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Performance Evaluation of Novel Piezoelectric Cantilever Beam Structure for Energy Harvesting

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Abstract

This study proposes an elastic compact Piezoelectric energy harvester (PEH) in multiple configurations, including a single cantilever beam, a single cantilever beam with a hole, two cantilever beams with a hole contributing towards a wider operating bandwidth. The cantilever beams are designed in multiple structural forms and section shapes, including symmetrical uniform section rectangle frames. Natural frequencies, vibration modes, and output voltages of PEH are estimated using Finite element software, with the frame acting as a rigid body and the cantilever plate acting as a deformed structure. A PEH with a rectangular cantilever plate surrounded by a rigid frame is designed and attached to the vibration platform with a customized fixture in the simulation software. The design meets the requirements of natural frequency and high output voltage in the low-frequency band. The PEH structure is simulated using a variety of piezoelectric materials, primarily PZT4 and PZT5H, barium titanate, lithium niobate, zinc oxide, and polyvinylidene difluoride (PVDF) using the finite element method. In the structural configuration of two cantilever beams with holes, PEH exhibited the maximum output voltage of 32.832 V for Zinc oxide compared to other materials. So, it can be concluded that insertion of hole and variation in the geometry of cantilever structure along with frame plays a vital role in achieving a large voltage from the vibrations in PEH.

Keywords: Vibration energy harvesting, Piezoelectricity, Mode shapes, Eigen frequency, Finite element method

Introduction

With the widespread use of wearable and portable electronic devices, several energy supply solutions have been developed in recent years. One of the most efficient energy supply systems is a vibration-based energy harvester. Mechanical vibration energy is abundant in life and has been extensively investigated due to its diverse sources, capability, and broad application domain. Self-powered sensors with energy harvesting could be used in any industrial complex to provide continuous sensing and data exchange without the need for power cables or batteries. Reducing the capital costs on cables and building massive architecture is a significant benefit with self-powered sensors that could power the system even during terrible natural disasters such as avalanches or catastrophes. So, much of the research revolves around maximizing the throughput from mechanical or alternative vibration sources. Balkrishna *et al*. has shown that a strip domain pattern with in-plane polarization is stable over an extensive range of externally imposed strain, and it could be used in a thin film energy harvester device and will provide sufficient vibration energy at its operating frequency [1]. Recently work by Wang *et al*., a random vibration narrowband energy from environment is converted into voltage by energy harvester made with potassium sodium Niobate [2]. A new structure in star-shaped mechanical energy harvester was designed and investigated to harvest energy from multiple directions with wideband frequency [3]. Ma *et al*. designed a nonlinear model of the Piezoelectric complaint mechanism (PCM) energy harvester, derived under massive base excitation to obtain the maximum power output. The sensitivity of the PCM power-strain sensor is found to be double that of the proof mass cantilever configuration [4]. According to findings by Maruccio *et al*., arrays of electro spun polyvinylidene difluoride (PVDF) nano fibre can yield roughly twice the electric energy in comparison to standard PVDF films [5]. Contantinou *et al*. developed a 3D printed electromagnetic vibration energy harvester generating power of 2.9 MW at a bandwidth of 4.5 Hz, which is comparable to existing in-plane systems [6]. Similarly, Bath *et al*. suggested a 3-dimensional folded zig-zag geometry, with increased flexibility with higher power density [7]. Cha *et al*. reported calculation of power transferred to varied load resistances under repeated knee motion and gloves using an electromechanical model of piezoelectric harvesting [8,9]. Bayike *et al*. developed a multi-mode Equivalent Circuit Model (ECM) that allow researchers to investigate the harvesting performance of piezoelectric patch-based harvesters attached to thin plates using any linear and nonlinear electrical components [10]. For optimizing the DC power, Wang *et al*. used experimental and analytical approaches to investigate the energy harvesting capabilities of a piezoelectric curved energy generator (Thin layer unimorph driver) [11]. To maximize the energy harvesting performance, Kh *et al*. investigated a geometry for the optimization of flexible PEH modules with embedded MFCS (Micro Fibre Composites) [12]. In another research air flow is used for generating the voltage for powering of wireless sensor with the assistance of piezoelectric energy harvester [13].

Cantilever beam geometries subjected to base excitations from an ambient source are common designs for piezoelectric-based devices. Cai *et al*. reported that laminated trapezoidal shapes with monostable configuration are the optimum choice for broadening the frequency range of increased dynamic behaviour, minimizing strain at clamped beam end, and maximizing rectifier output voltage [14]. Kim *et al*. investigated a flexible ring energy harvester made of PVDF and PDMS and observed the effect of shape changes in the cylinder, and input parameters on the electrical response. It was found that with the variation in cylindrical geometry dimensions at a constant frequency, the output power level increases [15]. Chen *et al*. developed a spiral-cantilever coupled structure with low resonance frequencies and a wider bandwidth to generate relative maximum power [16]. Wang *et al*. developed a single PZT ring a multi-functional composite device with an embedded piezoelectric actuator sensor. The developed energy harvester has generated a voltage of 67 V for an optimal resistance of 11.6 KOhm at a frequency of 40.0 KHz (305 MW) [17]. Dechant *et al*. suggested a mechanical energy harvester that transforms low-frequency mechanical vibrations into high-frequency transducer resonance oscillations. It can convert vibration with an amplitude of 9.81 m/s^2 in the frequency range of 7 - 25 Hz into electric power in the range of 0.1 - 0.8 MW [18]. In the design of the electromagnetic transducer, geometry variation was carried out to strengthen the coils' magnetic field. Klein *et al*. addressed the issue by introducing a revolutionary vibration energy harvester architecture for a linear electromagnetic generator that uses a complaint mechanism and proof mass system to enhance the vibrational velocity of machine vibration [19]. In contrast to typical non-tune-able energy harvesters, Hofmann *et al*. demonstrated a self-powered tuning mechanism based on a magnetic force method employing a circular tuning magnet [20]. Makihara *et al*. presented a self-powered analog circuit to improve the efficiency of piezoelectric material-based electrical energy harvesting devices [21]. Cha *et al*. reported the laminated trapezoidal shapes with monostable configuration to broaden the frequency range of increased dynamic behaviour, minimize strain at clamped beam end, and maximize rectifier output voltage [22]. Fernandes *et al*. reported a power solution for smart grid applications that harvest electromagnetic energy from current-carrying wire to replace the batteries. The energy harvesting device employs a symmetric architecture to increase power production by limiting the effects of torsional modes, and the system's overall strain nodes reduce electrode fabrication challenges. As a result, the design achieves a higher normalized power density than existing MEMS-based piezo electromagnetic devices [23]. Atitallah *et al*. examined the mechanical, electrical, and electromechanical properties of active fibre composites (AFCs) at different temperatures. As per observations, the structure has nonlinear piezoelectric behaviour due to the epoxy viscoelastic nature, which causes the piezoelectric coefficient to grow at higher temperatures and lower frequencies, making it a potential material for developing PEH [24]. A dual-piezoelectric-cantilever energy harvester (DPEH) model to accomplish optimal broadband energy harvesting under varied intensity realistic conditions presented by Gao *et al*. The elastically supported piezoelectric energy harvester (EPEHs) are more adaptive to realistic environments with large or medium intensity change than the rigidly supported piezoelectric energy harvesters (RPEHs), but less so to realistic environments with constant intensity [25]. On similar lines, Scarscelli *et al*. introduced a new power harvesting device for bistable composites based on the lever effect, intending to lower the activation force resulting in a considerable increase in power generation [26]. In comparison to linear vibration energy harvester (LVEH), Pan *et al*. claimed that a bi-stable vibration energy harvester is able to scavenge energy efficiently from ambient vibration over a wide frequency range [27]. For powering of Tire pressure monitoring systems, Eshghi *et al*. presented a reliable design for PEH applied to a revolving wire based on vibration, and the performance of the PEH was compared with deterministic design optimization (DDO) and reliability-based design optimization optimum designs (RBDO) [28]. The pressure fluctuations in water pipelines in the real world could be viewed as a low-frequency excitation source for energy harvesting. Cao *et al*. developed an enhanced pressure fluctuation energy harvester (PEEH) that can be integrated with a monitoring sensor to harvest energy from a hydraulic pressure pipeline system without the use of batteries or cable power sources [29]. Yan *et al*. investigated a new piezoelectric electromagnetic energy harvester with multiple permanent magnets with a wider working bandwidth and a high energy harvesting efficiency and can deliver power up to 28 MW [30]. Jiao *et al*. discussed enhancing the amounts of harvested energy for the buckling mode configurations by managing the snap through transitions of the energy conversion mechanism under a quasi-statically growing axial load, which triggered the harvester into free vibration [31]. The main research gap from the literature review is generation of low magnitude non uniform voltage with PEH structures. So, this study aims to enhance the output voltage of PEH structures at low frequency range.

Thus, this study proposes an elastic Piezoelectric energy harvester (PEH) structure with a wider operating bandwidth and appreciable output voltage in different configurations, including a single cantilever beam, a single cantilever beam with holes, and two cantilever plates with holes. In this investigation our prime objective is to maximize the power output by increasing magnitude of generated voltage. So we have considered different type of materials to evaluate which particular material could have the highest output voltage so that the output power of the PEH will be maximized. In addition, an eigen frequency analysis is carried out so as to observe the pattern of vibrations. The article is arranged as follow. Section 2 elaborates on the methodology and design considerations for the PEH. The modelling procedure of the designed PEH is discussed in Section 3. Finally, Section 4 focuses on the simulation results for validation of the developed model of PEH followed by the conclusion in the last section.

Methodology and design aspects

The piezoelectric materials generates the voltage when pressure is applied. For evaluating PEH, a mathematical model is required to evaluate the performance of the PEH. In this research, a proof mass or the pressure is applied on the top of the beam and deflection and voltage could be evaluated for different load variations. Mainly, a single mechanical degree of freedom system can be used to represent the PEH system around its first resonant frequency. A cantilever beam of stiffness K_{sc} with its free end attached to an inertial mass M and frictional forces represented by a linear damping coefficient D could be used as a mechanical resonator, and γ is external acceleration. The piezoelectric material experiences a force from the mechanical vibration due to strain-induced by oscillations. Due to the direct piezoelectric effect, the voltage is generated, which is proportional to the voltage across the piezoelectric element, v_p, in the first approximation. The second-order differential equation relates to the inertial mass displacement x under an external acceleration α is then given by following Eq. [32];

$$-M\gamma = M\ddot{x} + D\dot{x} + K_{sc}x + \alpha v_p \tag{1}$$

where α is the force factor, which is determined by the mechanical resonator geometry and the beam parameters and piezoelectric material. The piezoelectric material generates electrical charges due to the strain caused by the resonator oscillations. The electrical contact either stores or harvests these charges in the material dielectric capacitance C_p. The electrical dynamics of the harvester are governed by the below differential Eq. [33];

$$\alpha\dot{x} = C_p\dot{v}_p + i_p \tag{2}$$

The current drawn by the electrical interface is represented by i_p. As long as the mechanical linearity hypothesis holds, the dielectric losses in the piezoelectric material are low, and the effects of higher mechanical modes are low, the electromechanical model introduced by Eqs. (1) - (2) is valid. There is assumption that the inertial mass displacement is just a sinusoidal signal of magnitude X_m under harmonic excitation. As a result, the mechanical oscillator has a relatively high-quality factor as represented by below Eq. [34];

$$x = X_m\cos(\omega t) = X_m\cos(\theta) \tag{3}$$

where ω is the angular frequency of the harmonic excitation.

Modelling of PEH

Various structural combinations of PVEHs are designed in order to harvest the ambient mechanical vibrations. The **Figure 1** shows the block diagram of the proposed piezoelectric energy harvester, where multiple rectangular piezoelectric cantilevers beam with hole generates a voltage due to vibration. The cantilever beam structure generates the voltage due to vibrations which is supplied to the rectifier circuit. The rectifier circuit converts the ac voltage into dc voltage which is then forwarded to the battery charging circuit for charging of Li-ion battery. The Li ion battery is charged with the voltage available at its input and thus provides power to various auxillary devices such as weather monitoring systems, mobile charging systems, smart lighting systems, portable hand-held devices, wearable smart devices etc.

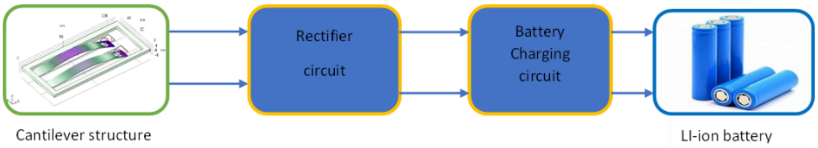
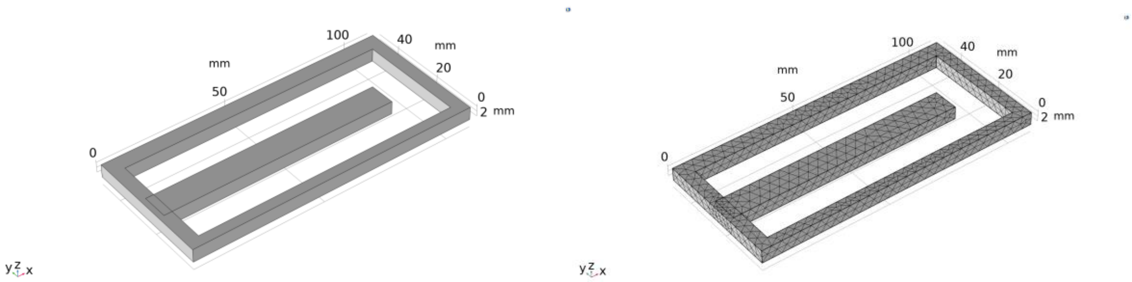
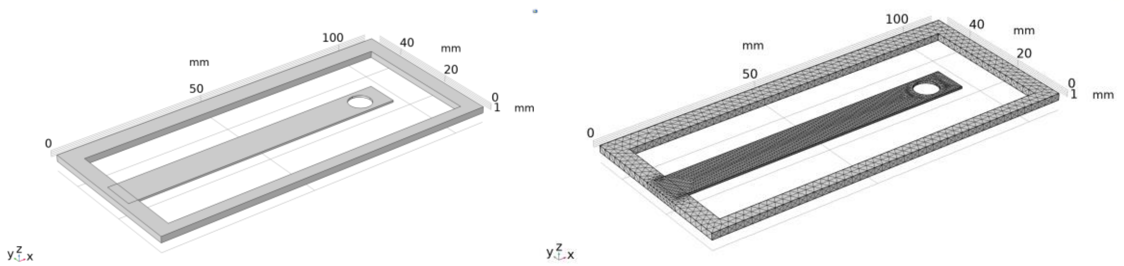


Figure 1 Block diagram of piezoelectric energy harvesting.

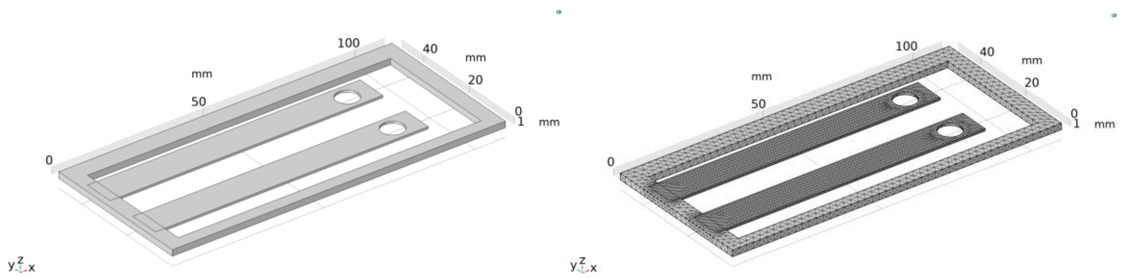
The developed PEH structure presented in this paper serves two research steps. The initial step is to calculate the multiple natural frequencies, which will assist in analyzing the workable frequency range. The second step is to estimate the output voltages and thus optimize the performance of PEH. The PEH is developed with 2 cantilever plates with a frame attached to one end of the cantilever plates in this study. The vibration modes of the structure are complicated when the frame is a rigid body with translation and rotation motion. As a result, multiple low-frequency vibration modes, with broader bandwidth are developed. Multiple cantilever structures configurations are proposed in this FEM based simulation illustrated in **Figure 2**: a) Single beam without hole; b) Single beam with hole; c) Double beam with holes. The material and geometric specifications used for FEM simulation are presented in **Tables 1** and **2**. All rectangular plates have a similar dimensions and steel/aluminum was selected as an elastic frame material for simulation. **Table 1** describes in much detail about dimensions of frame and piezoelectric beams i.e. the size of beam (90×10×0.6 mm^3) and size of frame (110×50×2 mm^3) along with dimensions of hole (3.6 mm) embedded in the beam. **Table 2** specifies the relevant properties of different piezoelectric materials which includes density (Kg/m^3), possion ratio, Young's Modulus (GPa) that are uitilised to carry out finite elemnt simulation in COMSOL.



(a) Single beam without hole



(b) Single beam with a hole



(c) Double beams with a hole

Figure 2 Geometrical configurations (a)-(c).

Table 1 Dimension of the frame and piezoelectric beam.

Structure	Dimension		
Beam size (mm)	90×10×0.6	90×10×0.6	90×10×0.6
Frame size (mm)	110×50×2	110×50×2	110×50×2
Hole size (mm)		3.6	

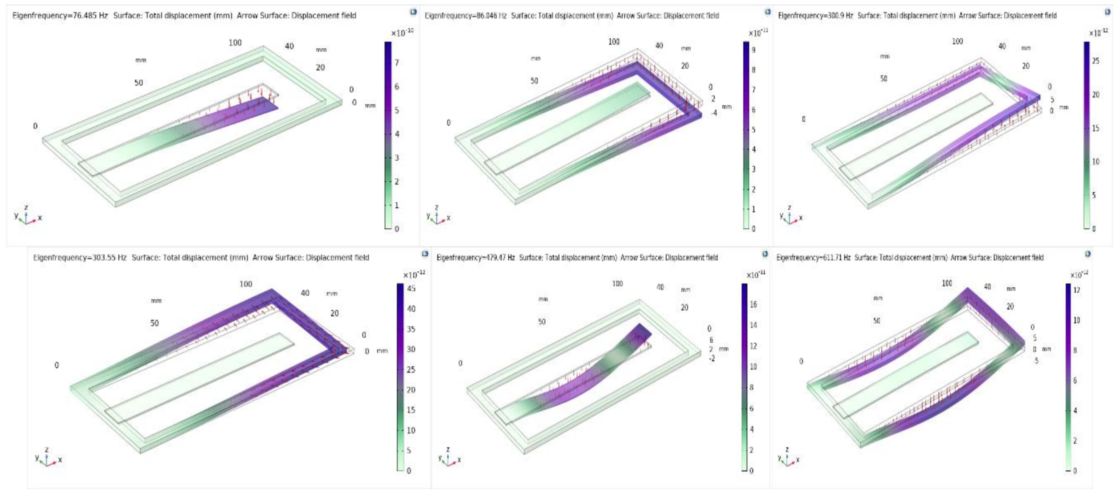
Table 2 Properties of piezoelectric material used in simulation.

Material	Density (Kg/m^3)	Poisson's ratio	Young's modulus (GPa)
Barium titanate	5,700	0.28	79
PZT4	7,500	0.30	63
PZT5H	7,500	0.33	64
PVDF	1,780	0.34	3
Lithium niobate	4,647	0.25	170
Zinc oxide	5,680	0.34	50

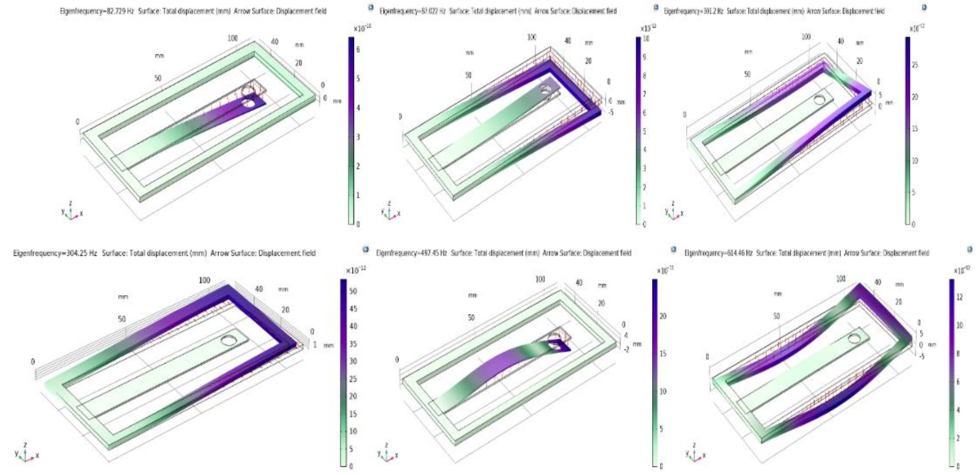
The first six natural frequencies and mode shapes of PEH are obtained by model analysis in COMSOL (trial version) FEM simulation. Each rectangular cantilever beam without a hole and with a hole is loaded with uniform load and the force after multiplying the area of uniform load on each type remains the same. A comparison of these structures with single cantilever beam without hole, single beam with hole, double cantilever beam with hole attached with proof mass is shown in **Figure 3**, showing the different Eigen frequency and mode shapes. **Table 3** lists the Eigen frequencies with 0.6 mm thickness cantilever beam for the Lithium Niobate material. The lowest frequency is 76.485 Hz for a single beam (without hole), and 614.46 Hz is the highest frequency for a single beam with a hole. So, this analysis assists in identifying the frequency range in which PEH is vibrating (76.485 - 614.46 Hz)

Table 3 Modes shapes of piezoelectric cantilever hollow rectangular strip.

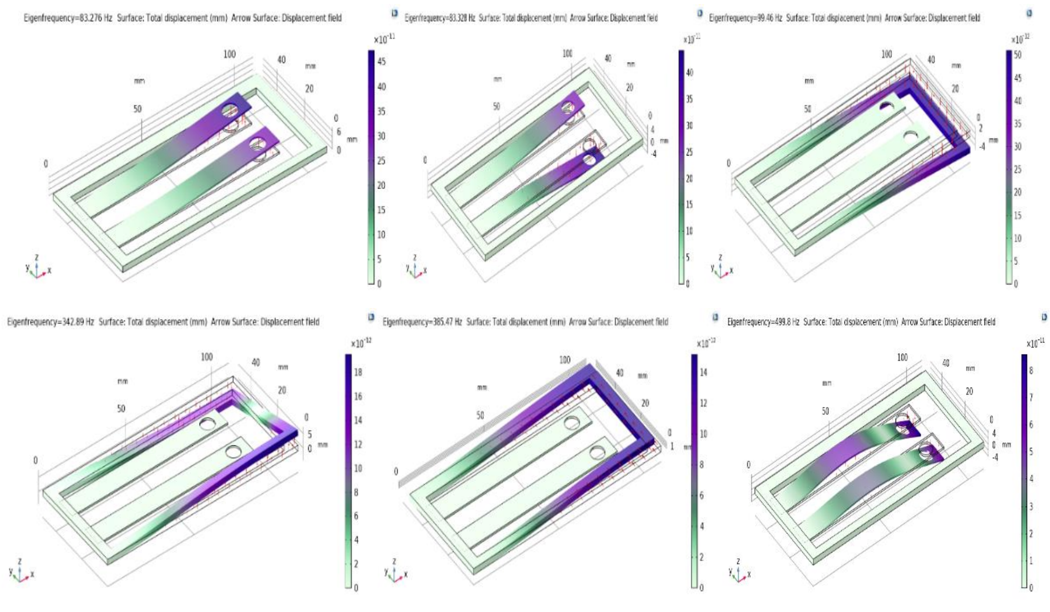
Structure	Material/ Eigen frequency	1st	2nd	3rd	4th	5th	6th
Single beam without hole	Lithium Niobate	76.485 Hz	86.046 Hz	300.9 Hz	303.55 Hz	479.47 Hz	611.71 Hz
Single beam with a hole		82.729 Hz	87.022 Hz	301.2 Hz	304.25 Hz	497.45 Hz	614.46 Hz.
Double beam with a hole		83.186 Hz	83.244 Hz	98.991 Hz	342.02 Hz	384.54 Hz	499.1 Hz



Single cantilever



Single cantilever with single hole

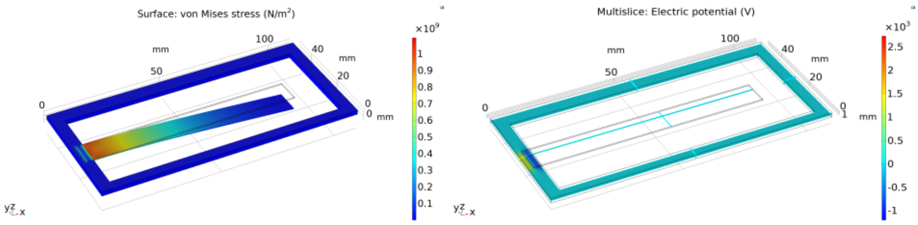


Double cantilever beam with a hole

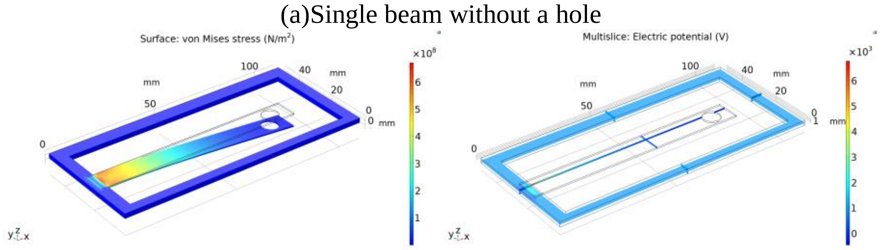
Figure 3 Modes shapes of the piezoelectric rectangular strip for lithium niobate (0.6 mm).

Modelling of PEH for estimation of energy output

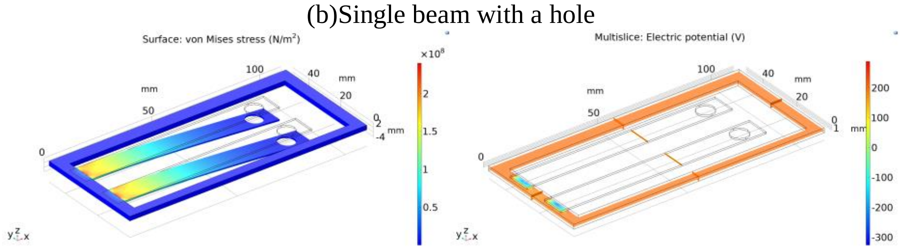
Figure 4 illustrates the deflection pattern and potential distribution of PEH due to mechanical vibrations for multiple cantilever configurations; a) Single Beam without Hole-The FEM simulation is carried out for different materials like PZT4, PZT5H, Barium Titanate, Lithium Niobate, b) Single Beam with a Hole-In this configuration, the hole is introduced in the cantilever beam and simulated for different materials, including PZT4, PZT5H, Barium Titanate and Lithium Niobate, and c) Double Beam with Holes-In other configurations, two cantilever beams with holes are simulated in COMSOL using finite element method. The simulation predicts the output voltage of these structures.



(a)Single beam without a hole



(b)Single beam with a hole



(c)Double beam with a hole

Figure 4 Deflection pattern and Potential distribution in PEH.

Results and discussion

In a single beam without holegeometry, a finite element simulation was carried out with four different materials PZT4, PZT5H, Barium Titanate, Lithium Niobate to observe the output voltage variation vs. thickness, output voltage vs. applied loads are shown in **Figures 5(a) - 5(b)**. The thickness was varied from 0.5 - 1.0 mm, and different loads were applied from 0 to 10 newton with a beam length fixed at 90 mm. It has been observed from the curves that PZT4 and Lithium Niobate-based single cantilever structure without hole has the most significant voltage generated from vibrations in comparison to other materials i.e. PZT5H, Barium Titanate.

Similarly, **Figures 6(a) - 6(b)** shows the variation of output voltage single cantilever beam with hole configuration for different materials in which thickness has been varied from 0.5 - 1.0 mm with the application of load varied from 0 to 10 newton. It is observed from the curves that PZT4 and Lithium Niobate has the highest voltage generated in comparison to the other two materials i.e. PZT5H, Barium Titanate. The **Figures 7(a) - 7(b)** shows the voltage variation with thickness and applied load for the double cantilever beam with hole configuration. It is observed from the curves that ZnO has maximum voltage generated compared to PVDF. However, the PVDF is more elastic as compared to ZnO. Under the concept of assuring the PEH strength and stiffness, the optimal thickness of cantilever-based PEH should not be less than 0.6 mm. However, the voltage is small due to the low amplitude of structural vibration (1 mm). In a single beam without a hole structure, as the thickness of rectangular plates increases the output voltage decreases in all simulated cantilever plate materials (PZT 4, PZT 5H, Barium titanate, Lithium Niobate).

Out of these materials, only Lithium Niobate showed a good performance having an output voltage of 21.016 V (0.5 mm). However, in the case of a single beam with a hole, the output voltage decreases as the thickness of the cantilever beam increases from 0.5 - 1.00 mm in all materials (PZT4, PZT5H, Barium titanate, Lithium Niobate). As a result, the Lithium Niobate demonstrated superior performance than the other materials, with a maximum output voltage of 21.88V (0.5 mm). In case of a double beam with holes, the output voltage increases in small incremental values as the thickness of cantilever plates increases from 0.5 - 1.0 mm. Out of all materials (Lithium Niobate, PVDF, Zinc Oxide), Zinc Oxide showed high output voltage around 32.832 V. By optimizing the thickness and length of the cantilever plates and the design of the frame, the output of the PEH could be enhanced. From the results, it can be concluded that insertion of holes and variation in the geometry of cantilever structure along with frame plays a vital role in achieving a large voltage from the vibrations in PEH.

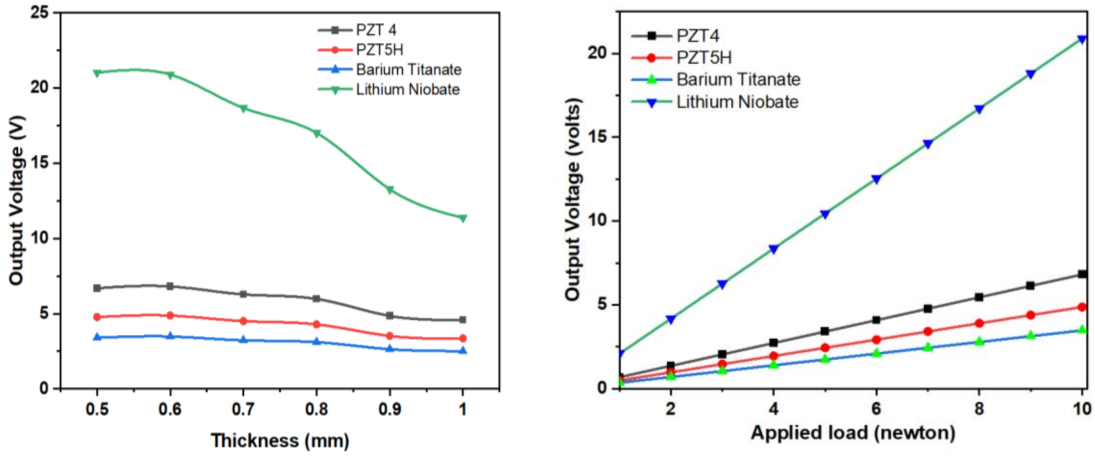


Figure 5 Single beam without a hole; (a) Output voltage (V) Vs. thickness (mm), (b) Output voltage (v) Vs. applied loads (N).

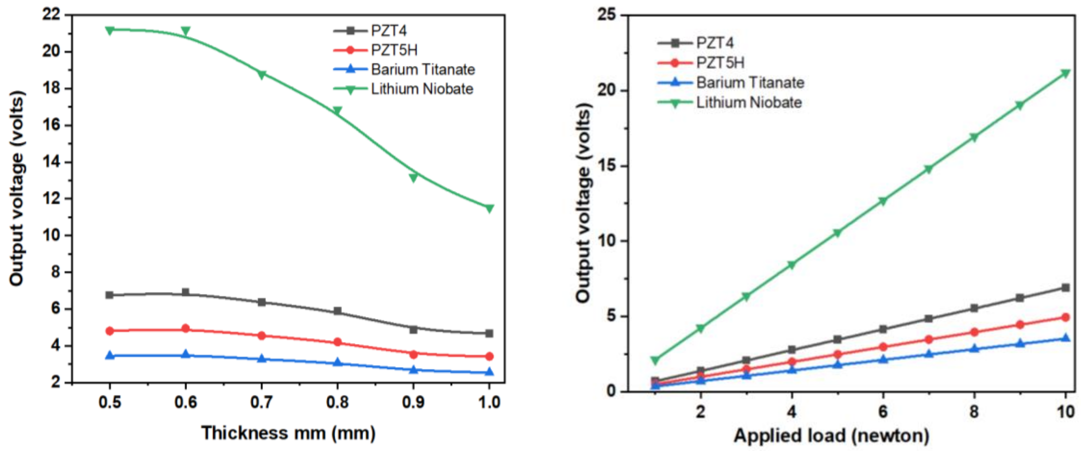


Figure 6 Single beam with a hole; (a) Output Voltage (V) Vs. thickness (mm), (b) output voltage (V) Vs. applied loads (N).

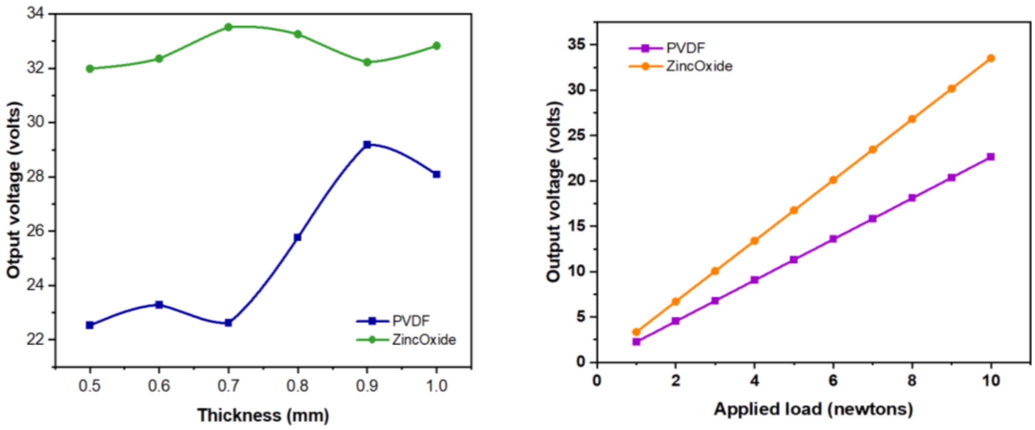


Figure 7 Double beam with a hole; (a) Output voltage (V) Vs. thickness (mm), (b) Output voltage (V) Vs. applied loads.

Conclusions

The effects of the thickness of rectangular cantilever plates. the mass and the size of the rigid frame on the natural frequency and output voltage of PEH are investigated using the FEM modelling platform. Due to mechanical vibration in the frame, the frame size influences the moment of inertia, which influences the natural frequency of the PEH, which in turn influences the strain in the cantilever, which ultimately affects the output of the energy harvester. The Lithium Niobate demonstrated superior performance than the other materials for single beam with hole, with a maximum output voltage of 21.88 V. (0.5 mm). In case of a double beam with holes, the output voltage increases in small incremental values as the thickness of cantilever plates increases. So present study involves the simulation and design of different cantilever structures to select the optimal PEH structure based on generated voltage, thickness, applied loads, and Eigen frequencies range. In the near future, most of the clean energy demand could be met with energy harvesting devices from the vibration with the aid of PEH.

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