B. TECH. PROJECT REPORT

On

Development of piezoelectric energy harvester beam made of polyvinylidene fluoride films

BY

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DISCIPLINE OF MECHANICAL ENGINEERING

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Development of piezoelectric energy harvester beam made of polyvinylidene fluoride films

A PROJECT REPORT

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

of
BACHELOR OF TECHNOLOGY
in
MECHANICAL ENGINEERING

Submitted by:
Aagam Shah & Nukul Goyal

Guided by:
Dr. Shailesh I. Kundalwal (Associate Professor)

INDIAN INSTITUTE OF TECHNOLOGY INDORE

DECEMBER 2019

<u>CANDIDATE'S DECLARATION</u>

We hereby declare that the project entitled **"Development of piezoelectric energy harvester made of polyvinylidene fluoride films"** 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, we declare that we have not submitted this work for the award of any other degree elsewhere.

Aagam Shah

Nukul Goyal

<u>CERTIFICATE by BTP Guide</u>

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

Dr. Shailesh I. Kundalwal

(Associate Professor)

PREFACE

This report on "Development of piezoelectric energy harvester made of polyvinylidene films" is prepared under the guidance of Dr. Shailesh I. Kundalwal.

In this report, we have given an insight in the design of a piezoelectric energy harvester beam, which can be used for energy generation as well as structural health monitoring. In order to build it one has to be well acquainted with the basics of piezoelectric and flexoelectric phenomena.

We tried our best to explain this content to a reader in a lucid and comprehensive manner; also we added models and experimental results to make it more illustrative.

Aagam Shah & **Nukul Goyal**

B.Tech. IV Year

Discipline of Mechanical Engineering

IIT Indore

Acknowledgements

We wish to thank **Dr. Shailesh I. Kundalwal** for his kind support and valuable guidance. We would also like to acknowledge Mr. Kishor Shingare (Applied and Theoretical Mechanics (ATOM) Lab, IIT Indore), Mr. Madhur Gupta (Applied and Theoretical Mechanics (ATOM) Lab, IIT Indore), Mr. Pavan Gupta (Solid Mechanics Lab, IIT Indore) and Mr. Maniknandan (Mechatronics and Instrumentation Laboratory, IIT Indore) for providing their sincere cooperation and guidance to our project. It is with their help and support that we were able to complete the design and technical report. Without their support this report would not have been possible.

Aagam Shah & **Nukul Goyal**
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Abstract

This study focuses on the measurement of flexoelectric response of a cantilever type piezoelectric vibration energy harvester (PVEH) beam via experimental and numerical investigations. The PVEH was made by attaching a thin PVDF film, coated with a copper electrode, on a glass fibre reinforced plastic (GFRP) plate. Firstly, numerical analysis was performed on the PVEH beam followed by the experimental investigations. Initially, modal analysis was performed on the beam to evaluate its natural frequencies using the finite element method (FEM). This was followed by the harmonic response analysis performed with a base excitation force and a damping factor. The variations of strains and strain gradients with the position on the beam were evaluated at some arbitrary frequency values. Also, the polarization frequency response function (FRF) due to piezoelectricity was studied. An experimental investigation was carried out to validate the modal results obtained by numerical analysis. In the experiment we conducted an impact hammer test using an impact hammer and digital acquisition system (DAQ). The beam was clamped as a cantilever and was excited at the base. The results so obtained using the NVGate software and the multi-mode polarization FRF (MMP-FRF) were plotted and analyzed. This fundamental study sheds a light on the possibility of developing lightweight and high-performance piezoelectric energy harvesting system.

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Chapter1- ***Introduction***

The quest for energy has ever engaged humans throughout history. The rapid economic growth that the world has witnessed in the last two centuries has increased the need for energy manifold (Fig.1). Due to the recent ominous projections of **increased global warming** and **rapid depletion of energy producing fuels**, there has been an increased focus on producing energy from **renewable and ambient sources** (Fig.2). Vibration energy harvesting is one of the most recent additions to this type of energy producing sources.

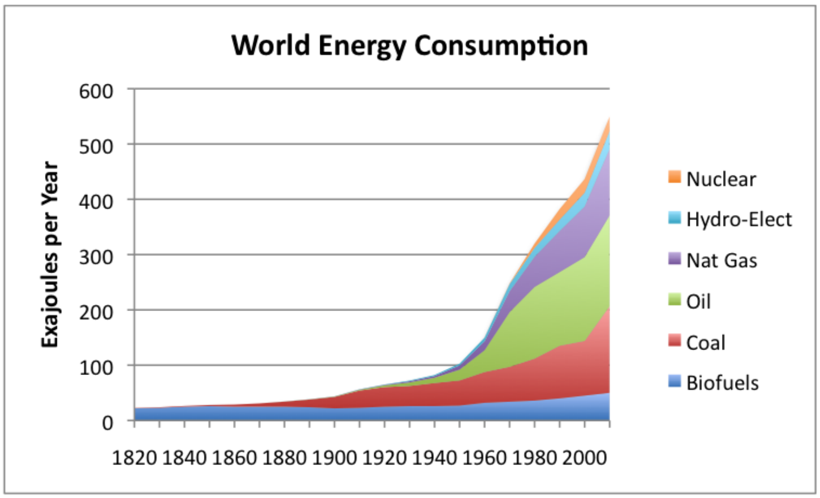

Fig.1 - World Energy Consumption by Source, (Based on Vaclav Smil estimates from Energy Transitions: History, Requirements and Prospects together with BP Statistical Data for 1965 and subsequent)

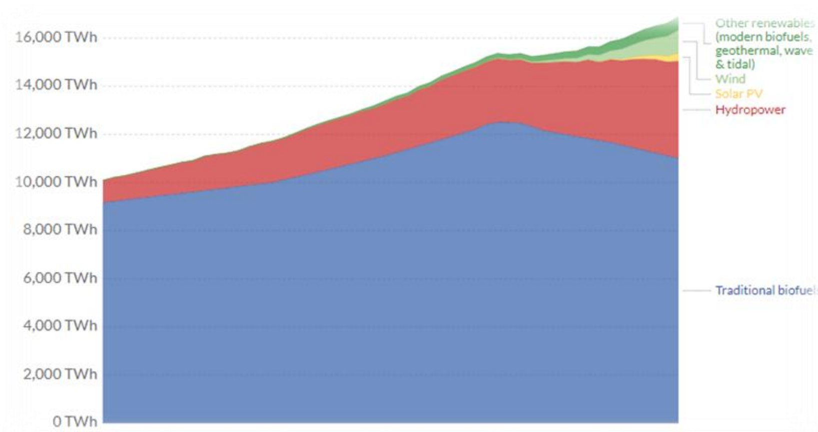

Fig.2 - Global renewable energy consumption (Source: Vaclav Smil (2017). Energy Transitions: Global and National Perspectives. & BP Statistical Review of World Energy)

Converting the available energy from the environmental vibrations allows a self-sufficient energy supply for small electric loads such as sensors and radio transmitters. The energy generating devices must be sufficiently robust to endure long-term exposure to hostile environments and have a broad range of dynamic sensitivity to exploit the entire spectrum of wave motions. There are various methods to convert mechanical energy from vibrating or moving objects into electrical energy such as electromagnetic induction, electrostatic induction, etc. In the last 50 years, a new type of energy harvesting device that converts ambient energy into electrical energy has attracted much interest of researchers. Kinetic energy can be directly converted into electrical energy by means of the **piezoelectric effect** wherein piezo elements convert the stress or strain produced by kinetic energy from vibrations or shocks into electrical energy. A piezoelectric substance produces an electric charge when a mechanical stress is applied (the substance is squeezed or stretched). Conversely, a mechanical deformation (the substance shrinks or expands) is produced when an electric field is applied. This effect is found in crystals that have no center of symmetry. Using suitable electronics, it can be used to create **self-sufficient energy supply systems**. This is of particular interest when power supply via cable is not possible and the use of batteries and the associated maintenance expenditure is not desired.

Piezoelectric materials, such as **PVDF** and **PZT**, can be used to transform ambient vibrations into electrical energy that can be stored and used to power other devices. With the recent surge of microscale devices, piezoelectric power generation can provide a convenient alternative to traditional power sources used to operate certain types of sensors/actuators, telemetry, and micro-electro-mechanical systems (MEMS) devices.

Quite recently, a much more novel approach towards piezoelectric energy harvesting is by using the **flexoelectric effect**. While piezoelectricity produces electric polarization using uniform/homogenous strain generally, flexoelectric effect makes use of strain gradient to induce the polarization. The use of strain gradient, along with strain, enhances the output polarization and thus provides greater energy density for the same structure. It is this effect that the project focuses upon. Both the piezoelectric and flexoelectric effect have similar effect (electric polarization) but differ in the cause of polarization (strain and strain gradient for piezoelectric effect and flexoelectric effect, respectively).

*Chapter 2- **Terminology***

1. **Energy harvesting:** Energy harvesting refers to the generation of energy from ambient sources such as temperature gradient, mechanical vibrations and wind.

2. **Strain:** Strain refers to the ratio of deformation to the original dimension of a deformed structure.

3. **Strain gradient:** Strain gradient is the rate of change of strain along a dimension of the structure.

4. **Piezoelectricity:** Piezoelectricity is a material property wherein the material has the ability to produce electrical charge when subjected to an external stress or homogenous strain.

5. **Flexoelectric effect:** Flexoelectric effect is the production of electrical charge by piezoelectric materials when subjected to an external stress or non-homogenous strain due to the presence of a strain gradient.

6. **Piezoelectric vibration energy harvester (PVEH):** PVEH is a device that generates electricity from vibrations using the piezoelectric effect.

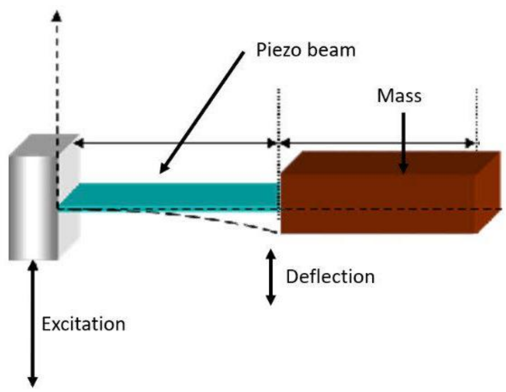

Fig.3- Vibration energy harvester beam (Source: www.allaboutcircuits.com)

7. **Polyvinylidene fluoride (PVDF):** PVDF is a thermoplastic fluoropolymer type piezoelectric material.

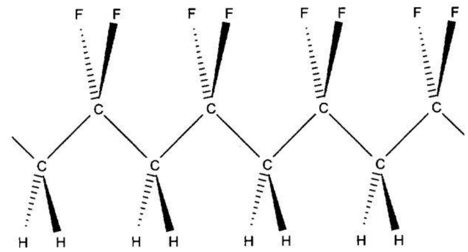

Fig.4- Chemical Structure of PVDF[1]

8. **Lead zirconate titanate (PZT):** PZT is a ceramic type piezoelectric material composed of lead, titanium and zirconite.

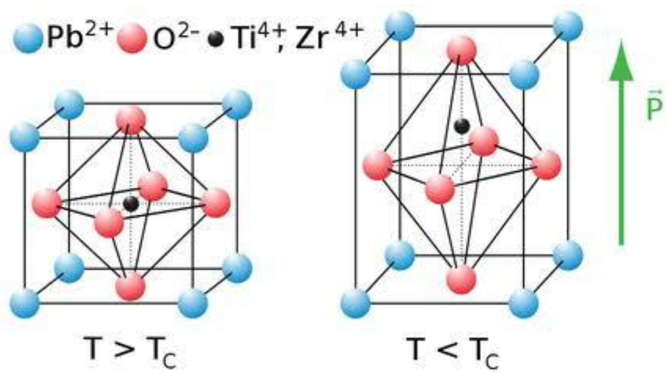

Fig.5 - Chemical Structure of PZT (Source: www.piezotechnics.com)

9. **Glass fiber reinforced plastic (GFRP):** GFRP is a composite material made of a polymer matrix reinforced with glass fibers.

10. **Natural frequency:** Natural frequency is the frequency at which a system tends to oscillate when not subjected to any driving or damping force.

11. **Modal analysis:** Modal analysis is the study of the properties of a system in the vibration domain. It is used to find the modal or natural frequencies of the system.

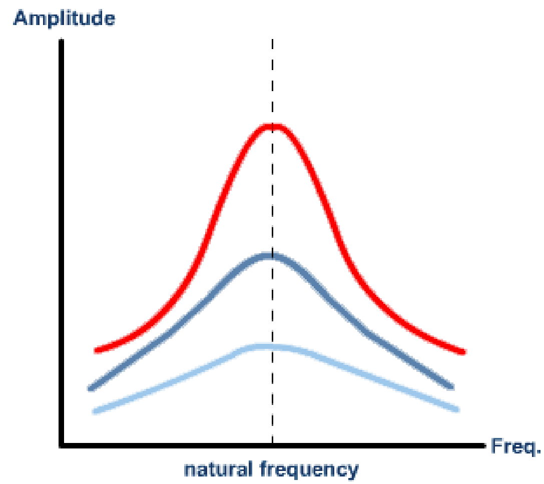

Fig.6 - Amplitude of oscillation vs. frequency (Source: www.s-cool.co.uk)

12. **Harmonic response analysis:** Harmonic response analysis is a technique used to determine the steady-state response of a structure that is subject to loads that vary sinusoidally (harmonically) with time.

13. **Polarization frequency response function (FRF):** Polarization FRF is a characteristic transfer function of a system that relates the measured response to the applied input.

14. **Multi-mode FRF:** Multi-mode FRF is the FRF of the flexoelectric effect output when the PVEH is provided with input signals.

3.1 Piezoelectricity

Piezoelectricity is an inherent material property of certain materials. In order to produce the piezoelectric effect in them, the poly-crystal is heated under the application of a strong electric field. The heat allows the molecules to move more freely and the electric field forces all of the dipoles in the crystal to line up and face in nearly the same direction (Fig.7).

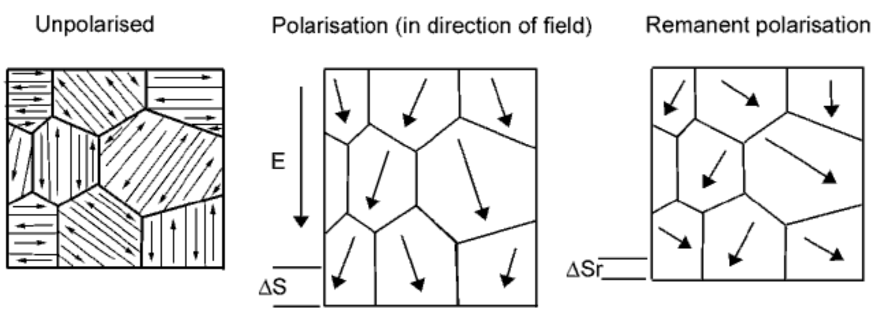

Fig.7 - Polarization of ceramic material to generate piezoelectric effect (Source: www.keramverband.de)

The dipoles thus arranged produce a remnant polarization in a particular direction. This polarization can be further enhanced by application of an external mechanical strain. The external strain causes distortion of the dipoles which results in the production of an electrical charge which can be stored (Fig.8). This is the phenomenon known as the **direct piezoelectric effect**. Conversely, the production of deformation (thus strain) in a piezoelectric material due to an external electric current is known as the **converse piezoelectric effect.**

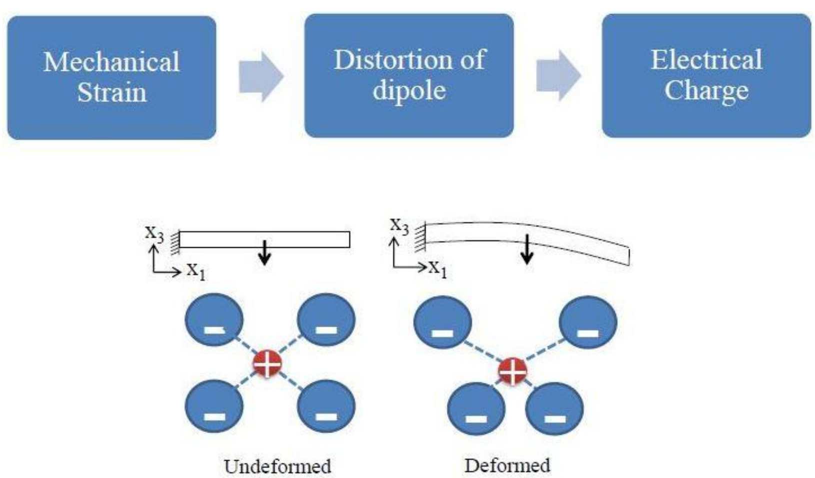

Fig.8 - Electrical charge production by external strain (direct piezoelectric effect)

3.2 Classification of piezoelectric materials

The piezoelectric materials can be divided into four categories based on their structural characteristics: ceramics, single crystals, polymers, and composites. Most piezoelectric ceramics and single crystals used for energy harvesting are a subgroup of piezoelectrics called "ferroelectrics." The typical examples are PZT (lead zirconatetitanate) and PMN-PT (the solid solution of lead magnesium niobate and lead titanate). Below a critical temperature called the Curie temperature, these materials possess spontaneous dipoles which bestow excellent piezoelectric properties. Thus, ferroelectric single crystals, ceramics, and composites have much better piezoelectric properties than polymers. Piezoelectric polymers, however, have the ability to sustain much higher strain due to their intrinsic flexibility making them better suited for applications where the device will be subjected to large amount of bending or conforming to a curved mounting surface (e.g., wearable devices).

3.3 Formulation of piezoelectricity

(In absence of external electric field) [2]

Direct effect:

$$\boldsymbol{P_i = d_{ij}\sigma_j} \qquad \ldots (1)$$

(Electric polarization) = (Piezoelectric coefficient) x (Stress)

[C/m^2] = [C/N] x [N/m^2]

Matrix notation:

$$\begin{bmatrix} \boldsymbol{P_1} \\ \boldsymbol{P_2} \\ \boldsymbol{P_3} \end{bmatrix} = \begin{bmatrix} \boldsymbol{d_{11}} & \boldsymbol{d_{12}} & \boldsymbol{d_{13}} & \boldsymbol{d_{14}} & \boldsymbol{d_{15}} & \boldsymbol{d_{16}} \\ \boldsymbol{d_{21}} & \boldsymbol{d_{22}} & \boldsymbol{d_{23}} & \boldsymbol{d_{24}} & \boldsymbol{d_{25}} & \boldsymbol{d_{26}} \\ \boldsymbol{d_{31}} & \boldsymbol{d_{32}} & \boldsymbol{d_{33}} & \boldsymbol{d_{34}} & \boldsymbol{d_{35}} & \boldsymbol{d_{36}} \end{bmatrix} \times \begin{bmatrix} \boldsymbol{\sigma_1} \\ \boldsymbol{\sigma_2} \\ \boldsymbol{\sigma_3} \\ \boldsymbol{\sigma_4} \\ \boldsymbol{\sigma_5} \\ \boldsymbol{\sigma_6} \end{bmatrix}$$

$$P_1 = d_{11}\sigma_1 + d_{12}\sigma_2 + d_{13}\sigma_3 + d_{14}\sigma_4 + d_{15}\sigma_5 + d_{16}\sigma_6 \ldots \text{(1a)}$$

$$P_2 = d_{21}\sigma_1 + d_{22}\sigma_2 + d_{23}\sigma_3 + d_{24}\sigma_4 + d_{25}\sigma_5 + d_{26}\sigma_6 \ldots \text{(1b)}$$

$P_3 = d_{31}\sigma_1 + d_{32}\sigma_2 + d_{33}\sigma_3 + d_{34}\sigma_4 + d_{35}\sigma_5 + d_{36}\sigma_6 \ldots$ (1c)

Converse effect:

$$\boldsymbol{\varepsilon_j = d_{ij}E_i} \qquad \ldots (2)$$

(Mechanical strain) = (Piezoelectric coefficient) x (Electric field)

[ ] = [m/V] x [V/m]

Matrix notation:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{21} & d_{31} \\ d_{12} & d_{22} & d_{32} \\ d_{13} & d_{23} & d_{33} \\ d_{14} & d_{24} & d_{34} \\ d_{15} & d_{25} & d_{35} \\ d_{16} & d_{26} & d_{36} \end{bmatrix} \times \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

$\varepsilon_1 = d_{11}E_1 + d_{21}E_2 + d_{31}E_3$ .. (2a)

$\varepsilon_2 = d_{12}E_1 + d_{22}E_2 + d_{32}E_3 \ldots$ (2b)

$\varepsilon_3 = d_{13}E_1 + d_{23}E_2 + d_{33}E_3 \ldots$ (2c)

$\varepsilon_4 = d_{14}E_1 + d_{24}E_2 + d_{34}E_3 \ldots$ (2c)

$\varepsilon_5 = d_{15}E_1 + d_{25}E_2 + d_{35}E_3 \ldots$ (2d)

$\varepsilon_6 = d_{16}E_1 + d_{26}E_2 + d_{36}E_3 \ldots$ (2e)

3.4 The flexoelectric effect

Though energy harvesting using the piezoelectric property of materials has been researched extensively in the last 50 years, the potential of the flexoelectric effect towards vibration energy harvesting has not been focused upon. In simple terms, where the piezoelectric effect is the generation of electric polarization due to uniform strain; the **flexoelectric effect refers to the generation of electric polarization due to strain gradient** which is produced by inhomogeneous deformation (Fig.9). Therefore, the flexoelectric coupling is between polarization and strain gradient, rather than homogeneous strain.

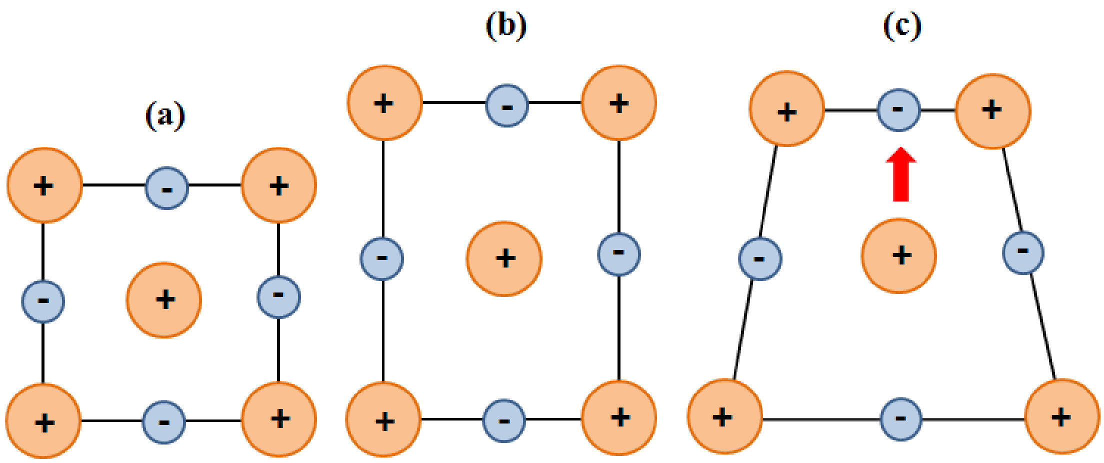

Fig.9 - Deformation at molecular level: (a) zero strain; (b) uniform strain (only piezoelectric effect present); (c) non-uniform strain (both piezoelectric and flexoelectric effects present)

3.5 Mechanism of flexoelectric effect

The mechanism of flexoelectric effect differs from that of the piezoelectric effect. When inhomogeneous strain is present in centrosymmetric materials, there exists a strain gradient which is able to break the inversion symmetry of the material thus causing the (flexoelectric) polarization. While in case of homogeneous strains, there is no strain gradient therefore inversion symmetry does not break thus resisting piezoelectric polarization. As a result, the piezoelectric effect requires non-centrosymmetric materials to cause polarization. Thus in simple terms, the flexoelectric effect occurs due to breaking of inversion symmetry by strain gradient while the piezoelectric effect occurs due to absence of centrosymmetry [3].

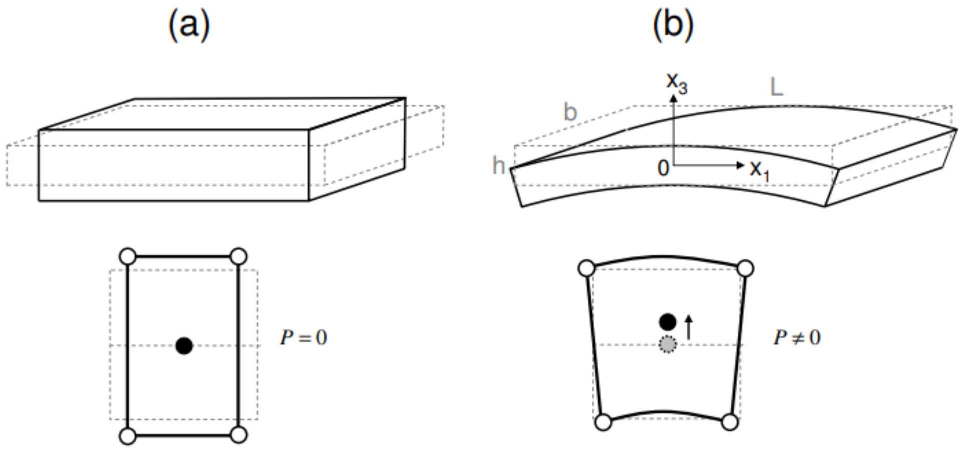

Fig.10 - Flexoelectricity (a) absent; homogeneous strain ($\nabla\varepsilon = 0$); (b) present; inhomogeneous strain ($\nabla\varepsilon \neq 0$) [3]

In Fig.10, flexoelectric effect will not be observed in (a) due to uniform deformation and therefore absence of strain gradient while it will be observed in (b) due to non-uniform deformation.

Due to its greater dependence on strain gradient as compared to strain alone, flexoelectric effect is more prominent in small scale devices as compared to large scale applications, and it provides for the great difference obtained in the output voltage by considering only the piezoelectric phenomenon.

Unlike the piezoelectric effect, a dissymmetry exists in the relation between the direct and converse flexoelectric effects. Where in the direct flexoelectric effect a strain gradient produces a homogenous polarization, a homogenous polarization does not produce homogenous deformation [4].

Chapter 4 - ***PVEH beam material and design***

The main aim of this project was the development of a piezoelectric energy harvester beam (EHB).We studied the energy harvesting capabilities and its related parameters involved in the development of such kind of a beam through numerical analysis using FE model and then with experimental analysis. Then we compared the results obtained from FE model with experimental results of the same EHB model.

4.1 Introduction

Energy harvesting in general refers to the generation of energy from external (usually unused and wasted) sources such as ambient vibration, temperature gradient, wind energy etc. Energy harvesting by vibrations alone can be through different techniques: electrostatic, electromagnetic and piezoelectric. Electrostatic energy harvesters collect energy from capacitance changes during the vibration cycle while electromagnetic energy harvesters collect energy from the current generated in coils by variations in magnetic flux which are induced by the movement of a permanent magnet. Compared to them, piezoelectric materials are the most appropriate ones for harvesting energy by employing vibration sources due to the fact that they can perform transformation of mechanical strain to an electric charge with high electromechanical coupling, no external power and have simple structures [6-7].

4.2 Modeling of PVEH Beam

4.2.1 Design

The PVEH beam was a cantilever type structure. The cantilever was chosen for the following reasons:

- In cantilever beam, large mechanical strain can be produced during vibration without structure failure.
- Construction of the cantilever-type beam is relatively easier as compared to other orientations.
- The resonance frequency of the fundamental flexural modes of a cantilever beam is much lower than the other vibration modes of the piezoelectric element.

A proof mass was also attached at the free end of the PVEH beam to further lower its natural frequency. Roundy had discovered that the power output of a cantilever energy harvester is proportional to the proof mass. Therefore, the proof mass should be maximized within the design constraints imposed by the beam strength and the resonance frequency [7].

The PVDF film was attached at the clamped end of the beam to obtain maximum polarization as the polarization is found to increase with the decrease in offset of the PVDF film from the clamped end (Fig.11).

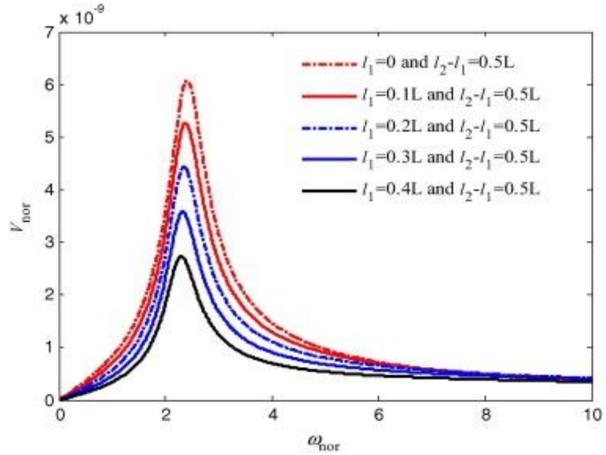

Fig.11 - Voltage v/s Frequency; at different positions of PVDF film[8]

4.2.2 Dimensions

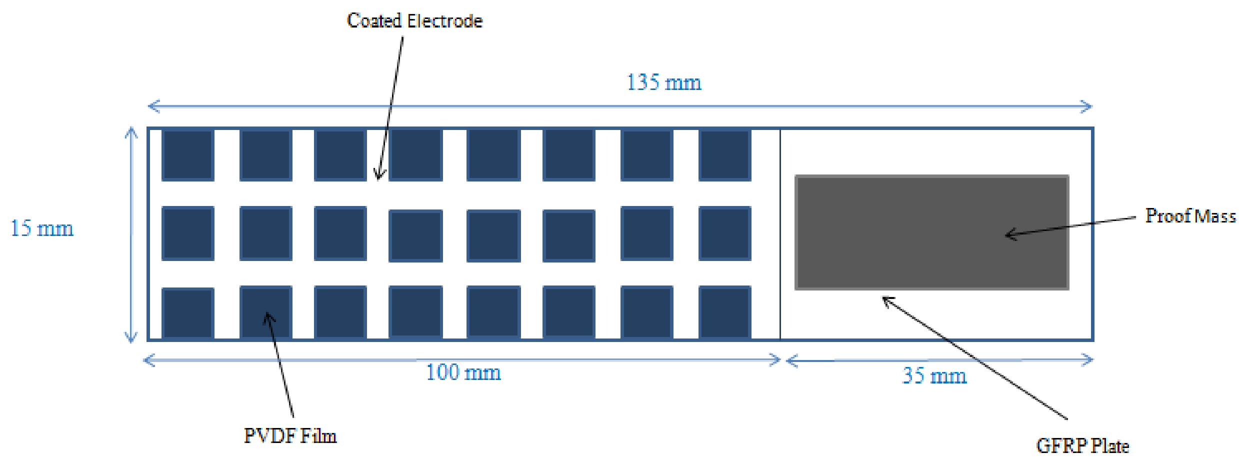

Fig.12- Schematic of beam model

4.2.3 Material

The material used for constructing the PVEH beam was GFRP. GFRP provides the following advantages:

- High Strength: GFRP has a very high strength to weight ratio (specific strength)
- Low cost: GFRP is much more cost effective than its counterpart CFRP (Carbon Fiber Reinforced Plastic) with similar characteristic properties.
- Lightweight: GFRP is available in small weights of 2 to 4 lbs. per square foot which provide fast installation, less structural framing and low shipping costs.
- Resistance: GFRP resists salt water, chemicals, and the environment and is unaffected by acid rain, salts, and most chemicals.
- Seamless Construction: Domes and cupolas are resined together to form a one-piece, watertight structure
- Able to Mold Complex Shapes: Virtually any shape or form can be molded
- Low Maintenance: Research shows no loss of laminate properties after 30 years
- Durability: Stromberg GFRP stood up to category 5 hurricane Floyd with no damage, while nearby structures were destroyed [9].

Though most of the materials utilized in classical piezoelectric energy harvesting are ceramics like PZT, we used the PVDF which is a polymer based material. The advantages of PVDF over PZT include:

- Flexibility and better bending ability: PVDF enables much greater strains to be generated in the structure without failure.
- Low density and low dielectric permittivity: The low density and low dielectric permittivity of PVDF results in a very high voltage coefficient.
- Greater ductility and higher failure strain: PVDF can be used to generate higher strains due to possibility of greater strains to be present in the material without failure.
- Higher d_{31} value: Higher d_{31} value of PVDF is advantageous in generating greater polarization at lower strain values.
- Biodegradability: It provides for environment friendly energy harvesting and material disposal due to absence of lead as opposed to PZT.

The material used for the proof mass was titanium and the proof mass weighed 5.5g.

4.2.4 Material Properties

Table 1: GFRP and Epoxy Properties [10]

Property	***GFRP***	***Epoxy***
Density (kg/m^3)	2370	2240
Young's Modulus (Pa)	1.95×10^{10}	2.76×10^{9}
Poisson's ratio	0.367	0.3

Table 2: PVDF Properties [10]

Young's Modulus	3 GPa
d_{31}(piezoelectric charge constant)	25 pCN^{-1}
μ_{31}(flexoelectricity coefficient)	0.05 pCm^{-1}

Chapter 5 - ***Equations applicable to the EHB***

5.1 Nomenclature

T_1 = Average applied stress in direction 1

$\bar{\varepsilon}_{11}$ = Average applied strain in direction 1

E = Young's modulus of piezoelectric film

$\frac{\partial \varepsilon_{11}}{\partial x_1}$ = Strain gradient along direction 1

d_{31} = Piezoelectric charge constant

μ_{31} = Flexoelectricity coefficient

P_{piezo} = Electric polarization due to pure piezoelectric effect

P_{flexo} = Electric polarization due to flexoelectric effect

P_i = Total electric polarization

Fig.13 – Direction sense of the PVEH beam

5.2 Polarization of cantilever beam

Polarization of the beam will consist of the piezoelectric as well as the flexoelectric components.

$$P_{piezo} = d_{31} T_1 = d_{31} E \bar{\varepsilon}_{11} \qquad \text{... (3)}$$

$$P_{flexo} = \mu_{31} \frac{\partial \varepsilon_{11}}{\partial x_1} \qquad \text{... (4)}$$

The total electric polarization is the sum total of the piezoelectric and the flexoelectric components.

By adding equations (3) + (4) we get

$$\Rightarrow \qquad P_i = P_{piezo} + P_{flexo}$$

$$\Rightarrow \qquad \boldsymbol{P_i = d_{31} E \bar{\varepsilon}_{11} + \mu_{31} \frac{\partial \varepsilon_{11}}{\partial x_1}} \ldots (5)$$

5.3 General formula for total polarization:

$$\boldsymbol{P_i = P_{piezo} + \mu_{ijkl} \frac{\partial \varepsilon_{jk}}{\partial x_l}} \quad \ldots(6) \; [10]$$

*Chapter 6 - **Finite element analysis***

The model was developed by a thin GFRP plate which was fixed at one end and a proof mass was attached at the free end. The GFRP was of dimensions 0.135 m x 0.015 m x 0.001 m. The structure also comprised of a base for the fixture. This structure was modeled in SolidWorks and exported to ANSYS workbench for the finite element analysis.

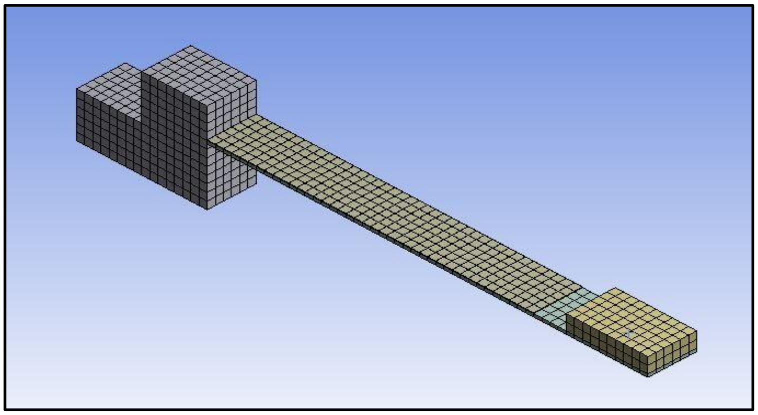

Fig.14 - PVEH beam model

The mechanical properties of the materials used were assigned to the model in ANSYS according to Table 1 and Table 2. The structure was meshed with element size 2.5mm.

Initially, a **modal analysis** was performed on the PVEH to evaluate the modal frequencies because the maximum power output of the PVEH beam is obtained at the modes. The boundary condition was a fixed support at the fixture end.

The modal analysis was followed by **harmonic response analysis**. An acceleration force boundary condition of $10ms^{-2}$ ($\approx$ 1g) was applied as a base excitation force and a damping ratio of 0.05 was applied. The variations of strain and strain gradient were obtained at various frequencies (Fig.23).

The harmonic response analysis results were also used to obtain the polarization frequency response functions (FRFs) (Fig.24) which were calculated based on the piezoelectrically induced polarizations while disregarding the flexoelectric effect of strain gradients.

The FRFs were calculated by equation (3), considering the average strain along the beam transverse direction and taking values of E and d_{31} as E = 3GPa and d_{31}= $25pCN^{-1}$(as mentioned in Table 2).

$$Polarization\ FRF = 20 * log_{10}(\frac{P_{piezo}}{Frequency}) \ \ldots (7)$$

The primary properties that are used for the FEM are given in Table 1.

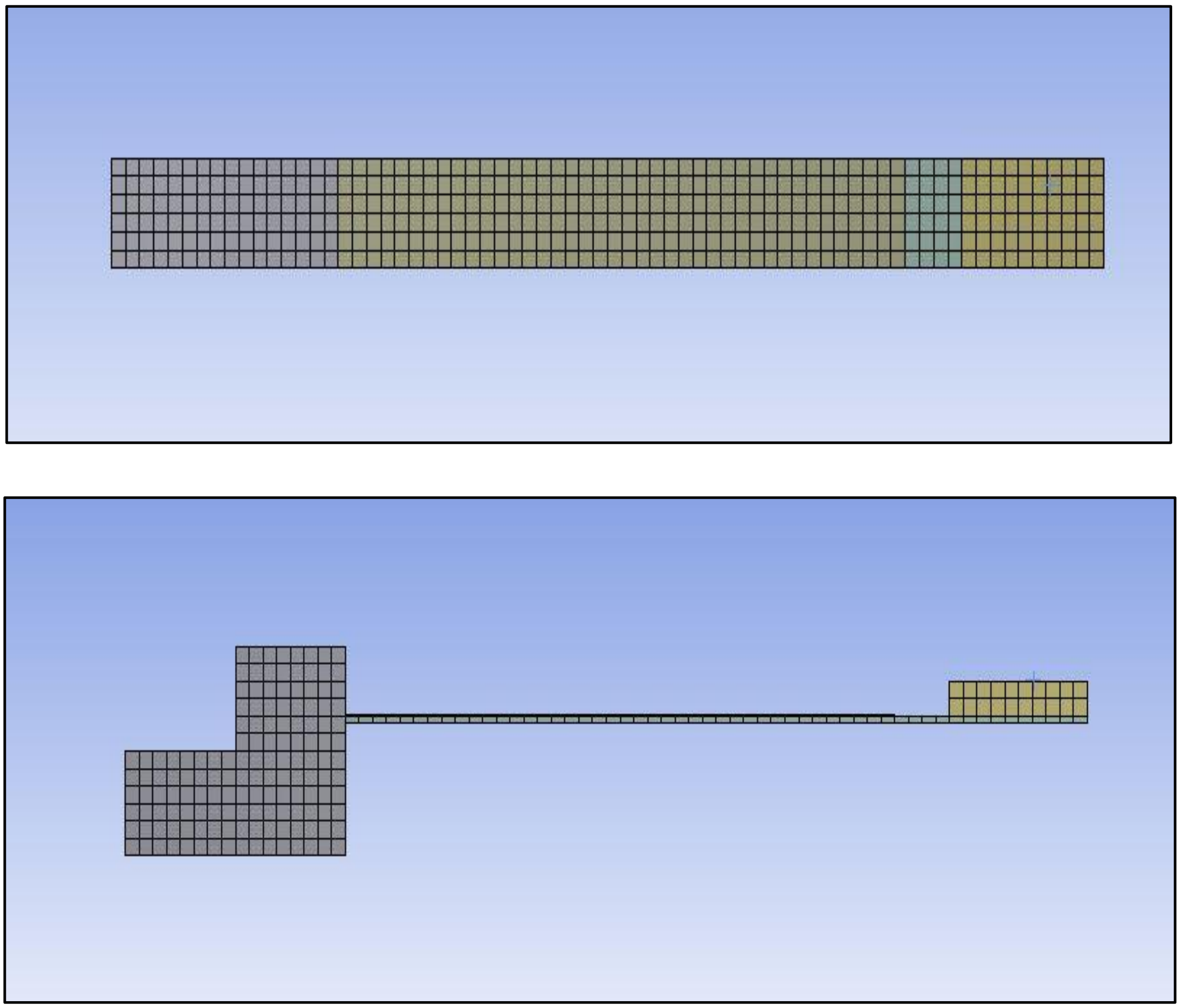

Fig.15 - FEM Model of PVEH beam: (i) top view; (ii) front view

The PVDF film was already poled to generate strong piezoelectric effect. The poled PVDF film of thickness 0.1mm was coated on both the sides with copper electrode. Two copper wires were attached on both the sides of the film i.e. on the upper and bottom electrode. This electrode coated PVDF film was attached on the GFRP plate with the help of a mixture of epoxy and hardener. A proof mass was attached at the free end of the beam. This composite PVEH beam was clamped at fixed end on the bench vise to give cantilever structure.

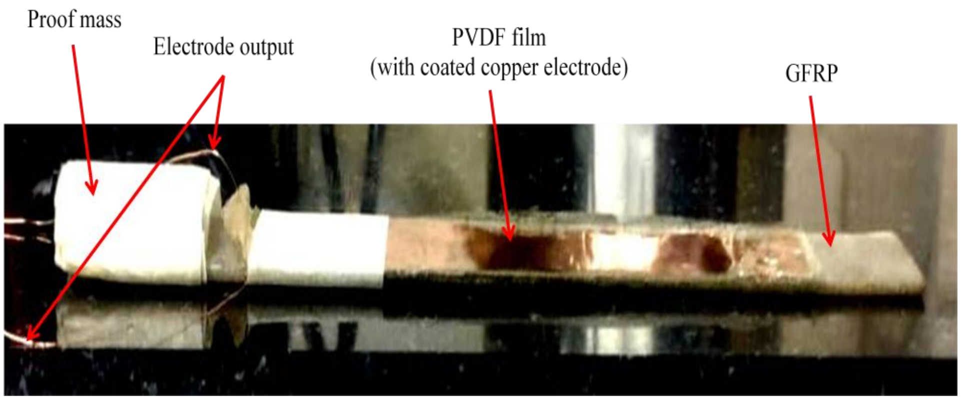

Fig.16 - PVEH beam

The most commonly used AC-DC rectifiers in energy harvesting systems are full-wave bridge rectifiers, which is an arrangement of 4 diodes in a bridge circuit to change the input AC power into DC power. We constructed the full wave bridge rectifier on a PCB (Printed Circuit Board). A capacitor of 1μF was used to store the generated electricity.

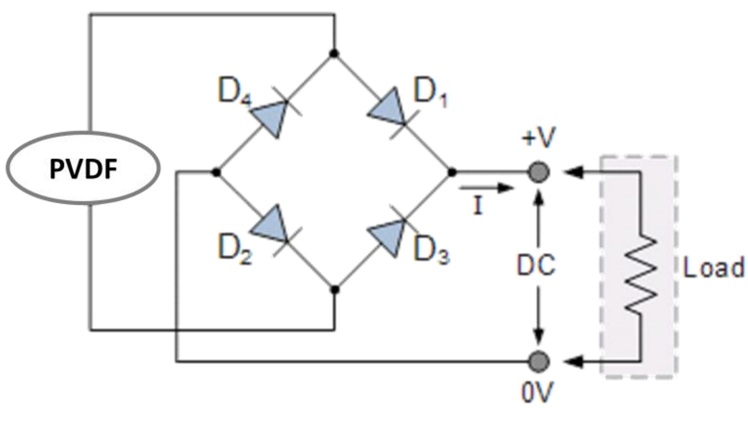

Fig.17 - Schematic of full wave rectifier circuit (Source: www.electronics-tutorials.ws)

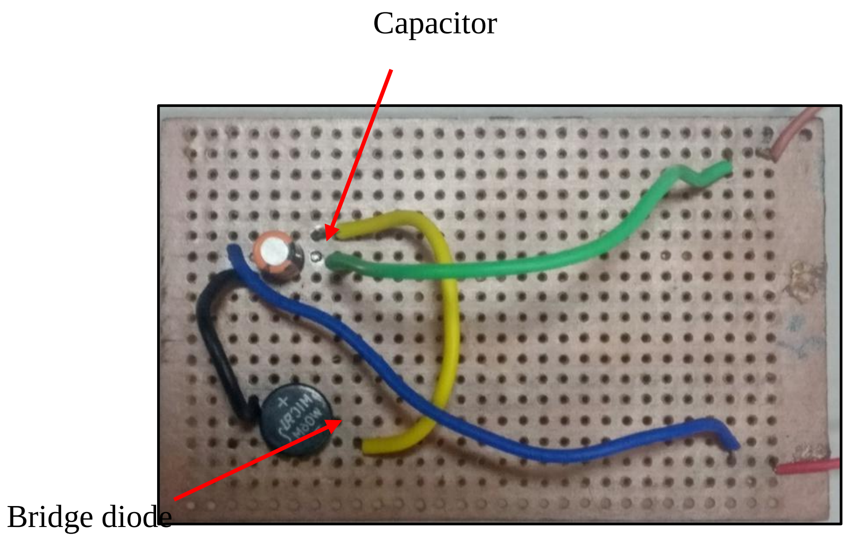

Fig.18 - Full-wave rectifier circuit constructed on PCB

In the experimental analysis, the equipment used was digital acquisition system (DAQ), impact hammer, bench-vise, PVEH beam, connecting cables, and a computer. Initially, the beam was clamped on the bench vise to provide the cantilever structure. The DAQ system was setup with three different channels connected with cables. First cable was attached to the impact hammer while the second and third cables were attached to the electrode wires (Fig.19, Fig.20). On the computer, NVGate software (from OROS) was launched and the respective model with specific parameters was made. Impact hammer with rubber tip was used because the area of interest was in low frequency range. The impact hammer was calibrated to get accurate results. It was struck on the beam at the base to replicate the base excitation force condition in FEM. Five impacts were recorded and averaged to give the required measurements. The software model processed the results and gave the data points for the FRF at different frequencies. Thereafter, the FRF data was post-processed to give the plot for the multi-mode voltage FRF (Fig.25).

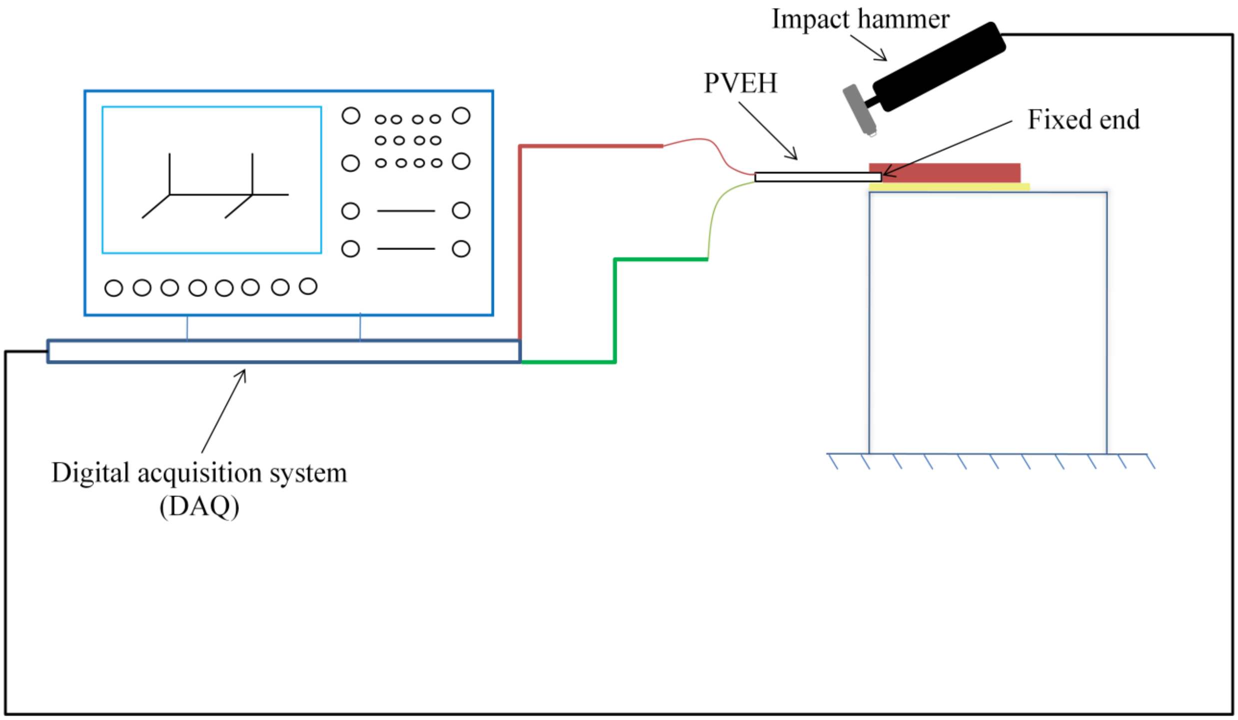

Fig.19 - Schematic of experimental setup

Fig.20 - Experimental setup: (i) PVEH beam connected to data acquisition system; (ii) NVGate software used to generate the FRF

Chapter 8 - ***Results and discussion***

8.1 Numerical analysis

a. Modal analysis

Mode	Frequency (Hz)
1	12.55
2	127.76
3	159.45
4	258.93

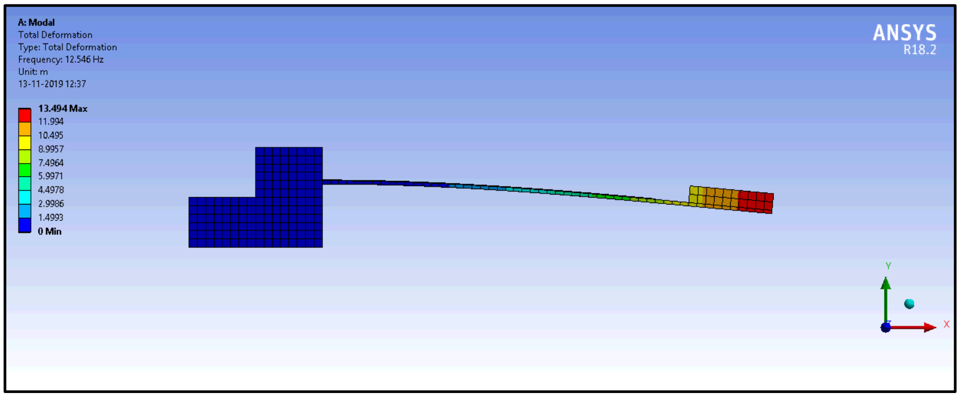

Fig.21- Deformation at 1st mode

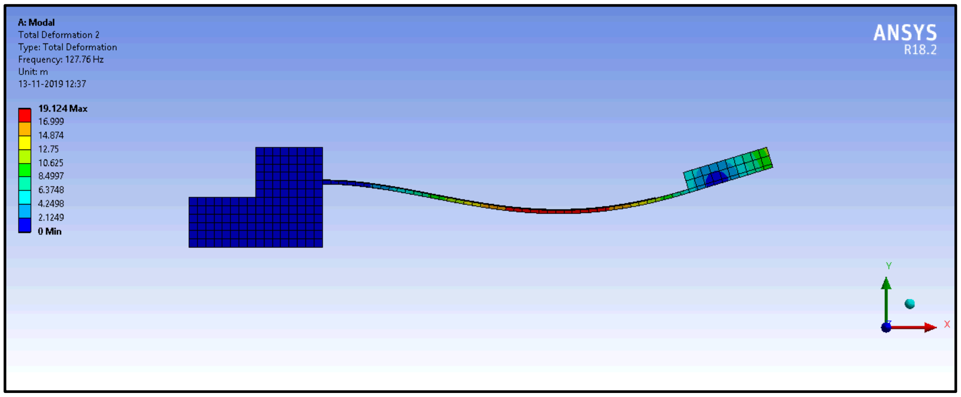

Fig.22 - Deformation at 2nd mode

b. Harmonic response analysis

The average strain distributions as well strain gradients' distributions were derived as a function of the beam length in the longitudinal (x) direction for arbitrarily taken frequency values of 15 Hz, 75 Hz and 175 Hz as shown in the figure (Fig.23).

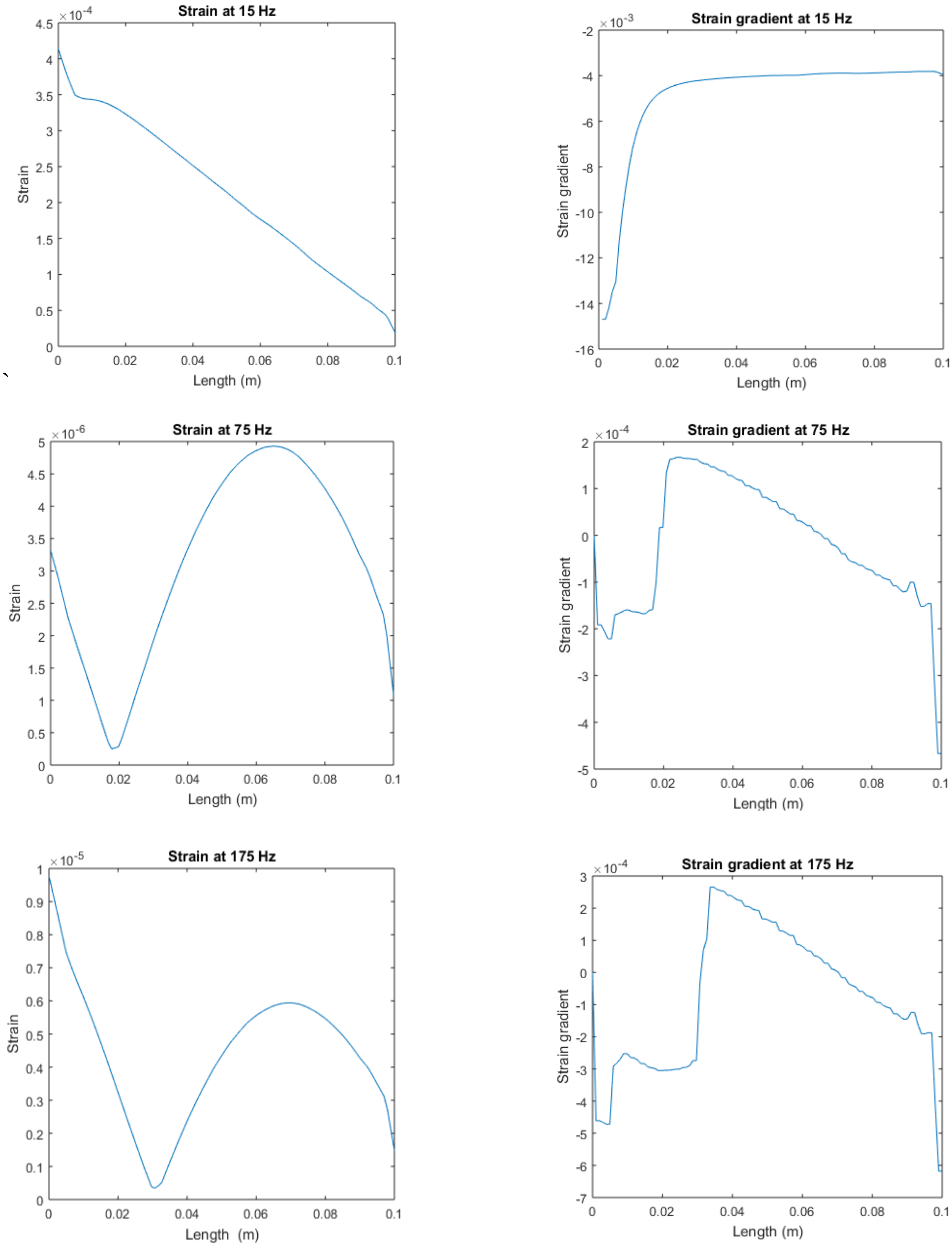

Fig.23 - Strain and strain gradients at different frequencies; (i) 15 Hz, (ii) 75 Hz, (iii) 175 Hz

For the 15Hz frequency, which is very close to the fundamental mode of 12.55 Hz, the strain was much higher at the base end and decreased thereafter with almost constant strain gradient along the beam length. For the 75Hz and 175Hz frequency values, strain decreased initially to a local minima value and then increased to a local maximum and further decreased.

It was also that the strain gradients at higher frequencies were non-uniform and considerably skewed as compared to those at lower frequency. A peak occurred for these strain gradients at length between 30mm and 40 mm, quite further from the minima location and from there the strain gradient decreased almost linearly till 90 mm length.

It was observed that the position of the greatest strain gradient on the beam converged towards a particular coordinate as the frequency was increased which was close to the position of the lowest strain magnitude. Thus, to maximize energy harvested from the beam, there must be a tradeoff between the values of strain and the strain gradient which will depend on the values of Young's modulus of the beam, the piezoelectric charge constant and the flexoelectric coefficient of the PVDF film.

Therefore, it was observed that the strain gradients vary appreciably along the length of the beam. This augmentation of the strain gradients at certain positions on the beam can be used in the harnessing of vibration energy through the PVEH beam. Also, though the maximal values of the strain gradient were positive, there were still existences of negative strain gradients which can reduce the polarization due to flexoelectricity (as obtained by equation (5)). Therefore, efforts must be made in the direction of increasing the value of strain gradients towards the positive side of the graph.

c. Polarization FRF

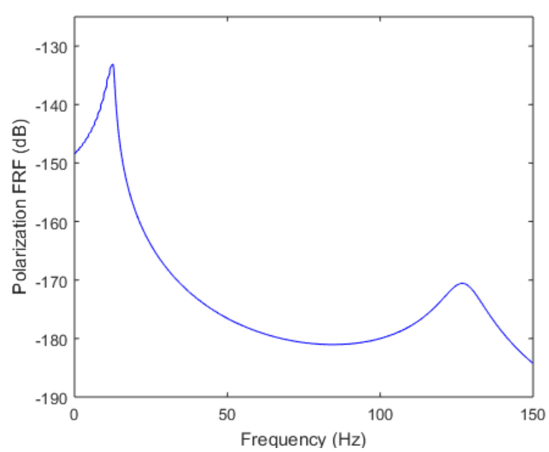

Fig.24 - Polarization Frequency Response Function (FRF)

The polarization FRF was estimated based on the polarization induced only by piezoelectricity. It was plotted using the formulae given in equations (3) and (6).

The peaks of the FRF graph were obtained at the first and second modes of vibration. The maximum polarization occurred at the fundamental mode. The peak obtained at the second mode was considerably diminished in value as compared to the first mode due to electrical cancellation which is caused by the dipoles which point in opposite directions at neighboring interfaces, leading to a cancellation of the piezoelectric response [3].

8.2 Experimental analysis

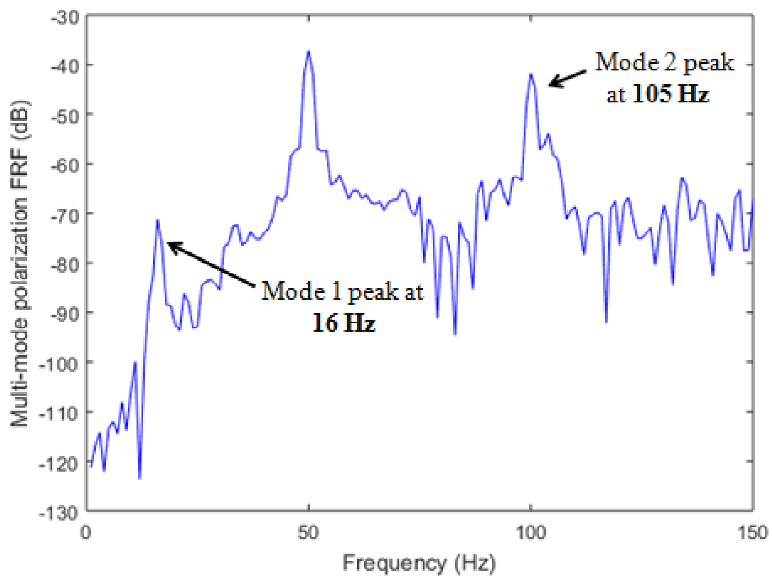

Fig.25 - Multi-mode polarization FRF (MMP-FRF)

The multi-mode polarization FRF (MMP-FRF) was obtained by the experiment of the impact hammer test. The polarization FRF was obtained by plotting the polarization due to combined piezoelectric and flexoelectric effects along with the frequency as obtained from the experimental results. The MMP-FRF has been plotted in Fig.25.

When compared with the polarization FRF obtained by pure piezoelectric effect (Fig.24), it can be seen that the presence of the flexoelectric effect greatly enhances the polarization obtained from the PVDF film in the MMP-FRF. The polarization is further amplified by the small thickness of the film.

The modal frequency peaks in the MMP-FRF were obtained at frequencies of **16 Hz** and **105 Hz** which were close to the numerically obtained modal frequencies of 12.55 Hz and 127.76 Hz respectively within the limits of experimental errors. At frequencies above the 2^{nd} mode, there were no major peaks due to smaller variations of strains and occurrences of electrical cancellation.

8.3 Sources of error

A peak value was also obtained at 50 Hz which was symmetric and sharp indicating it to be caused due to one of the following errors:

i. **Double impact error:** Due to the double impact of the impact hammer a double tap/impact error may occur which may show greater amplitude at some particular frequencies.

ii. **Finite record length:** The signal is acquired in limited recording time therefore finite record length error exists.

iii. **Leakage error:** Leakage error exists due to disagreement between period of signal and record length Since the peak value is strongly dependent on leakage error in short record length, it is a major source of error [11].

Therefore, record length should be long to reduce finite record length error and leakage error.

8.4 Scope for future work

- Efforts must be made to increase the value of strain gradient such that the obtained values are positive; thereby no harm is done to the hardware.
- Work can also be done to utilize this harvested energy to power wireless sensors.
- Instead of impact hammer, electromagnetic shaker can be used to excite the base of the structure which can provide accurate results of the multi-mode voltage FRF.

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