Finite Element Modeling of MEMS Piezoelectric Energy Harvester

L. Beker[a,b], A. Muhtaroğlu[c], H. N. Özgüven[d] and H. Külah[a,b,e]

[a] METU, Department of Micro and Nanotechnology, Ankara, Turkey
[b] METU-MEMS Center, Ankara, Turkey
[c] METU NCC, Department of Electrical and Electronics Engineering, Güzelyurt, Mersin 10, Turkey
[d] METU, Department of Mechanical Engineering, Ankara, Turkey
[e] METU, Department of Electrical and Electronics Engineering, Ankara, Turkey

ABSTRACT

This paper reports an improved method for modeling and optimization of a MEMS piezoelectric energy harvester (PEH) within desired frequency range with maximum voltage output using finite element method (FEM). Piezoelectric analysis is not trivial due to the difference between the information supplied by manufacturer and the inputs required by FEM tool. A translation procedure using piezoelectric constitutive equations is proposed to address this problem. A parametric MEMS PEH design is optimized with given dimension, natural frequency and stress constraints. Built-in optimization tool of FEM program is used with various optimization methods. Meshing problem of high-aspect-ratio structures is also discussed in the paper. Optimization results showed that within 7.5 mm x 4 mm area, 2.92 V can be generated by a PEH with 6.4 mm beam length, 2.2 mm piezoelectric material length.

1 INTRODUCTION

Self-powered microsystems are desired for many emerging wireless sensor applications. Developments in the integrated circuit (IC) manufacturing and low power circuit design have enabled energy harvesters to be used as a power source in sensor applications as an alternative to batteries. Among various energy harvesting methods, vibration energy harvesting is more advantageous due to its presence in closed areas. Three various methods of harvesting energy from vibrations are piezoelectric, electromagnetic and electrostatic. Piezoelectric energy harvesting received greatest attention due to high power density and ease of application [1].

MEMS fabrication techniques allow implementation of micro scale piezoelectric energy harvesters (PEH). Most of the MEMS PEH's are in cantilever beam form with fixed-free [2-5] or fixed-fixed [7,8] boundary conditions. Since piezoelectric materials exhibit anisotropic material behavior, it is important to model the system adequately to evaluate the stress or strain on piezoelectric material. It can be easily observed from coupled piezoelectric constitutive equations [13] that voltage output of the piezoelectric material is directly related with the stress on the material.

Although, single-degree-of-freedom (SDOF) modeling is a trivial method to obtain an initial insight about the problem, this method lacks sufficient complexity as highlighted in [1]. Distributed parameter modeling for analyzing MEMS PEH is not trivial due to complex geometry, non-uniform material distribution, and anisotropic nature of piezoceramics and silicon. On the other hand, most of the reported MEMS PEH geometry should be assumed as a plate instead of cantilever beam, since the width of the structure is comparable with its length, which increases the complexity of the problem. Finite element method (FEM) is widely used for design of piezoelectric energy harvesters to obtain natural frequencies [12] and stresses [3]. However, improved modeling of piezoceramics and silicon is required to maximize the voltage output of MEMS PEH. Models based on isotropic treatment lead to miscorrelations with experimental results [9], since mentioned materials exhibit anisotropic behavior. In addition to material behavior, micro scale energy harvesters consist of high aspect ratio structures (length-to-thickness ratio). Therefore meshing of the structure should be taken care of accordingly.

The aim in the present work is to develop a detailed FEM model for MEMS PEH, using experimentally verified material properties of piezoelectric material in our previous study. Proposed method would also give opportunity to optimize voltage output of the PEH for a desired frequency range with dimension constraints.

Section II explains modeling and design of MEMS PEH. Optimization procedure is discussed in Section III. Finally, conclusions from this work are provided in the last section.

2 MEMS PIEZOELECTRIC ENERGY HARVESTER FEM MODEL

Fig. 1 shows proposed MEMS PEH to be optimized for maximum voltage. Proposed PEH is modeled by considering properties of (100) silicon-on-insulator (SOI) wafer with 10 µm device layer, 400 µm handle layer and 2 µm burried oxide layer thickness. PZT-5A piezoceramics is considered for piezoelectric material due to its high performance characteristics. Bonding layer is considered as isotropic gold-indium layer as highlighted in [3]. Tip mass is used to decrease the natural frequency of the structure.

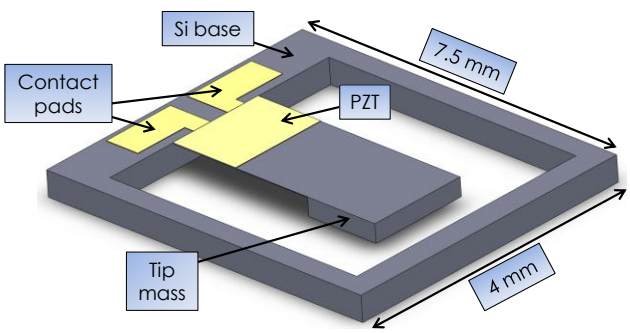

Figure 1: Proposed MEMS PEH.

Parametric MEMS PEH model is developed using ANSYS Parametric Design Language (APDL). Instead of modeling only PEH structure, case is also included into the model to account for the stiffness characteristics of the anchor. Modeling whole fabricated device makes it possible to apply realistic boundary conditions, such as vibrating device from the base of the case instead of fixing one end of the beam and providing oscillations from the fixed end. Dimensions of the case are held constant at 4 x 7.5 mm^2 with 412 µm thickness. Constraints, design variables, and state variables for proposed MEMS PEH is depicted in Table 1 and Fig. 2. Orthotropic material properties of (100) silicon wafer are given in [6].

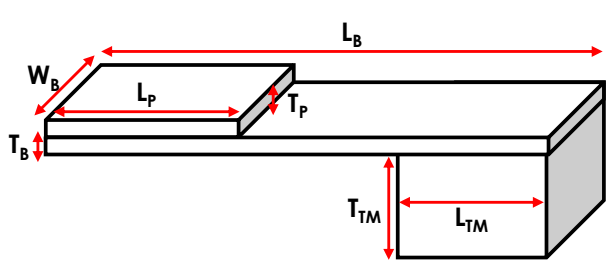

Figure 2: Parameters of MEMS PEH.

	Parameter	Unit	Min.	Max.
Design Variables	Beam Length	mm	1	6.5
	Beam Width	mm	1	2.5
	PZT Length	mm	0.1	3
	PZT Thickness	µm	5	60
	Tip mass Length	mm	0.1	3.5
Constants	Beam Thickness	µm	10	
	Tip mass Thickness	µm	400	
	Bond Thickness	µm	1.5	
State Variables	Natural Frequency	Hz	1450	1550
	Stress on PZT	MPa	-	10

Table 1: Constraints and constants of MEMS PEH.

ANSYS provides a coupled-field 20 node solid element SOLID226. This element is capable of relating mechanical strain with electrical charge with option 1001 as in the case of piezoelectric materials. However, piezoelectric material properties supplied from manufacturers are not compatible with the ANSYS piezoelectric material model. ANSYS requires input piezoelectric data to be compatible with the stress based constitutive equations as in Equation (1). Therefore, a translation procedure is required to compute the appropriate model inputs through the piezoelectric constitutive equations. Equations (2), (3) and (4) can be written using strain based constitutive equations. Input values required by ANSYS (Equation (5), (6) and (7)) can be written by comparing Equation (1) with Equations (3) and (4).

$$\begin{Bmatrix} T \\ D \end{Bmatrix} = \begin{bmatrix} c^E & -e \\ e^t & \varepsilon^S \end{bmatrix} \begin{Bmatrix} S \\ E \end{Bmatrix} \tag{1}$$

$$\{S\} = [s^E]\{T\} + [d]\{E\} \tag{2}$$

$$\{T\} = [s^E]^{-1}\{S\} - [s^E]^{-1}[d]\{E\} \tag{3}$$

$$\{D\} = [d]^t[s^E]^{-1}\{S\} + \left([\varepsilon^T] - [d]^t[s^E]^{-1}[d]\right)\{E\} \tag{4}$$

$$[c^E] = [s^E]^{-1} \tag{5}$$

$$[\varepsilon^S] = [\varepsilon^T] - [d]^t[s^E]^{-1}[d] \tag{6}$$

$$[e] = [s^E]^{-1}[d] \tag{7}$$

In our previous studies, we manufactured a piezoelectric energy harvester prototype [10] and tested under various excitation frequencies, to ensure developed material models. It is observed that modeling

s_{11}^E	16.40	pm^2/N	d_{31}	-171	pm/V
s_{12}^E	-5.74		d_{33}	374	
s_{13}^E	-7.22		d_{15}	584	
s_{33}^E	18.80		$\varepsilon_{11}^T/\varepsilon_0$	1730	-
s_{55}^E	47.50		$\varepsilon_{33}^T/\varepsilon_0$	1700	
s_{66}^E	44.30				

Table 2: Piezoelectric material properties used in simulation.

piezoelectric material as an anisotropic material and applying Rayleigh damping ratio instead of constant damping ratio increases accuracy. Used piezoelectric material properties during simulation can be seen in Table 2 [11].

Another issue that should be considered is the developed model geometry and to apply appropriate boundary conditions. Since most MEMS PEH's are fabricated as a whole structure including its casing, it is proposed to model the whole device structure instead of cantilever beam itself. This situation would bring advantage of applying realistic boundary conditions. Most of the developed models have fixed boundary condition at one end of the cantilever beam structure and oscillate the beam from the fixed end. However, in real case, oscillations are applied to the casing of the MEMS PEH. Therefore, it is more realistic to apply a boundary condition such as fixing bottom surface of the case and oscillate the structure from the fixed surface.

3 OPTIMIZATION OF MEMS PEH

ANSYS PDL has built-in optimization tool consisting of several methods. Parametric design code developed is embedded to optimization tool to maximize the objective function which is obtaining highest voltage from the piezoelectric material. Design code includes modal analysis to observe the natural frequency of the structure and harmonic analysis around the natural frequency of the structure to observe the voltage output from a given constant excitation (Fig. 3).

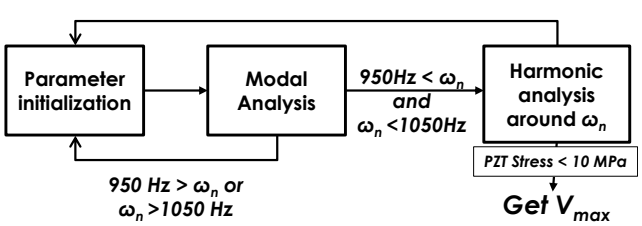

Figure 3: Optimization routine developed using APDL.

Design code is executed 2000 times consecutively using various optimization methods to find global maximum value for voltage within desired dimension and frequency range. It is obvious that the time required for the optimization process is heavily dependent on the meshing of the structure. Initially free mesh pattern is used during optimization, which requires shorter time segments. It is observed that as the dimensions vary during the optimization process, patterns of the free mesh also changes. In addition, since MEMS PEH has a high length-to-thickness ratio, most free mesh patterns formed only two elements through the thickness of the beam. However, stress on the piezoelectric material is critical for obtaining voltage value. Therefore, a meshing pattern is also embedded into design code to control the meshing of the structure.

There is a trade-off between accuracy and simulation time. Stress values on the piezoelectric material are observed while changing the number of element through the thickness. It is observed that stress value converges after 5 elements. Therefore, it is decided to use five elements through the thickness of the piezoelectric material and silicon cantilever beam (Fig. 4).

It is noted that meshing of the structure is particularly important in the harmonic analysis stage of the procedure suggested, since response of the piezoelectric material is obtained at this stage. Since free mesh also yields accurate results in modal analysis, it is also possible to implement free mesh in modal analysis to reduce total optimization time.

As depicted in Fig. 5, maximum voltage of 2.92 V is obtained by vibrating the MEMS PEH around its resonance frequency with 0.1 μm sinusoidal excitations. Optimization results converged to values such that L_B is 6.4 mm, L_p is 2.2 mm (Table 3).

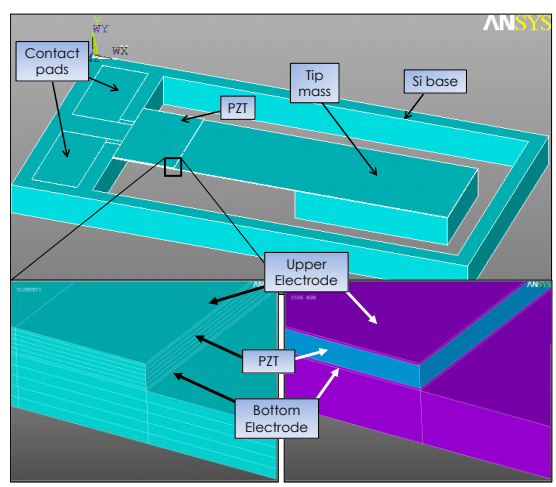

Figure 4: MEMS PEH FEM model and meshing.

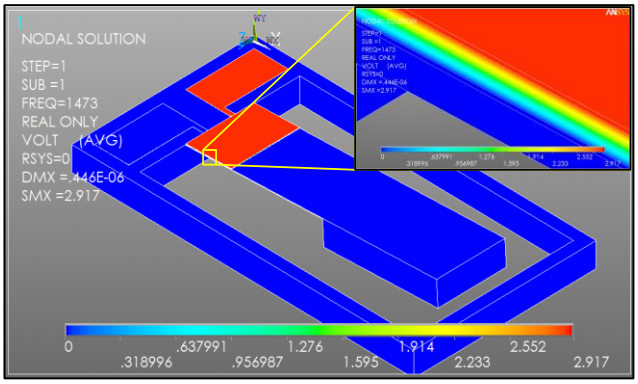

Figure 5: Voltage contour plot of optimized device.

	Parameter	Optimized Value
Design Variables	Beam Length	6.4 mm
	Beam Width	2.1 mm
	PZT Length	2.2 mm
	PZT Thickness	11 µm
	Tip mass Length	2.9 mm
	Results for optimized device	
State Variables	Natural Frequency	1449 Hz
	Stress on PZT	9.9 MPa

Table 3: Optimized values for MEMS PEH.

4 CONCLUSION

MEMS PEH is modeled and optimized using FEM tool. Dimension, natural frequency and stress constraints are applied for optimization procedure where objective is maximization of voltage output of piezoelectric material. Built-in optimization tool of FEM program is used with various optimization methods. Analysis routine is developed involving modal and harmonic vibration analysis and embedded into optimization tool. Some concerns about modeling piezoelectric materials with FEM tools are addressed and a translation procedure is derived to convert information supplied by manufacturers to input required by ANSYS FEM program. Studies related with the meshing properties of the structure pointed that appropriate meshing can reduce the time of the process and increase the accuracy of the model. As a result, for the applied constraints it is simulated that maximum of 2.92 V can be generated.

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