International Research Journal in Global Engineering and Sciences. (IRJGES)
ISSN : 2456-172X | Vol. 2, No. 2, June-August, 2017 | Pages 52-63

DESIGN AND SHAPE OPTIMISATION OF PIEZOELECTRIC SYSTEM FOR WIND ENERGY HARVESTING

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ABSTRACT: The work carried out in this paper is to generate power for low powered electronic devices; especially when being placed in a remote area, micro scale energy harvesting is preferable. One of the popular methods is via vibration energy scavenging which converts mechanical energy (from vibration) to electrical energy by the effect of coupling between mechanical variables and electric or magnetic fields. As the voltage generated greatly depends on the geometry and size of the piezoelectric material, there is a need to define an optimum shape and configuration of the piezoelectric energy scavenger. In this work, mathematical derivations for uni-morph piezoelectric energy harvester are presented. Mathematical calculations and software analysis using COMSOL are done to study the effect of varying the length and shape of the beam to the generated voltage. Theoretical and analytical results comparing triangular and rectangular shaped piezoelectric beam are also presented.

1. Introduction

In recent years the emergence of many developments in the field of so-called smart structures is been seen; that is, structures incorporating sensors and actuators coupled with a calculator and are able to control dynamic systems subject to external excitations. Among the many types of materials that can be found in nature, piezoelectric materials have a good ability of electromechanical conversion and small sizes, which simplify their use in widely dynamic structure applications[2]. Recently, the piezoelectric material is used to harvest energy from excited structures. Energy harvesting or energy scavenging is the process by which energy is captured and stored. A variety of different sources exist for harvesting energy, such as solar power, thermal energy, wind, and kinetic energy. Also in modern society, the influence of materials is still present. Piezoelectric effect is defined as the ability of a material to convert mechanical energy into electrical energy and vice versa. Piezoelectric effect is broadly classified into two types, The ***direct*** piezoelectric effect is that these materials, when subjected to mechanical stress, generate an electric charge proportional to that stress. The ***inverse*** piezoelectric effect is that these materials become strained when an electric field is applied, the strain again being proportional to the applied field. In this work the piezoelectric material used for the generation of power is Lead zirconate Titanate for the following reasons good flexibility , high impact resistance , high thermal resistance and its chemical resistance. [3] Daisuke Koyama et al.in this work the piezoelectric material used was polyurea thin film formed through vapor deposition polymerization with 4,40-diphenylmethane di-isocyanete(MDI) and 4,40-diamino diphenyl ether (ODA). The conversion efficiency from mechanical to electrical energy was calculated using finite elemental analysis (FEA) of the cantilever configuration. Higher conversion efficiency was obtained using a thinner and shorter cantilever configuration with increased resonance frequency of the device. Experiments were conducted using an electric power generation device with a 3 μm thick polyurea thin film attached to a 0.1-mm-thick, 18-mm-long beryllium copper cantilever.[4] Wei-Tsai Chang et al.This investigation examines a means of integrating high-performance ZnO piezoelectric thin films with a flexible stainless steel substrate (SUS304) to fabricate a double-sided piezoelectric transducer for vibration-energy harvesting applications.[7,11] Brijesh Kumar et al., A. Kathalingam et al. In this work the importance of energy harvesting using ZnO nanostructures and ZnO nano wires , mainly focusing on ZnO nanostructure-based photovoltaics, piezoelectric nanogenerators, and the hybrid approach to energy harvesting.[10] M. Amin Karami et al. This work presents a novel piezoelectric transducer where the rotation of the blades results in large oscillations of piezoelectric beams. The piezoelectric bimorphs are made bi-stable by incorporation of repelling magnetic force. The Magnetic force is due to interaction of permanent magnets at the tip of the beams with permanent magnets rotating with the blades. Since the magnetic force changes with blade rotation, the dynamics of the beams changes in time and the system is thus parametrically excited.[12] Xue-Feng He et al. An impact-based wind energy harvesting system composed of a thin metal sheet, a MEMS piezoelectric energy harvesting element, a rigid stop, a fixture and a bluff body was designed. When wind speed increased to the critical speed, the cantilever composed of the MEMS harvesting element and the metal sheet vibrated and impacted with the rigid stop repeatedly. The impact impulses caused the MEMS harvesting element to vibrate, and the piezoelectric layer of the harvesting element converted the vibration energy into electrical energy.

1.4 Selection of material

The piezoelectric material selected for the harvesting of energy from the cantilever beam are based on the following things

- Density
- Young’s modulus
- Moisture resistant
- High temperature withstand
- Availability
- Economic

1.4.1 Lead zirconate Titanate

Lead Zicronate Titanate (PZT) is preferable due to its abundant vibration accessibility and high piezoelectric constants[14].Lead(II) titanate is an inorganic compound the chemical formula $PbTiO_3$. It is the lead salt of titanic acid and has a high ratio of k_{33} to k_p with a high k_t. Lead(II) titanate is a yellow powder that is insoluble in water.

At high temperatures, lead titanate adopts a cubic perovskite structure. At 760 K,the material undergoes a second order phase transition to a tetragonal perovskite structure which exhibits ferroelectricity. Lead titanate is one of the end members of the lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$ $0 \le x \le 1$, PZT) system, which is technologically one of the most important ferroelectric and piezoelectric ceramics.

Lead titanate occurs in nature as mineral macedonite.

2. Design of piezoelectric system

Under the consideration and with respect to various books and journals reference the mathematical calculation is been performed.

The natural frequencies of the beam at k-th mode, ωk can be determined as [14]

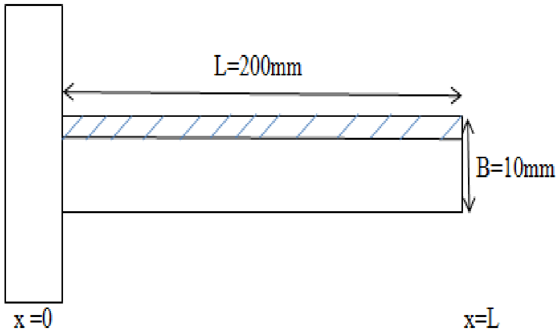


Fig 1 Rectangular beam

$$\omega_K = \lambda^2 \sqrt{\frac{EI}{mL^4}} \quad (1)$$

Where,

m=B $(\rho_b h_b + \rho_p h_p)$

EI=B $[E_b \left(\frac{h_b^3}{12}\right) + \frac{E_p}{3}\left(\left(\frac{h_b}{2} + h_p\right)^3 - \frac{h_b^3}{8}\right)$

Here, B is the width, ρ is the density and h represents the thickness. Also, the subscript b refers to the substructure (beam) while p denotes the piezoelectric layer.

2.2 Estimation of frequency for a non-rectangular beam

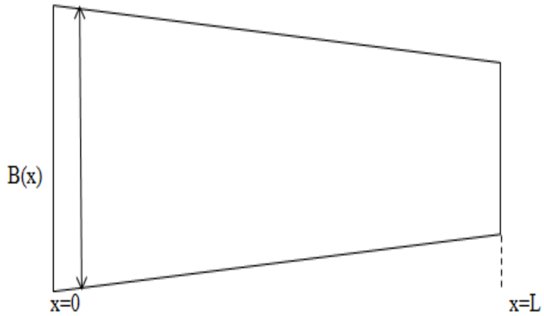


Fig 2 Non-rectangular beam

Taking the same equation for mode shape of cantilever beam as derived before. One can further develop the equation of natural frequencies for non-rectangular shape based on the

Rayleigh–Ritz method and the width function of the shape. In this paper, the width function of classical beam shape is presented and defined as
Based on law of conservation of mass,[14]

$$\omega_K = \left(\frac{\lambda}{L}\right)^4 \sqrt{\frac{EI \times \int_0^L B(x)\left[-\sin\left(\frac{\lambda}{L}x\right) - \sinh\left(\frac{\lambda}{L}x\right) + \beta\left[-\cos\left(\frac{\lambda}{L}x\right) - \cosh\left(\frac{\lambda}{L}x\right)\right]\right]^2 dx}{m \times \int_0^L B(x)\left[\sin\left(\frac{\lambda}{L}x\right) - \sinh\left(\frac{\lambda}{L}x\right) + \beta\left[-\cos\left(\frac{\lambda}{L}x\right) - \cosh\left(\frac{\lambda}{L}x\right)\right]\right]^2 dx}}$$

$$B(x) = (ratio \times B(0)) + \frac{B(0)(1-ratio)}{L}(L-x)$$

$$\beta = \frac{-\cos\lambda - \cosh\lambda}{-\sin\lambda + \sinh\lambda}$$

where B(0) is the width at the fixed end and ratio is the widths ratio of both ends of the beam(Fig. 2). Non-classical beam shape possesses different width functions.
Frequency of the beam is been determined by the following formulae,[13]

$$f = \frac{\omega}{2\pi} \qquad (2)$$

2.4 Velocity of wind

Velocity of the wind which [13]

$$Uc = 2.05\left(\frac{t}{L}\right)\sqrt{\frac{E}{\rho}} \qquad (3)$$

$\rho = 1.8\ kg/m^3$
t = 0.5 mm
L = 200 mm
$E = 5.2 \times 10^{10}\ N/m^2$
$Uc = 5.4\ m/s$

Table 1 Mechanical properties of the beam and piezoelectric material for theoretical studies

Cantilever beam	Piezoelectric
1.Material(beryllium copper)	1.Material(Lead zirconate titanate)
2.Length l= 0.2 m	2.Length l= 0.2 m
3.Breadth b= 0.01 m	3.Breadth b= 0.01 m
4.Thickness h1=0.001 m	4.Thickness h2= 0.0005m

5.Young's modulus Eb=11× $10^{10}\ N/m^2$	5.Young's modulus Ep=5.2× $10^{10}\ N/m^2$
6.Density ρb= 8700 kg/m^3	6.Density ρp=7800 kg/m^3

Table 2 Natural frequencies of three different shapes of beam

Frequency(Hz)

Mode k	Rectangle	Trapezoidal	Triangle
1	310.88	378.23	590.48
2	1949.18	2043.56	2150.75
3	5500.08	5521.36	6425.36

2.5 Estimation of power generated

Power generated to the corresponding frequency of the beam is determined as,[13]

$$E_{elec} = \frac{CV_{oc}^2}{2} \qquad (4)$$

Where

$$C = \frac{\varepsilon_{33} A_p}{h}$$

$$V_{oc} = \frac{d_{13} C_p E h}{\varepsilon_{33}}$$

Electrical properties of the piezoelectric material
Dielectric constant (@1 KHz) k= 1800
Piezoelectric co-efficient
d33= 390$\times 10^{-12}\ m/volt$
Peak strain C_p= 0.6%

Table 3 Power generated to the corresponding frequency generated in three beam shapes

Power(W)

Mode k	Rectangle	Trapezoidal	Triangle
1	21.67	26.36	41.16
2	135.87	152.45	169.92
3	383.39	394.88	447.89

3.Theoretical Results

3.1 Graph of frequency Vs voltage for rectangular beam and non-rectangular beam

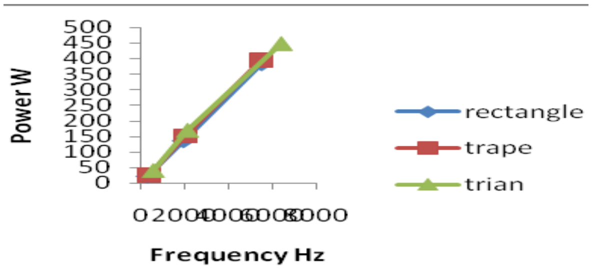


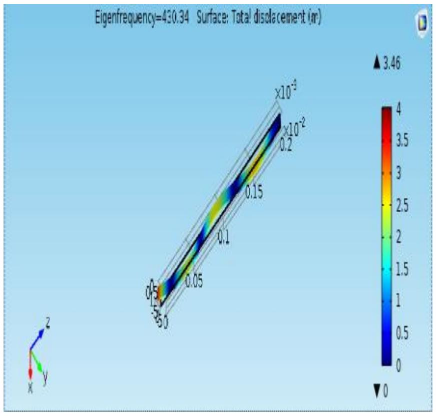
Fig 3 Frequency Vs Power for rectangular and non-rectangular beam

The graph shown in Fig 3 is been drawn between frequency and power generated from the piezoelectric material for both rectangular and non-rectangular beam ,which are shown in the Table 2 & 3. These values are calculated from the equation 2 & 4.

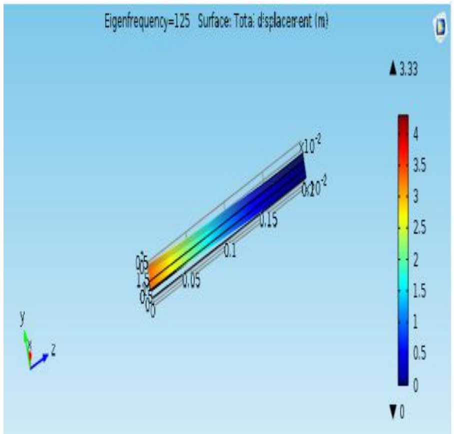
4.Analytical results

4.1 Rectangle shape beam

Here analytical results of frequency for various width and thickness of the rectangular beam is been presented with fixed length.The analysis is been performed using COMSOL Multiphysics software under the eigen frequency domain with some fixed parameters like density, dielectric constant and poison ratio of the beam material.

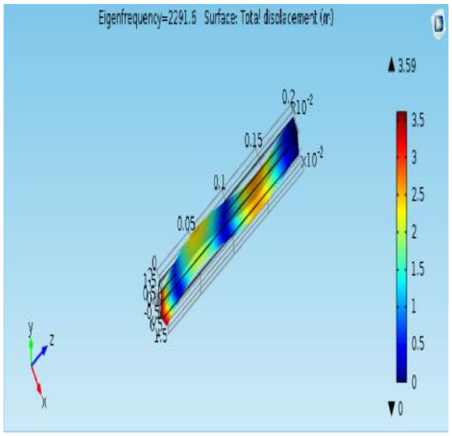


(a)

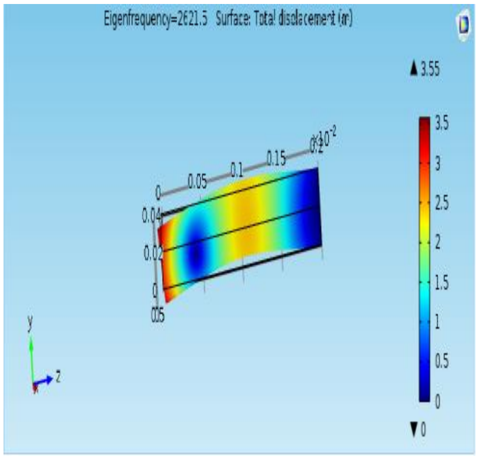


(b)

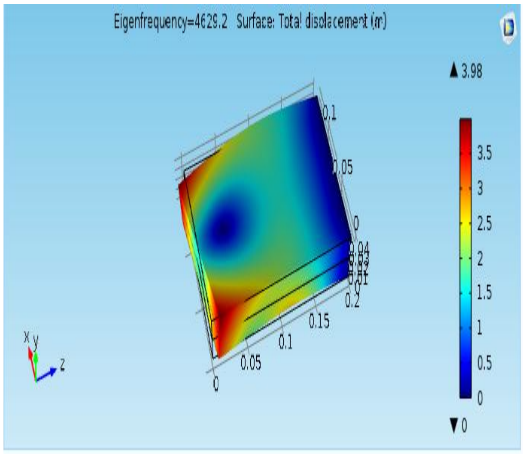
The figure represents the frequency analysis for various thickness, width and length of the beam. From the above analysis it is clear that , the frequency generated for a length of 200mm, width of 130mm, thickness of 20mm is more.



(c)



(d)

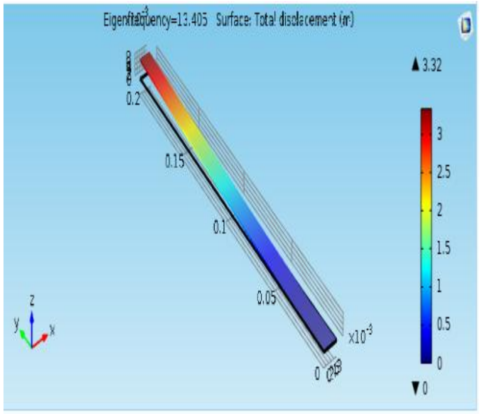


(e)

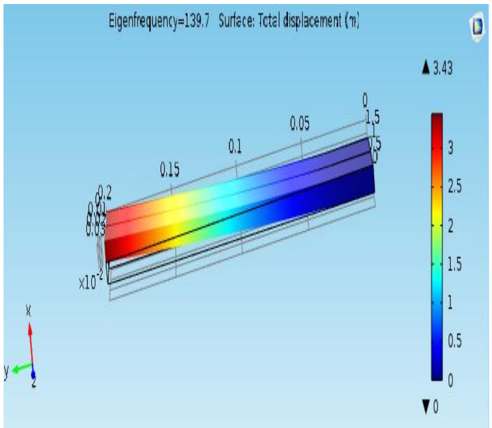
Fig 4 Frequency generated for various length, width, thickness of the beam.

4.2 Non-rectangle shape beam

Here analytical results of frequency for various width and thickness of the rectangular beam is been presented with fixed length.

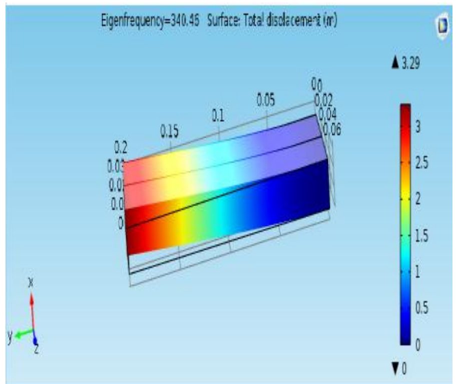


(a)



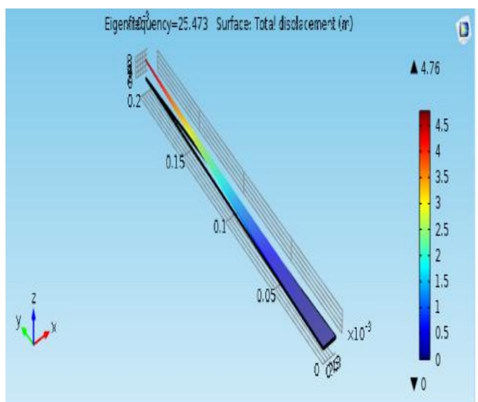
(b)

The analysis is been performed using COMSOL Multiphysics software under the eigen frequency domain with some fixed parameters like density, dielectric constant and poison ratio of the beam material.

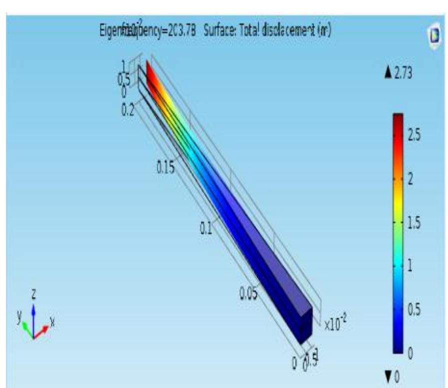


(c)

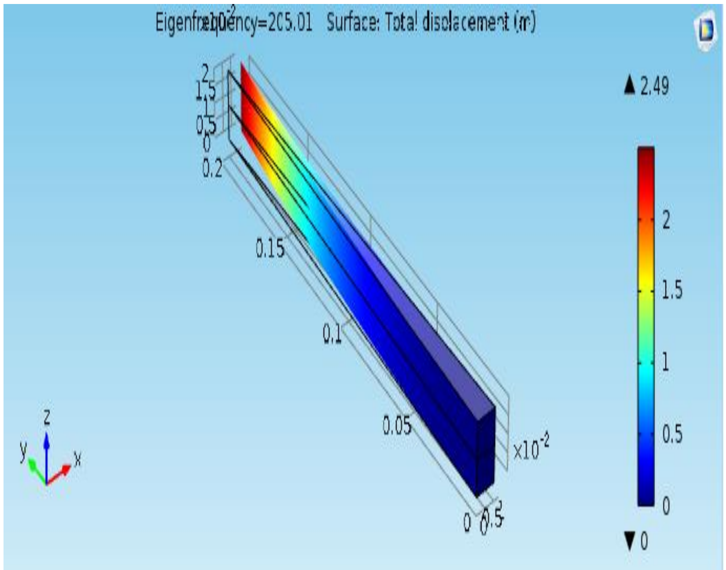
Fig 5(a,b,c) Frequency analysis for various length, width an thickness of trapezoidal beam



(a)



(b)



(c)

Fig 6(a,b,c) Frequency analysis for various length, width and thickness of triangular beam

From the above figures, triangular beam has the maximum power generation capacity then trapezoidal beam for various length , width and thickness.

4.3 Graphical representation of thickness Vs frequency

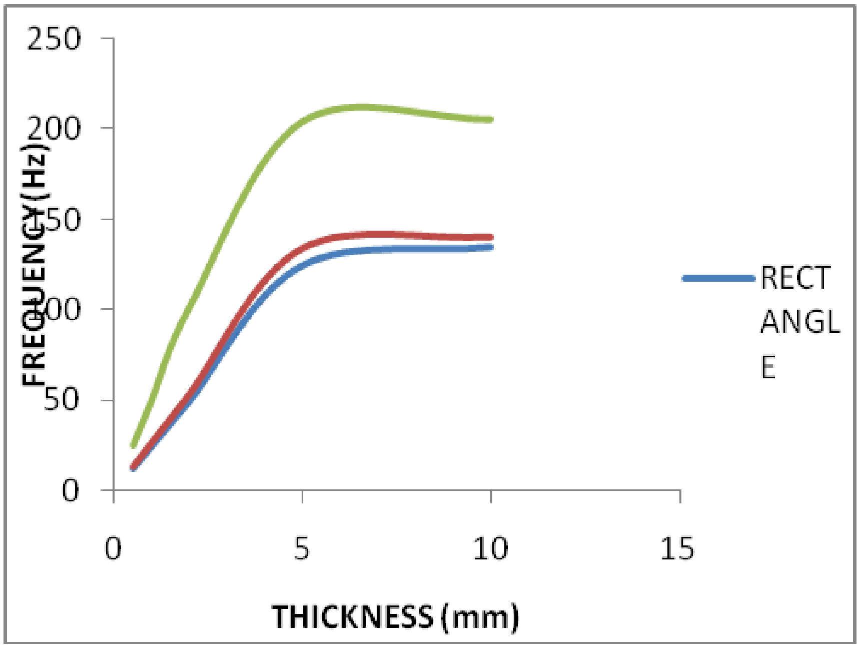


Fig 7 Graph between thickness Vs frequency

The above figure represents the variation of frequency with thickness of the beam .From the above graph it is clearly shown that the frequency generated in triangular beam is more when compared to other shape.

5.Result and discussion

The work is completely about the theoretical calculation performed for calculating the frequency and power generated by the cantilever beam coated with piezoelectric material and software analysis of the decided geometry of the beam.

In this work, the material selected and the reason for selecting the above mentioned piezoelectric material and beam material are discussed in the above chapter.

The formula's required for calculating the frequency of cantilever beam of different shapes and the relation for power generated from the piezoelectric material are taken with references of various journals and books.

From the calculated values that are tabulated in the table, the graph is drawn between frequency and power generated for different shapes of the beam and also analytical results for various thickness of the beams are also tabulated and graph is drawn between thickness and frequency.

The graph shows that the frequency and power generated for the non-rectangular beam is more and the relation between frequency and power is directly proportional.

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