Analysis of a multi-degree-freedom PDMS composite cantilever beam for energy harvesting

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Presented in National Conference on Micro System Technology (NCMST-2020), CMTI, March 4-6, 2020.

KEYWORDS

Energy Harvesting,
Multi-Degree Freedom,
Piezoelectric,
Eigen Frequency,
Finite Element Analysis.

ABSTRACT

Harvesting energy from moving bodies, especially automobiles and its local use to save external energy is the order of the day. Many attempts are made to harvest energy for car vibrations during travel and use it locally to energize devices like tire pressure monitors, dashboard lighting, etc. Vertical oscillations in a car during travel are with different displacement and frequencies. A harvester has to deform maximum for each of these so that more energy can be obtained. In the present work, a multi-degree-freedom cantilever made of polydimethylsiloxane and zinc oxide composite material is proposed and evaluated through Finite Element Analysis for base excitation at a natural frequency. Strain in the beam, which manifests as voltage due to piezo-electric property of the material, is found to be near maximum for most of the amplitudes and frequencies. The two-slot geometry of four beam structure is analyzed independently. It is concluded that the Eigen frequency reduces, and the device can be subjected to near resonance vibration during the service. Lowest Eigen frequency, highest displacement, and electric potential were observed for three-beam configurations.

1. Introduction

The process of gathering ambient energy surrounding a system and converting it into usable electrical energy is termed as Energy Harvesting (EH). The main sources of ambient energy for energy harvesting applications are solar, thermal, wind, mechanical vibration, etc. Additionally, combinations of energy harvesting sources can be used to gather power from different environments. Vibration-based energy harvesting is used in numerous applications ranging from common household devices, transportation tools, industrial machinery, and even human motion. In vibration-based EH, the optimal electrical power is achieved within a narrow frequency bandwidth, close to the resonant frequency of the device [1][2][3].

Many attempts have been made to analyze the energy harvesting devices based on mechanical vibrations [4][5][6]. Computation tools based on the Finite Element method are used for analyzing the above EH devices consisting of simple mechanical structures like cantilever beam [7]. Typically to transduce the mechanical energy into electrical energy, piezoelectric materials have found wide applications owing to the efficiency of the conversion, ease of availability/processing, and bias-less operation[8][9].

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Recently, a researcher on energy harvesting indicates that attempts to improve the performance of harvester are to include the usage of non-traditional geometries [10][11][12], particularly thickness-tapered cantilever [13]. The main factors influencing the efficacy of energy harvesters are their lowest natural frequency, deflections/stresses experienced by the vibrating member, and the transduction property of the material. Thus researchers have resorted to the usage of multi-degree freedom piezoelectric structures [14] to lower the natural frequencies [15] and attain improved performance in energy harvesting. It could be observed that a complete analysis of piezoelectric structures in a multi-DOF form is yet to be carried out with an end product in mind.

In the present work, a multi-DOF cantilever model is designed with slots. The Zinc oxide (ZnO) and polydimethylsiloxane (PDMS) composite material are used for the analysis of the beam. The energy harvesting device consisting of up to four multi-DOF beams is proposed and analyzed for the performance in terms of Eigenfrequency, displacement, and developed electric potential.

2. Methodology

Contemporary research on energy harvesting is directed towards the usage of multi-DOF piezoelectric members for improved performance. An energy harvesting device consisting of four limbs fixed to the edge of the base plate, as shown in Figure 1. Four design variations are proposed for the analysis of the energy harvesting beam. The design consists of two slots in between the single-beam, as shown in Figure 1(a). The dimensions are considered for the analysis is 50mm x 20mm x 2.5mm of a beam (B1) and is similar to other beams. The cantilevers are excited to create the multi-degree frequency of the device. The polydimethylsiloxane and zinc oxide composite material is adopted for the design of the cantilever beam in the proposed study.

Each of these cantilevers in the device is considered to be multi-degree freedom structures to lower the Eigen frequencies of the device. The number of beams attached to the base plate is four. The beam with slot 1 has two degrees of freedom, and beam with slot 2 is a three degree of freedom. Here, the degree of freedom is the same as the slot number. Thus, the code B3D2 represents the third beam has two degrees of freedom. The different beams and DOF configurations of this device are considered for analysis and are listed in Table 1.

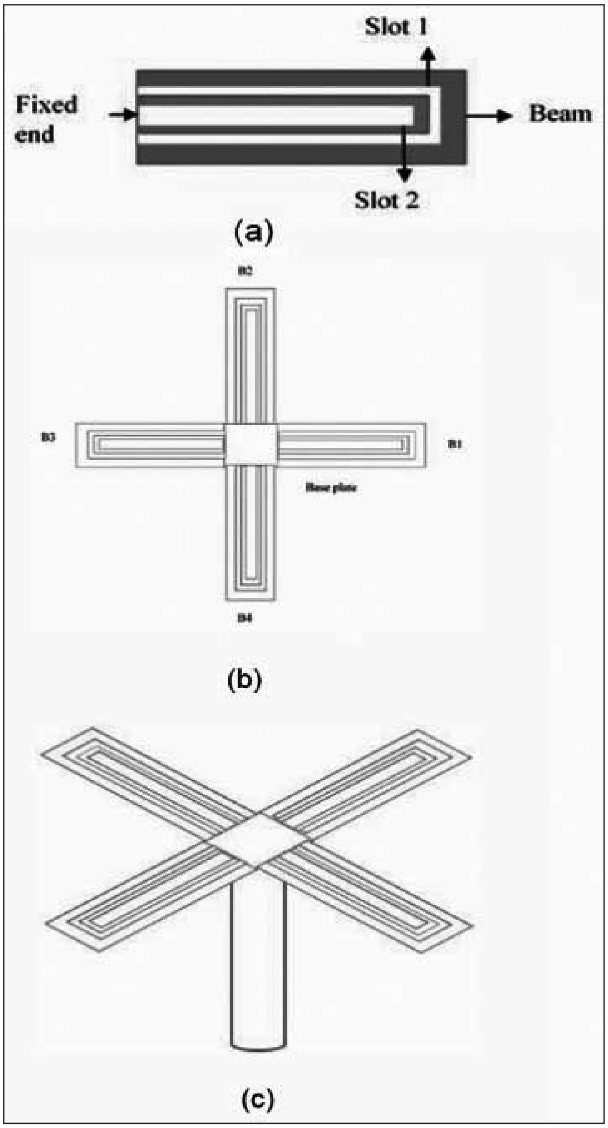

Fig. 1. The proposed concept on (a) single beam with two slots (b) Four limbs/beams with slots (c) Prototype view of the four beam energy harvesting system.

Table 1
Configurations and their codes.

Configuration				
Number of Beams	**One Beam**	**Two Beam**	**Three Beam**	**Four Beam**
DOF	2,3	2,3	2,3	2,3
Code	B1D2 B1D3	B2D2 B2D3	B3D2 B3D3	B4D2 B4D3

3. Modeling of Multi DOF

The modeling of the multi DOF cantilever is provided real facts and importance of the analysis, which can be understood in detail and verified experimentally. Also, modeling is helping to get a valuable solution and giving clear insights into the proposed system. Hence in the present analysis, FE modeling is carried out using the commercially available COMSOL multiphysics software. The steps involved in the study are pre-processing, processing, and post-processing. Initially, the geometry of the energy harvesting device is created, as shown in Figure 2. In continuing with this, FE Analysis of the cantilever beams required the material properties. The zinc oxide is one of the piezoelectric material, which is incorporated in the PDMS matrix with a volume fraction of 0.25. The properties of polydimethylsiloxane and zinc oxide composite

Table 2
Material properties used in FEA.

Properties Material	Density (ρ-kg/m3)	Young's modulus (E-Pa)	Passion's ratio (ν)	Dielectric constant (ε)
Polydimethylsiloxane	1030	1.84M	0.45	2.5-2.7
Zinc oxide	5600	90-110 G	0.33	10.2

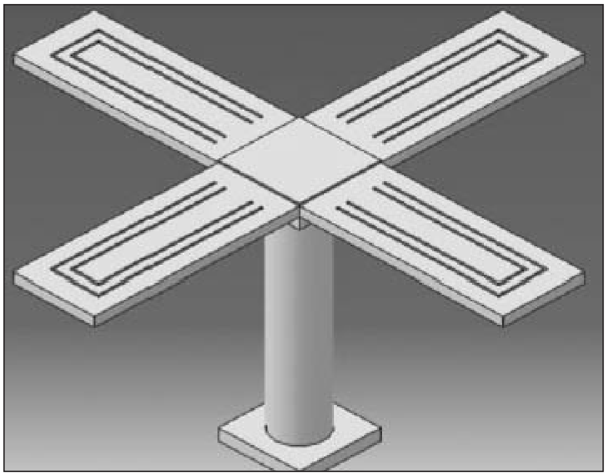

Fig. 2. Proposed geometry of the energy harvesting device.

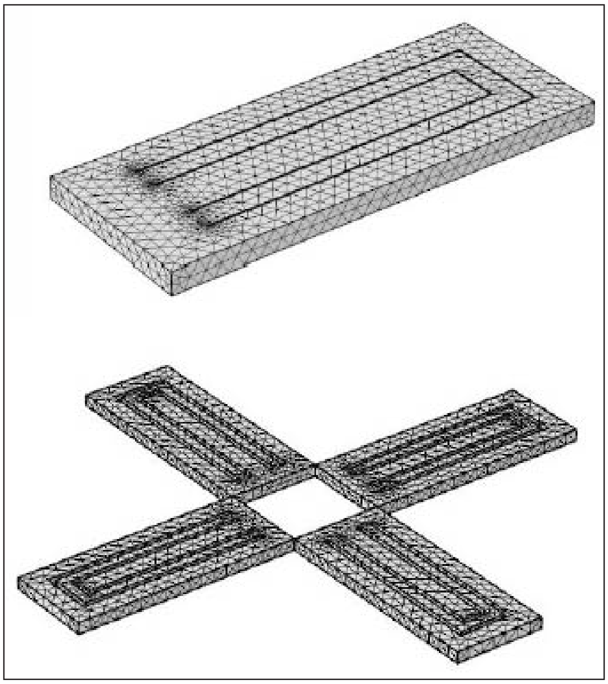

Fig. 3. Show the mesh analysis of the cantilevers beam (Tetrahedral meshing).

are determined using the rule of mixture, included in the modeling. The properties of the material used and their respective constituents are tabulated in Table 2 [16][17].

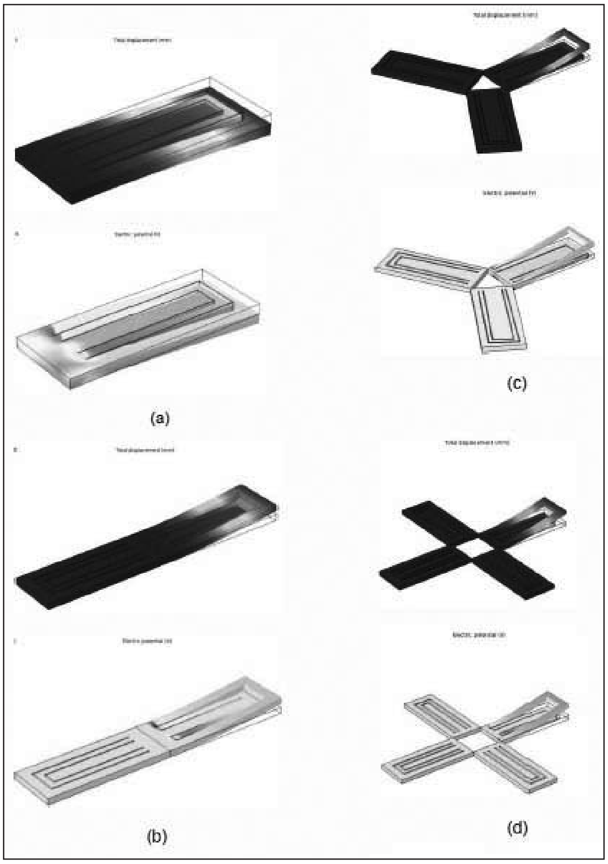

Fig. 4. (a) Displacement and potential induced at single beam (b) Displacement and potential induced at two beams (c) Displacement and potential induced at three-beam (d) Displacement and potential induced at four beams.

Figure 3 shows the meshed model of a one and four of two and three-degree freedom of the cantilever beam made of PDMS-ZnO composites. The cantilever model is discretized into an extra-fine mesh with free tetrahedral elements. Analysis of the cantilever beam is carried out by fixing the beam into the base plate as a fixed constraint. Eigen frequency, displacement, and induced potential are determined by solving

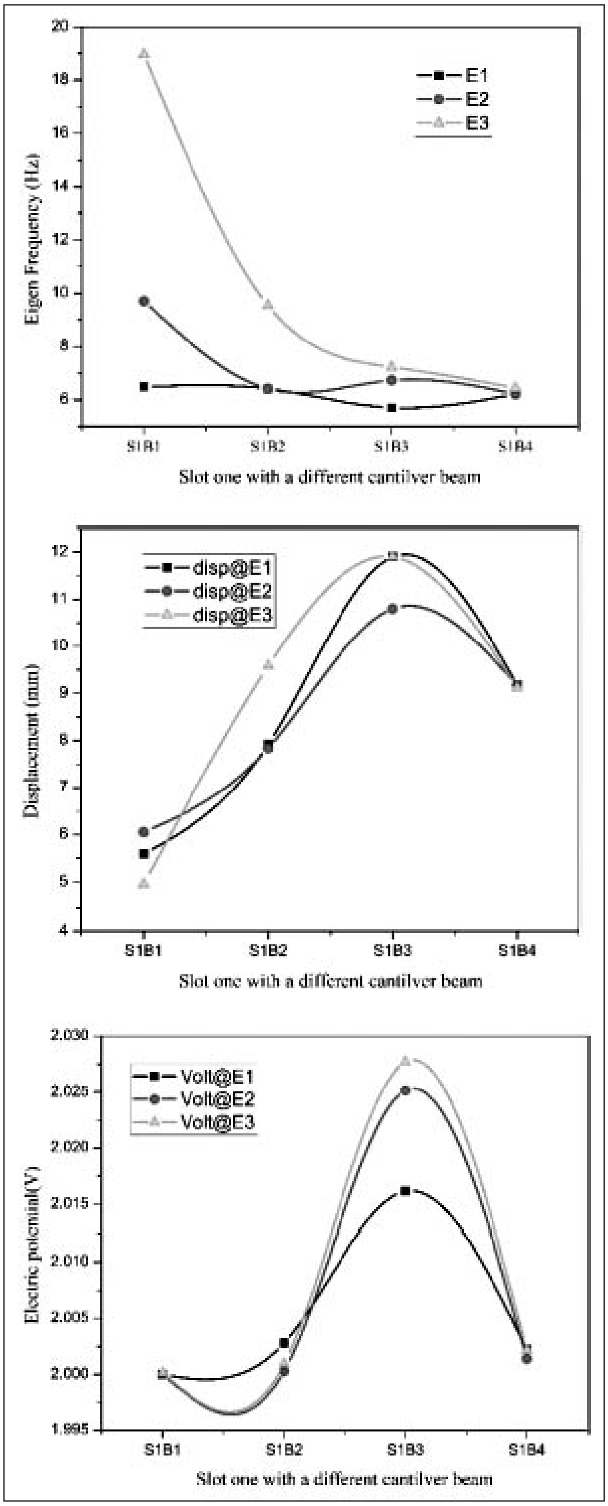

Fig. 5. Two-DOF multi-configuration of
(a) Eigen frequency variation,
(b) displacement variation,
(c) Induced potential voltage at a natural frequency.

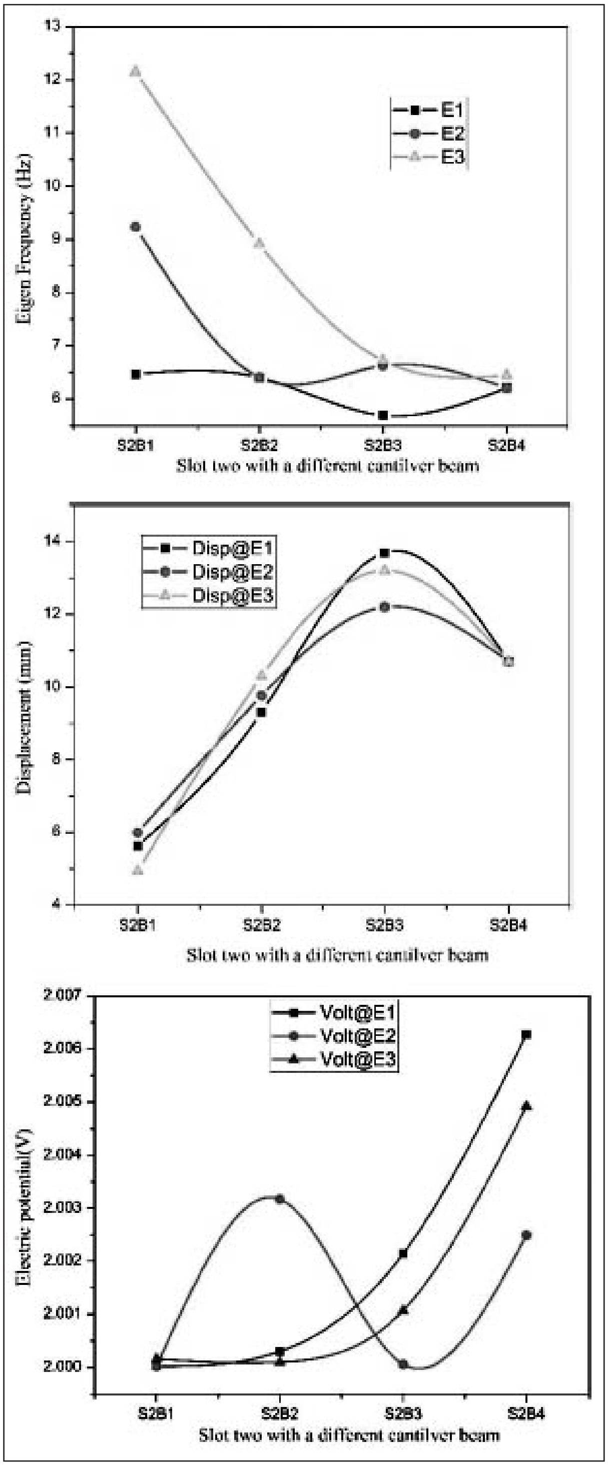

Fig. 6. Three –DOF multi-configuration of
(a) Eigen frequency variation,
(b) displacement variation
(c) Induced potential voltage at a natural frequency.

electrostatic and structural mechanics solvers. The above analysis was repeated for all configurations mentioned in Table 1. The modeling on multi-degree freedom of the cantilever beam provides the insight of the energy harvesting device. Hence, the further section presents the results of the proposed model.

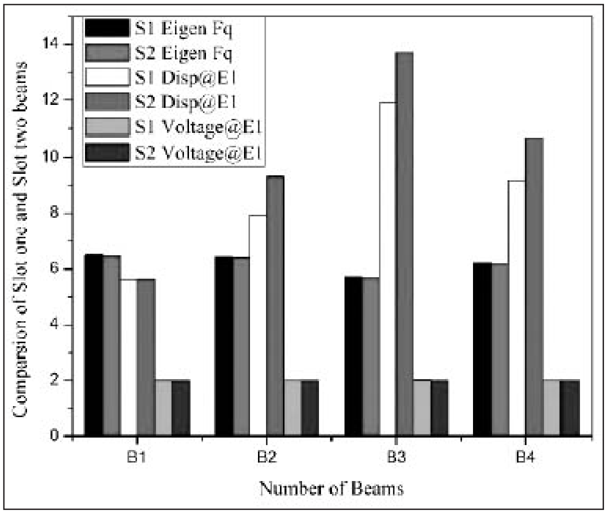

Fig. 7. Compare the Eigen frequencies, displacements, and potentials of 2-DOF and 3-DOF multi-beam configurations.

4. Results and Discussion

The modeling of varied beam configuration with different degrees of freedom is carried out using FE software. The FE analysis of the three DOF of the single beam to four beam configuration is shown in Figure 4. The Eigen frequency of these beam displacement and induced potential is shown in Figure 4(a)-4(d), respectively. It is observed that there is potential energy induced due to displacement of the composite beam with different Eigen frequencies.

The beam with slot 1 having the 2-DOF multi-configuration shown in Figure 5. The results show that natural frequency has low Eigen frequency produces the displacement and electric potential in the composite beam. It could be observed that when the multi-beam configuration, the Eigen frequency reduces, and the device can be subjected to near resonance vibration during the service. Lowest Eigen frequency, highest amplitude, and potential are observed for three-beam configurations.

Figure 6 shows the three-DOF configurations of Eigen frequencies, displacements, and potentials of multi-beam as observed earlier three-beam configuration possesses the least Eigen frequency and higher displacement in the three-DOF system also.

Figure 7 show the comparative analysis for the Eigen frequencies, displacements, and potentials of 2-DOF (slot-one) and 3-DOF (slot two) multi-beam configurations. As observed from the plot, 3-beam configuration possesses the least Eigen frequency and higher displacement in the 3-DOF system also. In Figure 7, potentially induced in different multi-beam configurations are compared where it could be observed that 3-DOF provides maximum voltage output compared to other configurations.

5. Conclusion

The multi-degree modeling of cantilever beam conducted and analysis brought out the following findings. Firstly, it was observed that as the number of degrees of freedom increases, the natural frequency of the cantilever beam reduces. Thus, it becomes easier for the beam to attain resonance and obtain maximum deflection. Due to the increased deflection, the stress-induced is increased, and also the potential developed by the piezoelectric beam increases.

Secondly, as the number of beams increases, the Eigen frequencies decrease thus providing ease of resonance. Also, by using multi-beam configuration, the different beams vibrating at resonance produce a respectable amount of electric potential which can be tapped onto and can be used for various purposes. Thus, by using the proposed design, maximum output can be obtained and it can be acknowledged as an optimum design.

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