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3D-Piezoelectric Vibration Energy Harvesters: Design Analyses and Performance Evaluation

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Abstract

Piezoelectric materials (PZT) possess the capability to generate electrical energy through deformation, making them ideal for energy harvesting system that transform vibrational energy into electrical power. This study explores the relationship between the design of PZT beams, their natural frequency, vibration response, and generated voltage using a three-dimensional (3D) finite element model. Three types of cantilever designs were considered, that is, L-beam, T-beam and I-beam with PZT-5A patches attached. Each design was subjected to modal analysis, harmonic response as well as voltage analysis performed through Ansys Workbench. The result of modal analysis shows that I-beam exhibits the highest fundamental natural frequency compared to T-beam and L-beam. The evaluation of vibration response at sinusoidal loading was then performed by conducting harmonic response analysis between 0 to 1500 Hz excitation range. It was found that the L-beam demonstrated the highest displacement amplitude at resonance as compared to the other designs. The amplified deformation was converted into voltage output that was verified by the coupled electromechanical analysis, where the L-beam produced the highest voltage output of 7 V at 35 Hz, which is 89% higher than the T-beam and 439% higher than I-beam. In conclusion, this study demonstrates that beam geometry is one of the keys contributing to the efficiency of piezoelectric vibration energy harvesting systems. By optimizing beam design, we do not merely record vibrations, but we can harvest power to the maximum.

1. Introduction

Piezoelectric materials, particularly lead zirconate titanate (PZT) have attracted considerable attention due to their ability to convert a mechanical stress to electrical energy. Because of this special feature, PZT has been highly applied in various engineering fields, including automotive systems, sophisticated medical devices, telecommunications and structural health monitoring applications [1], [2]. Their miniature size, durability and efficiency of converting energy have also contributed to their widespread use in sensors and vibration-based energy harvesting devices [3].

The automotive industry represents one of the major markets for piezoelectric technologies. Recent market research is projecting a USD 28.6 billion by 2023 and USD 50 billion by 2030 market size of the piezoelectric device market around the globe [4]. In automotive sector, PZT-based sensors are widely applied in the tire pressure monitoring system (TPMS) to improve vehicle safety and offers maximum efficiency. These sensors function by converting the tire deformation into an electrical signal, and the signals are processed to give real time feedback to display it to the driver. Besides, the implementation of PZT in the fuel injection systems has altered how engines perform. Piezoelectric injectors offer better fuel injection control and quicker reaction times than conventional electromagnetic injectors. This results in better engine performance, less emissions as well as higher efficiency [5]. Due to this fact, piezoelectric technologies have become even more significant part of the contemporary automotive engineering.

Piezoelectric materials are based on the fundamental principle that was first reported by Pierre and Jacques Curie in 1880. They found out that some crystalline substances were able to produce electric charges under mechanical stress. This is what is referred to as the piezoelectric effect. This phenomenon occurs because mechanical deformation alters the internal polarization of the crystal structure, resulting in the accumulation of electric charges on the material surfaces. The magnitude of the generated voltage is proportional to the applied mechanical stress, meaning that greater deformation generally produces stronger electrical responses [6]. At the microscopic level, this effect arises from the reconfiguration of ions within the crystalline structure or from the rearrangement of molecular dipoles when external forces are applied, as illustrated in Fig. 1.

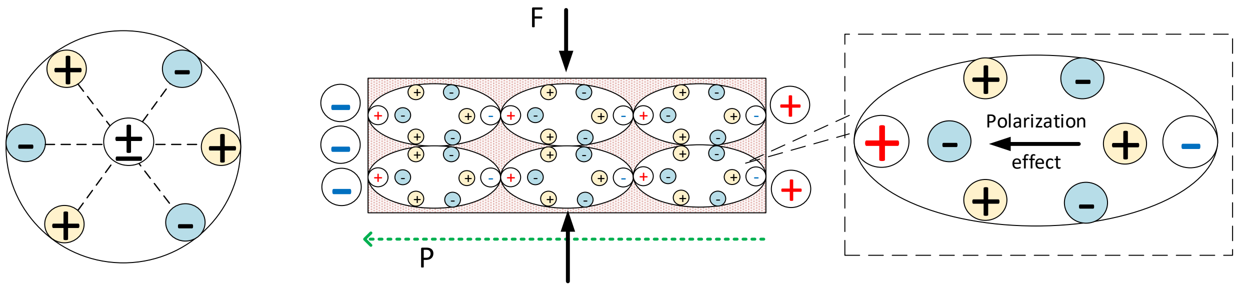

Fig. 1. *Comparison of PZT polarization states, showing (a) The molecule under neutral conditions; and (b) The resulting surface polarization when subjected to a compressive force, F*

Building on these fundamental characteristics, piezoelectric vibration energy harvesters (PVEHs) have gaining growing interest amongst researchers and industry over the last few years [7] - [11]. Such devices are designed to transform the mechanical vibrations that are present in the environment into useful electrical energy. This has found an application especially in powering small electronic devices, wireless sensors, and distributed monitoring systems which run on small power sources [12]. Over the last several decades, researchers have performed numerous studies on various aspects of piezoelectric energy harvesting, such as the choice of materials, device configuration, and strategies on how to enhance the energy conversion process [13].

Despite the potential of PVEH, there are a number of technical challenges. The low and intermittent power output of most piezoelectric harvesters in operational environment has been seen to be one of the most reported problems [14]. To overcome this shortcoming, many scholars have worked on enhancing structural layout of the harvesting system, so as to improve mechanical deformation and increase electrical generation.

One of the popular methods is to incorporate piezoelectric materials into cantilever-like substrate beams. These beams increase mechanical strain when subjected to vibration, which enables the piezoelectric element to produce an increased electrical output. Other work has been done to investigate alternative piezoelectric cantilever beam designs. Ferrari et al. explored electrical current generation of piezoelectric beam vibrating in a self-excited mode and demonstrated that the generated energy can be rectified and stored to improve energy conversion efficiency [15]. Zhao et al. were able to fabricate a low-frequency piezoelectric beam that could achieve an output voltage of more than 50 V with a natural frequency of approximately 9 Hz [16]. On a similar note, Sriram

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and Ma used a comprehensive finite element analysis to evaluate the effects of various structural parameters on the power generation capacity of piezoelectric cantilever beams [17].

Regardless many achievements in piezoelectric vibration energy harvesters, most of the previous studies have mainly dealt with conventional rectangular or flat cantilever beams. The literature on comparative studies of other beam geometries including I-beam, T-beam and L-beam system is still very limited [3], [8], [18], [19]. These geometries have different stiffness features and mass distributions, and this can impact the dynamic response of the beam and resultant strain on piezoelectric element. Thus, understanding on how these configurations affect the energy harvesting performance is important for developing efficient and robust piezoelectric systems.

This paper examines the effects of the three cantilever beam designs: L-beam, T-beam, and I-beam in a 3D finite element model. These geometries generate varying modal properties, which influence vibration response and strain distribution across the structure. With the help of Ansys simulation software, this work is based on the investigation of the effects of cantilever beam geometry variations on natural frequencies, vibration response and voltage generation. Later, the results can be used to design and optimize piezoelectric vibration energy harvesting systems that will be driven by realistic vibration conditions.

2. Design and Modelling

As discussed earlier, this paper dealt with the discussion of three distinct designs of 3D-PZT beam, that is, I-beam, L-beam, and T-beam. These designs were chosen to investigate the effect of structural geometry on vibrational behavior and energy harvesting performance. The designs were designed in ANSYS SpaceClaim with constant dimensions of 500 mm long, 20 mm wide, 20 mm high and 3 mm thick as shown in Fig. 2. To enhance energy capture near the fixed end where strain is typically maximized, a piezoelectric patch of PZT-5A, 450 mm long and 0.5 mm thick, was bonded along the upper surface, as indicated in Fig. 3. These dimensions were chosen as they represent a realistic lab-scale PVEH configuration and also because they allow the finite-element space to stay structurally manageable.

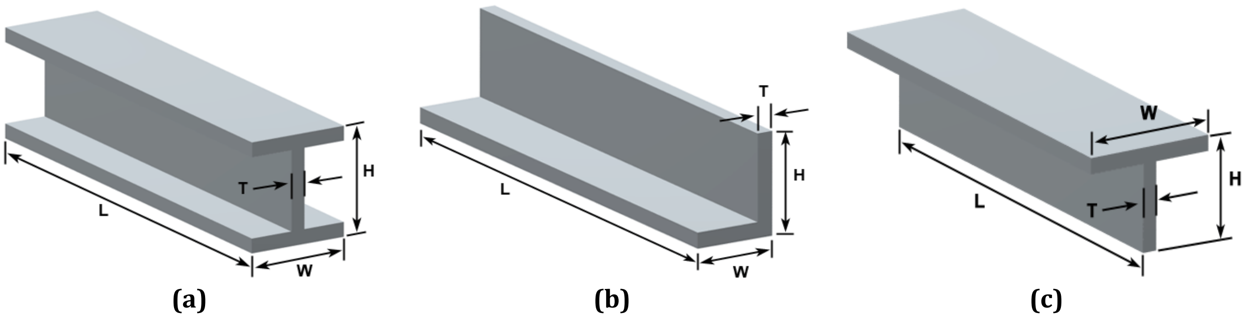

Fig. 2 *Dimensions of (a) I-beam; (b) L-beam; (c) T-beam*

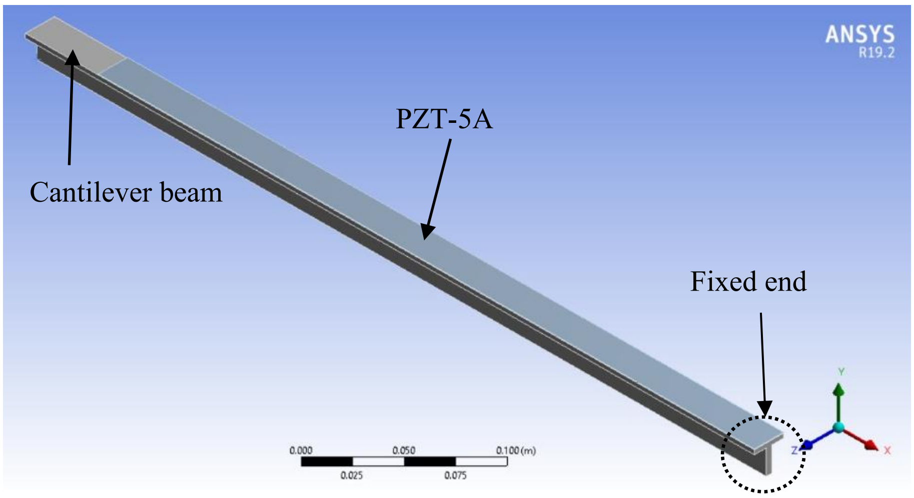

Fig. 3 *Schematic representationof the cantilever beam with surface mounted PZT-5A*

For the mechanical domain, all beam configurations were modeled as cantilever structures with one end was fixed, and the other one was free. To have vibrational input, a sinusoidal excitation force of 2 N was applied at the free end in the vertical direction. The frequency at which the excitation was varied was 0 Hz to 1500 Hz to represent the expected operating range of real-world vibration energy harvesting systems. For the electrical domain, the lower surface of the PZT patch was assigned ground potential, while the upper surface was defined as the output terminal. The ouput voltage was extracted from the terminal response.

In order to verify that the data is numerically accurate, Fig. 4 illustrates that the mesh convergence study was conducted using hexahedron elements with an element refined to 2 mm up to the point where the changes in the maximum deformation were less than 1%. All beam models used this last mesh size to be consistent across simulation. The ANSYS simulation setup made several assumptions, such as that there was ideal adhesion between the PZT patch and the beam substrate, that the adhesive layer was not thick, and that damping effects were not taken into account and were excluded in all setups.

Although direct experimental validation was not carried out in the present study due to resource limitations, the numerical model was developed based on established piezoelectric modeling procedures reported in the literature [20], [21].

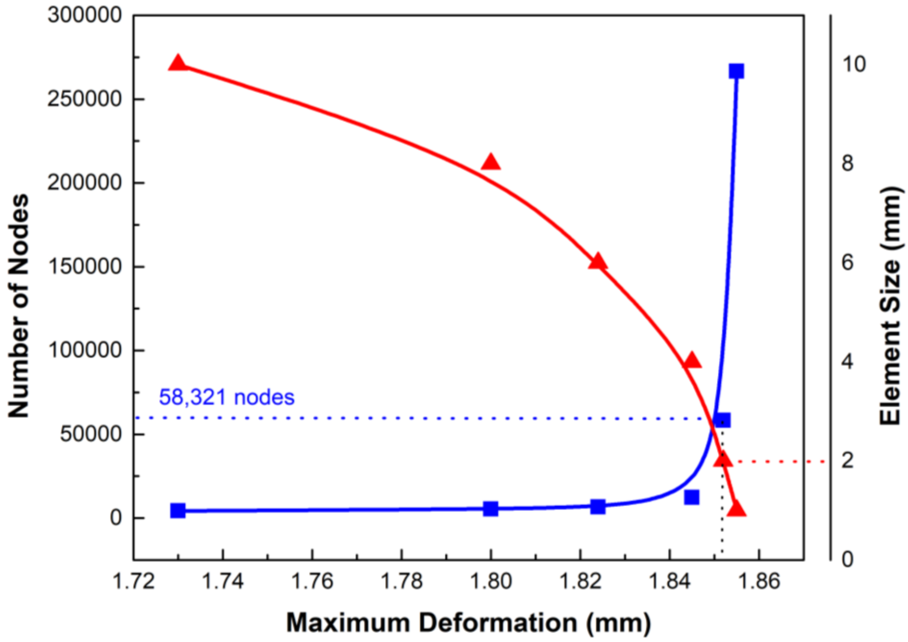

Fig. 4 *A mesh convergence analysis of I-beam*

3. Material Selection

Two particular materials were selected in the current research to construct the PZT beam system: the beam would be made of structural steel and PZT-5A would work as the piezoelectric part of the beam. These materials were chosen because they have established mechanical properties and proven suitable in energy harvesting applications. Table 1 tabulates the material properties of the structural steel and the PZT-5A. The properties are important in identifying the behaviour and performance of PZT beam system in different conditions.

Table 1 *The beam and piezoelectric material properties*

Parameters	Structural steel	PZT-5A
Density (kg/m^3)	7850	7700
Young's Modulus (GPa)	200	62
Poisson ratio	0.3	-

In the case of the piezoelectric material, Fig. 5 shows anisotropic elasticity of the material, and this was correctly specified in the ANSYS software in the "Engineering Materials" tab [6]. It is worth noting that the elasticity matrix is symmetrical along a diagonal thus making it efficient in data entry. As a result, it is only necessary to enter half of the matrix with the respective values of the material properties.

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Moreover, Fig. 6 presents the piezoelectric material properties at the form of piezoelectric matrix with a particular attention paid to such term as “PIEZ e31”. This name is used to denote the value of the permittivity matrix at maximum polarization axis in the Y-direction. These particular properties are important to understand the piezoelectric material behavior to mechanical deformation and electrical polarization to be accurate in the prediction of the piezoelectric material. It is the key in effective design and analysis of the PZT beam system [6].

Table of Properties Row 4: Anisotropic Elasticity

	A	B	C	D	E	F
1	D[*,1] (Pa)	D[*,2] (Pa)	D[*,3] (Pa)	D[*,4] (Pa)	D[*,5] (Pa)	D[*,6] (Pa)
2	1.32E+11					
3	7.3E+10	1.15E+11				
4	7.1E+10	7.3E+10	1.32E+11			
5	0	0	0	2.6E+10		
6	0	0	0	0	2.6E+10	
7	0	0	0	0	0	3E+10

Fig. 5 *Elasticity of PZT-5A anisotropic*

Details of "Piezoelectric Body"

Geometry	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Material Definition	Simplified
Polarization Axis	Y
Permittivity Constant	8.854E-12 [A A sec sec sec sec kg^-1 m^-1 m^-1 m^-1]
PIEZ e31	-5.2028 [A sec m^-1 m^-1]
PIEZ e33	1.50804 [A sec m^-1 m^-1]
PIEZ e15	1.27179 [A sec m^-1 m^-1]
DPER ep11	762
DPER ep33	663
RSVX	0 [kg m m m A^-1 A^-1 sec^-1 sec^-1 sec^-1]
RSVY	0 [kg m m m A^-1 A^-1 sec^-1 sec^-1 sec^-1]
RSVZ	0 [kg m m m A^-1 A^-1 sec^-1 sec^-1 sec^-1]

Fig. 6 *Permittivity constant of PZT-5A*

4. ANSYS Simulation

In order to be able to use piezoelectric materials in simulations in ANSYS Workbench R19.2, it is required to install certain extensions. With these extensions, piezoelectric properties can be incorporated into the piezo model in matrix form. In this case, ACT Piezo & MEMS extension facility is employed. This is made possible by integrating the ACT Piezo and MEMS functionality in ANSYS Mechanical allowing the broadening of the scope of simulations that can be made, presenting a flexible framework of analysis by which other types of analysis may be conducted as well.

To gain the performance of the PZT beam system in three dimensional, there are three crucial analyses that took place in ANSYS simulation. The analysis that was made included modal analysis, harmonic analysis, and voltage analysis. Each analysis presented useful information about various different aspects of the response of the system. The mode shape and natural frequency of the PZT beam under free vibration conditions were determined by using modal analysis [22]. By identifying the mode shapes and natural frequencies, the overall picture of vibrational behavior of the beam is obtained. The natural frequencies indicate the frequencies, in which this beam is most prone to vibration. The PZT beam response to the harmonic loads was studied using the Harmonic analysis. This discussion made it possible to understand the amplitude of the vibration of the beam and its behavior under the action of sinusoidal loads [23].

The voltage analysis was a major part of this research, which was to measure the electrical response that developed on the PZT patch upon sinusoidal mechanical excitation. When mechanical strain is applied to the PZT patch due to vibrational inputs to the PZT beam, the voltage is produced because of the piezoelectric effect. Equation (1) demonstrates the governing equation on which the couple electromechanical behavior between mechanical displacement and electrical potential in the piezoelectric structure has been described [21]. This is the coupled system of equations that can be used in the finite element modeling of piezoelectric structures in the standard formulation whereby the mass, damping, and stiffness matrices are assembled with proper material properties of the substrate material and the piezoelectric layers.

$$\begin{bmatrix} M_{UU} & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{U}} \\ \ddot{\boldsymbol{V}} \end{Bmatrix} + \begin{bmatrix} C_{UU} & 0 \\ 0 & -C_{VV} \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{U}} \\ \dot{\boldsymbol{V}} \end{Bmatrix} + \begin{bmatrix} K_{UU} & K_{UV} \\ K_{UV}^T & -K_{VV} \end{bmatrix} \begin{Bmatrix} \boldsymbol{U} \\ \boldsymbol{V} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{F} \\ \boldsymbol{Q} \end{Bmatrix} \quad (1)$$

Where $\boldsymbol{U}$ is the mechanical displacement vector, $\boldsymbol{V}$ is the electrical potential, M_{UU} is the structural mass, C_{UU} is the structural damping, C_{VV} is the dielectric dissipation, K_{UU} is the structural stiffness, K_{VV} is the dielectric permittivity, K_{UV} is the piezoelectric coupling, $\boldsymbol{F}$ is the external force vector and finally $\boldsymbol{Q}$ is the surface electric charge.

5. Result and Discussion

5.1.1 Natural Frequency and Mode Shape

Table 2 reveals the natural frequency results for three different PZT cantilever beam designs, namely I-beam, T-beam, and L-beam obtained from the Modal Analysis. The analysis was aimed at the measurement of the first four natural frequencies of each type of beam and respective mode shapes.

As a preliminary structural check, the first natural frequency of the I-beam was estimated using the classical Euler–Bernoulli cantilever beam equation for a fixed-free beam. which gave an approximate value of 112.9 Hz. The corresponding ANSYS result was 119.09 Hz. The small difference is attributed to the simplifications of the analytical model, which does not account for the full three-dimensional geometry, the bonded PZT patch, or the electromechanical coupling effect. Even so, the comparison provides a useful benchmark for assessing the structural behaviour predicted by the finite element model. In addition, the overall cantilever-based modeling approach adopted in this work is consistent with previously reported piezoelectric beam studies in the literature [16], [6].

Table 2 *Natural frequencies of 3D-PZT cantilever beams in unit Hertz*

Mode (η-th)	I-beam	T-beam	L-beam
1	119.09	45.59	34.36
2	203.84	67.63	64.97
3	338.39	281.35	214.98
4	709.59	419.22	367.78

According to Table 2, the natural frequency of the I-beam implies that it has got the highest natural frequency as compared to the T-beam and L-beam. This result indicates that the I-beam is more responsive to vibrations than the other designs. Thus, the implication on the vibration response characteristics and the possibility of utilizing them to generate energy could be extremely important in proposing alternative beam stiffness [24], [25]. Generally, the first natural frequency is the dominant mode shape of any type of beam. This mode shape represents the primary vibrational pattern exhibited by the PZT beam during free vibration conditions, and it is what referred to as the first bending mode as shown in Fig. 7. Interestingly, mode shape of the first natural frequency is observed to be similar in all the three beam types. This mode shape similarity indicates that the main vibrational mode is similar to all the beam designs.

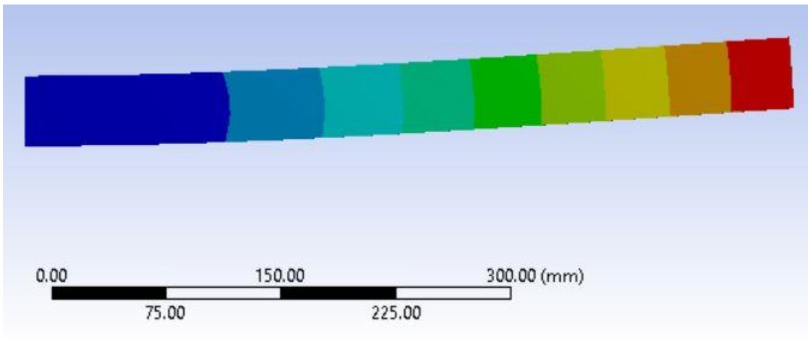

Fig. 7 *First bending mode shape of I-beam*

5.2 Harmonic Response

The vibration behavior of the PZT beam designs was further studied using harmonic analysis. Each beam was excited over a frequency range of 0 to 1500 Hz to observe how it responded under different loading frequencies. It should be noted that the harmonic response in this research was considered in a specific direction that is along the Y-axis, and that is the vertical orientation of the PZT patch. This selective axis monitoring was actually done with the purpose of generation of voltage being induced mostly by strain in the vertical axis where the piezoelectric patch is bonded.

Fig. 8 shows the frequency response function (FRF) of the PZT beam designs and the graph shows a plot of displacement versus frequency. The results showed that the L-beam had the most displacement peaks in the FRF with the highest amplitude registered at about 2.34 mm at 35 Hz. This means that the level of deformation is high as compared to that of T-beam and I-beam. These results are consistent with modal analysis, in which the stiffer is the beam, the lower the amplitude of vibration as shown by the I-beam. In addition, the peaks observed in the FRF plots are near to natural frequencies that are obtained in the modal analysis, which proves the presence of resonance in these points. This type of behavior confirms the connection between resonance, structural stiffness, and the energy harvesting efficiency.

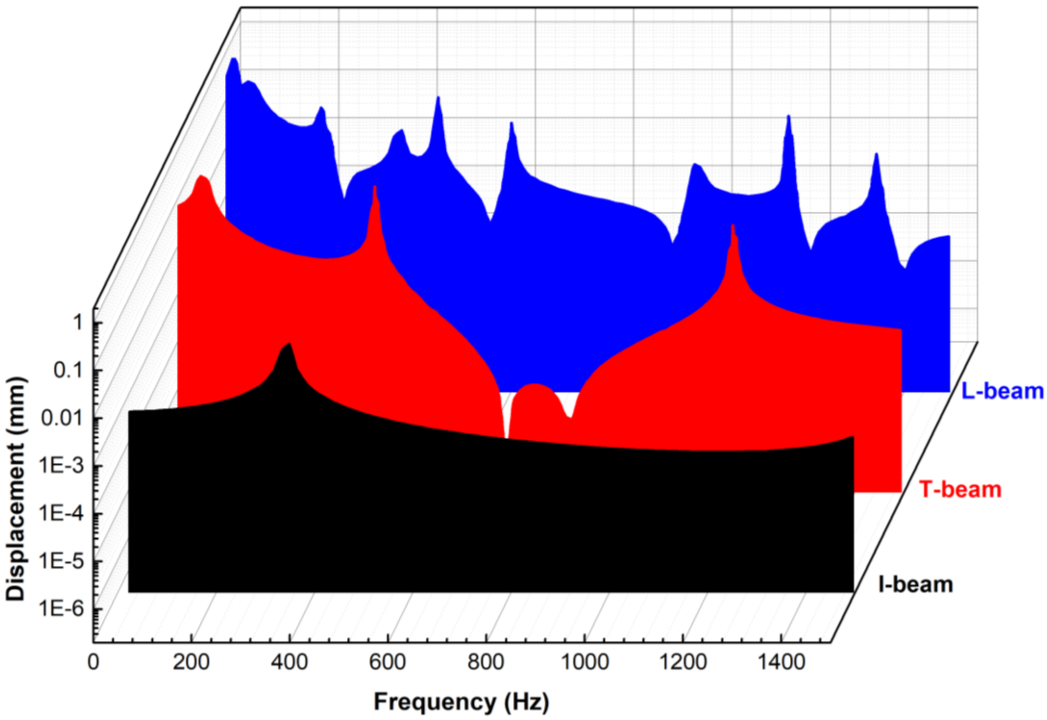

Fig. 8 *Frequency response of I-beam, T-beam and L-beam*

The present results should be interpreted as undamped comparative predictions. While the omission of damping simplifies the numerical model, it likely leads to an overestimation of the resonance amplitude and the corresponding voltage response. Therefore, the reported magnitudes should be regarded as upper-bound estimates rather than exact values expected under practical operating conditions.

5.3 Voltage Output

Fig. 9 shows the voltage frequency response of the three designs of PZT cantilever beam designs in which the voltage output was plotted against excitation frequency. The frequency range varies between 0 and 600 Hz that is the range with the maximum energy generation. As it would be anticipated, there would be an apparent peak on the graph to the natural frequency where PZT beams would produce the maximum power output, thereby pointing out their optimum energy harvesting potential. Among the PZT beam designs, the L-beam stands out, exhibiting the highest number of peaks throughout the frequency range. This suggests that the L-beam undergoes several displacements which induces strain on the PZT patch and resulting in a higher voltage generation.

Regarding the voltage output, the L-beam outperforms the other designs, producing the highest voltage output of 7 V at 35 Hz, which is 89% higher than the T-beam and 439% higher than I-beam. In comparison, the T-beam and I-beam generated 3.7 V and 1.3 V, respectively, at their respective peak frequencies. Using an equivalent resistive load of 1 MΩ, the peak power output of the L-beam at 35 Hz is estimated as 49 μW, compared to 13.7 μW for the T-beam and 1.7 μW for the I-beam. The load resistance of 1 MΩ was selected as a reference value for preliminary comparison because it lies within the range commonly used for high-impedance piezoelectric harvesters [26].

Fig. 10 provides a detailed representation of the voltage generated by the piezoelectric patch of the I-beam due to deformation on the beam. Although voltage generation is directly proportional to strain, the current simulation monitored beam deformation as a proxy for identifying high-strain regions. The outcome shows that the PZT patch produces the concentrated voltage in the central surface of the beam, which is the area of the best energy conversion. The findings are based on idealized simulation conditions. In practice, the piezoelectric response and long-term stability can be affected by temperature variations in the ambient and environmental humidity. Consequently, the future actions of experimental and environmental stress testing are needed to determine the feasibility of the proposed beam designs in practice.

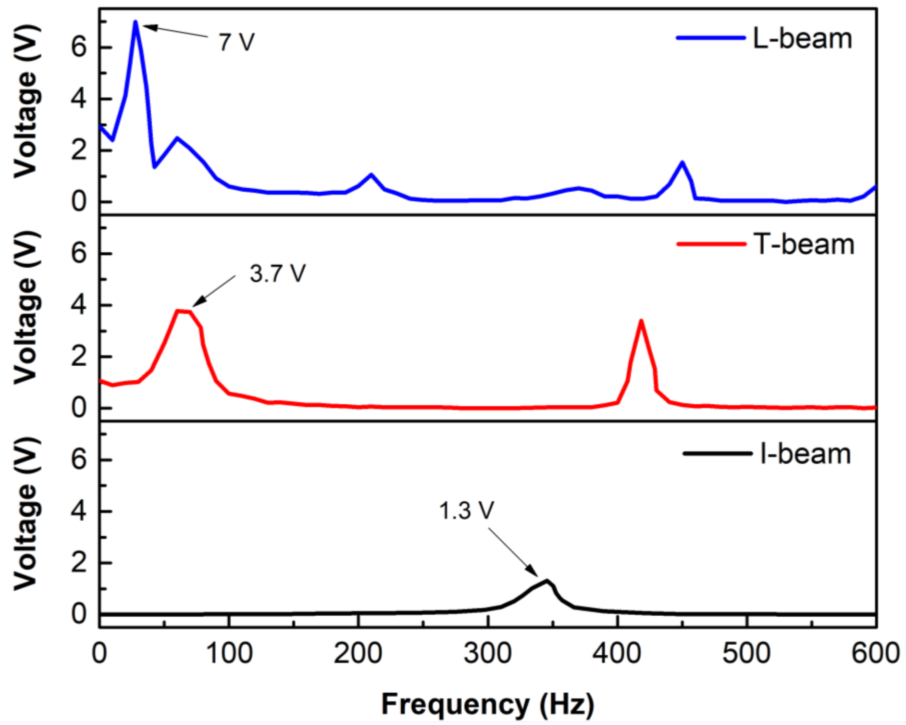

Fig. 9 *Voltage versus frequency for the 3D-PZT cantilever beams*

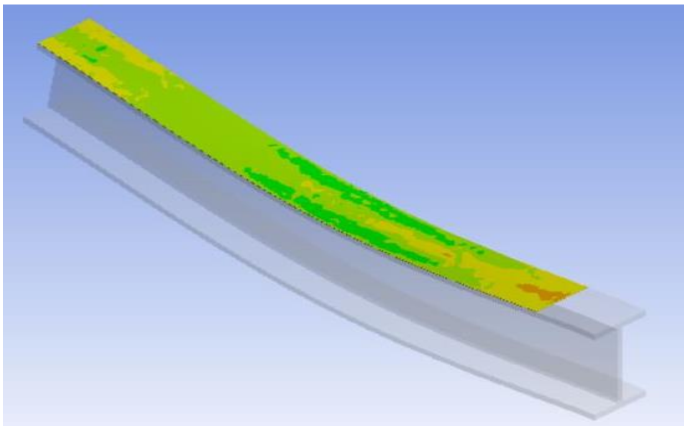

Fig. 10 *Voltage spectrum generated by I-beam*

6. Conclusion

Modal analysis, harmonic response, and voltage analysis were used in this study to obtain the complete picture of the behaviour of the 3D-PZT beam system. From the finite element simulation, clear differences were observed among the three beam designs. The modal analysis showed that the I-beam had the highest natural frequency than the T-beam, and the L-beam. These findings indicate the significance of structural stiffness in the determination of the dynamic response of the beams and performance of the potential energy harvesting. A different trend appeared in the harmonic response results. The L-beam had the greatest amplitude of displacement, which implies that it is more flexible than the other beam designs. The findings affirmed that, the stiffer the beam, e.g. I-beam, the less vibration response it would have. This is important in optimization of the beam designs in order to attain the desired vibration properties and energy harvesting efficiency. The voltage response followed the same general pattern. Distinct peaks were recorded at certain frequencies, and these are the natural frequencies where the PZT beams produce the greatest voltage. It is important to note that L-beam had the greatest number of peaks, implying a stronger and more frequent electromechanical response.

Overall, these findings suggest that beam geometry has a meaningful effect on the performance of PZT beam energy harvesters. The increased displacement and voltage of the L-beam is an indication that it would be applicable in low frequency vibration set ups such as in bridges or HVAC systems. However, its greater flexibility may raise concerns as this can decrease structural durability in long-term cyclic loading. On the other hand, the rigidity of the I-beam can be useful in structures where structure needs to be considered rather than energy. Therefore, a trade-off between the voltage production and mechanical robustness should be taken into account in order to apply it practically.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Izzuddin Zaman;* ***simulation model development and data collection:*** *Muhammad Mohamed Salleh, Mathan Sambu;* ***analysis and interpretation of results:*** *Izzuddin Zaman, Bukhari Manshoor;* ***draft manuscript preparation:*** *Sethupathi Saravanabava;* ***manuscript review and technical revision:*** *Ahmed A. Abuhatira. All authors reviewed the results and approved the final version of the manuscript.*

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