B. TECH. PROJECT REPORT

On

Design and development of piezoelectric energy harvester beam made up of PZT

BY

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DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Design and development of piezoelectric energy harvester beam made up of PZT

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

Submitted by:
Aniruddha Bante (160003012)

Guided by:
Dr. Shailesh Kundalwal (Associate Professor)

INDIAN INSTITUTE OF TECHNOLOGY INDORE
December 2019

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Design and development of piezoelectric energy harvester beam made up of PZT"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in Mechanical Engineering completed under the supervision of **Dr. Shailesh I. Kundalwal, Associate Professor, Mechanical Engineering, IIT Indore** is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Aniruddha Bante

160003012

CERTIFICATE by BTP Guide

It is certified that the above statement made by the student is correct to the best of my knowledge.

Dr. Shailesh I. Kundalwal

Associate Professor

Mechanical Engineering

Preface

This report on **“Design and development of piezoelectric energy harvester beam made up of PZT"** is prepared under the guidance of **Dr. Shailesh I. Kundalwal**.

Through this report, I have tried to give an elaborate insight on how the beam length and proof mass attached to the piezoelectric energy harvester affect its fundamental frequency which is a crucial criterion for determining its performance under the given environmental vibrations.

I have tried my best to explain the content to a reader in a lucid manner. I have also added figures and graphs for better understanding.

Aniruddha Bante
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Acknowledgment

I wish to thank **Dr. Shailesh I. Kundalwal** for his kind support and valuable guidance. I would also like to acknowledge **Mr. Vijay Choyal, Mr. Ankit Rathi** and **Mr. Madhur Gupta** (Ph.D. research scholars) for their sincere cooperation and guidance to my project.

I would also like to specially mention **Mr. Pawan Gupta** (Ph.D. research scholar) of **Solid Mechanics Lab, IIT Indore** for his valuable time and support. I would also like to acknowledge **Mr. Sandeep Gour** and **Mr. Deepak Rathod** of **Advanced Manufacturing Processes Lab, IIT Indore** for helping me in the completion of the project.

It is with their help and support, due to which I was able to complete the project. Without their support, this report would not have been possible.

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Abstract

This study focuses on the design and development of piezoelectric energy harvester (PEH) beam made up of PZT using numerical and experimental approaches. The unimorph cantilever beam type PEH was modeled by using finite element modeling (FEM). Here, PZT-5H (lead zirconate titanate) was used as the piezoelectric material. It was bonded to a substrate made up of phosphor bronze using epoxy. Proof mass of titanium was used to increase the effective mass and decrease the damping of PEH. This increases the output power generated by the PEH. The modal analysis was performed on the PEH for determining its fundamental frequency, which is an important parameter for its design. The effect of varying beam length and proof mass on the fundamental frequency was determined. The results for fundamental frequency obtained by considering PZT-5H as anisotropic (transversely isotropic) and isotropic material were compared. Next, the PEH was fabricated and the obtained numerical results were experimentally validated. An impact hammer was used to excite the clamped PEH. Voltage frequency response functions (FRFs) were obtained experimentally for various geometries of PEH. These voltage FRFs were then used to determine the fundamental frequency of the PEH. Our fundamental study highlights tailoring of performance of multifarious energy harvesting micro-electromechanical systems (MEMS) for applications such as sensors and actuators.

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Chapter 1

Overview

1.1 Introduction

Energy harvesting has been a topic of interest for a past decade. This is due to its potential of powering devices such as wireless sensor networks (WSNs), and to deal with the energy shortage problem. Batteries need replacement during the lifetime of the devices due to their limited life. This replacement process can be time-consuming and challenging when sensor networks are spread over a large area or rooted inside engineering structures. To solve this problem, energy harvesters can be used as an alternative to batteries. They could also overcome issues related to battery usage such as toxicity, battery disposal, etc. (Tufekcioglu and Dogan, 2014).

Energy harvesting (EH) is defined as capturing minute amounts of energy from surrounding energy sources such as solar, wind, liquid flow, thermal gradient, vibration, etc., and converting it to electrical energy and storing it for later use (Kim, Kim and Kim, 2011). Here, we have focused on vibration energy harvesting, i.e., extracting energy from the environmental vibrations which would otherwise be wasted. Vibrations can be found in most of the places such as machines, human motion, vehicles, railway tracks, floors and walls, and other civil structures. This vibration energy can be converted to electrical energy by different transduction mechanisms, such as piezoelectric, electromagnetic, electrostatic, etc. Among these EH techniques, the piezoelectric energy harvester (PEH) has received much attention due to its high electromechanical coupling effect, and no external voltage sources requirement (Yu *et al.*, 2014). So, piezoelectric material has been used for converting vibration energy to electrical energy.

Piezoelectricity is caused due to the lack of center of symmetry in the crystal. Due to this, polarization exists in the crystal. Piezoelectric material generates electric voltage on the application of mechanical stress. This is called the direct piezoelectric effect. Conversely, it undergoes mechanical deformation on the application of the electric field. This is termed as the converse piezoelectric effect. We have used the direct piezoelectric effect for EH applications. Fig. 1.1 shows the direct piezoelectric effect.

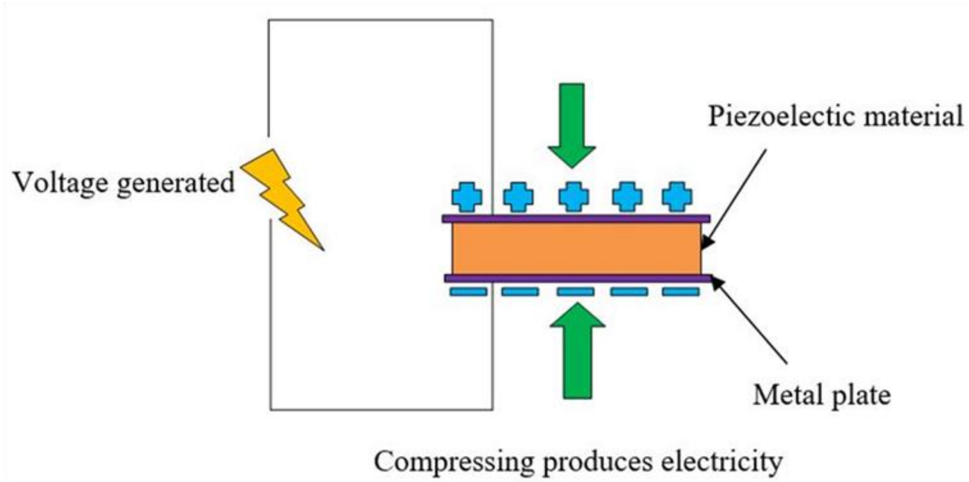
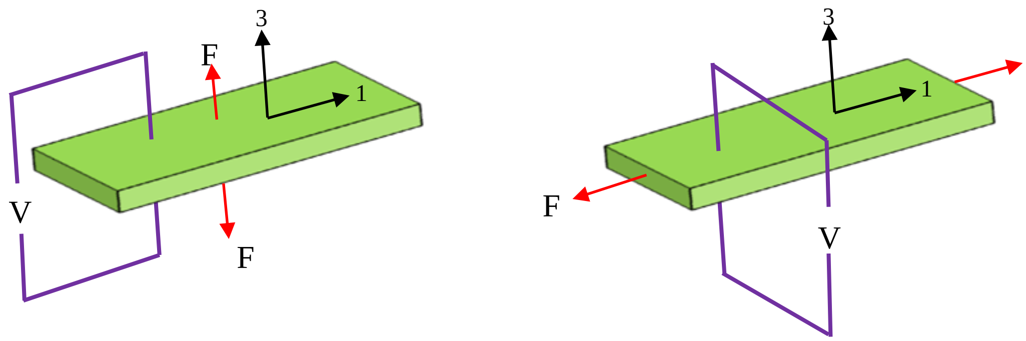


Fig. 1.1:- Direct piezoelectric effect

Naturally found piezoelectric materials have zero net polarization due to the random orientation of dipoles. When these materials are deformed, very small polarization and hence very minute voltage is generated. For maximizing the piezoelectric response, these materials should be poled before their use. Poling is the process of applying high electric field to the piezoelectric material usually at an elevated temperature (below their Curie temperature) for sufficient time. This aligns the dipoles in the poling direction and remnant polarization exists in these materials even after the electric field is released. This enhances the piezoelectric effect. In the context of piezoelectricity, Curie temperature is the temperature above which the material loses its piezoelectric characteristics.

1.2 Literature Review

We have used unimorph PEH which means there is only one layer of piezoelectric material present in the structure. Cantilever type PEH was used because it can apply larger strain to the piezoelectric material under vibration condition. Due to this high output can be obtained from the piezoelectric material (Kang *et al.*, 2016). The cantilever model can be used in two different modes of vibration,33 mode and 31 mode. In 33 mode (, voltage is obtained in the direction ‘3’ parallel to the direction of applied force. In 31 mode, voltage is obtained in the direction '1' which is perpendicular to the direction of applied force '3'. Here, poling direction is the '3' direction. The most useful mode in EH applications is 31 mode because an immense proof mass would be needed for 33 configuration (Roundy, Wright and Rabaey, 2003).



a) 33 mode

b) 31 mode

Fig. 1.2:- Different modes of vibration of piezoelectric energy harvester

Thickness of the piezoelectric material and substrate are taken to be equal. This is because, for given excitation energy and geometry of PEH, maximum electrical energy is stored when the ratio of thickness of the piezoelectric material and substrate is close to one (Guizzetti *et al.*, 2009).

Length of the piezoelectric material and substrate are taken to be equal. This is because, for given excitation energy and geometry of PEH, maximum output power is obtained when lengths of piezoelectric material and substrate are equal (Gao, Shih and Shih, 2010).

Due to the poling of the piezoelectric material, its properties along the poling direction are different from those in the plane perpendicular to the poling direction, i.e., the piezoelectric material is transversely isotropic (anisotropic).

The fundamental mode of vibration is considered for designing the PEH because with higher modes of frequencies acceleration decreases and hence there is less piezoelectric response (Roundy, Wright and Rabaey, 2003). As the common environmental vibrations are between 60 Hz and 200 Hz (Varadrajan and Bhanusri, 2012), we designed the PEH such that its fundamental frequency is below 200 Hz. A proof mass was also used to reduce the fundamental frequency of the PEH.

In this study, the effect of beam length and proof mass on the fundamental frequency of the PEH were determined. We also compared the fundamental frequency results obtained by considering the piezoelectric material as isotropic and anisotropic (transversely isotropic) material. Finally, the numerically obtained fundamental frequency results were experimentally validated.

Chapter 2

Methodology

2.1 Materials Used

1. PZT-5H

The piezoelectric material used was PZT-5H. It is modified Lead Zirconate Titanate having high electro-mechanical coupling coefficient (k) and high piezoelectric strain coefficient (d) (Song, Yue and Hu, 2018). A higher value of ‘k’ signifies higher efficiency in converting mechanical energy to electrical energy. Also, due to higher value of ‘d’ we get more piezoelectric response for the same level of excitation and hence more energy can be tapped.

2. Phosphor Bronze

The substrate of the PEH was made up of phosphor bronze. It has strong fatigue resistance and can bear larger deformation (Song, Yue and Hu, 2018). The mechanical properties used for phosphor bronze are: -

Density	Young’s Modulus	Poisson’s Ratio
8920 kg/m^3	106 GPa	0.35

Table 2.1:- Mechanical properties of Phosphor Bronze

3. Titanium (Ti)

The proof mass was made up of titanium. It is attached to increase the effective mass and decrease the damping of the cantilever beam. This increases the output power of the PEH (Varadrajan and Bhanusri, 2012). The mechanical properties used for titanium are: -

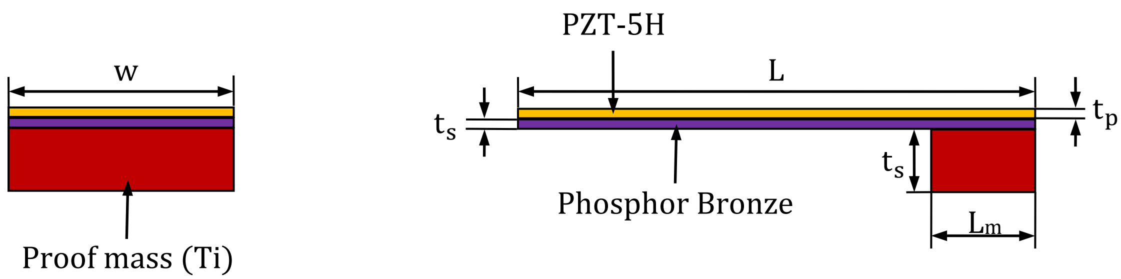
Density	Young’s Modulus	Poisson’s Ratio
4429 kg/m^3	110 GPa	0.31

Table 2.2:- Mechanical properties of Titanium

4. Epoxy

Epoxy was used to bond PZT-5H to phosphor bronze. The mechanical behaviour of the epoxy was neglected in the FE analysis due to its low thickness.

2.2 Terminologies and common geometric specifications



a) Front view b) Side view

Fig. 2.1:- Unimorph cantilever beam type piezoelectric energy harvester

The symbols used in the following text are given below:-

a) L = length of the beam
b) w = width of the beam
c) t_p = thickness of PZT-5H
d) t_s = thickness of phosphor bronze
e) E_p= Young's modulus of PZT-5
f) E_s= Young's modulus of phosphor bronze
g) ρ_p= density of PZT-5H
h) ρ_s= density of phosphor bronze
i) L_m= length of proof mass
j) t_m= thickness of proof mass
k) m = proof mass

Here, w = 25 mm, L_m = 12 mm and $t_p = t_s$ = 0.5 mm

2.3 Analytical Approach

The analytical approach was used to determine the fundamental frequency of PEH when PZT-5H is considered to be isotropic. The mechanical properties used for PZT-5H are:-

Density	Young's Modulus	Poisson's Ratio
7500 kg/m^3	54 GPa	0.34

Table 2.3:- Mechanical properties of PZT-5H

The relation used for calculating the fundamental frequency f of the PEH is:-

$$f = \frac{{v_n}^2}{2\pi}\sqrt{\frac{0.236 D_p w}{\left(L - \frac{L_m}{2}\right)^3 (m_e + m)}}, \qquad (1)$$

where, $v_n = 1.875$; $m_e = 0.236 m' w \left(L - \frac{L_m}{2}\right) + m' w \frac{L_m}{2}$; $m' = \rho_p t_p + \rho_s t_s$ and

$$D_p = \frac{{E_p}^2 {t_p}^4 + {E_s}^2 {t_s}^4 + 2 E_p E_s t_p t_s \left(2{t_p}^4 + 2{t_s}^4 + 3 t_p t_s\right)}{12\left(E_p t_p + E_s t_s\right)}$$

At a fixed length, L = 60 mm of PEH, fundamental frequencies were obtained for various values of proof mass thickness t_m using equation (1. t_m was varied from 3 mm to 5 mm in steps of 0.5 mm which denotes the variation of proof mass m from 3.986 g to 6.644 g. These frequencies, which were obtained analytically by considering PZT-5H as isotropic material were then compared with those obtained numerically by considering PZT-5H as anisotropic material. This comparison is shown in section 3.1.1.

2.4 Numerical Approach

The numerical approach was used to determine the fundamental frequency of PEH when PZT-5H is considered to be anisotopic (transversely isotropic). For numerical analysis, ANSYS Workbench software was used. Using this approach, we calculated the fundamental frequencies of PEH for various values of L and t_m. L was varied from 50 mm to 70 mm in steps of 5 mm and t_m was varied from 3 mm to 5 mm in steps of 0.5 mm.

The elasticity matrix used for PZT-5H is shown in Fig. 2.2. The density of PZT-5H was taken as 7500 kg/m^3.

Table of Properties Row 3: Anisotropic Elasticity

	A	B	C	D	E	F
1	D[*,1] (Pa)	D[*,2] (Pa)	D[*,3] (Pa)	D[*...	D[*...	D[*...
2	1.7149E+11	1.1766E+11	1.2093E+11	0	0	0
3	1.1766E+11	1.4231E+11	1.1766E+11	0	0	0
4	1.2093E+11	1.1766E+11	1.7149E+11	0	0	0
5	0	0	0	2.299E+10	0	0
6	0	0	0	0	2.299E+10	0
7	0	0	0	0	0	2.528E+10

Fig. 2.2:- Elasticity matrix of PZT-5H entered in ANSYS Workbench

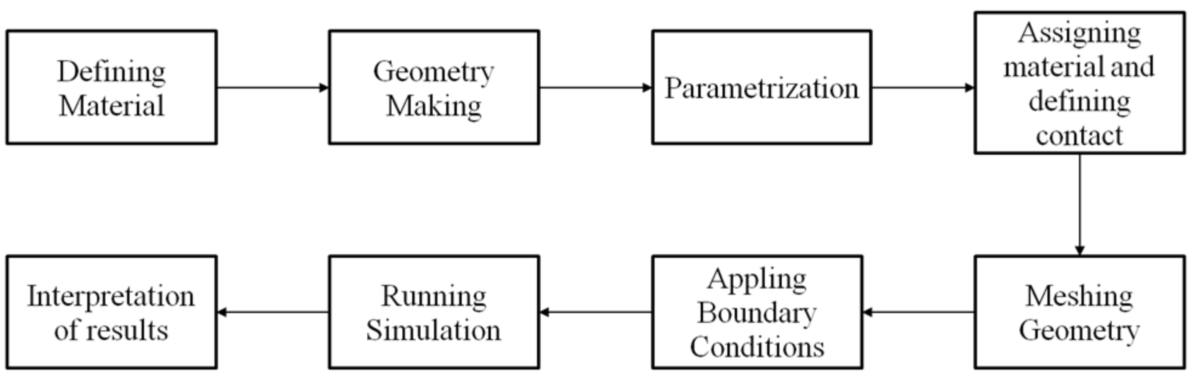


Fig. 2.3:- Block diagram of the numerical approach

Fig. 2.3 shows the block diagram of the steps performed for simulating the PEH model. First, we defined the mechanical properties of the materials of PEH. Then, the geometry of PEH as shown in Fig. 2.1 was made in the Design modeler. As we need to vary L and t_m in the geometry, we parametrized it for them. This helps us to define new geometry of PEH by simply changing L and t_m in the parameters tab, thus, preventing the creation of new geometry each time from the start.

After the geometry is made, we assigned material to each part. The upper layer was assigned as PZT-5H and the bottom layer was assigned as phosphor bronze. The part below the substrate (phosphor bronze), which is the proof mass, was assigned as titanium. The contact type at the surfaces in contact was defined as bonded. This ensures that there is no separation and relative motion between these surfaces.

As the geometry of PEH is simple, hex dominant meshing method was used to generate a quality mesh [see Fig. 2.5]. The number of elements and nodes generated were 4200 and 28083 respectively. Further refining the mesh resulted in a negligible change in the fundamental frequency and hence no more mesh refinement was done.

Then, the end of the PEH, opposite to proof mass was constrained to be fixed [see Fig. 2.4]. Finally, after running the simulation, the fundamental frequency results for PEH were obtained and analysed. These results are shown in section 3.1. Fig. 2.4 shows the isometric view of the simulated model of PEH and Fig. 2.6 shows the first modal shape of the PEH.

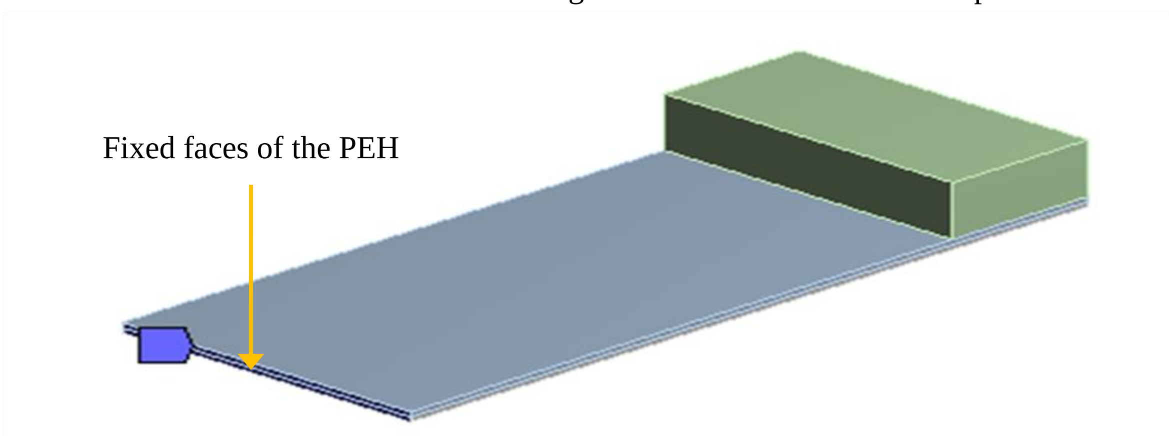


Fig. 2.4:- Isometric view of the PEH

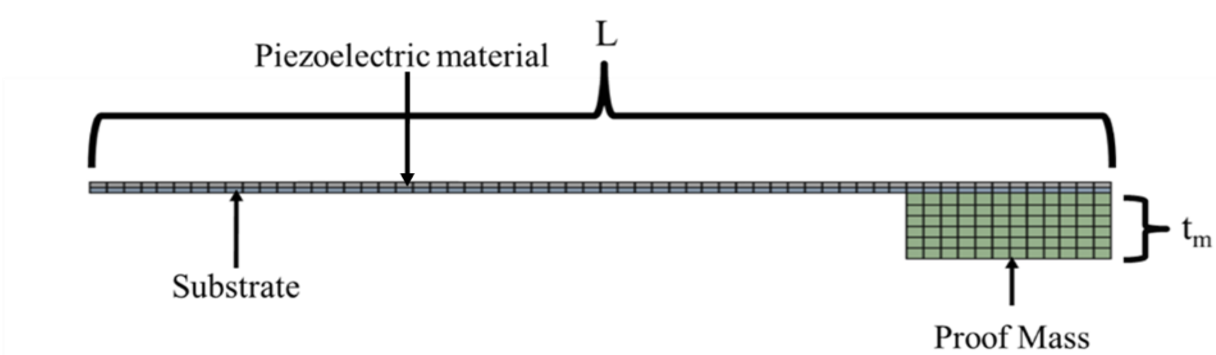


Fig. 2.5:- Meshed geometry of PEH

Fig. 2.6:- First modal shape of PEH

2.5 Experimental Approach

The numerical results were experimentally verified by using the **impact hammer**. The fundamental frequencies were obtained for PEH without proof mass and with proof mass at various lengths. Proof mass of 5.315 g was used and L was varied from 50 mm to 70 mm in steps of 5 mm.

Fig. 2.7 a) shows the PZT-5H plate used for experimental analysis. We have used commercially available poled (along thickness) PZT-5H plate of dimensions 76.2mm x 25mm x 0.5mm coated with silver wrap-around electrodes. Lead wires were then soldered on each electrode for external connections. Phosphor bronze sheet of 0.5 mm thickness was machined to the dimensions 76.2mm x 25mm x 0.5mm [see Fig. 2.7 b)] by using wire electronic discharge machine (EDM). Ti sheet of 6 mm thickness was also machined using wire EDM to the dimensions 25mm x 12mm x 6mm. Then, its thickness was reduced to 5 mm using the polishing machine. Epoxy was used to bond PZT-5H to phosphor bronze and proof mass of Ti [Fig. 2.7 c)] was then attached to them to make the experimental model of the PEH as shown in Fig. 2.8. The clamped PEH is shown in Fig. 2.9. We performed the experiment for various lengths of PEH by simply changing the effective length of the PEH [see Fig. 2.9].

a) PZT-5H b) Phosphor bronze substrate c) Ti proof mass

Fig. 2.7:- Components of the PEH

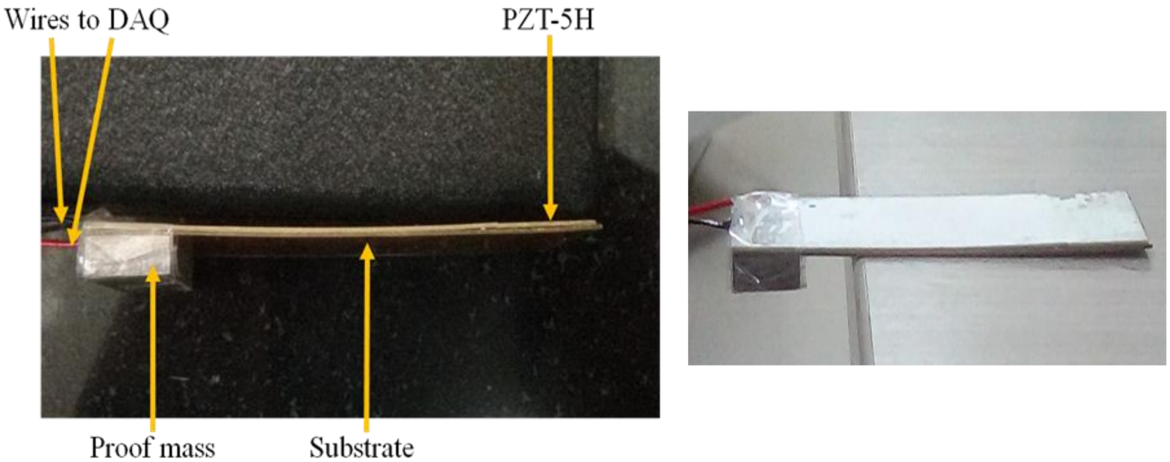


Fig. 2.8:- Experimental model of the PEH

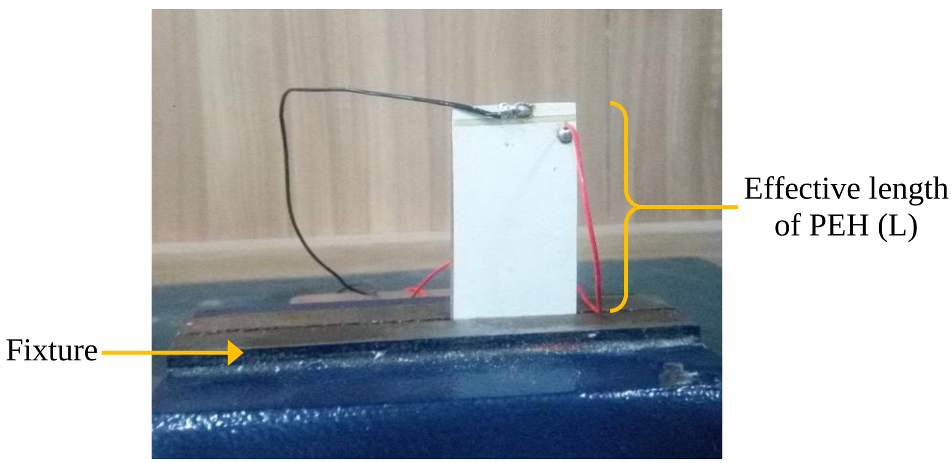


Fig. 2.9:- Clamped PEH

The instruments used for experimental analysis are:-

a) <u>Impact Hammer</u>

We used an impact hammer to excite the PEH. As the rubber tip provides good excitation for low frequencies and the fundamental frequency of the PEH is below 200 Hz, we used the rubber tip for excitation. To reduce random noises, we used 5 averages for this experiment. Averaging only reduces random noises while instrument noise remaining unaffected.

Fig. 2.10:- Impact Hammer

b) <u>Data Acquisition System (DAQ)</u>

DAQ measures the excitation (input) and responses (output) of the structure under test. Here, impulse force exerted by the impact hammer is the input and voltage generated by the PEH is the output. NVGate software was used which displayed the voltage frequency response function (FRF). FRF is a function that quantifies the response of a system to an excitation, normalized by the magnitude of this excitation, in the frequency domain. Using the generated voltage FRF, we found the fundamental frequency of the PEH.

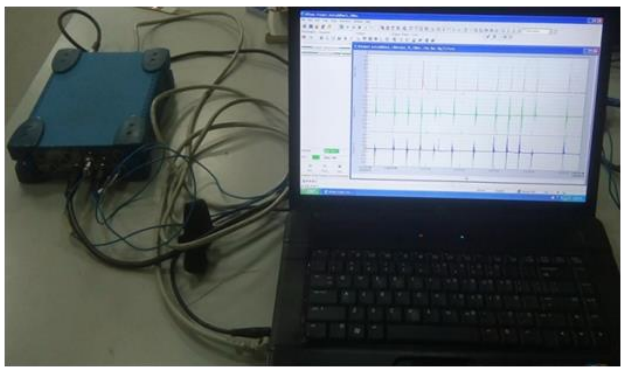


Fig. 2.11:- Data Acquisition System

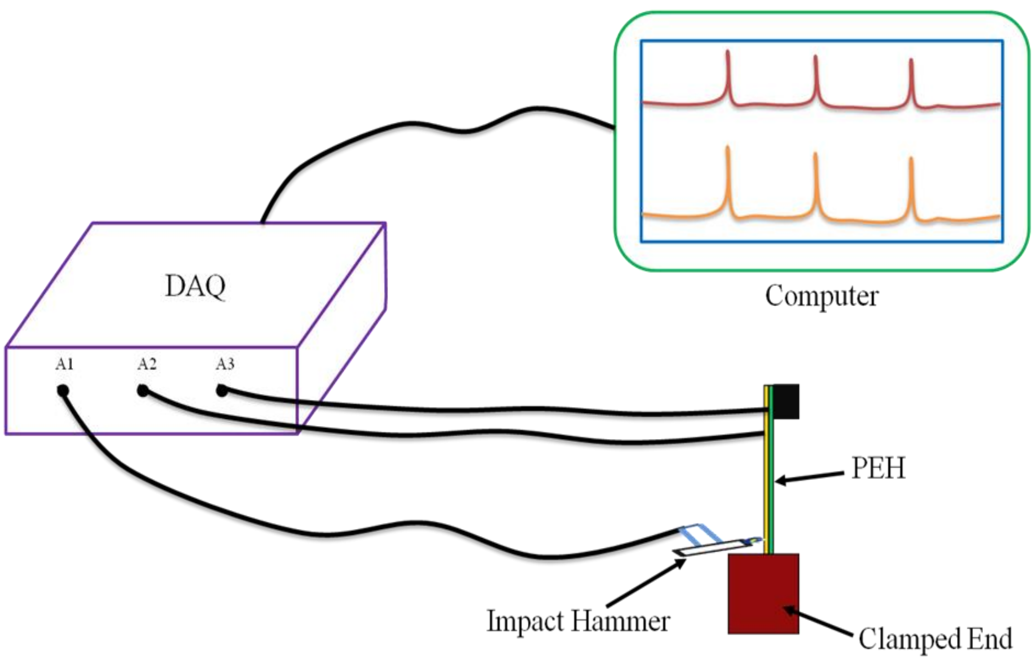


Fig. 2.12:- Schematic representation of the experimental setup

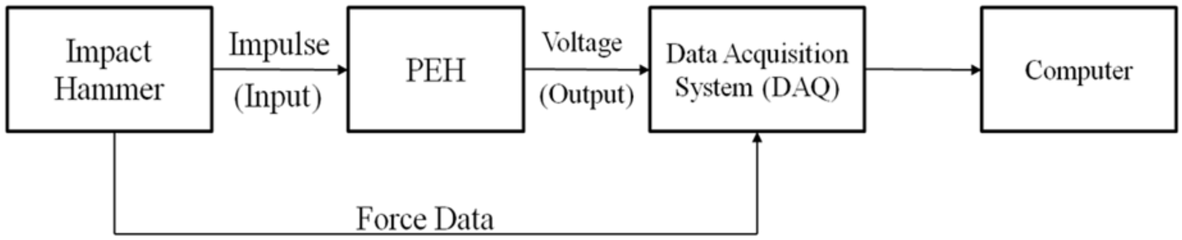


Fig. 2.13:- Block diagram for the experiment

Fig. 2.12 shows the schematic representation of the experimental setup used. The impact hammer excites the clamped PEH near the base. This excitation is in the form of impulse. The impact force results in the vibration of the PEH. Due to these vibrations, voltage is generated across the electrodes coated on the piezoelectric material. These electrodes are connected to the DAQ. The impact hammer is also connected to the DAQ. There is a force sensor present in the impact hammer which transmits an electrical signal corresponding to the impact force to DAQ. DAQ along with NVGate software display the voltage FRF on the connected computer using the acquired voltage and force data. The frequency at which the voltage FRF peaks is the fundamental frequency of the PEH. Fig. 2.13 shows the block diagram for the experiment.

Chapter 3

Results and Discussion

3.1 Numerical and Analytical Results

3.1.1 Anisotropic vs Isotropic

L = 60 mm			
Proof Mass (g)	Anisotropic (Numerical) (Hz)	Isotropic (Analytical) (Hz)	Error (%)
3.986	104.43	95.928	8.14
4.650	100.33	92.101	8.20
5.315	96.662	88.699	8.24
5.979	93.36	85.648	8.26
6.644	90.364	82.892	8.27
7.308	87.629	80.386	8.26
7.972	85.116	78.094	8.25

Table 3.1:- Frequencies obtained numerically and analytically

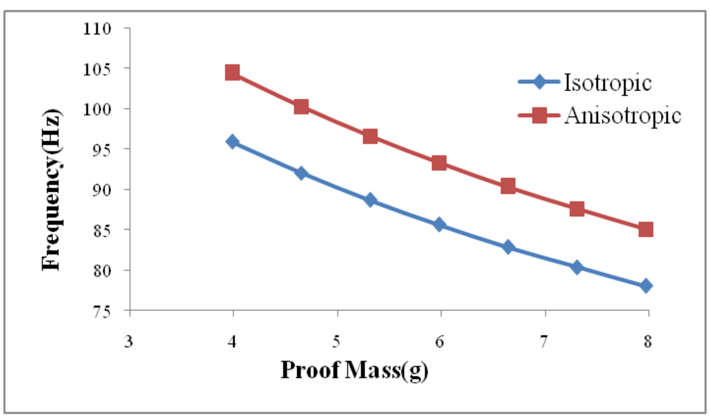


Fig. 3.1:- Results obtained by considering PZT-5H as anisotropic and isotropic material

- Table 3.1 and Fig. 3.1 compare the results obtained by considering PZT-5H as anisotropic and isotropic material.

- An error of more than 8% is seen when PZT-5H is being treated as an isotropic material.
- As small deviation in fundamental frequency can lead to significant difference in power generated, it must be calculated with precision.
- So, PZT-5H must be treated as anisotropic (transversely isotropic) material rather than isotropic.

3.1.2 Frequency vs Proof Mass

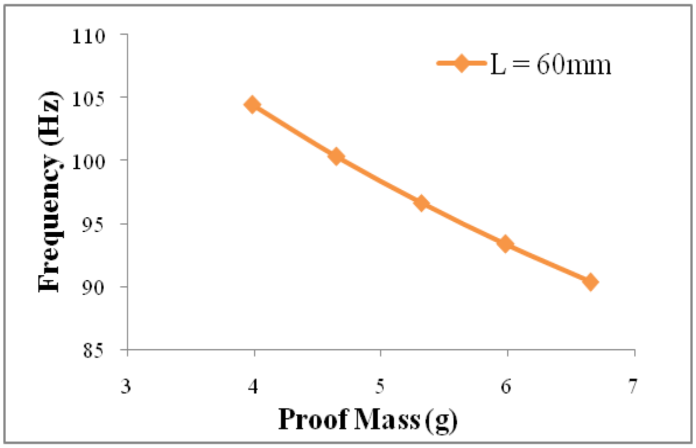


Fig. 3.2:- Effect of proof mass on fundamental frequency

- Fig. 3.2 shows how the fundamental frequency of piezoelectric energy harvester (PEH) varies with the attached proof mass.
- For the fixed length of the beam, as we increase the proof mass, the fundamental frequency of the PEH decreases.

3.1.3 Frequency vs Length

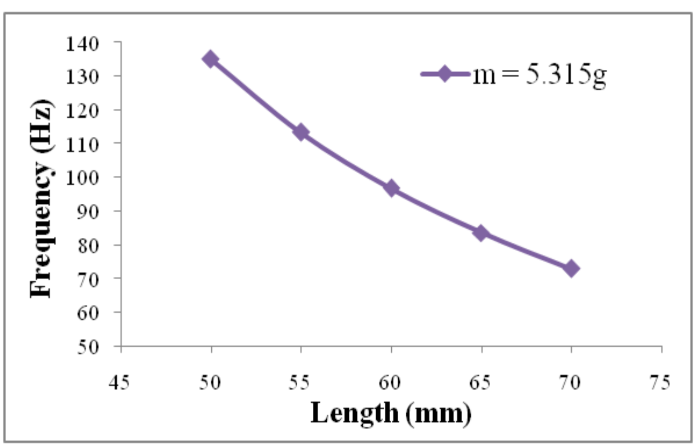


Fig. 3.3:- Effect of beam length on fundamental frequency

- Fig. 3.3 shows how the fundamental frequency of PEH varies with beam length.
- For the fixed proof mass, as we increase the beam length, the fundamental frequency of the PEH decreases.
- Also, from Fig. 3.2 and Fig. 3.3 we see that the effect of increasing the proof mass thickness by 0.5 mm on the fundamental frequency of PEH is less than that of increasing the beam length by 5 mm.

3.1.4 Frequency as a function of beam length and proof mass

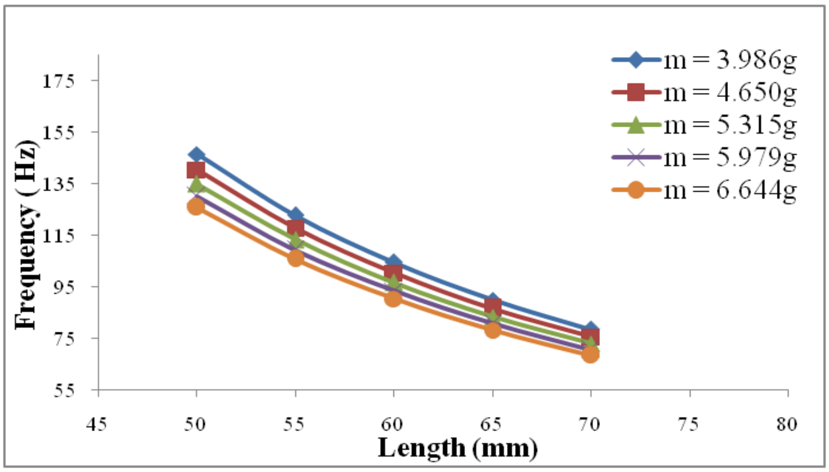


Fig. 3.4:- Fundamental frequency as a function of beam length and proof mass

- Fig. 3.4 shows the combined effect of the proof mass and beam length on the fundamental frequency of PEH.
- The graph shifts towards origin as we increase the proof mass. This is due to the increase in the effective mass of PEH which in turn decreases its fundamental frequency.

3.1.5 Effect of presence of proof mass

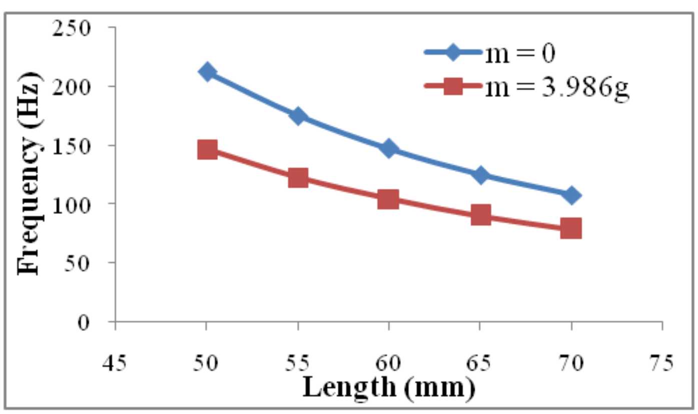


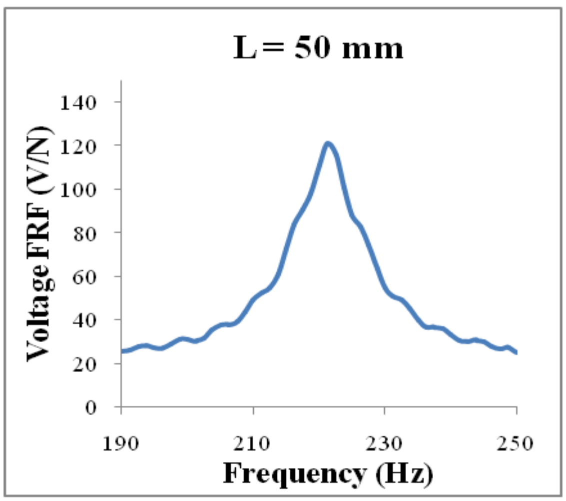
Fig. 3.5:- Effect of presence of proof mass on the fundamental frequency

- Fig. 3.5 shows what effect does the presence of proof mass has on the fundamental frequency of PEH.
- The fundamental frequency of PEH is significantly decreased when a proof mass is attached to it. The effect of proof mass on the fundamental frequency seems to decrease as the beam length increases.

3.2 Experimental Results

3.2.1 Voltage FRF plots

1. For m = 0,



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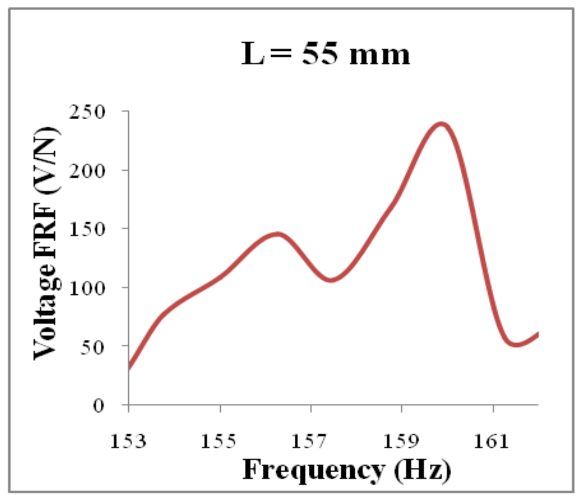

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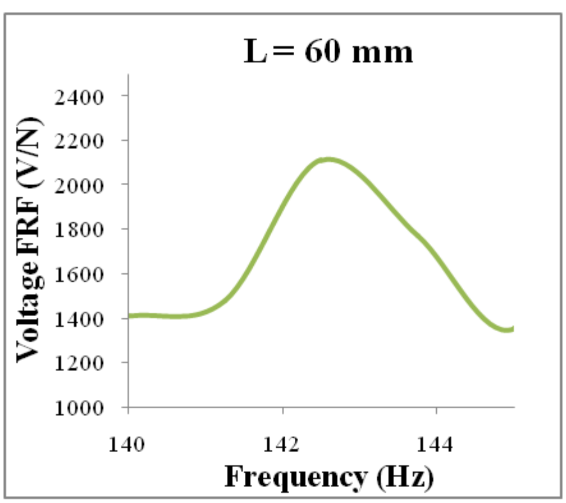

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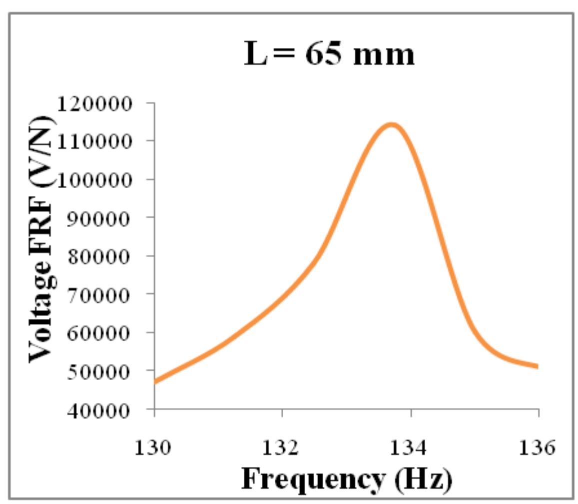

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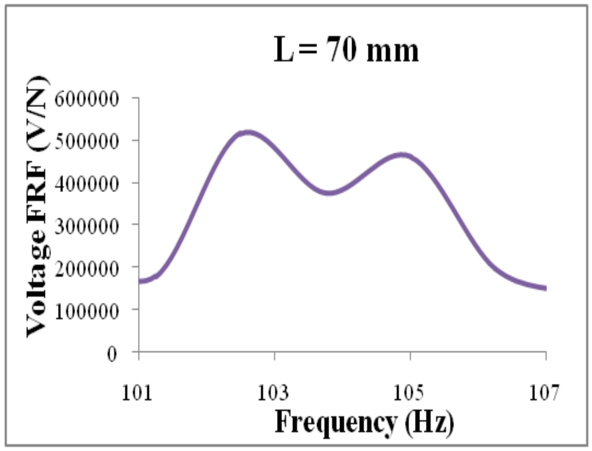
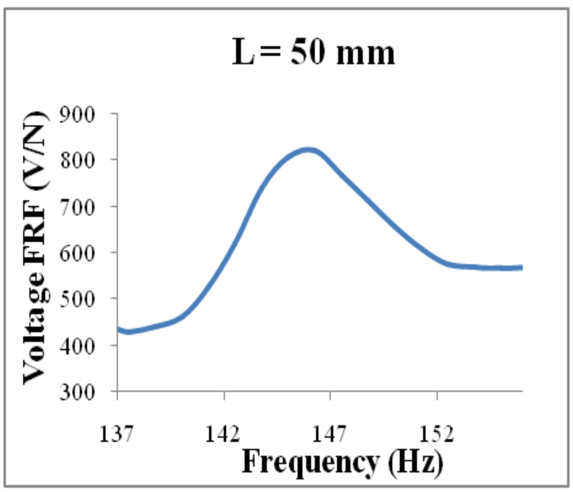


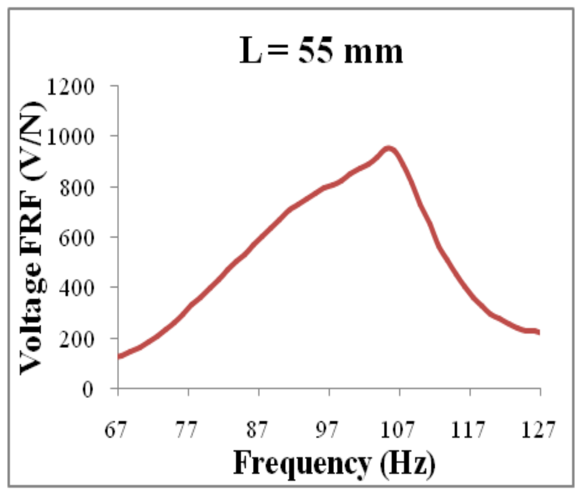
e)

Fig. 3.6:- Voltage FRF plots at various lengths without proof mass

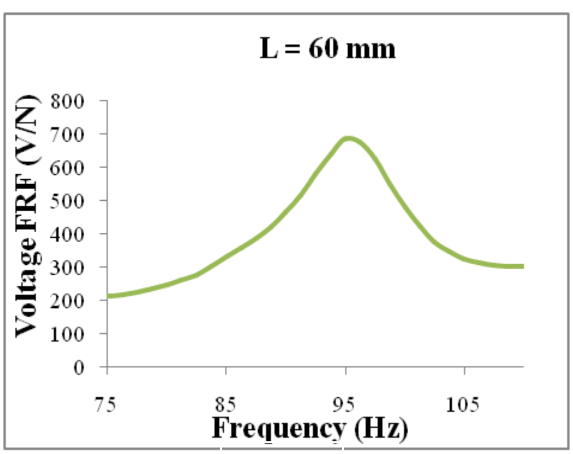
2. For m = 5.315 g,



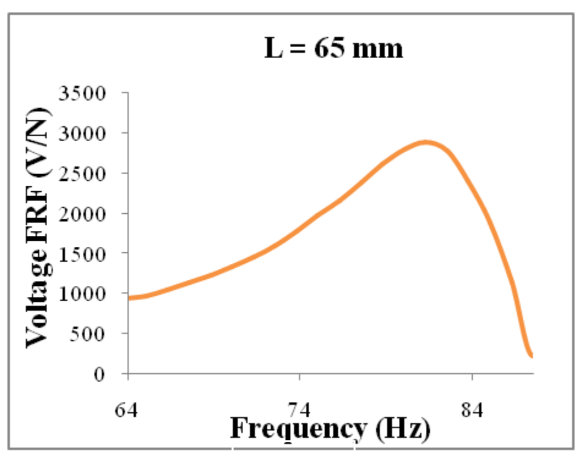
a)



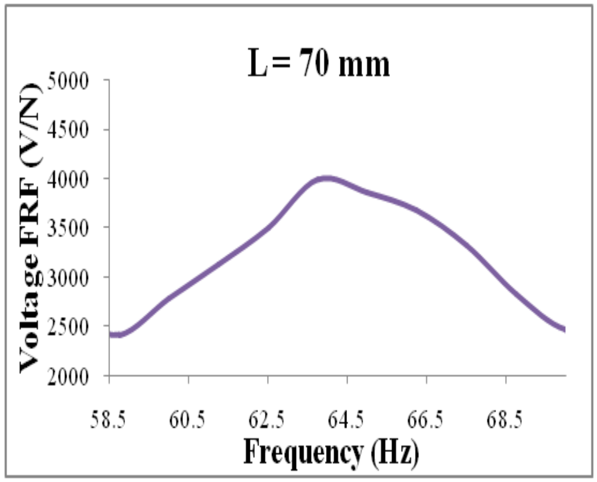
b)



c)



d)



e)

Fig. 3.7:- Voltage FRF plots at various lengths with proof mass

- Fig. 3.6 and Fig. 3.7 show the voltage FRF plots for PEH without proof mass and with proof mass respectively at various lengths.
- Voltage FRF plots are peaking at a certain value of frequency. This frequency is the fundamental frequency of the PEH.
- In certain plots [b) and e) in Fig. 3.6], two peaks are seen. This is due to the presence of certain errors such as instrument noise, leakage, etc.

3.3 Comparison between Numerical and Experimental results

1. For m = 0,

m = 0 (t_m = 0)				
S. No.	Length (mm)	Frequency (Hz)		Error (%)
		Numerical	Experimental	
1.	50	212.35	221.25	4.19
2.	55	175.15	160	8.65
3.	60	146.91	142.5	3.00
4.	65	124.98	133.75	6.71
5.	70	107.61	102.5	4.75

Table 3.2:- Numerical and experimental results for various lengths without proof mass

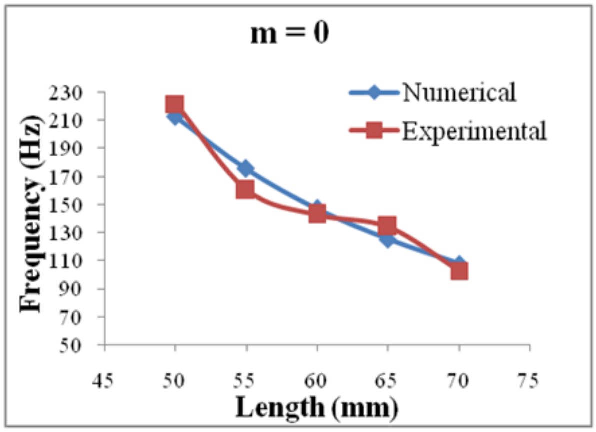


Fig. 3.8:- Comparison between results when no proof mass is attached

2. For m = 5.315 g,

m = 5.315 g (t_m = 4 mm)				
S. No.	Length (mm)	Frequency (Hz)		Error (%)
		Numerical	Experimental	
1.	50	135	146.25	8.33
2.	55	113.34	105	7.36
3.	60	96.662	95	1.72
4.	65	83.528	81.25	2.73
5.	70	72.979	63.75	12.65

Table 3.3:- Numerical and experimental results for various lengths with proof mass

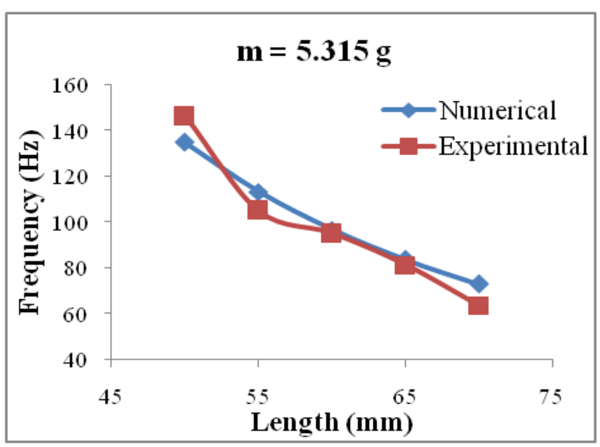


Fig. 3.9:- Comparison between results when proof mass is attached

- Fig. 3.8 and Fig. 3.9 compare the results obtained numerically and experimentally for various lengths of PEH without proof mass and with proof mass respectively.
- We see that the fundamental frequency results obtained experimentally agree well with those obtained numerically.

Chapter 4

Conclusion and Scope for future work

4.1 Conclusion

- PZT–5H should be treated as anisotropic (transversely isotropic) material instead of isotropic while calculating the fundamental frequency of the PEH. A significant error in the fundamental frequency is seen when PZT-5H is treated as isotropic material. As fundamental frequency is an important criterion in determining the performance of PEH, it must be determined precisely. As poling the PZT-5H makes it transversely isotropic so it should be treated as the same.

- Fundamental frequency of the PEH depends on the beam length as well as the proof mass attached. For the fixed beam length, as we increase the proof mass, fundamental frequency of PEH decreases. For a given proof mass, as we increase the beam length, fundamental frequency of PEH decreases. The effect of increasing the beam length by 5 mm on the fundamental frequency is more than that of increasing the proof mass thickness by 0.5 mm.

- Presence of proof mass has a considerable effect on the fundamental frequency of the PEH. For a given beam length, the fundamental frequency of the PEH with proof mass is less than that without proof mass. This is due to increase in the effective mass of PEH which decreases its fundamental frequency. In order to perform well under environmental conditions where vibrations are usually below 200 Hz, this effect can be used to further decrease the fundamental frequency of PEH if we have constrained geometry.

- Fundamental frequency results of PEH obtained experimentally by using impact hammer agree well with those obtained numerically.

4.2 Scope for future work

- Effect of thickness and width on the fundamental frequency of PEH can be studied by using the FE model in this work.
- Modal shaker can be used to perform voltage analysis of the PEH by giving base excitation.
- Effect of load resistance on the power output of the PEH can be studied using the modal shaker.

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