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FINITE ELEMENT ANALYSIS OF THE PIEZO ELECTRIC ENERGY HARVESTER FOR THE PERFORMANCE EVALUATION USING ANSYS.

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Abstract – Now a days, most of the electronic gadgets makes use of batteries and external power supplies to energize themselves. As the usage of various electronic devices increases day by day, a non- conventional, clean and reliable energy sources are required as an alternative to meet the increasing demands. In this scenario, vibration energy harvesting exhibits a promising opportunity without negotiating the actual functionality of the structure. Vibration energy harvesting is the procedure of transforming vibrations into usable electrical energy. For the conversion, we can make use of electromagnetic, electrostatic, and piezoelectric materials. Among the above techniques, piezoelectric material has the highest power density in comparison with others. In piezoelectric energy harvester, piezoelectric crystals are used to convert the mechanical energy in to electrical energy. As the voltage sensitivity and stability is higher, in this work PZT 5A is used for harvesting the vibrational energy. In this paper, modal and harmonic analysis of two rectangular plates with piezoelectric unimorph, one with proof mass and the other without proof mass is analyzed and compared its results in terms of the output voltage generated.

Keywords - Modal Analysis, degree of freedom, piezoelectric, energy harvesting, proof mass, harmonic analysis.

I INTRODUCTION

Over the decade usage of various handheld portable electronic devices and wireless sensors have gained enormous growth which led us to think many alternate powering solutions to fulfill the increasing demand. Now a days most of the portable devices are powered by the conventional chemical batteries [1]. But when we use conventional batteries, the disadvantages are short life span and frequent replacement which requires human interference. In order to solve the above shortcomings, a non- conventional, reliable and a clean energy source for powering all types of devices without affecting the environment is a hot subject of investigation. One such solution is piezoelectric energy harvester which makes use of mechanical vibrations to generate electrical energy. Piezoelectric tiles are used for harnessing the mechanical energy otherwise wasted, with minimum intervention to the normal mechanical activities[2].

Vibration can be defined as the oscillation of a system about a fixed reference point. One of the key parameters in the structural dynamic analysis is 'resonance'. The natural frequency of the vibrating structure represents its resonant frequency. When a system vibrates at its natural frequency, then it forms a maximum displacement [3]. Modal analysis can be performed to study the natural frequency and different mode shapes of the vibrating structure. When an external force is applied, the structure will vibrate differently from node to node and the time response of the structure can be studied by the dynamic response of the system [4].

In this research work, two rectangular plates with same dimensions having piezoelectric plates attached to them is modelled. Modal and harmonic analysis of rectangular plates of one with proof mass and the other without proof mass is analyzed and compared its results in terms of the output voltage generated.

II VIBRATION ENERGY HARVESTING METHODS

The idea of vibration energy harvester (VEH) is to convert mechanical vibration energy into electrical energy. In a VEH, at first, vibrations are transformed into a relative motion between two components utilizing mechanical to mechanical converter and then this relative motion is converted into electrical energy by employing mechanical to electrical converters like piezoelectric materials or variable capacitors. Fig. 1 represents the basic block diagram of a vibration energy harvesting system. The most common conversion techniques are electro static, electromagnetic and piezoelectric. Among these, piezoelectric energy harvester is the most popular one due to its easier development and simple construction, easy real – time monitoring and control, it can harvest the energy over a larger frequency and it is having a larger conversion efficiency.

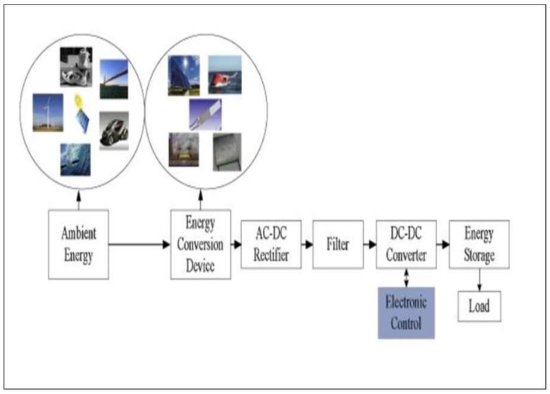


Fig. 1. Block Diagram of VEH system.

III PIEZOELECTRIC ENERGY HARVESTING TECHNIQUE

In the past decade, energy harvesting utilizing piezoelectric materials has gained a wide acceptance with the current hike in the advancement of low – power electronics devices such as micro electronics and wireless sensors. Fig. 2. represents the basic block diagram and schematic of a PEH module [5].

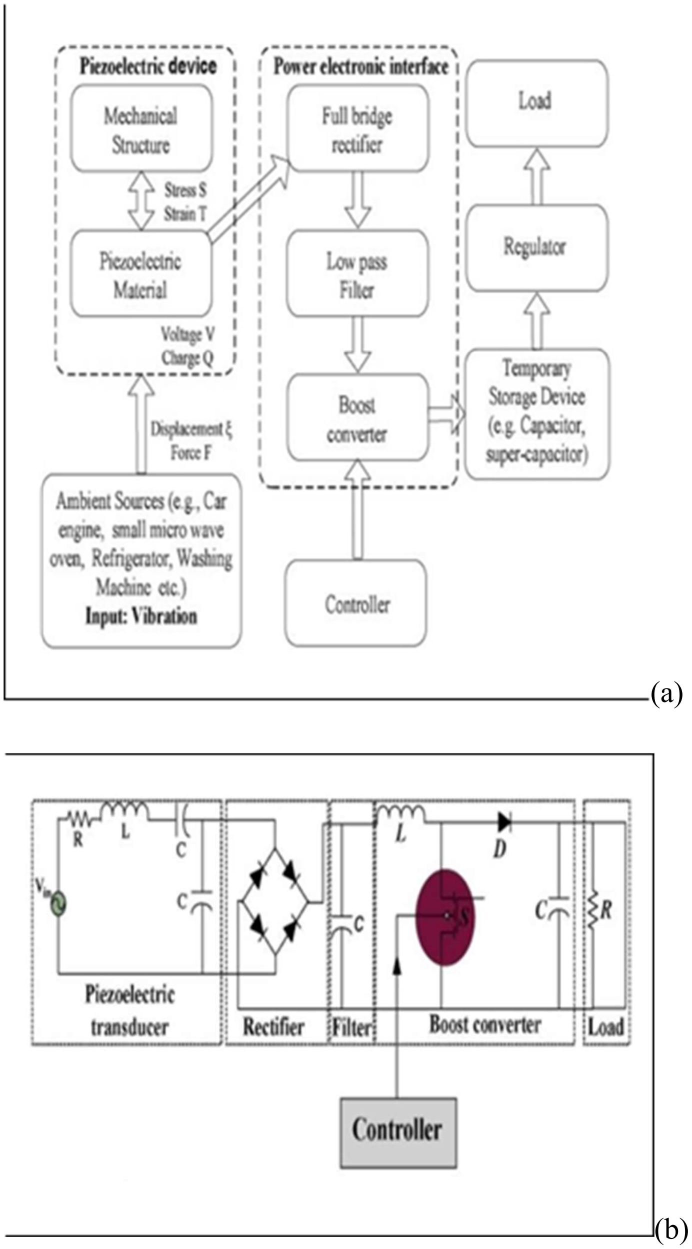


Fig. 2. (a) Block diagram (b) Schematic diagram of a typical Piezoelectric Energy Harvesting Module.

Generally, a piezoelectric Energy Harvester (PEH) uses three basic mechanisms. First is piezoelectric device, second is power electronic interface and the third electrical energy storage. The major objective of the harvester is to improve the harvesting power. This is accomplished by employing materials which has a greater electrical conversion potential. The output of the VEH system which uses piezo electric material can be enhanced by using electronic power converter circuit. The designing of the converter is very crucial as it can effectively enhance harvesting performance of the entire system.

IV PIEZOELECTRIC EFFECT AND LAYER DESIGN

A. Piezoelectric Effect

When a piezoelectric material is subjected to a mechanical force, pressure or vibration, the material undergoes some deformations which will create an induced electric field. The piezoelectric effect is a reversible process in which a material which shows a piezoelectric effect can show a reversible effect also that is the internal production of a strain in accordance with the applied electric field [6]. The direct piezoelectric effect was invented by Curie brothers in 1880 on quartz (SiO2) single crystals. In addition to the quartz crystals, piezoelectricity can be visualized in many other material classes like ceramic materials and compositions, polymers, bone, wood and certain viruses. Piezoelectric effect can be found in both materials with a spontaneous polarization as well as in nonpolar materials that lack a centre of symmetry, such as zincite (ZnO) with a non- centrosymmetric hexagonal wurtzite-type crystal structure. The largest piezoelectric properties can be seen in perovskite crystals, whose single crystal layer can display piezoelectric coefficients three times the magnitude of a quartz crystal that was demonstrated by the Curie brothers.

Mathematically, the piezoelectric effect can be represented as the electromechanically coupled linear relationship between mechanical (e.g., strain and stress) and electrical (e.g., electric displacement and electric field) field quantities. The magnitude and nature of the resultant piezoelectric effect can be found by the relative direction of the electric field and the stress or strain developed with respect to the direction of polarization.

The electrical charge produced by the piezoelectric material can be formulated by the following equations

$$S_1 = S^E_{11} T_1 + d_{31}E_3 \qquad (1)$$

$$D_3 = d_{31}T_1 + \varepsilon^T_{33} E_3 \qquad (2)$$

Where $T1$ and $S1$ are the stress and strain produced inside the piezoelectric material, the piezoelectric strain constant can be expressed as $d31$, $D3$ - the electric charge density, $S11$ is the elastic compliance in a constant electric field, $E3$ is termed as the electric field developed in the “3” direction and $\varepsilon 33$ is the dielectric constant of the piezoelectric material [7]. Different modes of operation for piezoelectric energy harvester are presented in Fig. 3.

material. PZT 5A is used in low power systems and it has got a very high voltage sensitivity, volume resistivity and has a high stability over a wide range of temperature [8]. For harvesting the energy, PZT5A material with density 7750 $Kg/m3$ and having area 0.2m2 is modelled. Material property of PZT 5A is listed in Table1.

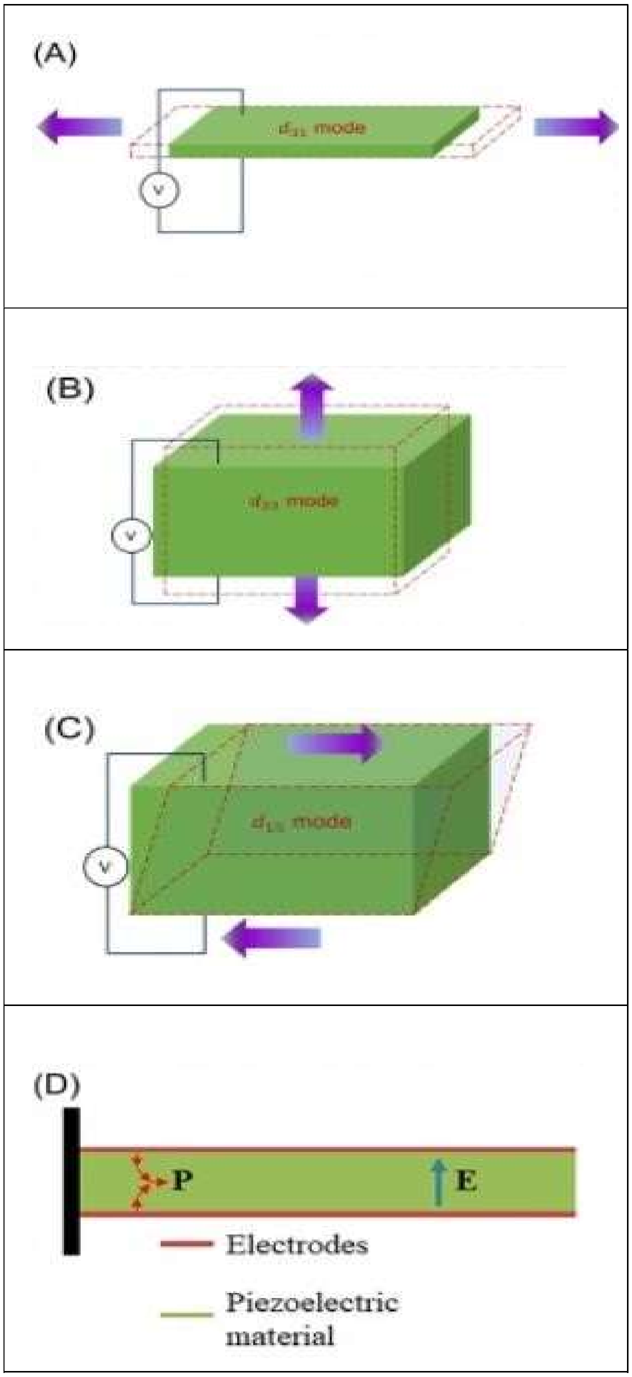
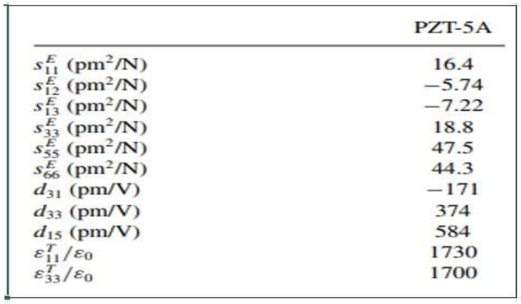


Table1. Three Dimensional Properties of PZT 5A



	PZT-5A
s_{11}^{E} (pm^2/N)	16.4
s_{12}^{E} (pm^2/N)	−5.74
s_{13}^{E} (pm^2/N)	−7.22
s_{33}^{E} (pm^2/N)	18.8
s_{55}^{E} (pm^2/N)	47.5
s_{66}^{E} (pm^2/N)	44.3
d_{31} (pm/V)	−171
d_{33} (pm/V)	374
d_{15} (pm/V)	584
$\varepsilon_{11}^{T}/\varepsilon_0$	1730
$\varepsilon_{33}^{T}/\varepsilon_0$	1700

V ENERGY HARVESTER STRUCTURE DESIGN

In order to get the maximum energy while scavenging the vibrations, structures with lower resonant frequencies are used. Among all other structures, cantilever beams produce lower resonating frequency in ambient vibration conditions. Resonating frequency can further be reduced by attaching an extra mass called proof mass at the end of the structure. Due to inertia, beam with end mass will vibrate more. Resonant frequency can be varied by changing the dimensions of the structure and material properties which is given by the equation

$$\omega = \sqrt{k}/m$$

Fig.3. Different modes of operation for piezoelectric energy harvesting. (A) transverse (d31) mode, (B) longitudinal (d33) mode, (C) shear (d15) mode; (D) graded mode for having transverse mode at top and bottom of the beam.

B. Piezoelectric Layer Design

PZT (Lead Zirconate Titanate) is used as the piezoelectric material as this is one of the most widely used piezo ceramic Where k is the stiffness of the material and m is mass of the structure [9]. The geometrical model for the FEM simulation was done in ANSYS design modeler. Rectangular base plate with aluminum material having area 0.75m2 and a proof mass attached at the free end of the base plate with tungsten material having area 0.025m2 was designed (Fig.4). PZT 5A piezoelectric unimorph material is placed almost at the centre of the base plate for scavenging the vibrational energy. Material properties of the base plate and proof mass is given in Table 2.

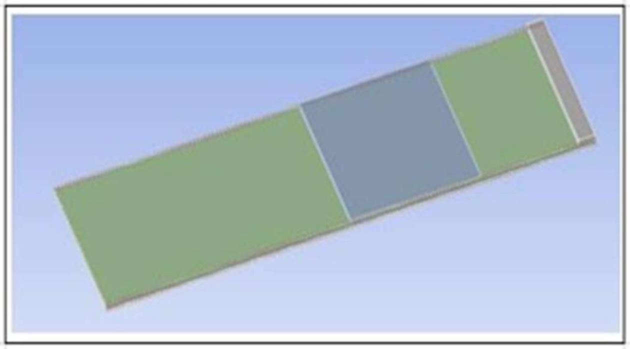
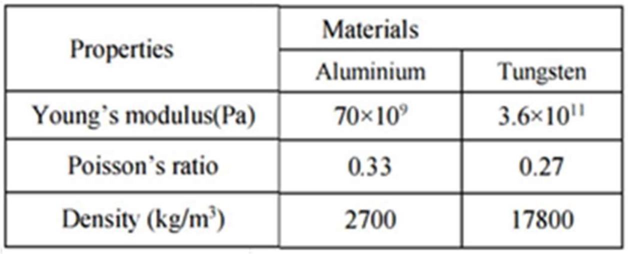


Fig. 4 3D Representation of Energy Harvester with Proof mass



Properties	Materials	
	Aluminium	Tungsten
Young's modulus(Pa)	70×10^9	3.6×10^{11}
Poisson's ratio	0.33	0.27
Density (kg/m^3)	2700	17800

Table 2. Material properties of Aluminum and Tungsten.

VI SIMULATION TECHNIQUES

The basic components of a standard piezoelectric energy harvester are a cantilevered beam with a proof mass which is attached to the free end and the other end fixed to a base structure which is vibrating. The vibrating base structure along with the proof mass provides a strain to the piezoelectric plate, which then transformed to an electrical energy by means of direct piezoelectric effect [10]. Here, a small-scale energy harvester was simulated. This work examined a unimorph cantilevered beam with and without proof mass. For analysis, the finite element method was adopted. The proposed model was designed and was simulated in ANSYS. Modal as well as harmonic analysis has been carried out for finding the natural frequencies and the different modeshapes of a rectangular cantilevered plate. Harmonic analysis has been done to find the generated output in terms of voltage with and without the end mass and the results were plotted.

A. Degrees of Freedom (D.O.F)

Degrees of freedom (DOF) represents the total number of independent variables that has the freedom to vary in a data sample. This can be calculated by subtracting one from the total number of elements within the dataset [11]. In a system if the motion is described fully by one-time dependent coordinate then it can de stated as having single degree of freedom (SDOF). Whereas if it requires more than one coordinates, can be termed as having multi degrees of freedom (MDOF). Degrees of freedom is very essential in describing the nature of a system [12] With N number of coordinates, the system's overall damping, mass and stiffness characteristics, can be represented by matrices of size NxN.

B. ANSYS

For the simulation, one of the numerical techniques -Finite Element Method is adopted which makes use of Finite Element Analysis (FEA). This technique is used to find the approximate solutions to various engineering problems with complex loading, geometries and material properties. In FEA, the whole structure is divided into small finite elements and the corner points of these elements are called nodes. Functions in the finite elements are found in terms of nodal values. That is, a continuous complex physical problem is changed into a discrete finite problem where the nodal values are calculated. After this, the entire global system of equations is formulated and the unknown nodal values are computed. Mathematically, FEM provides a relative numerical solution to a given physical problem. However, it is very difficult to find if the obtained result is desirable for all problems in hand. Analytical or experimental results can effectively verify the result of finite element analysis.

In recent years, one of the powerful Finite Element Analysis tools is Analysis of Systems (ANSYS). ANSYS enables the professional to do the following functions.

a) To construct computer models or CAD models of complex structures, systems or products.
b) To study the physical feedback like stress levels, temperature distributions, electromagnetic fields etc.
c) To employ operating loads or constraints.
d) To optimize the design during development process.
e) To perform prototype testing under adverse undesirable environments.

In this work, Modal and Harmonic analysis has been carried out. Modal analysis is used to find the beam’s natural frequencies and the mode shapes. The modelling procedure is represented in fig. 5.

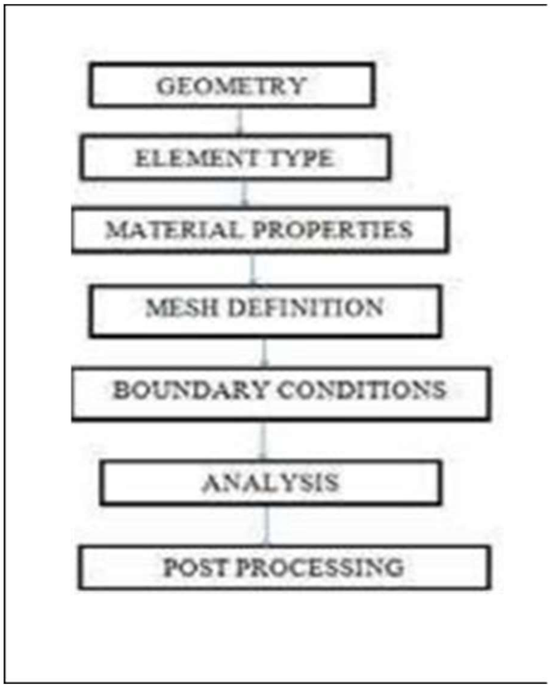


Fig.5. Modelling Procedure.

Vibration analysis of the energy harvester in ANSYS can be done by giving structural data and load conditions on different supports. After assigning the appropriate material properties and real constant values, meshing is done. In meshing, the whole matrix is subdivided into small parts so that the results can be more accurate. After meshing, the mass element is attached to the free end and the other end is fixed so that its degree of freedom is zero. After this. Six mode shapes and six frequencies are generated by performing the modal analysis.

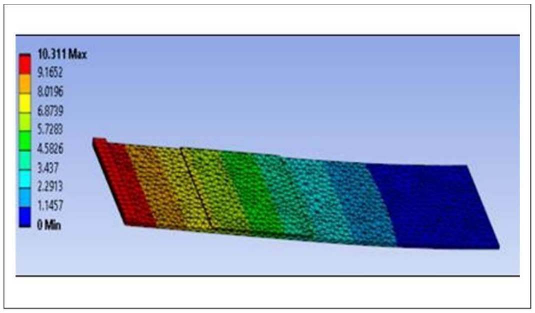
After the natural frequencies are determined, harmonic analysis has been carried out to find the generated voltage with and without proof mass. The harmonic analysis calculates only the steady state, forced vibrations of a structure. The transient vibrations which occur at the starting of the external excitation are not counted during harmonic analysis. Harmonic analysis provides the information about the dynamic behavior of the structure so that one can verify whether the system can survive the fatigue, resonance and other harmful effects of forced vibrations. Harmonic analysis provides the steady state response to the loads that varies sinusoidally with respect to time.

VII Structure Analysis and Result

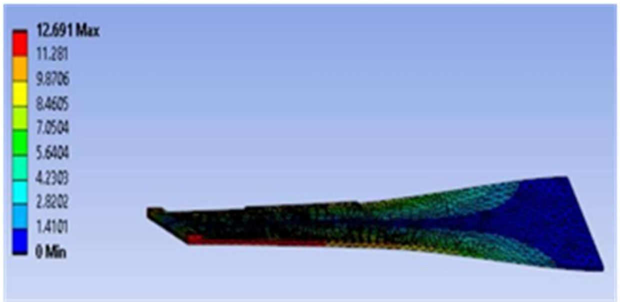
Generally, mode shape and natural frequency of a vibrating system can be determined by performing modal analysis. Periodic forces exerting on the structure are combined with that of the natural frequency to develop resonance in a system. Hence natural frequency must be found to estimate the periodic load resonance condition [13],[14]. To have a maximum energy generation, in a cantilevered harvester we can use a proof mass of any shape and dimension [15].

Once the harvester is modelled, it was subjected to meshing for doing finite element analysis (FEA). FEA uses calculations, models and simulations for predicting the behavior of the structure under different physical conditions [16]. In this work, a tetrahedron meshing with an element size of 30mm is used for simulation as shown in the Fig.6. Meshing statistics is represented in Fig.7.

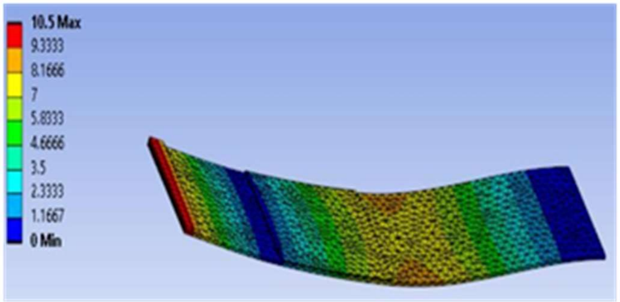
After meshing the structure, modal analysis has been conducted for finding the natural frequency and the mode shapes as shown in Fig.8. Natural frequency was found for 6 mode shapes.



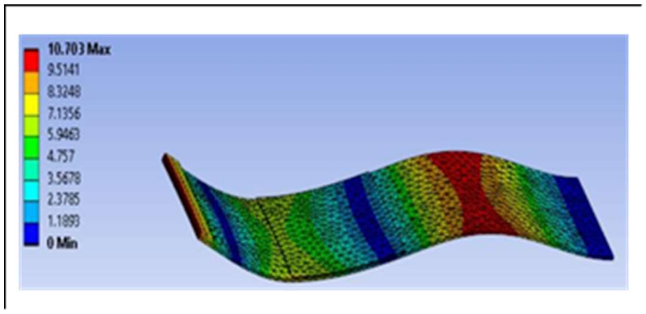
(a)



(b)



(c)



(d)

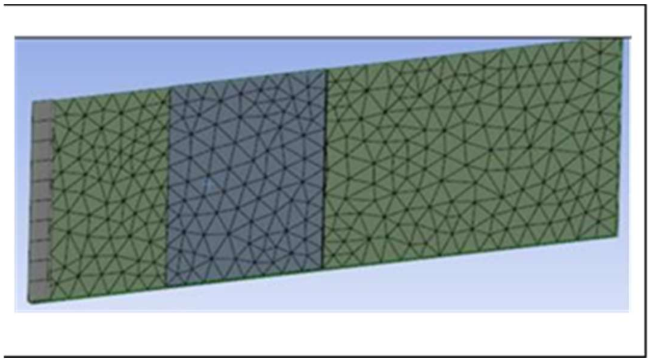
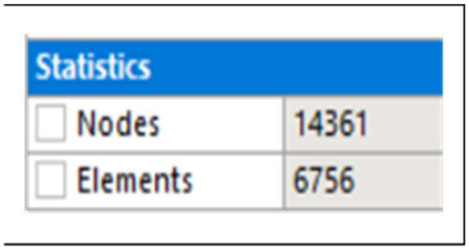


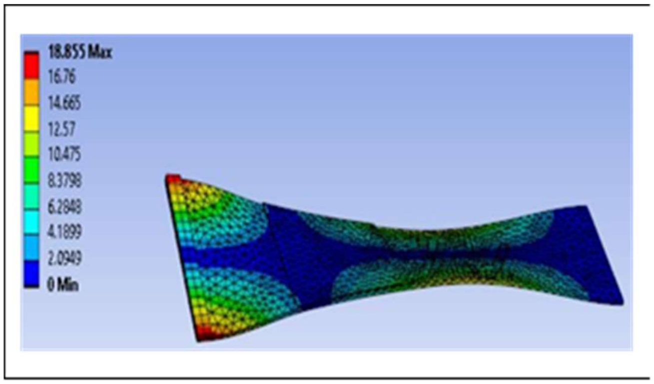
Fig. 6 Mesh diagram of the structure.



Statistics	
☐ Nodes	14361
☐ Elements	6756

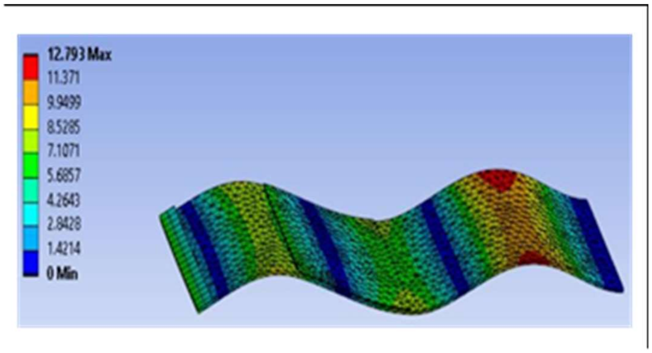
Fig. 7 Mesh Statistics

For performing the harmonic analysis, a force of 2N is applied at one of the vertices in the downward direction for analyzing the performance of the structure as shown in Fig.10.

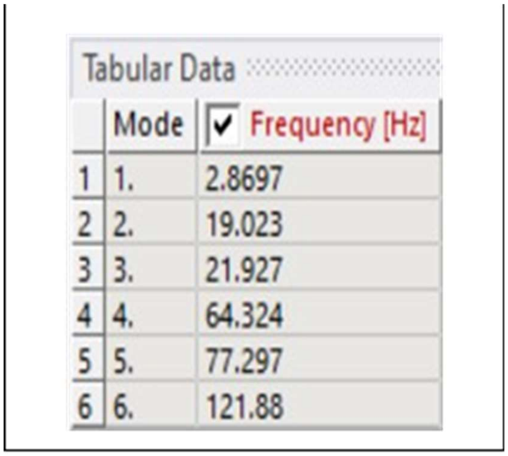


(e)

(e)



(f)



Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	2.8697
2	2.	19.023
3	3.	21.927
4	4.	64.324
5	5.	77.297
6	6.	121.88

Fig. 9 Natural frequencies obtained for six mode shapes.

Harmonic analysis is performed and the voltage to frequency plot is obtained to find the generated voltage in the structure with and without the proof mass as shown in Fig. 11.

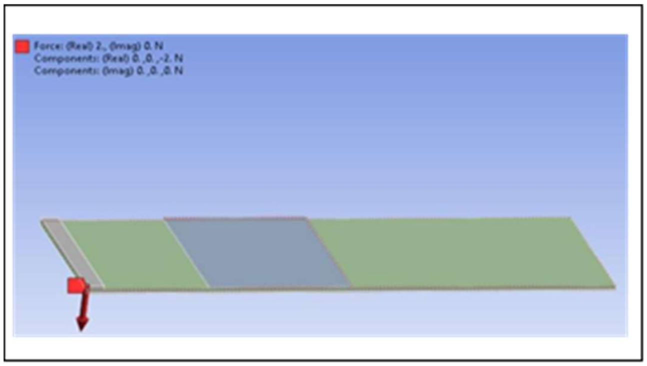
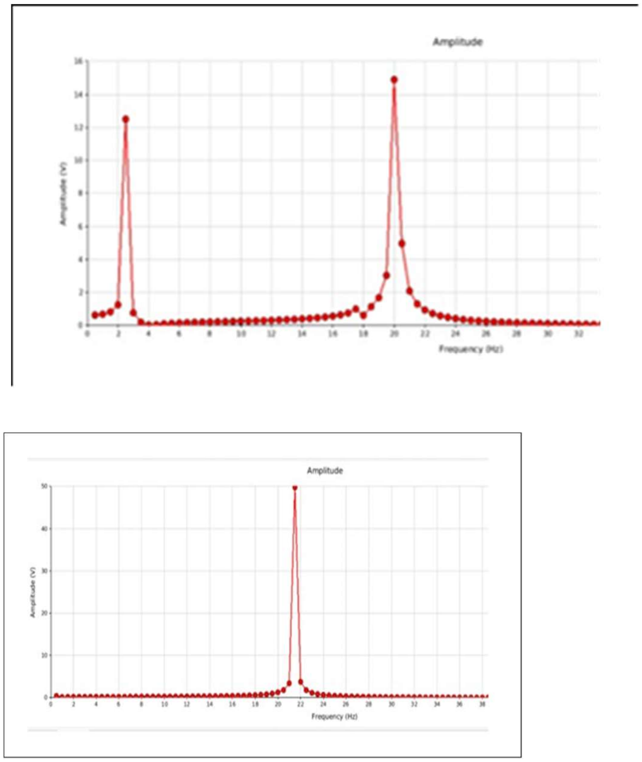


Fig. 10 Force applied

(a)



(b)

Fig.11 (a) Voltage generated without proof mass (b) Voltage developed with proof mass.

VI CONCLUSION

Finite Element Analysis of the cantilevered plate structure with and without proof mass has been performed. The obtained graph suggests that the generated output voltage in a cantilevered plate harvester with proof mass was able to deliver much more voltage than the harvester without the proof mass. The presented result suggests a reasonable outcome on the dimensional parameters of the harvester and may guide to designing it with greater efficacy in their functionality.

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