Develop A Vibration Based MEMS Piezoelectric Energy Harvester Using Micro Cantilever Beam

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Abstract
Energy harvester is a self-generating energy source which is able to run small scale electronic devices. It largely reduces the dependency on external power source. This paper represents the utilization of micro cantilever beam to develop a vibration based electromechanical systems (MEMS) piezoelectric energy harvester system. The proposed micro cantilever part has been developed by finite element method (FEM) using COMSOL. The motivation behind this research is to calculate the resonant frequency of the harvesting and electrical voltage behaviour considering cantilever beam length and thickness. The materials (i.e., silicon, PZT-5H) have been studied to improvevoltage efficiency. The proposed micro cantilever beam has been able to generate 0.4V in COMSOL. Finally, the result of proposed method is compared with other existing methodsto validate the outcomes.

Keywords: Energy harvesting, Piezoelectric, Material, FEM

Introduction
The concept of “piezoelectric” has been received much attention in the past decade as a global interest with the development of low-power electronic devices such as microelectronics, wireless sensor nodes and etc. Wireless sensor network (WSN) which is consisted of hundreds or thousands of sensor nodes uses in many areas (i.e. different environmental conditions) [1]. The WSN has many real world applications in the field of industrial automation [2, 3], structural health monitoring [4], healthcare [5], Fluid Interactions[6] and civil and military applications [7]. Most of the commercial wireless nodes are powered by standard batteries [8]in which the life span of battery is limited. Besides this, the other disadvantages are maintenance, environmental effect and frequent replacement.

The capability of energy conversion from mechanical vibration to electrical energy is comparatively high. A large number of researches have been carried out to improve the ordinary and effective energy harvesting from vibration using piezoelectric materials. Many methods have been utilized to improve the harvested power of micro electromechanical systems (MEMS). One of the methods to improve harvested power is the modification of device configuration accomplished by changing and adding multiple piezoelectric materials to the harvester. Piezoelectric materials are available in many forms including single crystals (e.g. silicon), ceramics e.g. lead Zirconate-Titanate (PZT) and polymeric materials e.g. Polyvinylidene fluoride (PVDF) [9]. The energy harvester can generate more energy with proper combination of above materials. The energy harvesting based on vibration should be able to react to the low frequency that generally exists in the ambient source. A power producing device of PZT thin file with electrodes can generate an average power of 1.0 µW from 108 m/s² vibration acceleration at its resonant frequency of 13.9 kHz [10].

The most usable vibration based energy harvesting modes are electrostatic, electromagnetic and piezoelectric transducer. Among the three modes of harvesting, piezoelectric energy harvesting has received the most attention due to its simple configurations, precise control and high converting efficiency [11]. The ultimate goal of this research work is to design a low resonancelfrequency (10.77Hz to 202.435Hz) based MEMS micro cantilever module (i.e. piezoelectric energy harvester) that can generate high voltage. The rest of the paper is organized as follows: Section 2 describes configuration of the MEMS cantilever beam. Section 3 presents developed micro cantilever beam using COMSOL. Section 4 represents Simulation results in micro cantilever beam using COMSOL platform. Finally conclusion is given in section 5.

Configuration of the MEMS cantilever beam
There are two types of piezoelectric materials, piezoceramics like Lead Zirconate Titanate (PZT) and piezopolymers like Polyvinylidene Fluoride (PVDF). This work has been designed a single layer material (i.e. PZT-5H, silicon) based piezoelectric cantilever beam to harvest the energy. One of the most important parameter to design a piezoelectric cantilever beam vibration based energy harvesting device is resonant frequency has been considered. The range of frequency is common for environmental vibrations between 60 Hz and 200 Hz [12]. The resonance and governing equations frequency of bimorph cantilever is given by Eq. shown in (1) to (4). A bimorph cantilever consists of two layers of piezoelectric material, and can improve mechanical strength at the centre. Figure.1 shows the schematic diagram of the Unimorph cantilever [13]. There have various kinds of PZT the highest electromechanical coupling coefficient and Curie temperature (maximum temperature in a piezoelectric material) among the other piezoelectric materials as shown in Table. 1. Mostly, a PZT is suitable piezoelectric material easily poled and has a large range of dielectric constant. The mechanical and electrical behavior can be modeled by Eq. (5) to (8) constitutive equations.
Figure 1: Conventional bimorph cantilever.

\[
f = \frac{z_n}{2\lambda} \left( \frac{33}{140} K_p w \left( l - \frac{l_m}{2} \right) \left( b_m + m \right) \right)
\]

(1)

Where,

\[ m = \rho_p t_p + \rho_s t_s \]

(2)

\[ b_m = \frac{33}{140} m w \left( l - \frac{l_m}{2} \right) + m w \frac{l_m}{2} \]

(3)

\[ K_p = \frac{(E_p t_s^4 + E_s t_p^4 + 2E_p E_s t_p t_s (2t_p^2 + 2t_s^2 + 3t_p t_s))}{12(E_p t_p + E_s t_s)} \]

(4)

Young’s modulus of piezoelectric material and Young’s modulus of substrate are \( E_p \) and \( E_s \). Length of proof mass \( l \) and \( m \) mass of piezoelectric material. The thickness of the piezoelectric material and thickness of substrate are \( t_p \) and \( t_s \). The density of piezoelectric material and the density of substrate material are \( \rho_p \) and \( \rho_s \). The length of the piezoelectric beam \( l \) and width of the cantilever is \( w \). The fundamental mode of the cantilever is \( z_n = 1.875 \).

\[ S_{ij} = S_{ijkl} T_{kl} + d_{ijkl} E_k \]

(5)

\[ D_i = d_{ijkl} T_{kl} + e^{ijkl} E_k \]

(6)

\[ S_{ij} = S_{ijkl} G_{ij} + g_{ijkl} D_k \]

(7)

\[ E_i = g_{ijkl} T_{kl} + \beta^{ijkl}_l D_k \]

(8)

where \( i, j, k, l \) is the value 1, 2, 3 and the notations, \( s \) is the elastic compliance constant (m/2N), \( S \) is the strain component, \( T \) is the stress component (N/m2), which \( T \) means at point of constant stress, \( d \) is the piezoelectric constant (m/V or c/N), \( E \) means at constant electric field, which \( E \) is the electric field component (V/m), while \( D \) means at constant electric displacement, \( g \) is the piezoelectric constant (V/m/N or m2/C), \( \varepsilon \) is the dielectric constant of piezoelectric device (m/F).

Table 1: Piezoelectric Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>( d_{31} ) (pC/V)</th>
<th>( T_c ) (°C)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz (single crystal)</td>
<td>2.3</td>
<td>-</td>
<td>[14]</td>
</tr>
<tr>
<td>BTO (polycrystalline)</td>
<td>79</td>
<td>80~100</td>
<td>[15]</td>
</tr>
<tr>
<td>PVDF (film)</td>
<td>23</td>
<td>80-100</td>
<td>[6]</td>
</tr>
<tr>
<td>PZT (sol-gel thin film)</td>
<td>190-250</td>
<td>-</td>
<td>[7]</td>
</tr>
<tr>
<td>ZnO (sputtered thin film)</td>
<td>10.5-11.5</td>
<td>-</td>
<td>[7]</td>
</tr>
<tr>
<td>PZT (sputtered thin film)</td>
<td>100</td>
<td>-</td>
<td>[8]</td>
</tr>
<tr>
<td>AlN (thin film)</td>
<td>-</td>
<td>-</td>
<td>[9]</td>
</tr>
</tbody>
</table>

Developed micro cantilever beam using COMSOL

The proposed micro cantilever beam is designed using COMSOL software as shown in Figure 2. All the mentioned steps in the flow chart will be explained in details throughout the design and simulation steps on the coming sections.
The COMSOL multiphysics 4.3a has been used to model a vibration based piezoelectric energy harvester. The resonance frequency is used between 10.799 Hz to 202.435 Hz to design the model. The cantilever beam is a two-layered bending element mounted. The PZT-5H and silicon material is used as a layer both side on the cantilever beam. In this model, silicon material is added on the piezoelectric surface to design cantilever beam and the performance of the beam is tested using above mentioned frequency ranges. It is important to note that the one end of the beam is kept fixed while other end is free to move. It is done by using structural mechanics module of the COMSOL.

Selecting Physics and study type
Finite element model of the micro energy harvester is executed in COMSOL by employing “structural mechanics” with piezoelectric devices applications mode from ADD PHYSICS tree and selecting Eigen frequency from STUDIES.

Geometry Modelling and defining materials
The COMSOL multiphysics drawing tools are used to create the three dimensional (3-D) micro cantilever. The model of PZT-5H micro cantilever beam is consisted of length 0.01 m, width 0.003 m and thickness 0.0001 m with the. However, the silicon mass is composed of length 0.0015 m, width 0.003 m and height 0.0002 m as shown in Figure2. The coordinate(x = 0.0053 m, y = 0.003 m and z = 0.0001 m) is selected for proper placement of silicon mass on PZT cantilever beam. The cantilever beam is orientated along the global x-axis. Table. 3 and Table. 3 summarizes the geometric range and material values of the micro cantilever beam.

Table 2: Geometry properties of micro cantilever in COMSOL

<table>
<thead>
<tr>
<th>Model segment</th>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
<td>0.01</td>
<td>m</td>
</tr>
<tr>
<td>PZT-5H layer</td>
<td>Width</td>
<td>0.003</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>0.0001</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>0.0015</td>
<td>m</td>
</tr>
<tr>
<td>Silicon Layer</td>
<td>Width</td>
<td>0.003</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>0.0002</td>
<td>m</td>
</tr>
</tbody>
</table>

Table 3: Property of material of micro cantilever in COMSOL

<table>
<thead>
<tr>
<th>Materials</th>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT-5H</td>
<td>Density</td>
<td>7500</td>
<td>kg/m³</td>
</tr>
<tr>
<td></td>
<td>Young’s modulus</td>
<td>170e2</td>
<td>Pa</td>
</tr>
<tr>
<td>Silicon</td>
<td>Poisson’s ratio</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>2329</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

Meshing
The mesh application, which defines the relation between the 3-D structure and reference structure, solves mash smoothing equations inside the COMSOL to define the coordinate transformations of the beam. Figure 4 depicts the mesh modelling of cantilever beam.

Simulation results in micro cantilever beam using COMSOL Platform
The vibration based piezoelectric energy harvester model is simulated in COMSOL surface. It provides different beam displacement corresponding to resonance frequency and electrical voltage corresponding to beam length and thickness. Figure 5 (a, b, c, d) represent the beam displacement corresponding to resonance frequency 10.799 Hz, 34.535 Hz, 178.62 Hz and 202.435 Hz respectively. The vertical colour bar denotes the model displacements in meter of each point in the structure. The performance of the developed micro cantilever generates voltage corresponding different resonance frequency. The different modes of a simple micro cantilever beam with resonance frequency as shown below:

Figure 5(a): First mode resonance frequency 10.799 Hz.
The paper also studies how variation the resonant frequencies of the piezoelectric energy harvester structure are affected by the length, the width and the thickness of the cantilever beam. Different simulation results are plotted in Figure 6(a), (b), (c) shows below that compare with the analytical results. Figure 6(a) represents the cantilever beam length is increases with the resonance frequency is decreases when the width and thickness is fixed. Figure 6(b) represents the thickness of the beam has great effect with the resonance frequency. Figure 6(c) represents the cantilever beam width slowly increases with the resonance frequency that no significant effect like beam length and thickness. It is concluded from the graph thickness dramatically increase with the resonance frequency.

The output voltages of the suggested method are shown in Figure 7(a) and Figure 7(b). Figure 7(a) shows the output voltage with beam length where beam length varies from 1cm to 10cm. The maximum output voltage is obtained when beam length 10cm. Similarly, Figure 7(b) shows the output voltage where beam thickness various from 0cm to 0.7cm. The maximum output voltage is obtained when beam thickness 0.1cm. The results obtained in this study is compared with others method as shown in Table 4. The results clearly
represented that the proposed method outperforms the others methods.

![Figure 7(a): Variation voltage with length of beam.](image)

![Figure 7(b): Variation of voltage with thickness of beam.](image)

**Table 4**: Comparison with previous work

<table>
<thead>
<tr>
<th>Beam Length</th>
<th>Beam Width</th>
<th>Beam Thickness</th>
<th>Materials</th>
<th>Voltage</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>110mm</td>
<td>-</td>
<td>-</td>
<td>PVDF</td>
<td>0.2 V</td>
<td>[13, 17]</td>
</tr>
<tr>
<td>-</td>
<td>90mm</td>
<td>-</td>
<td>PZT-5H</td>
<td>0.35 V</td>
<td>[13, 16]</td>
</tr>
<tr>
<td>10cm</td>
<td>1.3cm</td>
<td>0.1cm</td>
<td>PVDF</td>
<td>0.4 V</td>
<td>This work</td>
</tr>
<tr>
<td>10cm</td>
<td>1.3cm</td>
<td>0.1cm</td>
<td>PZT-5H</td>
<td>0.4 V</td>
<td>This work</td>
</tr>
</tbody>
</table>

**Conclusion**

This paper represented the modelling, simulation of piezoelectric energy harvester based on micro cantilever beam. The micro cantilever was developed using COMSOL multiphysics software. The developed micro cantilever beam with the silicon and PZT-5H material in COMSOL was produced 0.4V. Thereafter, the results obtained in this study were compared with others well known methods. Finally, it is concluded that the proposed method performs better than other methods.

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**References**


