SIMULATION AND OPTIMIZATION OF MEMS PIEZOELECTRIC ENERGY HARVESTER WITH A NON-TRADITIONAL GEOMETRY

S. Sunithamani¹, P. Lakshmi¹, E. Eba Flora¹
¹Department of EEE, College of Engineering, Anna University, Chennai, India.

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Introduction

• The energy harvesting devices converts ambient energy into electrical energy.
• It is the concept by which energy is captured, stored and utilised.
• 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.
Theory

- Conversion of Mechanical vibration into electrical energy
  - Electromagnetic
  - Electrostatic
  - Piezoelectric.
- Piezoelectric generators are mostly used because piezoelectric materials have the advantage of large power and ease of application.
- Direct piezoelectric effect: surface charge induced by a mechanical stress.
- 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.
- 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.
- Also the results are compared with other geometries such as rectangular and triangular.
Use of COMSOL

Geometry
The geometry consists of two subdomains,
1. substrate layer - stainless steel.
2. piezoelectric layer - active layer of unimorph.

Figure 1. Structure of piezoelectric energy harvester with non-traditional geometry. L=27000µm, L₀=2000µm, L₁=18000µm, L₂=7000µm, W=3000µm, W₀=W₁=1000µm, T₀=200µm, T₁=210 µm.
Meshing and Governing Equations

Meshing
• The mesh consists of 238 quad elements for a total number of degrees of freedom 10639.
• The swept mesh tool is used.

Figure 2. Piezoelectric Energy Harvester mesh.

Piezoelectric Equations
\[ S = s^E T + d E \]  \hspace{1cm} (1)
\[ D = \varepsilon^T E + d T \]
Where
S - the mechanical strain vector
\( s^E \) - elastic compliance tensor (Pa\(^{-1}\))
T - mechanical stress vector (Nm\(^{-2}\))
D - elastic displacement vector (Cm\(^{-2}\))
\( \varepsilon^T \) - the dielectric permittivity tensor (Fm\(^{-1}\))
E - the electric field vector (Vm\(^{-1}\))
d - the transverse piezoelectric coefficient tensor (CN\(^{-1}\)).

For the substrate layer only mechanical behaviour is considered using stress-strain relationship.
\[ S = sT \]  \hspace{1cm} (2)
s is the compliance of stainless steel substrate.
Subdomain settings

• The material parameters of the substrate are as follows: its density $\rho=7850$ kg/m$^3$, Young’s modulus $E=200 \times 10^9$ Pa, Poisson’s ratio $\mu=0.33$.

• The active layer of unimorph 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 $\rho = 3000$ kg m$^{-3}$
Boundary conditions

• **Vertical acceleration**: 
  - body load $F_Z = a\rho$ in each subdomain, $a = 0.1\text{g}$ and $\rho$ is the density of the material.
  - One end of the unimorph cantilever is fixed while other is free for vibration.
  - fixed constraint condition is applied for the vertical faces of both the layers.
  - while all other faces are free of displacement.

• **Electrostatic boundary conditions**: 
  - 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.

• **Mesh boundary conditions**: 
  - to optimize the thickness of the PZT layer, Moving mesh application mode is used.
  - bottom face: clamped,
  - vertical faces: clamped along thickness,
  - upper surface: tangentially constrained and displaced in the normal direction to the surface by a given displacement (deltathickness).
  - $\textit{deltaThickness}$ is changed from $10\mu\text{m}$ to $400\mu\text{m}$ obtaining parameterized moving mesh.
Modelling and Optimization

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

Figure 4 Tip displacement (nm) Vs Thickness(μm).
Figure 5 voltage (mV) Vs thickness (µm) and charge (e-13) Vs thickness (µm).
Results-Stored energy

Stored electrical energy

\[ E = \frac{1}{2} QV \]

Figure 6 Stored electrical energy (fJ) Vs thickness (μm).
Results-Frequency analysis

Figure 7 Voltage (V) Vs Frequency (Hz) for three different geometries.
Results - Strain analysis

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

a) Strain.

b) Deformation.
Summary

- 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 210μm.
- 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.
- The simulation results suggest that such structures can be used for energy generation in wireless sensor networks.
References


Thank You!

Questions???