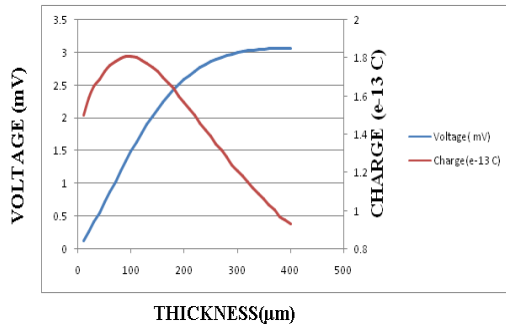


Figure 5 voltage (mV) Vs thickness (μm) and charge ($e-13$) Vs thickness (μm).

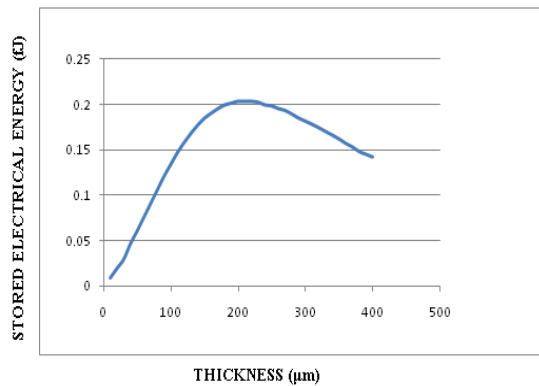


Figure 6 Stored electrical energy (fJ) Vs thickness (μm).

The energy shows a maximum for a thickness value of $210 \mu\text{m}$ and it is considered as the optimal piezoelectric layer thickness. In the optimal condition the thickness ratio $t_{\text{PZT}}/t_{\text{substrate}}$ has a value of 1.05.

5. Results

5.1 Frequency analysis

In order to obtain the resonant frequency, frequency analysis is carried out at the optimal thickness value of PZT layer which is $210 \mu\text{m}$. The Eigen frequency for non-traditional, rectangular and triangular geometry are obtained and plotted in figure 7. The graph shows that at resonant frequency, the generated voltage of non-traditional geometry is greater than that of other two geometries.

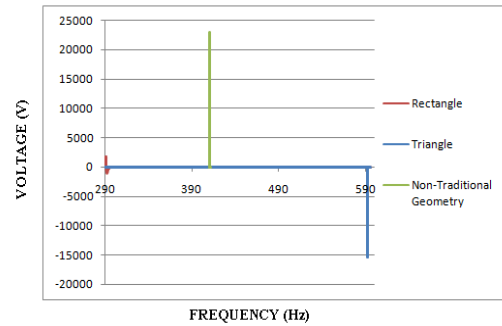


Figure 7 Voltage (V) Vs Frequency (Hz) for three different geometries.

5.2 Strain analysis

The strain is the most important factor of affecting electric energy generation. According to piezoelectric effect equation, the generated voltage output of the piezoelectric vibrator is proportional to strain. In other words, the more strain of each location is the more generated voltage output. Finite element simulation used to obtain strain curves of a rectangular, triangular and non-traditional piezoelectric energy harvester in the direction of length and is shown in figure 8.

It can be seen from figure 8, the strain of the piezoelectric energy harvester with non-traditional geometry is more than those of rectangular geometry and triangular piezoelectric energy harvester. Simulation result shows that the distribution of strain can be improved effectively by using piezoelectric energy harvester with non-traditional geometry, which will be useful to harvest more vibration energy.

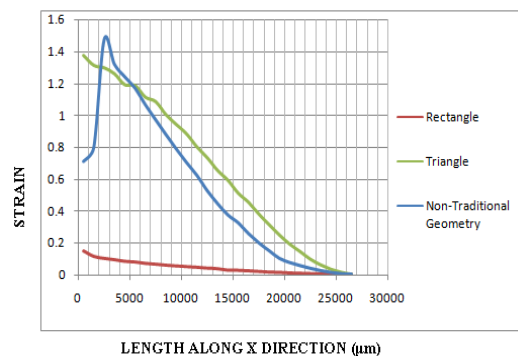


Figure 8 Strain curves of three different geometries along X direction.

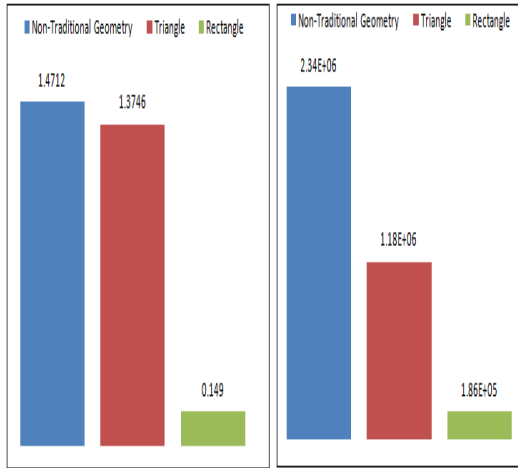


Figure 9. Performance comparison.

Figure 9 shows the comparison of deformation and strain of three different piezoelectric energy harvester geometries.

Conclusions

A piezoelectric energy harvester with non-traditional geometry was designed and simulated in COMSOL Multiphysics. The thickness of PZT layer was optimized to give maximum stored electrical energy. Frequency analysis and strain analysis were carried out for the optimized thickness of $210\mu\text{m}$. Simulation results demonstrate that the piezoelectric energy harvester with non-traditional geometry improves strain and generate more voltage at resonant frequency than the rectangular and triangular piezoelectric energy harvester.

7. References

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