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Exploring the Influence of Geometrical Parameters on Piezoelectric Vibration Energy Harvester: From Experiment to Simulation Investigation

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ABSTRACT

Vibrational energy has recently become one of the most sought-after targets and an ideal source of energy because of its widespread existence, and one of the effective methods of storing vibrational energy is to use piezoelectric. Nevertheless, the design of piezoelectric vibrational energy harvesting systems continues to be a challenging task, as the behavior of various subsystems influences the energy harvested. Most typical strategies concentrate on improving the piezoelectric system, while the effects of other subsystem in particular the substrate layer, are either simplified or not considered at all. Therefore, the paper is obliged to investigate a method to design a substrate layer for a piezoelectric vibrational energy harvesting system that is optimized to boost energy efficiency. In this study, a piezoelectric PZT-5A patch attached to a substrate cantilever beam with proof mass at the free end was modelled using finite element analysis (FEA) in ANSYS Workbench which was later verified through experiments. The proof mass, beam length, and PZT position were used as variable parameters in the studies. The preliminary results of FEA demonstrate that a 180 mm beam length with a 17 g proof mass and PZT-5A positioned in the middle of the beam produced a maximum voltage output of 4.75 V at 9.8 Hz. These results are in agreement with the experimental results even though there are discrepancies in terms of the peak width owing to damping. Thus, the implications of these findings lead to two conclusions: 1) the reliability of FEA as a tool for identifying the optimum design and cost-saving options and 2) a better understanding of how the geometric parameters of the substrate layer influence the performance of vibration energy harvesters.

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1. Introduction

The rapidly diminishing supply of fossil fuels and non-renewable energy sources, which is made worse by rising global energy demand brought on by population increase, has made the energy crisis a critical concern. Researchers have therefore concentrated their efforts on researching renewable energy sources as fossil fuel alternatives, taking into account social and economic issues [1]. In contrast to fossil fuels, such as coal, gas, and oil, renewable energy originates from natural sources that replenish themselves more quickly than they are utilized. When compared with the installation rates of non-renewable energy sources like fossil fuels and nuclear power plants in 2021, the yearly capacity for renewable electricity has increased significantly by over 314 Gigawatts (GW) [2].

There are several primary types of renewable energy that can be harnessed in this world, including solar, wind, geothermal, hydro, and mechanical vibrations. Research trends on these types of energy have only been increasing year by year, as technology has become more advanced. Figure 1 shows individual energy research trends that have been captured through research databases, such as ScienceDirect, over the years. From Figure 1, it is clear that renewable energy has attracted the interest of researchers around the globe over the past decade. However, the availability of most renewable energy sources varies greatly from day to day, season to season, year to year, and even from one geographical location to another [3]. Mechanical vibration energy, on the other hand, does not depend on environmental factors like the others; instead, vibration can be produced by human needs and can also be controlled. For this reason, vibration energy can be harnessed throughout the year without interruptions. The only question is how?

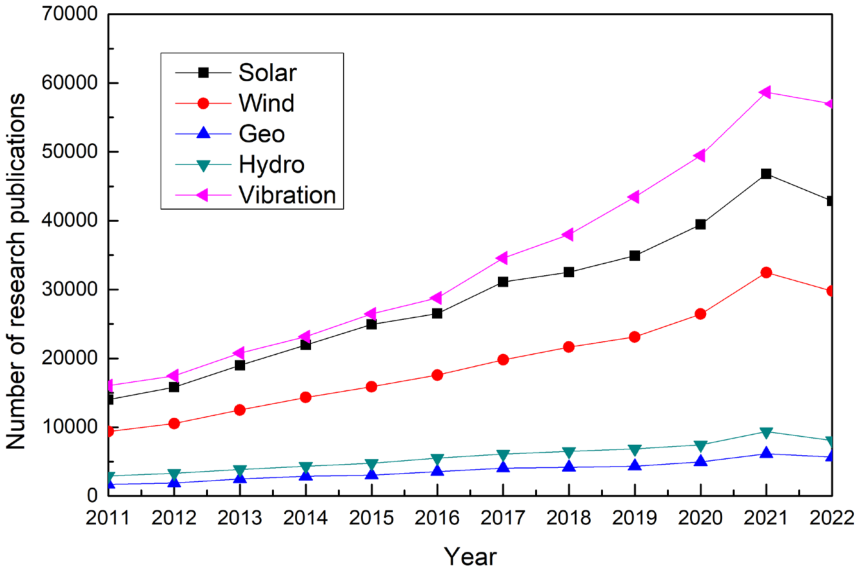

Fig. 1. Renewable energy research trend from 2011 to 2022 retrieved from ScienceDirect

Since vibrations are common in many contexts, such as automobiles, buildings, machinery, and fluid structures, the field of vibration attenuation has long presented significant challenges to researchers. As a result, many methods have been developed to capture energy from outside sources to sustain self-powered gadgets. The use of ambient energy, particularly vibrations, for micro-energy harvesting has recently received attention [4-6]. Ambient energy is appealing owing to its dependability and affordability, which makes it a perfect energy source for applications involving energy collection [7]. Vibration energy harvesting is a technology that harnesses waste kinetic energy from the surrounding environment and converts it into electrical energy. Kinetic energy produced mechanically can be harnessed by three methods: electrostatic induction, electromagnetic induction, and the piezoelectric effect [8,9]. Energy harvesting using piezoelectric materials has been the most studied approach compared to electromagnetic and electrostatic approaches, since it offers a higher energy density and greater versatility in device integration [10-12]. However, the use of piezoelectric transduction technology in vibration energy harvesters is full of challenges and limitations, such as narrow bandwidth [13], low power extraction [14], and sensitivity to temperature variations [15].

Typically, the main goal of piezoelectric energy harvesting is to maximize the electrical power output from a low-vibration source. Therefore, structural resonance is used to amplify the average strain inside the piezoelectric element, which can subsequently increase the output power [16]. This method has its own limitations because the unit only resonate at a single driving frequency. Determining the resonant frequency is very important as resonance can produce fatal effects on structures or systems. Nonetheless, in this case, tuning towards resonance frequency is the main objective when harvesting vibrations.

Therefore, scientists are continually seeking ways to improve the effectiveness of piezoelectric energy harvesters (PEH). The dynamic properties of a PEH beam, especially its resonance frequencies, and their relationship to the voltage output produced by the piezoelectric material is one of the focuses of this work. The main goals of this research are to investigate the effects of different mechanical parameters on the resonance frequency of the beam in the context of piezoelectric energy harvesting, as well as to experimentally model a PEH system.

2. Vibration Energy Harvesting

Mechanical energy harvesting is currently viewed favourably in both industries and academia. Their main drawbacks include low dependability, low environmental adaptation, low efficiency, low power output, and low efficiency. Researchers have been intrigued to harness this mechanical energy in order to eliminate the need of batteries for small devices. Batteries have a very limited lifespan and require recharging and replacing. Not to mention that batteries have a very poor effect on the environment and are hard to dispose of or recycle. Moreover, energy harvesting has become important for powering wireless electronic devices such as battery-free sensors by recapturing ambient energy [17].

Recently, more researchers are very interested in energy harvesting devices, which take energy from the environment and turn it into usable electrical energy to provide a sustainable power source for wireless electronic devices [18]. Figure 2 depicts an overview of alternative energy sources in terms of their power density and lifespan. Apparently, battery power is insufficient for long-term usage when compared to solar cells and vibration generators. Even though solar power offers the highest power density, such performance is significantly reduced when it is used on a cloudy day or indoors [19].

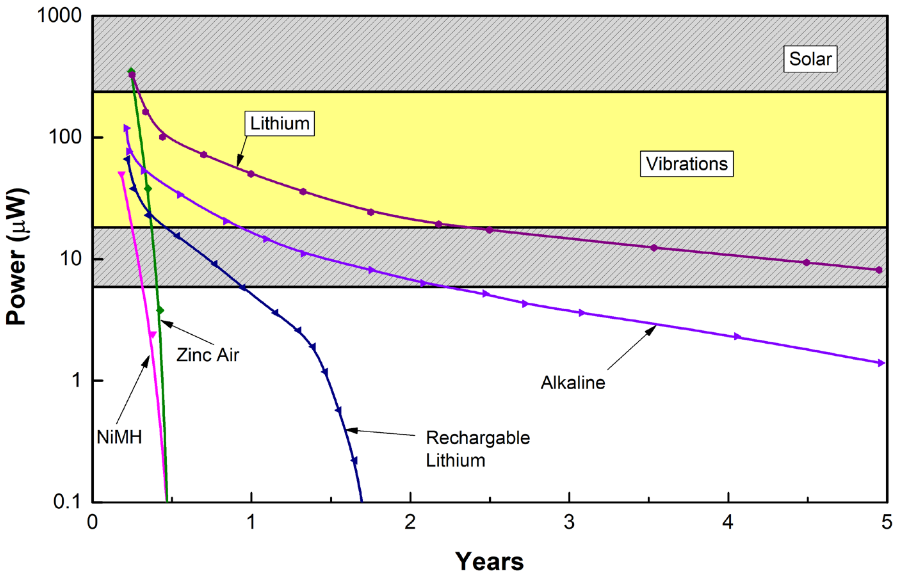

Fig. 2. Comparison of alternative energy to various type of batteries

The abundant renewable energy resources such as solar, wind, thermal, pressure, acoustic, and mechanical energies are generally underutilized for energy harvesting. Despite having greater kW-scale power production capacity, solar, thermal, and wind energy are not practicable for powering wireless electronic devices since they are dependent on vast surface areas and weather conditions [20]. For systems requiring less than µW of power, mechanical vibrations can be the most alternative and attractive source of power. Applications for vibration-based energy harvesting include common household appliances, transportation technology, industrial gear, and even human movement [21].

2.1 Transduction Mechanism

Different transduction mechanism has been introduced and designed to harvest kinetic energy that is piezoelectric, electrostatic, and electromagnetic [22]. The transduction mechanism in electromagnetic devices is velocity, whereas in electrostatic devices it is relative position [23]. The strain is used in the piezoelectric transduction mechanism. Among these mechanisms, piezoelectric energy harvesting is the most capable due to its affordability, simplicity of integration, robustness, high conversion efficiency, and capacity to tolerate a variety of demanding situations [24,25]. The advantages and disadvantages of vibration-induced energy conversion mechanism are summarised in Table 1.

Table 1
Advantages and disadvantages of different type of energy conversion

Conversion mechanism	Advantages	Disadvantages
Electrostatic	• Ease of integration with other electronics.	• Initial voltage source needed • Intricate fabrication process
Electromagnetic	• No initial voltage source needed • Mechanical contacts among the components are not required	• Intricate fabrication process • Hard to integrate with other system • Greater constraints to miniaturization • Lower levels of available voltage
Piezoelectric	• Direct conversion principle • Highest energy density • Relatively easy fabricated • Various configurations available • No initial voltage source needed • Combine most advantage of both electromagnetic and electrostatic converts	• Need to be poled when integrate with microelectronic • Most often require tuning to ambient frequencies • Require overload protection

2.2 Piezoelectricity

According to the linear theory of piezoelectricity, the tensor relation to describe the interaction between mechanical stress, mechanical strain, electric field, and electric displacement is expressed as [7]:

$$S_P = sT + dE \tag{1}$$

$$D_i = dT + \varepsilon E \tag{2}$$

In these equations, *S* stands for strain, *s* for elastic compliance, *D* for electric displacement, *d* for piezoelectric constant, *T* for stress tensor, *ε* for permittivity, and *E* for electric field tensor. The mathematical modelling of electromechanical coupling for PEH is derived from the constitutive Eq. (1) and (2), and these can be developed in the form of a matrix such as Eq. (3) and (4). The strain-charge for a substance like PZT or BaTiO^3 can be expressed as for example [8]:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2(s_{11}^E - s_{12}^E) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{11} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{4}$$

Two frequently employed coupling modes for piezoelectric power generators can be distinguished by the direction of the mechanical force and electric charge. The '3' direction is the usual name for the polarisation direction. The coupling factor of the 33-mode is often greater than the 31-mode in piezoelectric materials. Eq. (5) and (6) illustrate how the electromechanical coupling factor, k, can be represented.

$$k^2 = \frac{\text{Converted Mechanical Energy}}{\text{Input Electrical Energy}} \tag{5}$$

$$k^2 = \frac{\text{Converted Electrical Energy}}{\text{Input Mechanical Energy}} \tag{6}$$

3. Methodology

The methodology study involves identifying piezoelectric materials, constructing a substrate layer which is the cantilever beam, and analysing the dynamic properties of the piezoelectric cantilever beam in terms of resonance frequencies. In order to complete this study as needed, proper tool and procedure usage are designed. Software such as ANSYS Design Modeller was used to model the PEH beam prototype design. The performance of energy harvester in terms of voltage output was numerically analysed using ANSYS simulation software which was later verified through the experiment conducted at the Noise and Vibration Laboratory.

3.1 Design and Materials Selection

Considerations such as length, width, and mass of PEH beam are taken into account during the design and fabrication process. Table 2 displays the nominal dimensions for the energy harvester beam used in this investigated study, while Figure 3 displays the PEH design consisting of the beam, proof mass and piezoelectric patch. The boundary conditions of the beam were fixed at one end and free at another end. The geometric parameters of the beam, such as length and proof mass varied from 180 to 240 mm, and 17 to 34 g, respectively. The position of piezo patch is altered in the middle of the beam and at the fixed end beam.

Table 2
Piezoelectric cantilever beam dimensions

Element	Dimension (mm) (L x W x t)		
Beam	180/ 210/ 240 × 20 × 0.6		
Piezo Patch	41.40 × 20 × 0.15		
Proof Mass	17 g	26 g	4 g
	20 × 20 × 5.41	20 × 20 × 8.28	20 × 20 × 10.83

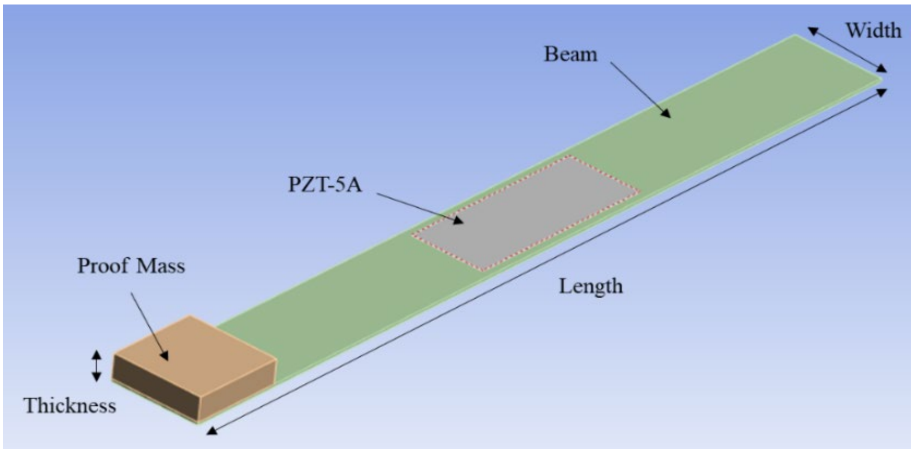

Fig. 3. Schematic representation of piezoelectric energy harvester beam

Aluminium alloy and PZT-5A were the materials used in this study for the piezoelectric energy harvester system. In Tables 3 and 4, the attributes of the two materials used are displayed, respectively.

Table 3
Aluminium alloy properties

Material	Density (g/ cm^3)	Young's modulus (GPa)	Poisson's ratio
Aluminium alloy	2700	70	0.33

Table 4
PZT-5A properties

Material	Resonant frequency	Minimum deflection, δ	Maximum Input Voltage	Resonant Mode
PZT-5A	2 KHz±5%	2mm	100V peak-to-peak	Deflection

3.2 ANSYS Simulation

The numerical modeling was conducted using Ansys Workbench 2021 R2, employing two important analyses: Modal and Harmonic Response, as shown in Figure 4. The voltage response was captured with the help of the ACT Piezo & MEMS extension, which enabled precise simulation of the behaviour of the piezoelectric material. The structural representation employed an 8-node rectangular solid element to ensure accuracy in the depiction of deformations and strain distribution. This resulted in a fine mesh consisting of 140 elements and 1176 nodes.

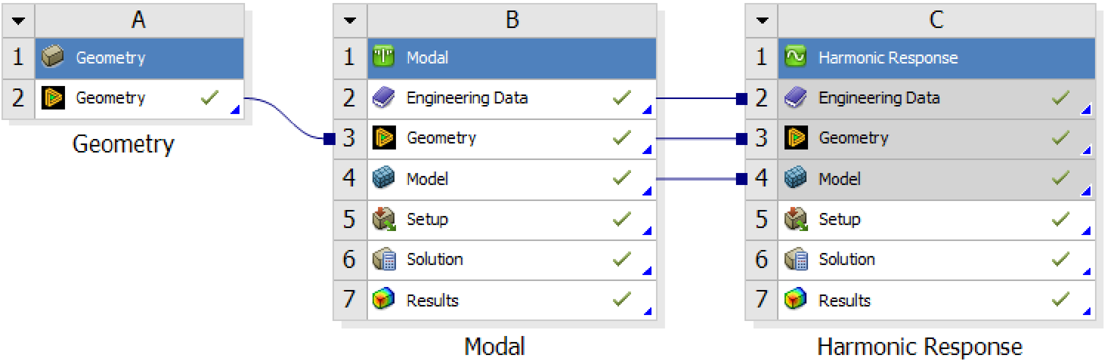

Fig. 4. Piezoelectric cantilever beam setup

During the simulation, several assumptions were made for practical considerations, including perfect bonding between the piezoelectric material and the substrate layer, negligible adhesive thickness, and the absence of damping effects across all harvester configurations. These modeling decisions were made to provide a robust representation of the piezoelectric vibration energy harvester's behavior under various conditions.

3.3 Experimental Setup

A piezoelectric material PZT-5A was attached on top of a cantilever beam as part of the experimental setup for the study, which also required securing the cantilever beam to a vibration shaker. A data analysis tool was coupled to two signal accelerometers that were mounted on the beam, one at the proof mass and one at the base of the shaker. The output of the piezoelectric material was linked to an Arduino system for data collecting and recording after being connected to a microcontroller for signal conversion. Figure 5 depicts the experimental diagram for this investigation.

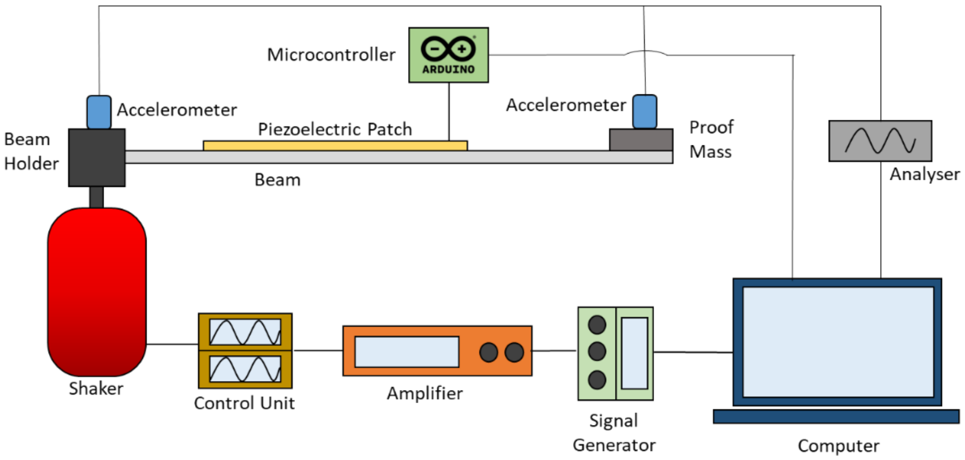

Fig. 5. Piezoelectric cantilever beam setup

The input parameter for the shaker used in the experiment can be seen in Table 5. Similar parameters were applied in the ANSYS simulation using Modal analysis and Coupled Field Harmonic analysis.

Table 5
Input parameters

Conditions	Excitation acceleration	Excitation Frequency	Excitation Type
Value	0.001 m/s^2	3 -50 Hz	Single frequency

4. Results and Discussion
4.1 Resonance Frequency

In the early investigation, dynamic characteristics such as the resonance frequency and mode shape of PEH beam with different geometric parameters were established using ANSYS's finite element analysis. Table 6 summarizes the results of resonance frequencies obtained by this approach using Modal Analysis. It was discovered that lengthening the beam lower the stiffness, thus allowing the resonance frequency of the design to be significantly reduced. With the addition of proof mass, the resonance frequencies were found to decrease slightly.

Table 6
Summary of the effect of the beam length, proof mass and position of PZT-5A

	Cantilever beam w/no proof mass and PZT in the middle			Cantilever beam w/180 mm length and PZT in the middle			Beam w/180 mm length, 17 g proof mass and PZT in the fixed end
Variables (length/ proof mass/ PZT position)	180 mm	210 mm	240 mm	17 g	26 g	34g	
Resonant Frequency (Hz)	15.5	11.3	8.6	9.7	8.3	7.8	11.8

Meanwhile, placing the PZT patch at the fixed end of the beam should increase the resonance frequency as the beam becomes stiffer. This relationship can be further understood from Eq. (7) where f_n is the resonant frequency, k is the stiffness and m is the mass.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{7}$$

Figure 6 illustrates the correlation of beam length and proof mass with the resonance frequency, thus prove that the increased stiffness and weight of PEH beam are directly and inversely proportional to frequency, respectively [26,27]. On the other hand, the mode shape of PEH beam for all different variables chosen in the study has a similar first bending mode, where the maximum deformation occurs in beam's free end as depicted in Figure 7.

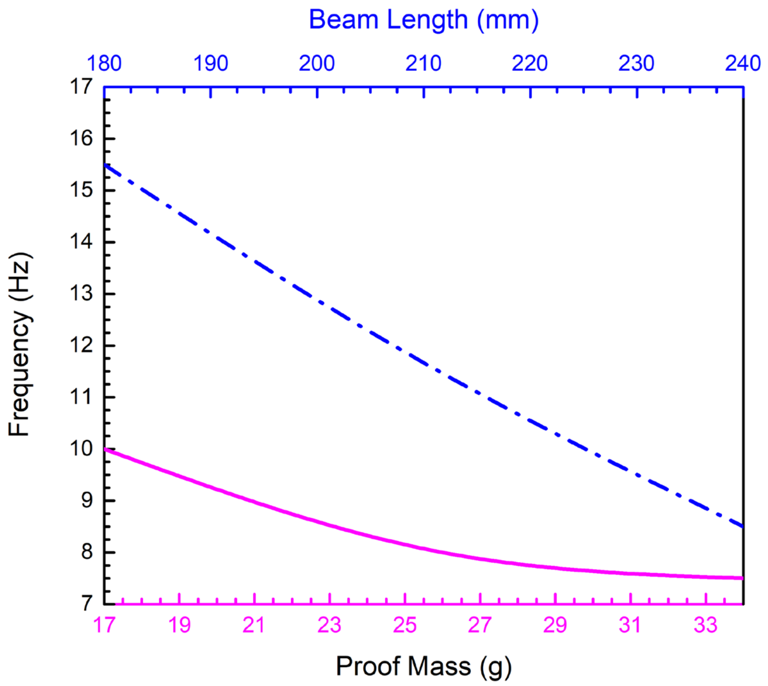

Fig. 6. Effect of the variation of beam length and proof mass on the PEH's resonance frequency

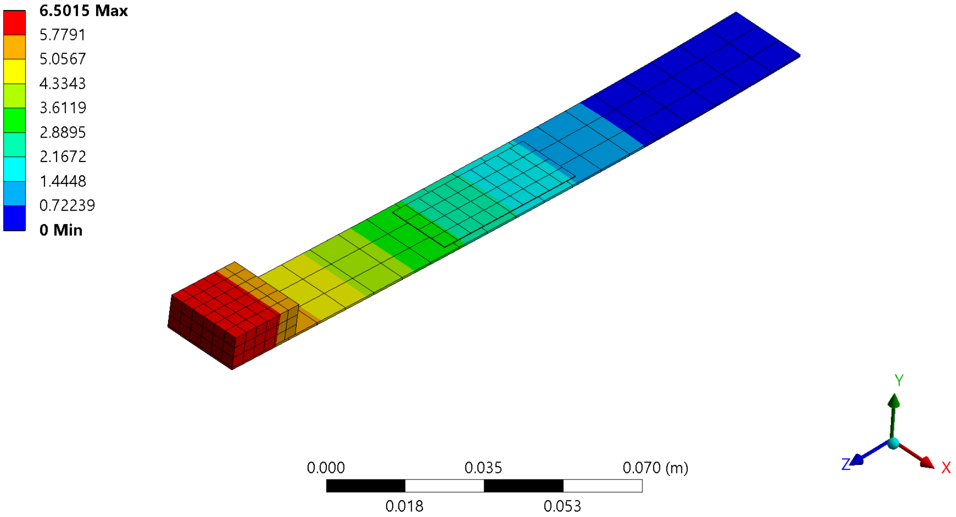

Fig. 7. First mode shape of PEH cantilever beam with 180 mm length and 17 g proof mass

4.2 Effect of Beam Length

In the following work, the effect of varying beam lengths on the resonant frequency and voltage output of a piezoelectric vibration energy harvester is investigated because of both parameters are crucial to determine the performance of energy harvesting devices. PZT-5A was positioned at the centre of the beam, with no proof mass. The beam length varied at 180, 210, and 240 mm, and the corresponding results were obtained through both simulation and physical experiments.

Figure 8 illustrates the frequency response of a piezoelectric vibration energy harvester, where the voltage output as a function of excitation frequency. The frequency range spans from 3 to 30 Hz, which corresponds to the range exhibiting the highest energy generation. As expected, the plot displays a pronounced peak representing the resonant frequency of the harvester. The peak indicates the frequency at which the harvester achieves a maximum power output, highlighting its optimal energy harvesting capability.

It is clearly demonstrated from Figure 8 that the experimental results closely aligned with the trends observed in the simulation. Longer beam lengths indeed led to a decrease in resonant frequency, confirming the expected behaviour. This finding is consistent with existing literature on the topic [28]. Even though the overall trends and qualitative behaviour observed in both simulation and experiments were in excellent agreement as reflected in Figure 9, there are still slight variations in the peak width and resonance frequency. When compared with the simulation results (as shown in Table 6), the resonance frequencies measured from experiments for beam lengths of 180 mm, 210 mm and 240 mm are 15.8 Hz, 12.6 Hz, and 6.9 Hz, respectively. These discrepancies can be attributed to various practical factors in the experimental setup and the simplifications made in the simulation model.

Figure 9 presents the voltage output of PEH at different beam length. As evident from the graph, shorter beam lengths result in higher voltage outputs, whereas longer beam lengths exhibit lower voltage outputs. This can be explained by the strain distribution along the beam, where shorter beams experience higher level of strain under the same excitation, resulting in greater PZT voltage generation [29]. Nevertheless, it is important to note that there is a trade-off between resonant frequency and voltage output. While shorter beams offer higher voltage outputs, they also exhibit higher resonant frequencies, limiting their energy harvesting efficiency to specific frequency ranges.

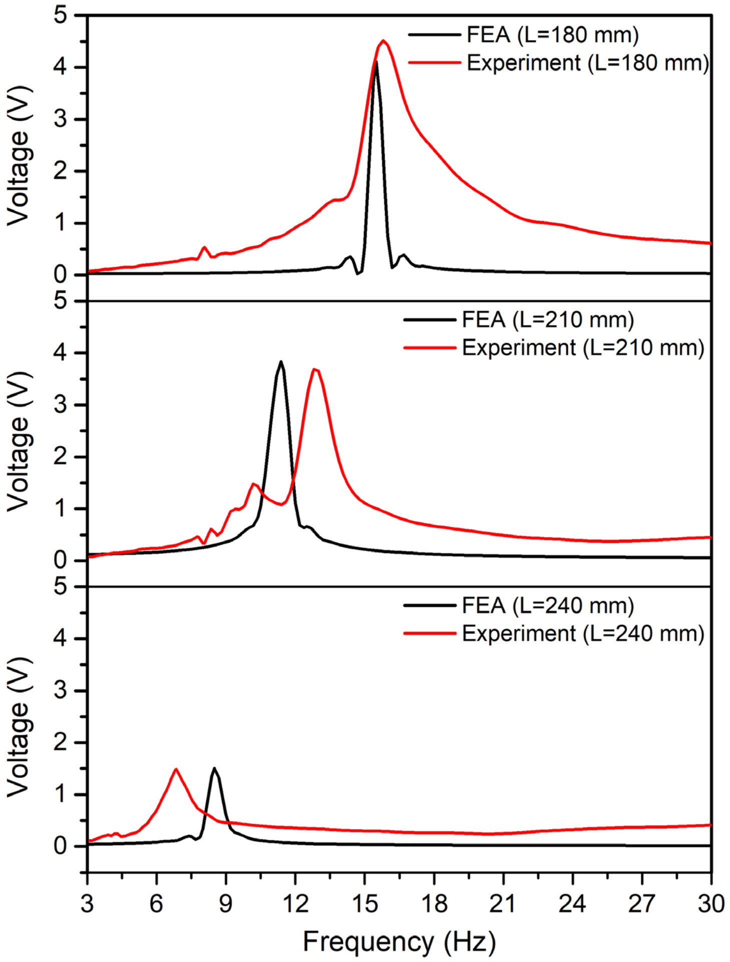

Fig. 8. Voltage frequency response of the PEH beam for different lengths 180 mm, 210 mm and 240 mm

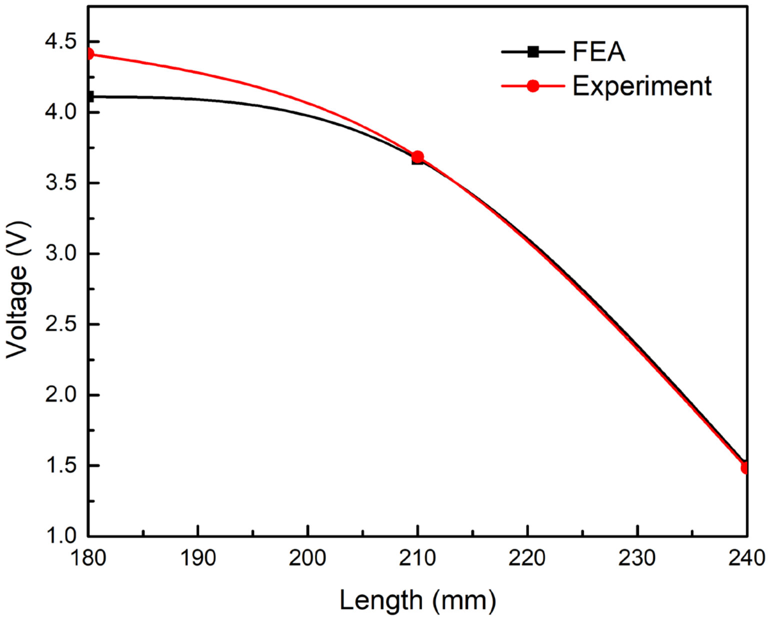

Fig. 9. Comparison between simulation and experiment for voltage output vs beam lengths

4.3 Effect of Proof Mass

To enhance the voltage generated by the PEH, a cantilever beam with a length of 180 mm is selected as it yielded the highest voltage output. This is because by understanding the effect of proof mass in the subsequent analysis, we can optimize the harvester performance.

Figure 10 shows the frequency response of the piezoelectric vibration energy harvester at different proof mass weights of 17 g, 26 g and 34 g, which were obtained from both numerical simulation and experiments. In the simulation, the 17 g proof mass exhibited the highest voltage output of 4.77 V at a resonance frequency of 9.7 Hz, followed by 26 g and 34 g proof masses, which generated 4.25 V at 8.3 Hz and 2.74 V at 7.8 Hz, respectively. These trends were similarly observed in the experiments, with 17 g proof mass achieving the highest voltage of 4.75 V at 9.8 Hz, followed by the 26 g and 34 g proof masses producing readings of 4.26 V at 8.3 Hz and 2.75 V at 7.80 Hz, respectively. This finding again reveals a remarkable agreement between FEA simulations and experiments in both resonance frequency and voltage output.

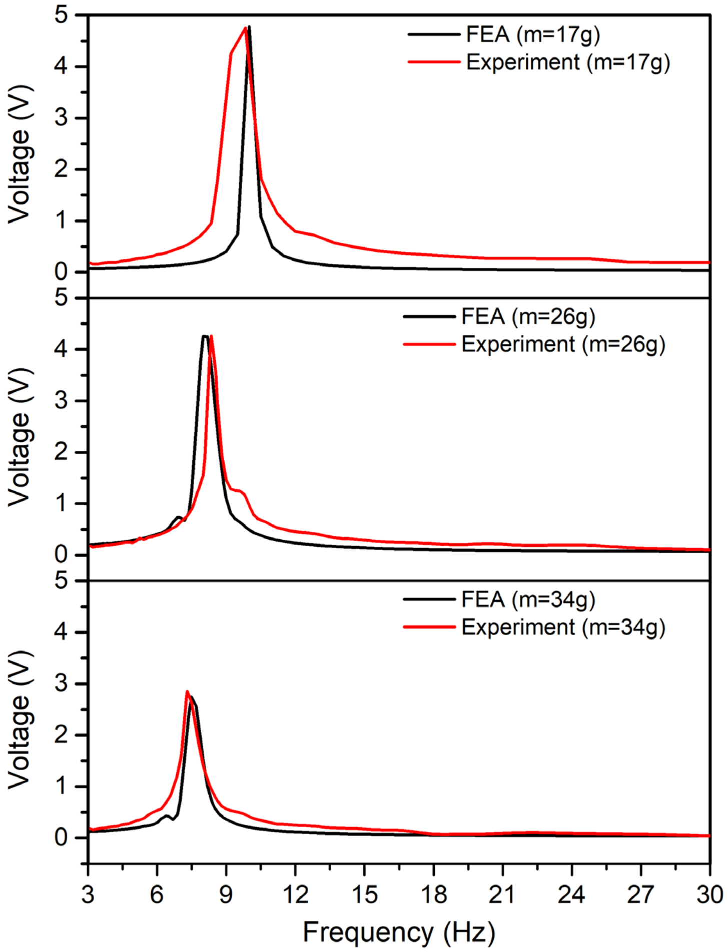

Fig. 10. Voltage frequency response of the PEH beam for different proof masses 17 g, 26 g and 34 g

Figure 11 depicts the voltage output of the PEH as a function of the weight of proof mass. As can be seen, adding proof mass to the beam's tip causes its voltage output to drop, and at the same time lowers the resonance frequency as well. The relationship between the weight of proof mass and voltage output follows a nearly linear trend which similar to resonance frequency. The experimental results exhibit close agreement with the simulation trends, thereby validating the predictive capabilities of the FEA. This alignment between simulations and experiments substantiates the practical feasibility of using proof mass adjustments to optimize the harvester's electrical power generation potential [30].

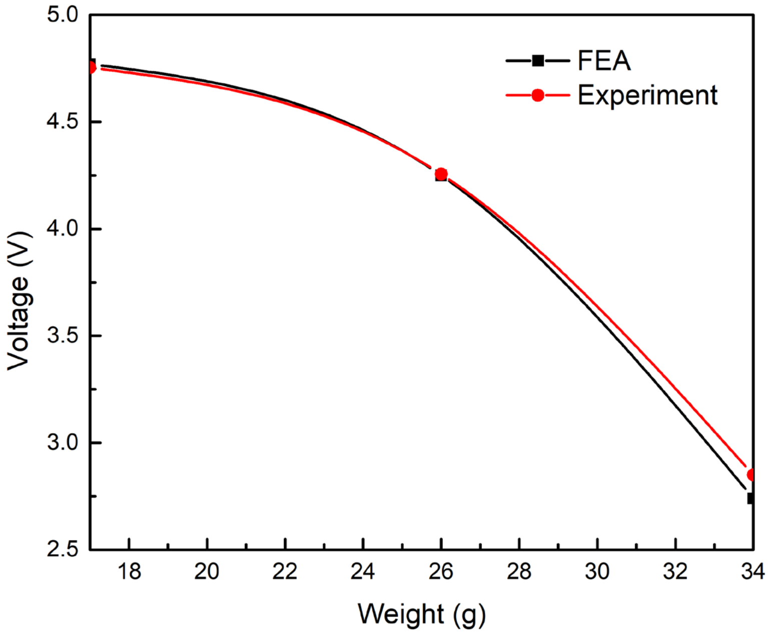

Fig. 11. Comparison between simulation and experiment for voltage output vs weight of proof mass

4.4 Effect of PZT Position

In the last analysis, we focus more on the influence of PZT patch location on the generated voltage. For this purpose, two positions are taken which are in the middle of the cantilever beam and at the fixed end of the beam. The cantilever beam sample selected in this analysis consists of a beam length of 180 mm and a proof mass of 17 g.

According to the graphic representation in Figure 12, the experimental results obtained for voltage are coherent with the simulation results and it shows that the highest voltage of 4.75 V at 9.7 Hz produced when the PZT material attached at the middle of the beam. On the other hand, when the PZT material is positioned closer to the fixed end of the cantilever beam, the harvester produces a voltage of 1.91 V at a slightly higher resonance frequency 11.8 Hz. This observation can be attributed to the strain and deformation levels experienced by the PZT material. When placed near to the fixed end, the material experiences higher stiffness with small beam deflection, and in turn causes a higher resonance frequency and low voltage output. This result is consistent with previous literature where piezoelectric material was used to harvest energy from higher vibrational modes causing the presence of strain nodes that can result in charge cancellation [31].

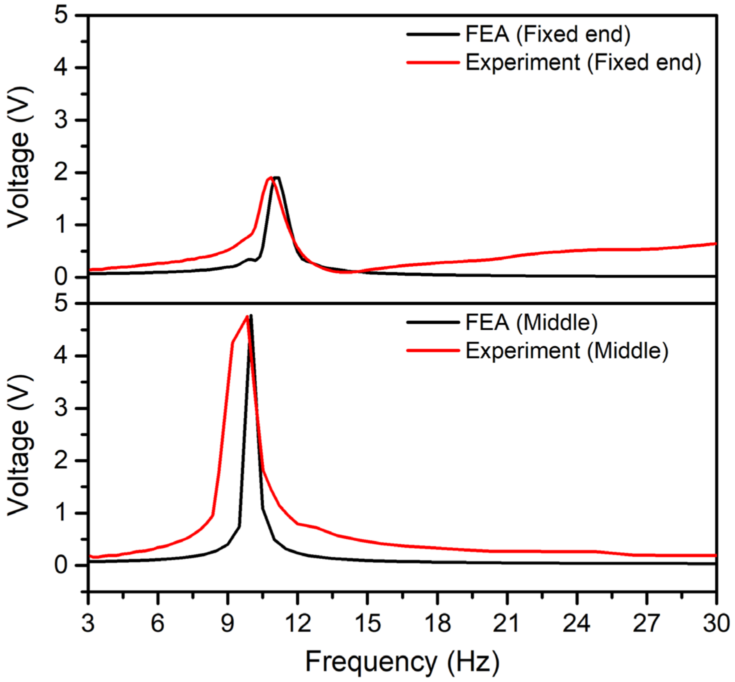

Fig. 12. Voltage generated by piezoelectric at the middle and fixed end of the beam

5. Conclusions

In conclusion, the combination of numerical simulations and experimental investigations allowed us to comprehensively explore the effect of beam length, proof mass and PZT patch position on the resonant frequency and voltage output of the piezoelectric vibration energy harvester. The simulations offered valuable theoretical insights and predictions, which were effectively validated by the experimental results. Our findings from both approaches indicated that the highest voltage was achieved when the beam was designed with a length of 180 mm, attached with 17 g of proof mass at the tip, and the PZT material placed at the centre of the beam. FEA simulations and experiments demonstrated a consistent trend of decreased resonant frequency and voltage output with increasing beam length and proof mass. This collective evidence supports the notion that adjusting the beam length, proof mass and the positioning of the PZT patch are viable methods to optimize the performance of PEH for specific applications. This optimization allows for tailoring the harvester to desired resonant frequencies while maximizing voltage outputs. Overall, the findings from this study significantly contribute to the advancement and design optimization of sustainable energy harvesting technologies. The insights gained can pave the way for the development of more efficient and effective piezoelectric vibration energy harvesters, ultimately promoting the use of sustainable energy sources in various applications.

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