PZT BASED ENERGY HARVESTING BY ENGINE VIBRATION

Submitted in the fulfillment of the requirements
Of the degree of

MASTER OF TECHNOLOGY
IN
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By

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Abstract

Energy harvesting is the most important topic of research these days. Due to higher energy consumption by the human, the resources are decaying day by day which can result the drainage of the resources for the next generation. To save the energy resources several technologies are invented by which the energy can be produced by changing one form of waste energy into the useful energy. Among these technologies, one is very popular i.e. use of piezoelectric materials.

In piezoelectric material energy is generated due to its behavior against the loading conditions or ambient vibrations. Using stress generated on the material the electrical energy is extracted by means of the electrode material spread over the material surface and an electrical circuit.

In this work study on piezoelectric material properties and its application on energy harvesting is done. The work is based on engine vibration which is used as the source of vibration and the arrangement is to be applied on the engine to carry out the electrical energy. A new design is also proposed by which the efficiency is increased within the same frequency range. Solidworks 2016 is used for modelling while in Ansys 18.0 the simulation is carried out.

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Chapter 1

Introduction

In this modern era of technologies, human developed several techniques to make his life easier. By using these time and physical work both can be saved. He can do such works in minutes which can take whole day or 2-3 days. The technology becomes so updated so that a small battery can keep large amount of power or can produce electricity by having only chemical reactions inside the case. Due to these technologies and human comfort, consumption of the energy is rapidly increased which results the resources is approaching to end. It is estimated that if we use the resources in such amount, it will not be available for the next generation. Another concern is that pollution index is also increasing due to repetitive use of these resources which affects the earth's environment and the ozone layer.

To save the earth and the resources many inventions have been done. The main aim of the inventions is to reuse the resource and generate the energy into the form of electricity and another form by using different mechanism. The ambient energies that can be extract from the environment are: Wind energy, Water energy, Solar energy, Chemical energy etc and the inventions done corresponding to the sources are: Windmills, Dams, nuclear plants.

1.1. Wind Energy: It is the ambient source of energy which is harvested by the windmills by means of wind turbines connected to the different components. It is a type of renewable energy resource which is widely used and contributed a large percent of the power generation. In these types of power generation plants wind speed is the important criteria for the best power output. These are placed at the coastal locations and the mountains because of the high wind speed as compared to the other locations. According to WWEA the wind power capacity increased to 597 GW in the end of 2018.

1.2. Water Energy: Water energy is generally called hydraulic energy in which flow energy of the water is used to generate the electric power by means of dams (consist of turbines). In this type of power generation water is flown from the height to the turbine blade due to which the shaft connected to the turbine rotates and further electric energy is stored at the powerhouse by means of generator. Flow of the water determines the energy generation by the mechanism, more the flow rate more will be the water energy in it. Generally energy generated by these sources is supplied to the industries due to high and continuous demand of electricity. According to IHA (International Hydropower Association) at the end of 2018 hydropower projects generated 4200 TWh electricity and the hydropower capacity increased to 1292 GW.

1.3. Solar Energy: The most important source of energy is sun which is always available for the earth. The technology to convert solar energy into electrical energy evolves day by day and it is becoming more efficient by using the latest technologies. Solar panels are used to extract the electric energy by solar energy through electric circuit in the panel. It converts radiant light and heat from the sun into electric energy. Various range of materials are used in the solar panel. This type of energy is also having the major percentage of power generation globally.

1.4. Chemical Energy: It is used to generate the electric energy from chemical reactions taken place either in batteries or in reactors. Chemical reaction causes some valance electrons which results the current flow in the electric circuit. Some of the examples in which chemical energy is directly converted into electrical energy are: Battery, Nuclear Reactor etc.

There are more sources available by which electric energy can be generated, these are: Geothermal energy, Hydrogen energy, Hydroelectric energy, Tidal energy, Biomass energy, Wave energy etc.

Some of the inventions are made for extract energy from these Among all the mechanisms piezoelectric material turn out to be a revolutionary technology for converting the mechanical vibration and stress into the electrical energy by means of electrical circuit. Piezoelectric material is a range of materials which are basically used for the making of self-energizing devices in which the required electric power can be generated by itself. It has the property to act against the stresses generated on itself and with the help of electrode on the surface electric energy is generated and stored in the storage devices (batteries, capacitor etc.). There are mainly two types of piezoelectric material exist: Lead based piezoelectric material and Lead-free piezoelectric material. Generally lead based materials are good according to the better output then the other materials but due to their hazardous effect on human health as well as on the earth it is banned globally to some extent. In the place of this material researchers found some new range of materials with similar properties and the main characteristic of that material is that it has no lead content. That materials are called lead-free piezoelectric material. By having some of the modifications the output can be improved from lead-free piezoelectric materials.

Lead based piezoelectric materials have lead in the material composition. Some of the lead-based materials are: PZT (lead zirconium titanate), lead titanate ($PbTiO_3$)[1], lead meta 3iobite[2], lead barium lithium 3iobite[3] etc. While the lead-free piezoelectric materials are: barium based lead free piezoelectric material, Bismuth sodium titanate based lead-free ceramic fiber, Sodium niobite, Bismuth ferrite etc.

1.5. Working Principle

Piezoelectric material works on the principle of piezoelectric effect which states that it is the ability of a piezoelectric material to produce the electricity when the mechanical stress is applied on it.

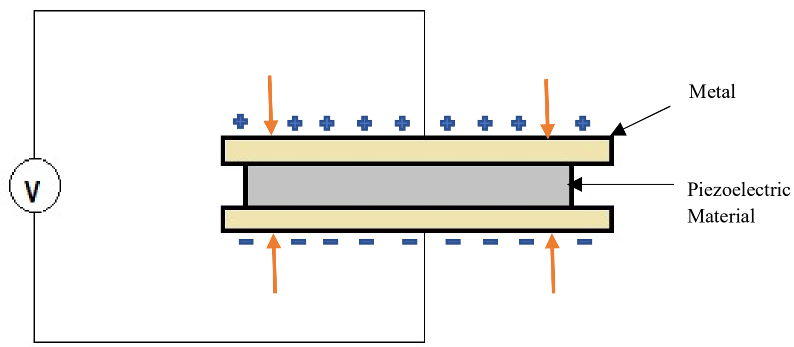


Fig. 1. Piezoelectric effect

This type of materials has the property to polarize when it undergoes through stress or is subjected to external loading. To extract the current from stress generated on the surface it must be covered with a metal layer which helps valance electrons to flow through the circuit. The generated electric current is not proper and continuous so that capacitor is generally used to store the charge and then according to the requirement the current is supplied to the location. Here the capacitor behaves like a battery in which the charge is stored and on requirement the current is supplied as shown in fig.2.

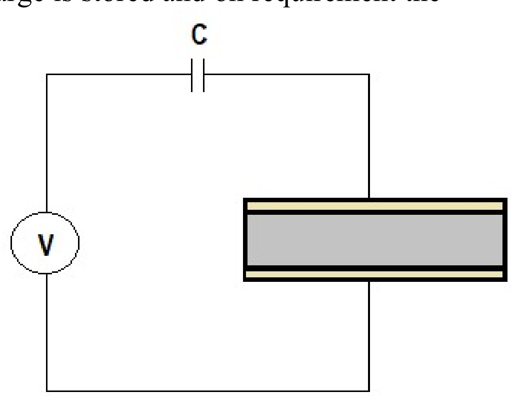


Fig. 2. Equivalent Circuit

1.6. Types of Piezoelectric structures for Energy harvesting

There are many types of structures used for energy harvesting purpose these are: Cantilever beam (Unimorph, Bimorph), Cymbal, Moonie, Multimoonie, Thunder, Stacks, circular, cylindrical etc. In unimorph cantilever beam two layers are there (one is of some material and another one is of piezoelectric material) while in bimorph three layers are there (one of some material and two are of piezoelectric material). Cantilever works against the ambient vibration which is the main cause of stress generation on the material and all other structures subjected to direct loading conditions due to which stress is generated on the piezoelectric material.

In the cymbal structure there are three parts: two endcaps of some material and one piezoelectric layer. The endcaps have cavity on their middle section of lower half cone like shape of some height while the other section is just like a circular plate. Moonie structure is quite similar to the cymbal structure. In this structure the cavity is circular in shape and the other part is same as cymbal. In multimoonie structure there are multiple piezoelectric material layer between the endcaps. The endcap material is of some material while the layers between them is of piezoelectric material. Stack structure is like multilayers of piezoelectric material between two layers of some material. When the bunch of piezoelectric layers are placed between two layers then it is called Stack or Multilayer structure of transducer.

1.7. Application of Piezoelectric material

Piezoelectric material can be used in two ways i.e. direct piezoelectric effect and Converse piezoelectric effect. Direct piezoelectric effect is that when mechanical energy is converted into electric energy while in Converse effect electric energy is converted into mechanical energy. For example, applications where direct piezoelectric effect is used are microphones, vibration sensors, photograph cartridges, gas igniters, photoflash actuators, accelerometer, fuses etc while converse piezoelectric effect is used in valves, speakers, emulsifiers, sonic transducer, ultrasonic cleaners, micropumps etc. Now these days these materials are used to generate electricity in self-energising devices by means of converting mechanical vibrations into electrical energy.

The piezoelectric material is used in every industry either it is medical, IT, agriculture, biology, life science, automobile industry, Microelectronics etc. With having so much advancements and engagements in almost every industry it becomes very hot topic for research. With having some advancements, efficiency is improved so that better results can be obtained.

Chapter 2

Literature Survey

2.1. Introduction

As the piezoelectric material is widely used in most of the self-energizing devices nowadays. So the research has been continuously done to improve the efficiency of the piezoelectric transducer. The main objective to do the research in this particular field is to use piezoelectric effect phenomenon in every possible area from where energy can be extracted.

2.2. Literature Reviews

Abhay khalatkar et al. worked on energy harvesting using the concept of piezoelectric micropower generators. In this paper author did the mathematical calculation for getting analytical output. Author did the calculations for the different positions of piezoelectric material on a cantilever beam and then having the model results were obtained from Ansys. Author did the experimental analysis also by placing the cantilever on the 4-stroke car diesel engine and according to the engine vibrations, analysis was done and generated charge was measured. Author firstly did the basic analysis based on the power cycles results were obtained. Then author varied the position of the piezoelectric on the surface of the material and compare the results among them and best position of piezoelectric was determined. The results were validated by comparing them with the mathematical results. From the results author concluded that when the piezo is placed nearer to the fix end then the output is optimum in a range of engine speed. At that position strain found out maximum which is the best for maximum power generation from it [4].

Steven R Anton et al. reviewed about the harvesting of power by using piezoelectric material. The study was mainly focused on the self-energizing devices where the piezoelectric material is used. Autor discussed about how electrochemical batteries are replaced by the energy scavengers in the portable wireless electronics. The wireless sensors need to be placed in remote locations so that it must be easily available for modifications and it should allow the smooth and accurate working of sensing device. Since the piezoelectric material is more sensitive to the ambient vibrations so that it is used with the wireless sensor. Further author discussed about the significance of the piezo in energy harvesting. The concept of energy harvesting is basically used for the self-energizing devices which can replace the power supplies devices in a particular machine. It is very useful where ambient vibration, waste heat, electromagnetic waves, wind, flowing water etc. are present in the surrounding of the device. Different structures and orientations were discussed in this paper and different materials also considered and study was done[5].

Anuruddh Kumar et al. studied about different lead-free piezoelectric materials in this paper. Six materials are taken into consideration among which five were lead-free piezoelectric material while one was PZT (lead-based piezoelectric material). The lead-free piezoelectric material was KNN-LS, KNN-LS-CT (1% wt.), KNN-LS-CT (2%wt.), BNKLBT, ZnO and lead zirconium titanate (PZT). A design of a unimorph- cantilever was taken and piezoelectric layer was spread over the cantilever. The comparison was done for all six piezoelectric materials with and without having proof mass at the free end of cantilever. The results were analysed on doing simulations in simulation software. The power was calculated in different frequencies and author concluded that the lead-free piezoelectric material gave best results among them and KNN-LS-CT (2% wt.) had the best results. It gives the maximum power output in same frequency range. Author also analysed that it has 35% more power density than PZT material[6].

Frank Goldschmidtboeing et al. did analysis of different piezoelectric energy harvester beam shapes. Author used Rayleigh–Ritz method for the analytical results. Author designed the different shapes of the cantilever from triangular to rectangular shape of beam and then author compared the results between them with or without having proof mass at the free end of the cantilever. By doing comparison author concluded that the efficiency is weakly influenced by only beam shapes. The triangular shaped beam gave the best results than all other beam shapes, it gave maximum power output and best excitation amplitude[7].

Akarapu Ashok et al. worked on microcantilever beam which is placed inside the sensors and actuators. In this work author proposed new design for the microcantilever beam of having trapezoidal shape. Author made different designs of trapezoidal shape microcantilever beam i.e. single double, three and four step trapezoidal beam. The rectangular beam was also analysed in this work. These all designs were analysed in simulation software and also experimentally and numerically. The beam was fabricated by silicon dioxide material. Author used laser vibrometer to measure the quality factor and natural frequency of the beams. The natural frequency and quality factor were analysed for the all designs and then based on the results optimum design for the microcantilever beam was determined. After obtaining all the results author concluded that four step microcantilever beam gives the highest output than all other designs. On placing a concentrated mass of 1 picogram on the cantilever beam it gave much better results[8].

Debesh Kumar Sahoo et al. did the performance analysis of non-uniform cantilever piezoelectric energy harvester. In this paper author studied about the effect of linear and quadratic varying width on non-uniform piezoelectric beam. Author modified electrochemical formulation of unimorph cantilever beam to the non-uniform beam width. After doing that author calculated the voltage, power and current with respect to natural frequency at different resistive load applied on the beam with varying tapering parameters. After analysis was done author concluded that the diverging beam can produce the power 3833% more than the uniform beam. Author also did the mathematical calculations for the design parameters. Author also designed the array type design for both non-uniform and uniform cantilever beams. And author concluded that array of two coupled beam gives the peak voltage 48% more than unimorph cantilever beam and natural frequency also increases with increase in coupling length. More numbers in one array give more peak voltage as compared to unimorph beams[9].

Sajal Sagar Singh et al. studied about effect of the mass on non-uniform microcantilever beam when it is used in various sensing applications. Author mentioned that there is conventional method of increasing the sensitivity of biosensor by reducing the size of the cantilever beam to nanoscale. In this paper, analysis of mass sensitivity was done on non-uniform cantilever beam with linear and quadratic variation in width. For the mathematical analysis Eular-Bernoulli beam equation was used. Author studied the mode shapes of different types of beam having tip mass for linear, undamped and free vibration case. All the boundary conditions were applied to the different cantilever beams and then analysis was done. Galerkin approximation method was used for non-linear analysis. Author concluded that sensitivity increases at the highr mode for non-uniform beam. Linear response analysis shows that sensitivity increases by varying planner geometry of beam. Having tip mass on the cantilever beam the peak amplitude increases exponentially[10].

Akarapu Ashok et al. made the design of arrow shaped microcantilever beam and further analyzed the result. Analysis was done on the basis of step length, width and free end width of beam as well. Microcantilever beam was fabricated from silicon dioxide material. Laser vibrometer was used by author for the vibrational analysis, natural frequencies were obtained by FEM software at different step length and width as well on the natural frequencies. Further analysis was done for different orientations of the arrow shaped cantilever beam and maximum deflection, quality factor and torsional end rotation were determined. Author concluded that the rectangular step microcantilever beam has higher frequency of transverse bending than conventional cantilever beam. Also, maximum deflection and torsional end rotation were higher for the same design which had proposed by the author[11].

Kim Insung et al. studied and designed a triple-morph cantilever beam. Author used AMN-PZT ceramic for the fabrication of energy harvester. The behavior of the cantilever was analyzed in dynamic conditions. The boundary conditions were applied to the beam before the analysis was done. The cantilever beam was analyzed under external force and tip mass was added to the cantilever beam. Author concluded that when mass, load resistance were increases the output voltage of bimorph cantilever improved while natural frequency decreased and triple-morph cantilever beam gives the better results in terms of output power[12].

Jian-fu LV et al. investigated about the behavior of stack structure of piezoelectric transducer embedded in asphalt pavement. The analysis was done on finite element analysis software. With the PZT disks of different thickness and diameter stack was made which were made to connect in parallel. Author analyzed the difference between pavement surfaces in the presence and absence of transducer. Then the cylinder cover was made by four materials and after analysis nylon was selected for the cover material. Author concluded that voltage of the transducer increases with increase in thickness and radius of cover and decreases with increase in radius of PZT disks[13].

Haocheng Xiong et al. had done experimental analysis of piezoelectric energy harvester. This paper contains the installation and on-site evaluation of the energy harvester embedded in public roadways. Author discussed that good amount of energy wasted due to the vehicles on the road. So this wasted energy can be converted into electrical energy by means of piezoelectric energy harvester. Author fabricated six prototype of energy harvester and then put them under the real roadways to evaluate the parameters and check whether it is feasible or not. Thus, the voltage output and power calculated which was generated by energy harvester. Author concluded that electricity generated by the device was feasible and gave relevant results and was depends upon the number of axles in the vehicle and frequency of vehicle passed over the surface. Author also suggested that the design modifications can be done for better results[14].

Hyeoung Woo Kim et al. also studied about the behavior of piezoelectric energy harvester, but in the condition of pre-stressed cyclic vibrations. Author discussed in the paper that among all the structures cymbal transducer is the best for energy harvesting under high value of force in cyclic conditions. The endcap material was taken steel while for piezoelectric layer ceramic was selected. In this paper diameter of piezoelectric layer was fixed while thickness varied. On setting all boundary conditions analysis was done experimentally as well as analytically. Thus, author concluded that small thickness piezoelectric layer cymbal transducer has more power output then other thicknesses. The result showed that the piezoelectric layer thickness directly affects the output charge. Author also suggested that this type of piezoelectric energy harvester can be used in automobile application[15].

Chapter 3

Problem Description

Great amount of power is wasted in an automobile during the operation. To convert that wastage of power into useful form power some of the mechanisms are invented. Among them piezoelectric transducers are used to convert the stress, strain into the electric charge. With the property of piezoelectric effect the voltage is generated according to the strain on the piezoelectric material.

So the main problem is to keep the voltage continuous throughout the operation of an engine. A single cantilever beam can not harvest much energy than a cascaded system. In a specific range of frequency there is only one peak voltage can be obtained which is not enough to supply to any electrical part in it. So we have to put capacitor in the electrical circuit for the storage of electric charge. In that case the generation of electric charge will remain same but, in the capacitor, charge will be stored slowly.

To overcome this sporadic generation of electric charge some design modifications must be done. New optimized design is proposed in this dissertation in which a cascaded system will be placed on the engine. The cascaded system includes multiple unimorph cantilever piezoelectric transducers arranged in parallel arrangement. Further, the analysis for voltage output and power will be done. The model will be designed in Solidworks 2016 and the analysis will be done in Ansys 18.0.

Chapter 4

Mathematical Derivation

There are some of the methods by which power generation can be calculated by piezoelectric transducers. The methods are Pin-Force method, Enhanced-Pin force method and Euler-Bernoulli's method.

For the calculation of cantilevers Euler-Bernoulli's method is chosen. So the beam equations for modeling the unimorph cantilever beam is[16].

$$\rho A \frac{\partial^4 y}{\partial t^4} + EI \frac{\partial^4 y}{\partial x^4} = F(t) = F_o \sin \omega t \tag{1}$$

Where

ρ = Density of material,

y = Transverse Displacement,

A = Cross Sectional Area,

F(t) = Applied Force.

The general solution for the n mode shape of the above equation is [16]:

$$y = \sum_{i=1}^{n} q_i (t) X_i(x) \tag{2}$$

Where

qi = i^th^ modal coordinate equation for the beam

Xi = i^th^ mode shape for the beam .

Now equation for mode shape can be written as[16]:

$$X_i(x) = \cosh(\beta_i x) - cos(\beta_i x) - \frac{\sinh(\beta_i L) - sin(\beta_i L)}{\cosh(\beta_i L) + cos(\beta_i L)} \sinh(\beta_i x) - sin(\beta_i x) \tag{3}$$

Where L is Beam Length.

$$\beta_i^4 = \frac{\omega_{ni}^2}{c^2} \tag{4}$$

Where

$$c = \sqrt{\frac{EI}{\rho A}} \tag{5}$$

and

ω_{ni} can be found from the characteristic equation:

$$cos(\beta_i L) \cosh(\beta_i L) = -1 \tag{6}$$

By selecting the external impendence equal to internal impedance we can obtain maximum power for each mode. Here we have calculated the power for only first mode[16]:

$$P = \sum_{i=0}^{n} \frac{V^2(t_i) R_L}{(R_L + R_s)^2 \times n} \tag{7}$$

Where:

Vs=Source voltage

n=number of time steps.
R_s=Resistance value for the source
R_L=Resistance value for the load

Piezo-electric material produces charge and voltage on the basis of strain produced in the material. The Coupled equation can be written as:

$$\varepsilon_1 = s_{11}^E \sigma_1 + d_{13} E_3 \tag{8}$$

$$D_3 = d_{31} \sigma_1 + e_{33}^T E_3 \tag{9}$$

Where,
ε is Strain,
σ is stress,
E is electric field,
D is electric density,
S is elastic compliance,
d is piezoelectric strain coefficient and
e is electric permittivity[16].

Thus, by using above equations the generated power can be calculated.

Chapter 5

Model Description

5.1. Introduction

In this chapter we will get to know about actual design of the transducer, finite element modelling of the model and material for the piezoelectric transducer.

As we know the significance of the piezoelectric material in energy harvesting devices. So it is one of the hot topic of research these days. For conserving our energy resources, we have to convert the waste energy into some useful energy and use it instead of to use energy resources for that. For this purpose many types of mechanisms are made to harvest the energy among which piezoelectric transducer which works on ambient vibration is being used in this dissertation. For this purpose cantilever beams will be designed to work in the ambient vibration surroundings.

The cantilever beam can be in different shapes and size but in this work, we are using trapezoidal shape piezoelectric cantilever beam. The flow chart for the whole process is shown below:

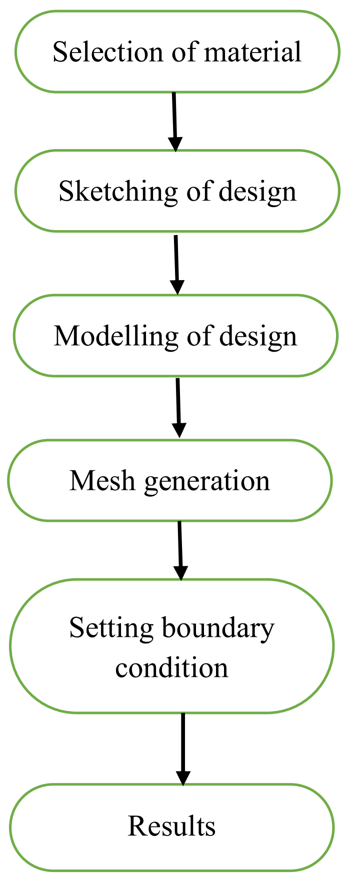


Fig. 3. Flow chart of whole process

5.2. Model specification

Trapezoidal shape of the unimorph cantilever piezoelectric transducer is used for the modelling. Sketching will be done in Ansys 18.0 having following measurements shown in table1:

Table I. Dimensions of the trapezoidal cantilever beam

Parameters	value
Length of Proof Mass (L_p)	4 mm
Thickness of Proof Mass (t_p)	0.2 mm
Width of Proof Mass (B_p)	4 mm
Length of substrate(L)	28 mm
Thickness of Substrate(t)	0.2 mm
Width of Substrate(a & b)	2 mm & 6 mm

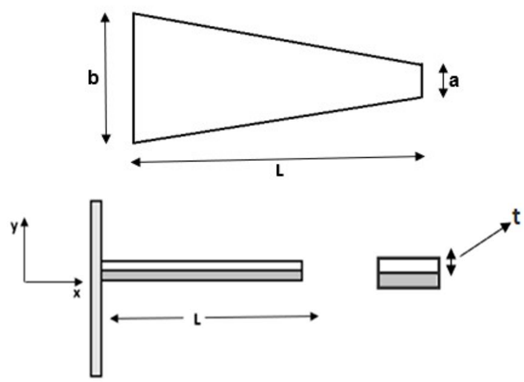


Fig. 4. Trapezoidal cantilever sketch

Proof mass is often called tip mass. In this work each tip mass is having 3.2mm^3 volume and there are 5 proof masses are place at the free end of cantilever beam.

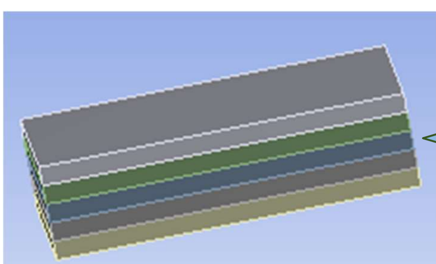


Fig. 6. Proof mass

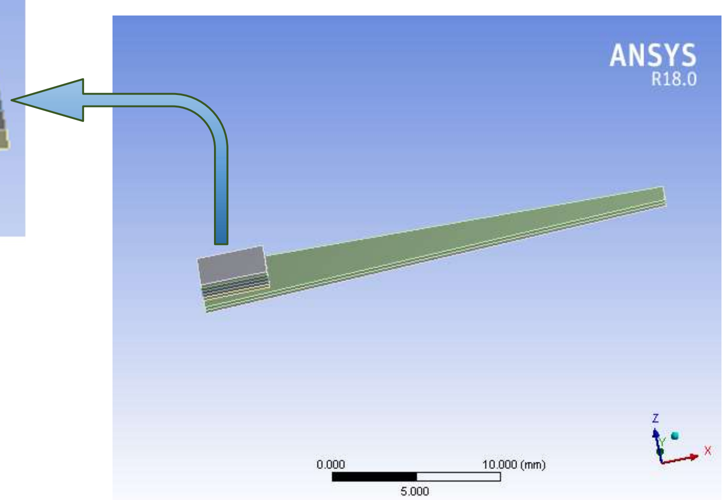


Fig. 6. Piezoelectric cantilever uni-mporph transducer

The beam will be analyzed with 1,2,3,4,5 proof masses and without proof mass individually. And then will be analyzed by applying boundary conditions on it.

5.3. Material specification

Material selection an important criterion for these types of applications. Since the ductility of piezoelectric material is less, so it is always used with a material which is called **Substrate**. So brass is taken as a material for the substrate. And since lead-based piezoelectric material is banned so lead-free ceramic (barium-based ceramic) will be used for the piezoelectric material. The properties of the material are listed below:

Table II. Material Properties

Property	Young's Modulus in Gpa	Density in kg/m^3	Poisson ratio
Ceramic Material	88	5600	.30
Brass	110	8600	.35

5.4. Meshing of model

Meshing is essential thing to do while doing finite element analysis. This includes dividing the model into small elements by which the stress can be measured in each point on the model. Fig. 7 shows the meshed model of cantilever beam in which the element size is 0.5 mm taken. So the meshed model contains 8079 nodes and 1004 quadrilateral elements (4-noded).

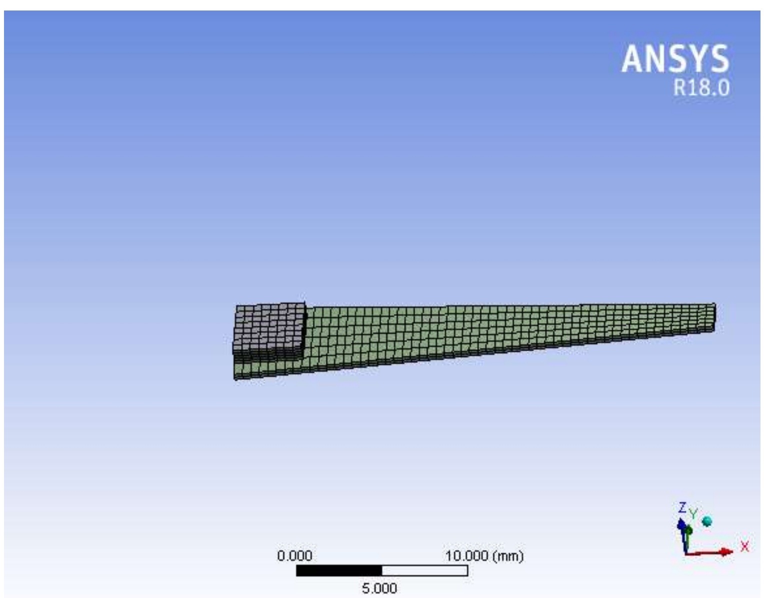


Fig. 7. Meshed Model of cantilever

5.5. Boundary conditions

The boundary condition is applied on the smaller side face of the cantilever beam. The side face is fixed and at the free end 5 proof masses are placed. Fig. 8 shows the fixed end of the cantilever beam.

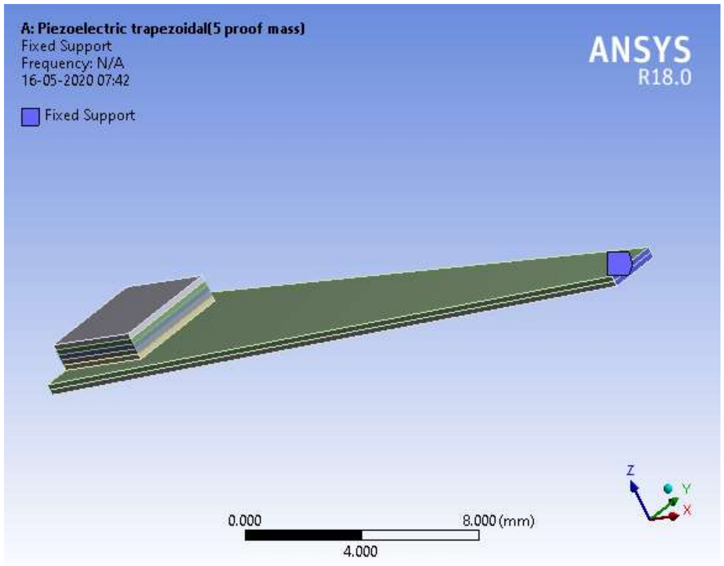


Fig. 8. Boundary conditions (Fixed support)

Chapter 6

Result and Discussion

Since the piezoelectric cantilever works in ambient vibrations so vibration analysis will be done to get the results. For the vibrational analysis of the piezoelectric unimorph cantilever beam modal analysis is done in Ansys 18.0 considering various parameters. By doing the simulation following results are obtained:

6.1. Variation of 1st mode resonance frequency w.r.t. proof mass

Table III. Normal elastic strain and 1st mode natural frequency w.r.t. proof mass

No. of proof mass	Natural Frequency (1st mode) in Hz	Max. Normal elastic strain in m/m
1	200.45	95.02
2	185	86.98
3	172.62	80.65
4	162.42	75.51
5	153.83	71.23

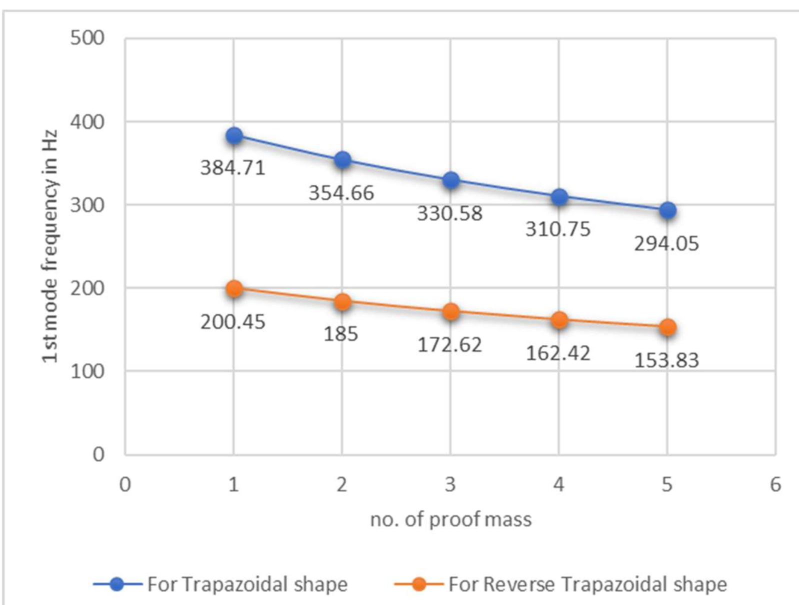


Fig. 9. Graph of 1st mode natural frequency w.r.t. proof mass

6.2. 1st mode natural frequency w.r.t. thickness

Table IV. Normal elastic strain and 1st mode natural frequency w.r.t. thickness of substrate

S. No.	Thickness of Shim in mm	Max. Normal elastic strain in m/m	Natural Frequency (1st mode) in Hz
1	0.2	71.23	153.83
2	0.4	98.60	249.05
3	0.6	119.19	347.73
4	0.8	139.35	448.66
5	1.0	157.39	550.83

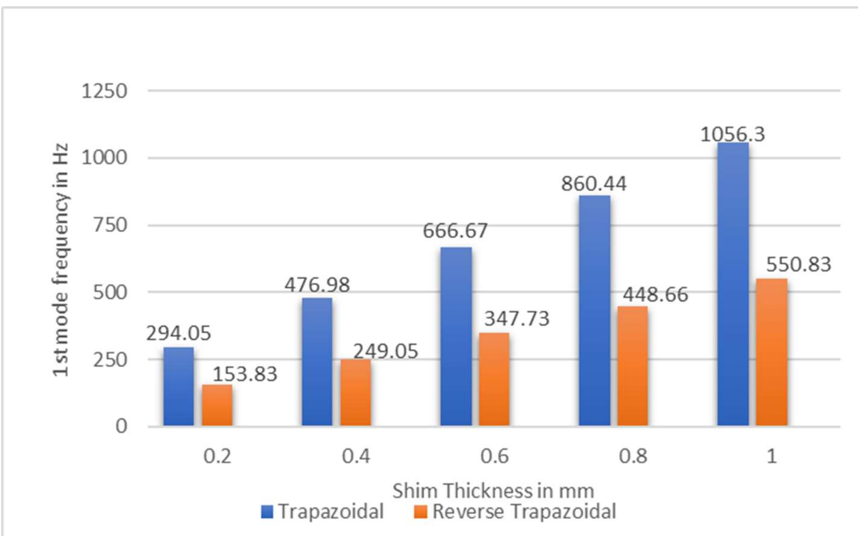


Fig. 10. Graph of 1st mode natural frequency w.r.t. thickness of substrate

6.3. 1st mode natural frequency w.r.t ratio of sides of cantilever

Table V. Normal elastic strain and 1st mode natural frequency w.r.t. side ratios

S. No.	Side ratio of cantilever	Max. Normal elastic strain in m/m	Natural Frequency (1st mode) in Hz
1	0	428.47	45.16
2	0.2	87.41	131.98
3	0.4	66.89	163
4	0.6	60.24	186.26
5	0.8	57.40	205.33
6	1.0	55.65	220.26

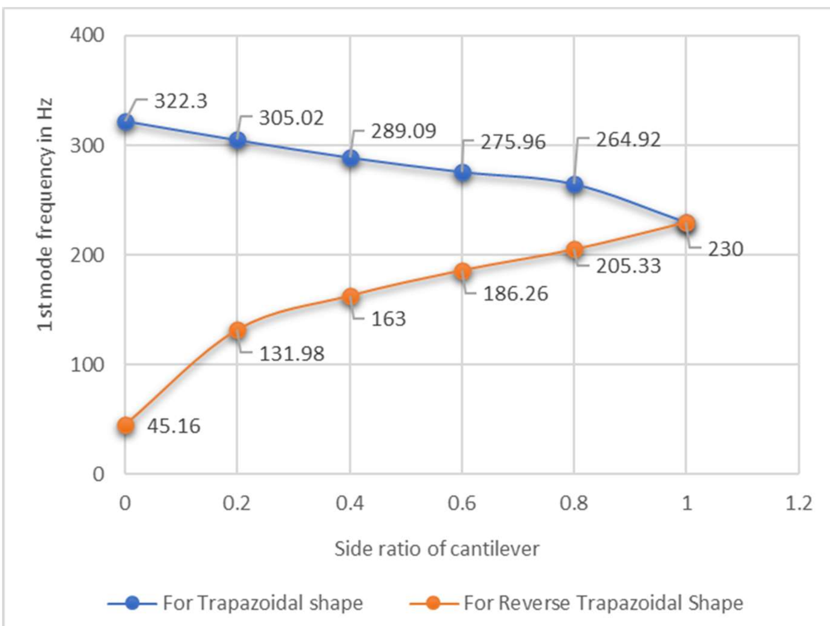


Fig. 11. Graph of 1st mode natural frequency w.r.t. side ratio of cantilever

As mentioned in topic 6.1, 6.2 & 6.3 there are the variations in natural frequency with respect to the various parameters taken. The comparison is done between trapezoidal and reverse trapezoidal (i.e. fixed at large side face and at smaller side face respectively) for all the parameters. And it is obtained that we get the better result when the smaller side face is fixed, and large side is free with having 5 number of proof masses on the tip. Now the voltage will be calculated by using the mathematical equations mentioned in chapter 4. So the result for voltage and power generated by piezoelectric unimorph cantilever beam are shown in fig. 12 & 13:

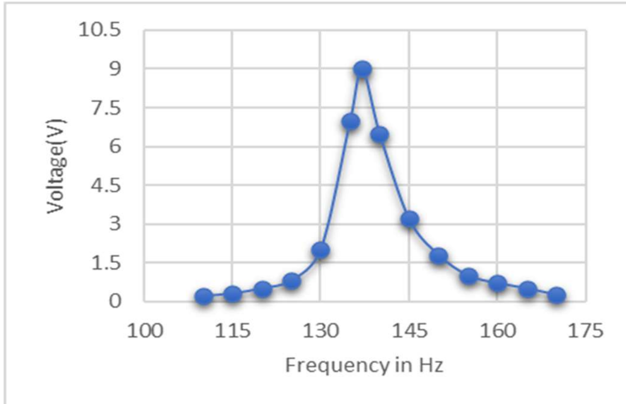


Fig. 12. Graph of voltage generated by piezoelectric cantilever

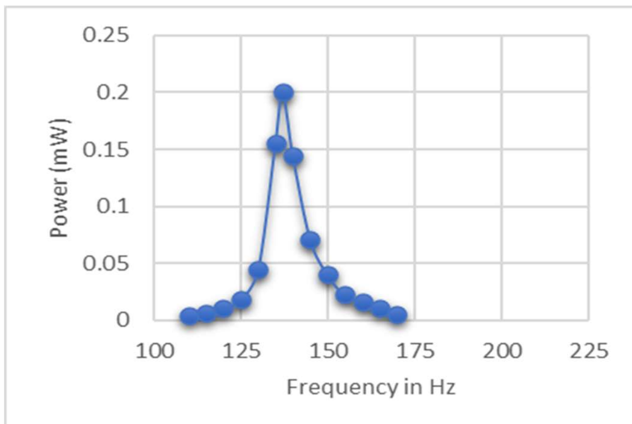


Fig. 13. Graph of power generated by piezoelectric cantilever

By the above graphs it is clear that at 137 Hz frequency the amplitude is maximum which means at that particular frequency the piezoelectric unimorph cantilever beam will give maximum output i.e. voltage and power.

6.4. Mode shapes of the cantilever beam

Following are the graphics of the mode shapes of the piezoelectric unimorph cantilever beam:

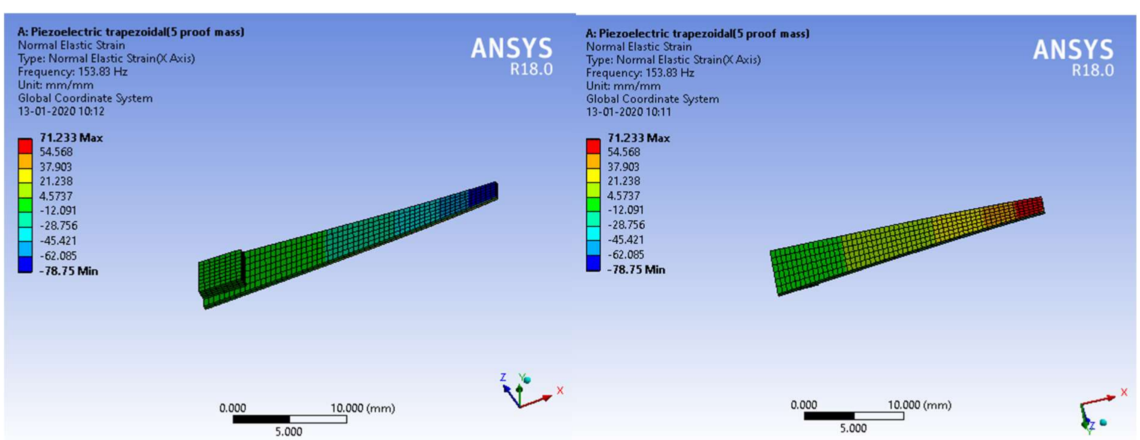


Fig. 14. First mode natural frequency of cantilever

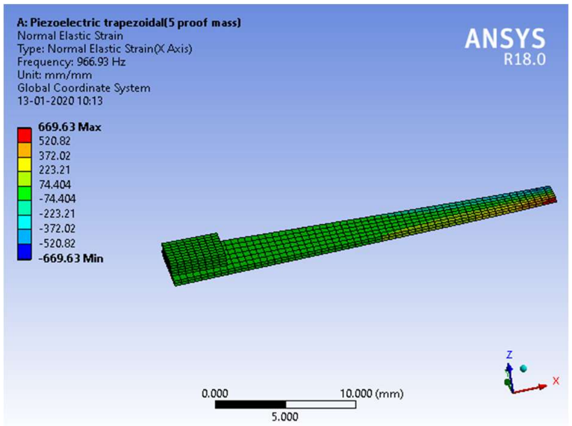


Fig. 15. Second mode natural frequency of cantilever

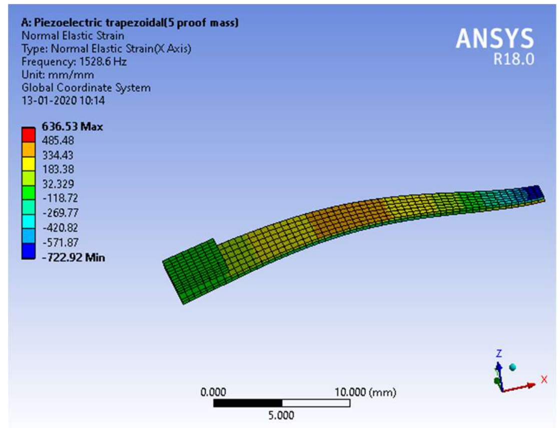


Fig. 16. Third mode natural frequency of cantilever

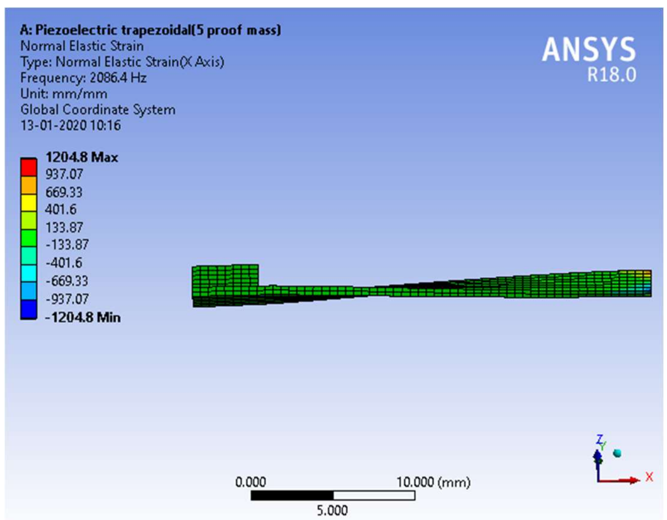


Fig. 17. Fourth mode natural frequency of cantilever

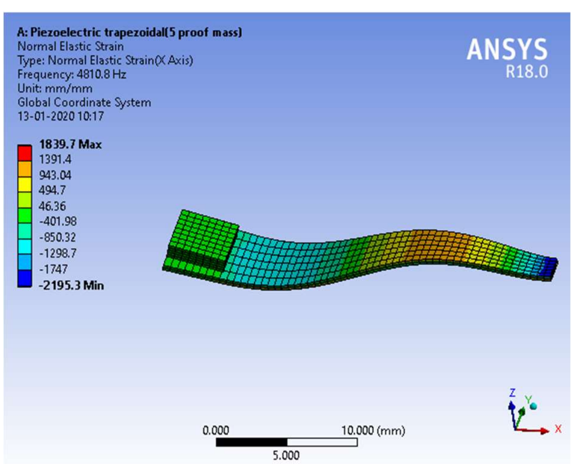


Fig. 18. Fifth mode natural frequency of cantilever

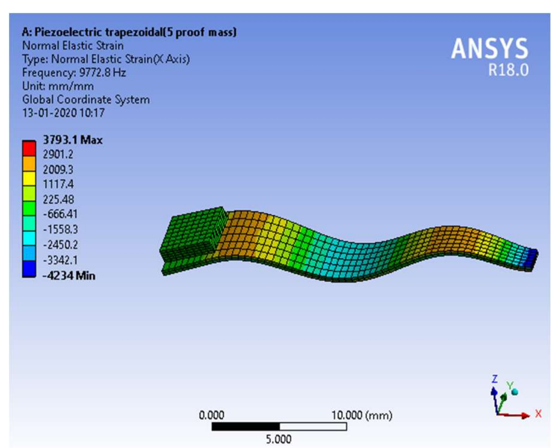


Fig. 19. Sixth mode natural frequency of cantilever

6.5. Conclusion

1. Single unimorph piezoelectric cantilever beam give better output in reverse trapezoidal orientation in which smaller side face is fixed and the other end is set free with some tip mass on it.
2. This design can be used where ambient vibrations are present in the surroundings.
3. Thickness of the substrate is also playing major role in the output power, as we increase the thickness normal strain will also increase.
4. Natural frequency is also having effect in power generation as it decreases strain increases also.

Chapter 7

New Model description

7.1. Introduction

For improving the voltage output from the piezoelectric materials, new design is proposed in which 3 piezoelectric unimorph cantilever beams are arranged in parallel and bonded to a cuboid. By chapter 6 we get the results which showed that the trapezoid shaped (fixed at smaller end) piezoelectric unimorph cantilever beam is optimum for the best results. So this type of beam will be used in new design.

The new design is called cascaded system of piezoelectric cantilever beams. This design consists of two main components: a cuboid and piezoelectric unimorph cantilever beam. In this design three cantilever beams are bonded parallelly to a face of the cuboid through smaller end face as shown in fig. 20. The dimension for the components is discussed below in the topics.

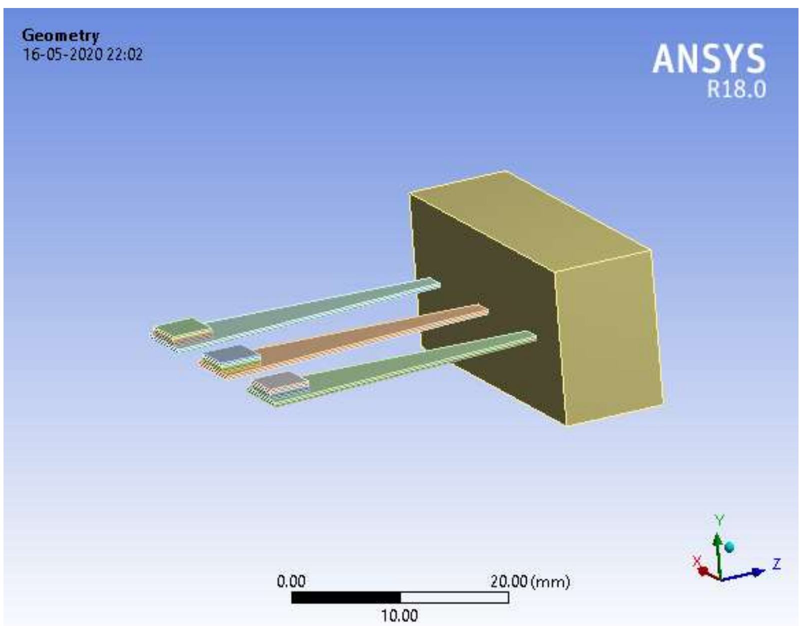


Fig. 20. Proposed design of energy harvester

7.2. Specification

The modelling is done on Solidworks 2016. For the dimension of the piezoelectric cantilever beam refer to table I and the dimension of the cuboid is 30mm× 15mm× 1mm (length× width× thickness). The cantilever beams are placed at the centerline of the face of the cuboid 10mm from each other (fig. 20).

7.3. Material Specification

Since lead-based piezoelectric material is not good for the human health as well as environment so lead-free piezoelectric material is used for the cantilever beam. For substate an proof mass brass material is used. The specifications of the material are listed in table II.

7.4. Meshing of the Model

Fig. 21 shows the meshed model of cantilever beam in which the element size is 0.5 mm taken. So the meshed model contains 10335 nodes and 1410 quadrilateral elements (4-noded).

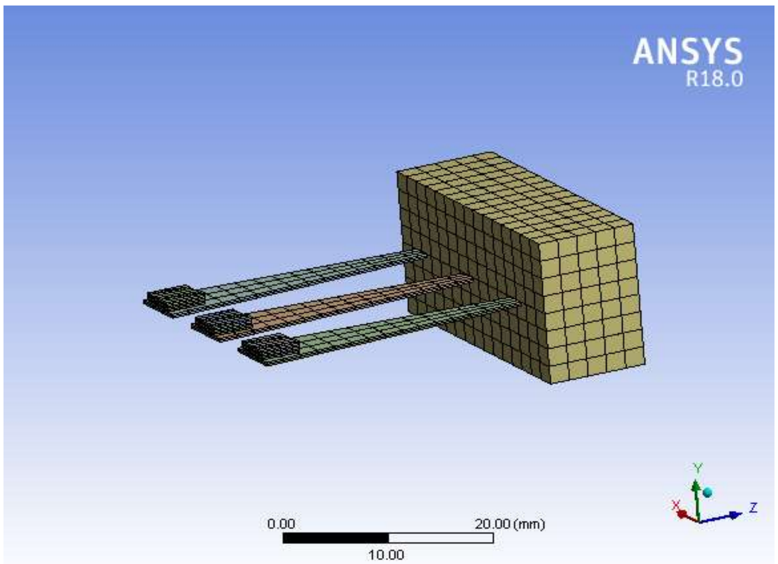


Fig. 21. Meshed model of new design

7.5. Boundary Conditions

The face opposite to the face of connection with cantilever beams is fixed and the free end of cantilever beam is loaded with 5 proof masses of 3.2 mm^3 volume.

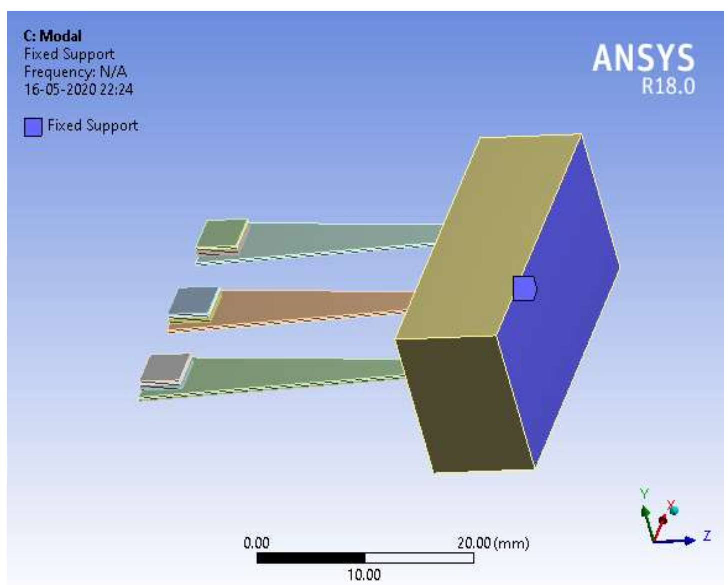


Fig. 22. Fixed face on the cuboid (boundary condition)

Chapter 8

Results and Discussion

8.1. Modes of frequencies

18 modes of natural frequencies are obtained in the result of the simulation in Ansys 18.0 (see table VI):

Table VI. Modes of Frequency

Mode	Natural Frequency in Hz
1	153.39
2	153.39
3	153.39
4	952.16
5	952.28
6	952.32
7	1524.5
8	1524.5
9	1524.5
10	2089.1
11	2089.1
12	2089.1
13	4799.4
14	4799.4
15	4799.4
16	9764.5
17	9764.6
18	9764.7

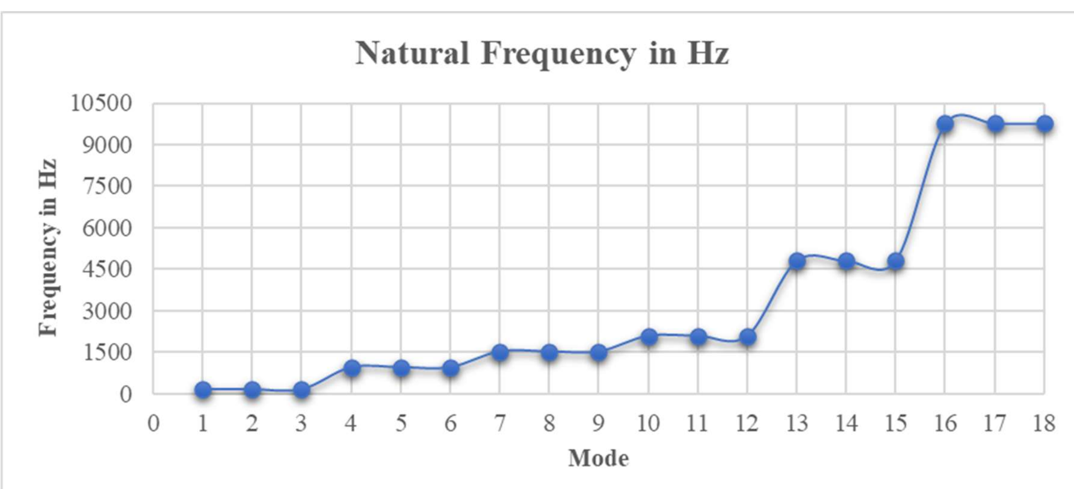


Fig. 23. Graph of natural frequency at 18 different modes

8.2. Strain on the cascaded system

The values of strain generated on the cantilever beam are listed in table VII below:

Table VII. Strain w.r.t. 18 modes of natural frequency

Mode	Strain in mm/mm
1	2.37
2	2.29
3	2.27
4	19.37
5	18.36
6	18.34
7	19.66
8	18.76
9	18.52
10	30.72
11	30.32
12	30.32
13	54.27
14	55.32
15	55.73
16	99.87
17	105.14
18	107.17

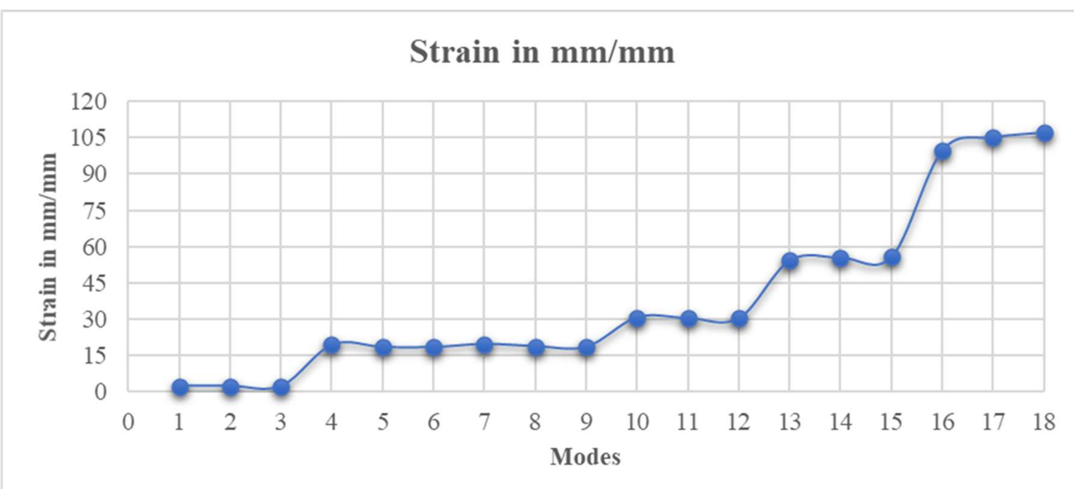


Fig. 24. Graph of strain at different natural frequencies

8.3. Voltage and Power

Voltage generated by the cantilever beam over the range of frequency is shown in the graph (see fig. 25, 26). In the range of frequency voltage is normalized and cascaded system gives the maximum voltage over the frequency (fig. 27).

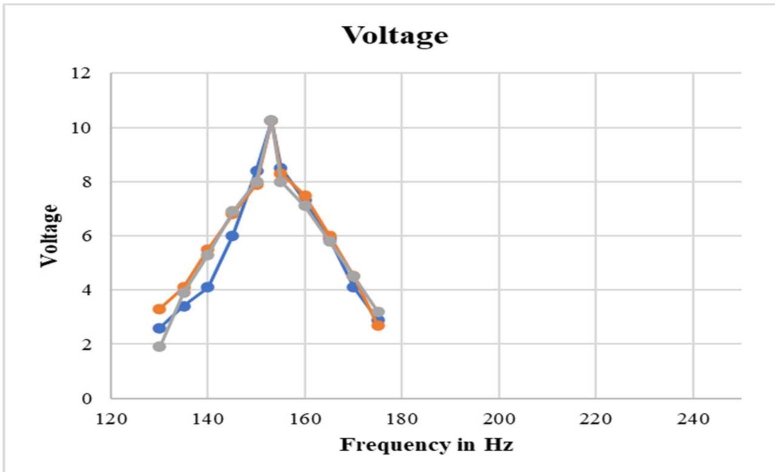


Fig. 25. Graph of voltage between 1st mode frequency range

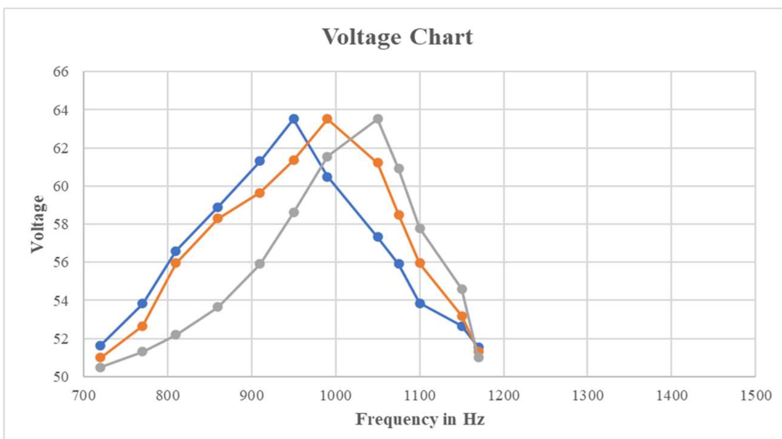


Fig. 26. Graph of voltage between 2nd mode frequency range

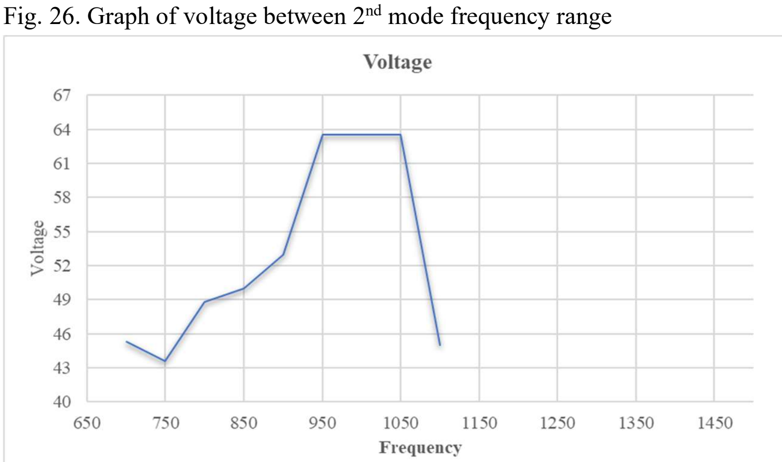


Fig. 27. Graph of normalized voltage between 2nd mode frequency range

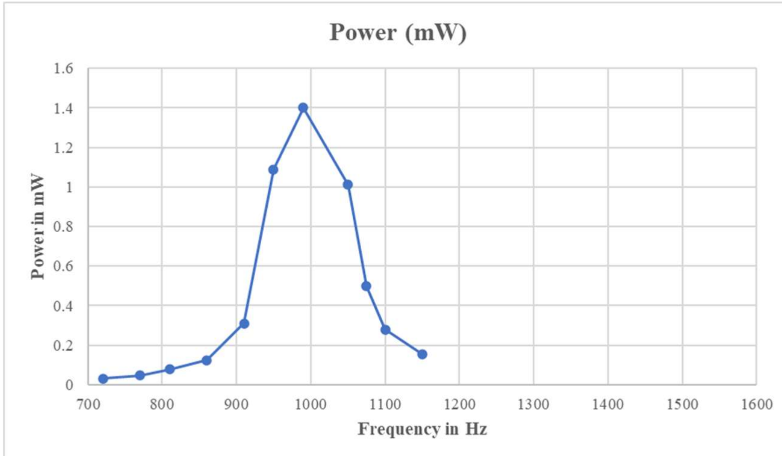
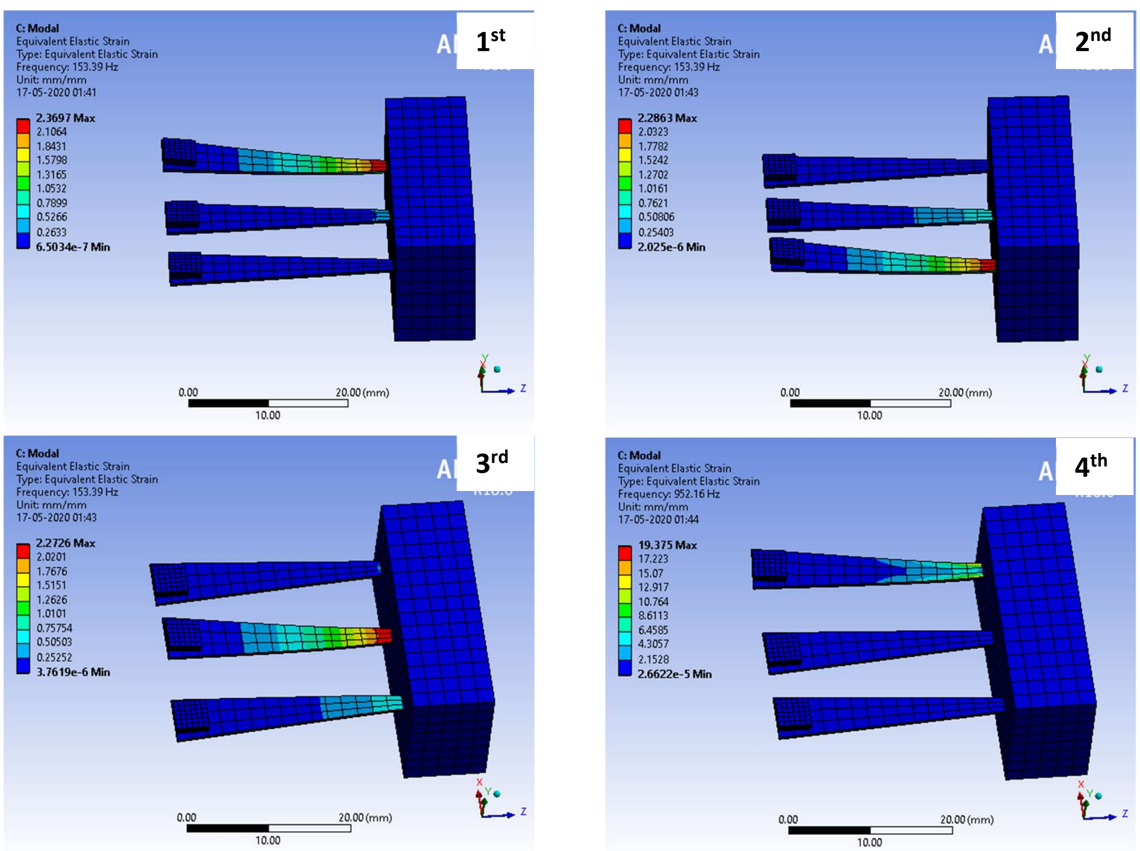


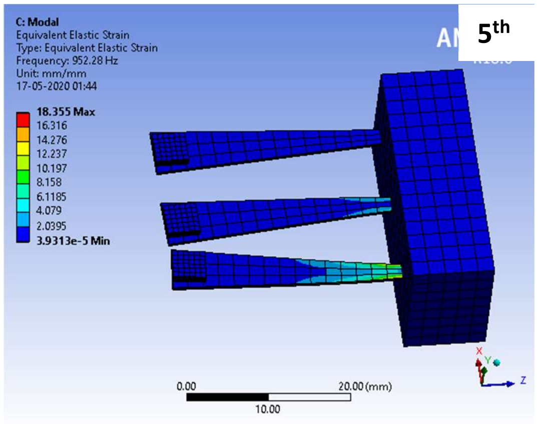
Fig. 28. Power generated by piezoelectric cantilever beam

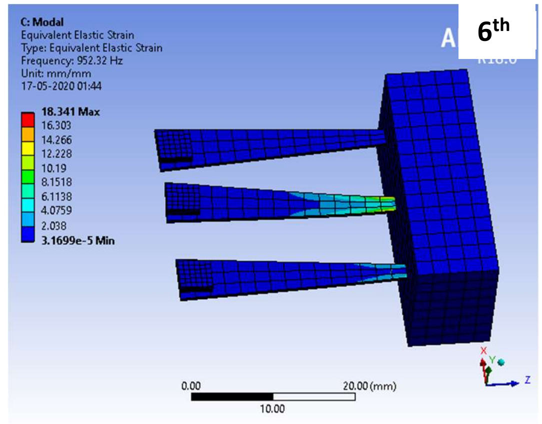
Thus by the graphs mentioned above it is clear that if we use cascaded system of piezoelectric energy harvester the voltage and power generation can be improved to the great extent. The voltage and power can be calculated by the mathematical equations mentioned in chapter 4.

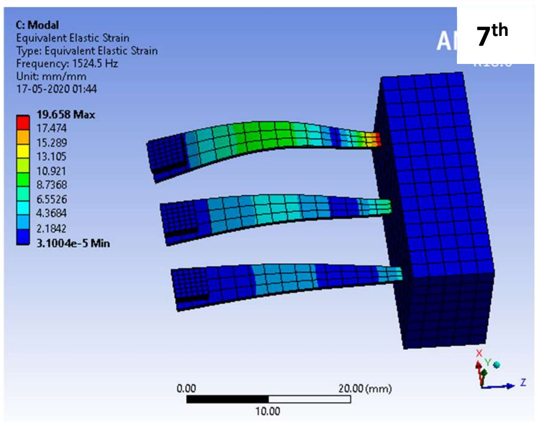
8.4. Mode shapes of the design

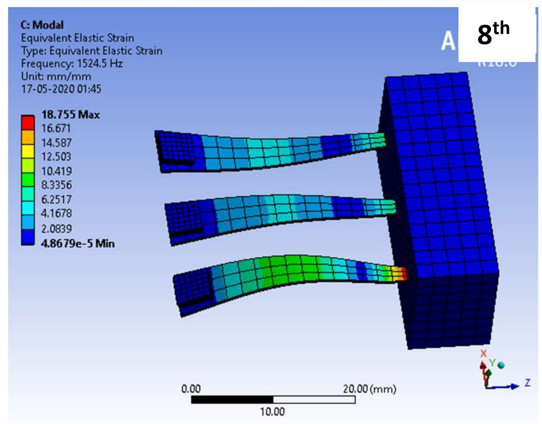
Following are the 18 mode shapes of the cascaded system:

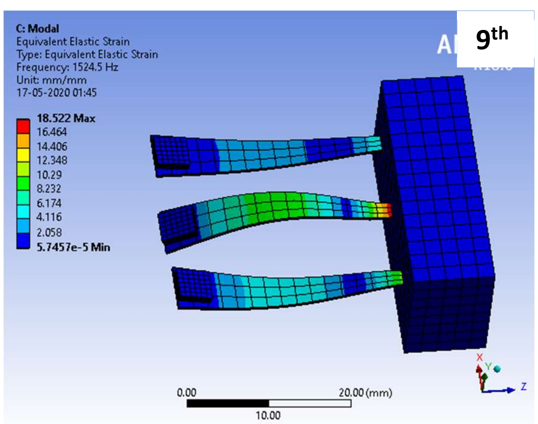


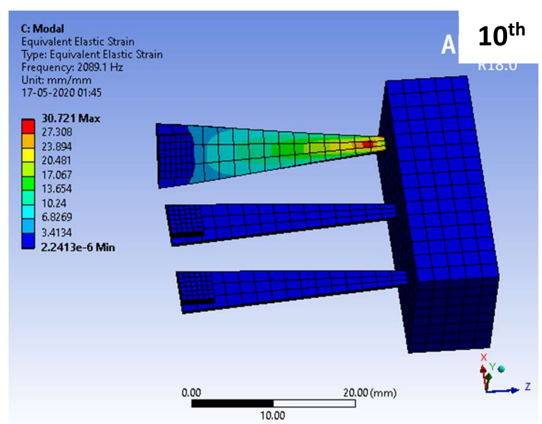

5th
C: Modal
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Frequency: 952.28 Hz
Unit: mm/mm
17-05-2020 01:44
18.355 Max
16.316
14.276
12.237
10.197
8.158
6.1185
4.079
2.0395
3.9313e-5 Min
0.00
20.00 (mm)
10.00

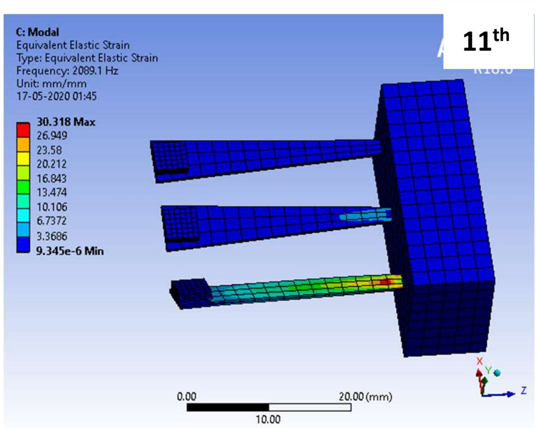

6th
C: Modal
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Frequency: 952.32 Hz
Unit: mm/mm
17-05-2020 01:44
18.341 Max
16.303
14.266
12.228
10.19
8.1518
6.1138
4.0759
2.038
3.1699e-5 Min
0.00
20.00 (mm)
10.00

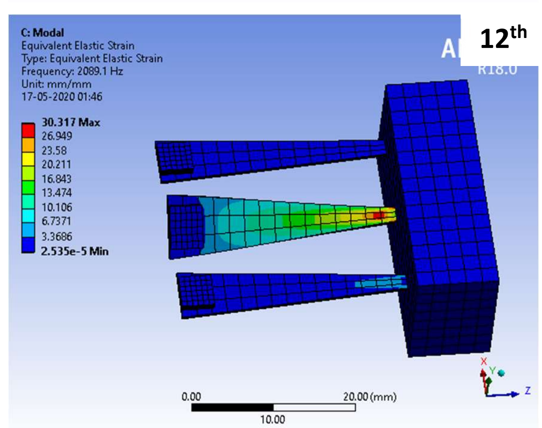

7th
C: Modal
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Frequency: 1524.5 Hz
Unit: mm/mm
17-05-2020 01:44
19.658 Max
17.474
15.289
13.105
10.921
8.7368
6.5526
4.3684
2.1842
3.1004e-5 Min
0.00
20.00 (mm)
10.00


8th
C: Modal
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Frequency: 1524.5 Hz
Unit: mm/mm
17-05-2020 01:45
18.755 Max
16.671
14.587
12.503
10.419
8.3356
6.2517
4.1678
2.0839
4.8679e-5 Min
0.00
20.00 (mm)
10.00


9th
C: Modal
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Frequency: 1524.5 Hz
Unit: mm/mm
17-05-2020 01:45
18.522 Max
16.464
14.406
12.348
10.29
8.232
6.174
4.116
2.058
5.7457e-5 Min
0.00
20.00 (mm)
10.00


10th
C: Modal
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Frequency: 2089.1 Hz
Unit: mm/mm
17-05-2020 01:45
30.721 Max
27.308
23.894
20.481
17.067
13.654
10.24
6.8269
3.4134
2.2413e-6 Min
0.00
20.00 (mm)
10.00


11th
C: Modal
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Frequency: 2089.1 Hz
Unit: mm/mm
17-05-2020 01:45
30.318 Max
26.949
23.58
20.212
16.843
13.474
10.106
6.7372
3.3686
9.345e-6 Min
0.00
20.00 (mm)
10.00


12th
C: Modal
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Frequency: 2089.1 Hz
Unit: mm/mm
17-05-2020 01:46
30.317 Max
26.949
23.58
20.211
16.843
13.474
10.106
6.7371
3.3686
2.535e-5 Min
0.00
20.00 (mm)
10.00

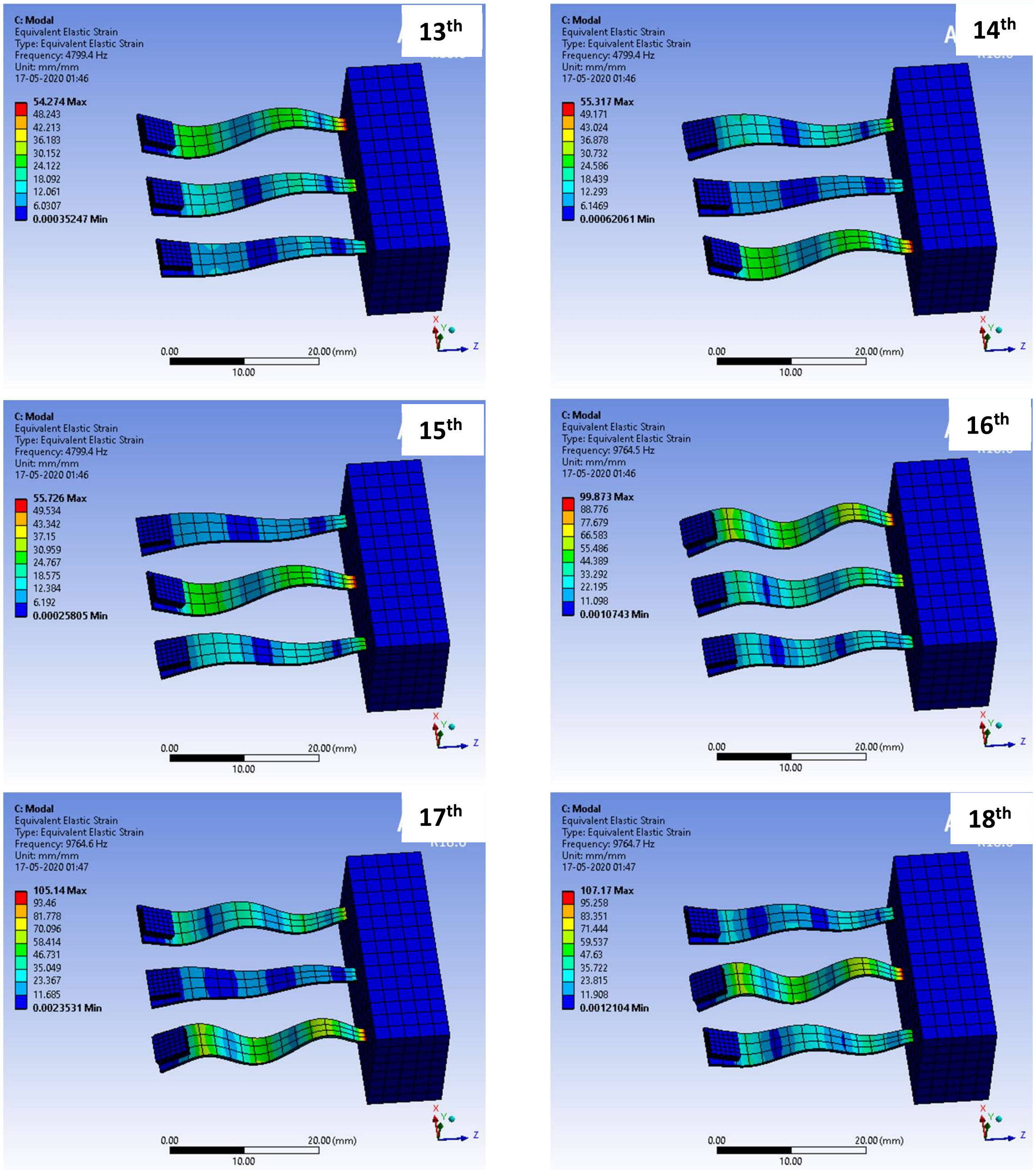


Fig. 29. 18 mode shapes of the cascaded system

Chapter 9

Conclusion and Future Scope

9.1. Conclusion

In this dissertation research work is done in the area of piezoelectric material. The whole work is focused on following three points:

1. To use the lead-free piezoelectric material in the design.
2. To improve the efficiency of the system.
3. To harvest maximum possible energy from ambient vibrations.

As we discussed about different research works in chapter 2 and gained some knowledge about piezoelectric material so that in chapter 5 & 6 we could able to do the designing and simulation of the piezoelectric unimorph cantilever beam in Solidworks and Ansys 18.0 respectively. By having results from that we concluded that the trapezoid shaped piezoelectric unimorph cantilever beam with having proof mass at the free end gives best results among all other arrangements when smaller side face is fixed.

By having the information from chapter 6, new design was proposed in chapter 7 which was the cascaded system having three cantilever beams arranged in parallel configuration. So, after applying the boundary conditions on cascaded design simulation was done in Ansys 18.0. And the simulation showed that in a frequency range the voltage is continuous, and the power is maximum at that instant. Thus this design gives optimum solution for the problem discussed in chapter 3.

9.2. Future Scope

Since the innovations being invented day by day in the field of piezoelectric materials. Thus it is one of the trending topics of research these days. So, some of the following work can be done to carry forward this research:

1. Design optimization can be done in cascaded system of piezoelectric cantilever beam.
2. In the place of unimorph piezoelectric cantilever beam bimorph can also be used for better results.
3. More number of piezoelectric cantilever beam can also enhance the result. So it can be used.
4. In the place of cuboid multilayer structure of piezoelectric transducer can also be tested for better results.
5. Various designs of the beam can also be tested so that the best design can be obtained for the best efficiency.

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Publication Details

1. **Paper Title:** Enhanced Vibration Energy Harvesting from Lead Free Ceramic $0.5Ba(Zr_{0.2}Ti_{0.8})O_3$-$0.5(Ba_{0.7}Ca_{0.3})TiO_3$.

   Publication: Materials Today: Proceedings Journal.

   Status: Accepted and published (2020).

2. **Paper Title:** Design and Simulation of PZT based energy harvester embedded in Asphalt Pavement.

   Publication: IEEE Journal.

   Status: Accepted and yet to publish (2020).

3. **Paper Title:** Design and Simulation of bimorph piezoelectric cymbal transducer.

   Publication: IEEE Journal (GUCON-2020).

   Status: Submitted and waiting for confirmation.

4. **Paper Title:** Finite Element Analysis of Lead-Free Ceramic based Cymbal Transducer for Energy Harvesting.

   Publication: Integrated Ferroelectrics (Taylor & Francis).

   Status: Submitted and waiting for confirmation.