Design and Simulation of Piezoelectric MEMS Cantilever

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Abstract: In this paper, a Micro – Electrical Mechanical System (MEMS) energy harvester is developed, using the phenomenon of Piezoelectricity. Zinc Oxide (ZnO) was chosen as the piezoelectric material. A multi – d_{31} mode cantilever design was used with varying dimensions of cantilever, to form an array. The individual cantilevers can be either connected in series or parallel to achieve different output characteristics. Present paper focuses on providing power for remote operations like vehicle tyre pressure sensors by harnessing the vibrations of the vehicle and converting it into electrical energy. An array of cantilevers thus designed and simulated, varying the length and thickness of the piezoelectric material to harness different vibrational frequencies. Simulations were performed on finite element software - COMSOL Multiphysics, which revealed the wide range of resonance frequencies between 1 kHz to 150 kHz.

Keywords: Vibrational energy harvesting, Zinc Oxide (ZnO), Piezoelectric cantilever

1. Introduction

Energy sources on the surface of Earth are limited. Energy harvesting techniques through non-conventional energy resources are thus being researched at an increasing rate. One such technique is to harvest energy at micro domain. The advantages of micro level energy harvesting are: small size leading to ease of mass production; reduced manufacturing cost and time; and ease of integration into other systems. Many real-life applications require long term usage and the continuous power which is not feasible with conventional batteries. If these requirements are achieved the unit cost increases exponentially. As a result, different types of MEMS vibration energy harvesting techniques are developed to suit different applications. The advantage of harnessing vibration energy are high power density, no external physical connection requirements and reliability in harsh environments. Human motions, Fluid actuation and energy harnessed through impact are such examples to harness energy as cited in [1], [2] and [3].

Chief energy harvesting techniques at micro domain are through the use of phenomena of Piezoelectricity, Electrostatics and Electromagnetics. A systematic comparison amongst the three techniques has been done by Boisseau et al. [4]. Amongst these methods, piezoelectricity has received much attention due to the high conversion efficiency of vibration energy into electrical energy with a high power density and potential miniaturization with simple structure [5].

Many studies have been reported to improve the power density of energy harvester such as Eba Flora.E et al. [6] analyzed and simulated different cross sections and geometries of the cantilever. Other cantilever designs include using an E-shaped cantilever [7]. A single proof mass connected to an array of cantilevers was developed by Huicong Liu et al. [8]. The concept of array to harness a range of ambient vibration being at different frequencies was simulated and developed by Levent Beker at el. [9]. The cantilever design can be excited through different techniques depending on the type of ambient energy required to be harnessed. Some of these techniques is through use of UV rays, mechanical vibration [10] and magnetic actuation [11]. Amongst the many piezoelectric materials available present work focuses on use of ZnO as the piezoelectric material.

2. Theory and Governing Equations

Piezoelectricity is a coupling mechanism relating the mechanical and electrical properties of a material. Thus an electrical charge is produced when the piezoelectric material is mechanically deformed and vice versa. The linear constitutive piezoelectric equation defining stress (T), electric field (E), and electric displacement (D) is as follows [12] and [13]:

$$D_i = d_{iq}T_q + e^E_{kp}E_k$$

Where, d_{iq} is the piezoelectric coefficient and e^E_{kp} the dielectric permittivity. Comparing to the Cartesian Co-ordinates, the subscript “1” can be referred as the X-axis, the mechanical drawing direction, “2” refers to Y-axis, and “3” refers to Z-axis, the poling direction. The present study focuses on use of d_{31} mode. Thus constitutive equations used in this configuration become [13]

$$D_3 = d_{31}T_1 + e^E_{33}E_3$$

In addition, if the external applied electric field E is zero, the relations are simplified further. Therefore, the relevant piezoelectric equation becomes:

$$D_i = d_{iq}T_q$$

The electric displacement D is related to the charge generated by the following relation:

$$q = \iint [D_1 \quad D_2 \quad D_3] \begin{bmatrix} dA_1 \\ dA_2 \\ dA_3 \end{bmatrix}$$

where dA_1, dA_2 and dA_3 are the components of the electrode area in the 2-3, 1-3 and 1-2 planes respectively. An additional constant related to piezoelectricity is the electromechanical coupling coefficient (k), which quantifies the fraction of the electrical energy converted from mechanical energy or vice versa. It is defined by

$$k^2 = \frac{\text{electrical energy converted}}{\text{input mechanical energy}}$$

The performance of the energy harvester depends chiefly upon the piezoelectric material used. The common thin film Piezoelectric material used are lead zirconium titanate (PZT) family, zinc oxide (ZnO), aluminum nitride (AlN), Poly vinylidene Fluoride (PVDF) and $BaTiO_3$ (BTO). Table 1 shows the coupling coefficient of the common piezoelectric material [13].

Materials	*Coupling coefficient (k)*
Quartz	0.1
ZnO	0.33
BTO	0.4
PZT	0.5 ~ 0.7

Table 1: Coupling coefficient of common piezoelectric materials

PZT is most used piezoelectric in Energy harvester due to its excellent coupling coefficient. ZnO is chosen as a piezoelectric material as its coupling coefficient is not very inferior compared to PZT. ZnO also has high mechanical quality factor (Q_m) and is highly compatible with CMOS processing making it attractive to be applied in MEMS vibration based energy harvesting for self-powered microsystems. ZnO has been chosen as the piezoelectric material mainly because of (1) relatively high piezoelectric coupling coefficient compared to aluminium nitride (AlN) and low dielectric constant compared to PZT (2) low deposition temperature and well known standard sputter deposition technique (3) excellent bonding to silicon substrate (4) non ferroelectric materials which does not require poling or post deposition annealing (5) the production of ZnO is environmental friendly and does not cause serious environmental pollution compared to PZT production [15].

As highlighted earlier the proposed energy harvester is used to harness ambient vibration in a car tyre. Figure 1 explains the practical application of the intended usage of the energy harvester. The vibration due to unevenness in the road surface are assumed to transfer onto the piezoelectric material through the surface of tyre. The figure also explains a schematic model where the tyre is assumed to behave as a linear spring system with k and c the equivalent stiffness and damping constant of the tyre.

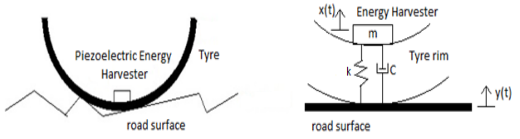

Figure 1: Effect of road surface on piezoelectric harvester

Assuming the road surface giving a displacement y(t) to the tyre and the corresponding motion of the mass is x(t), the differential equation of motion becomes [16]:

$$m\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0$$

leading to:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = 2\zeta\omega_n\dot{y} + \omega_n^2 y$$

Where m is the equivalent lumped cantilever mass neglecting the mass of the tyre, ζ is the damping ratio and ω_n is the natural frequency of the system under consideration.

Letting a sinusoidal road profile equation $y(t) = \mathrm{Re}\,(Ae^{i\omega t})$, the response on the cantilever assembly x(t) is given by :

$$Re\left[\frac{1+\frac{i2\zeta w}{w_n}}{1-\left(\frac{w}{w_n}\right)^2+\frac{i2\zeta w}{w_n}}Ae^{i\omega t}\right]$$

Thus the force on the cantilever assembly is m$\ddot{x}$(t), varying with time. Also a centrifugal force comes into play due to rotation of the tyre causing a permanent deflection. Table 2 shows the values required to calculate the force on the cantilever. The theoretical equations thus led to ζ >> 1, resulting in the over-damped case of vibrations. Coupling the forces attained due to high damping and the centrifugal force, a static force of 5 x 10^{-8} N was used throughout the simulations of the cantilever.

k	100 kN/m
C	4.45 kN-s/m
M	3.5812 nkg

Table 2: Analytical model values [17]

3. Use of COMSOL Multiphysics

The cantilever structure under consideration consists of five layers, viz. Poly-Silicon as metal base, Silicon dioxide (SiO_2) as insulation material, Aluminium (Al) as metal electrodes, Nickel (Ni) as proof mass and Zinc oxide (ZnO) as the piezoelectric material as shown in figure 2. Al was chosen as the material for metal electrode to reduce the cost of the device.

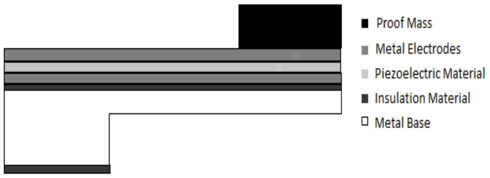

Figure 2: Schematic diagram of the cantilever design

As mentioned, simulations were performed for d_{31} mode. Table 3 shows the dimensions used for simulations. The steady-state analysis is conducted to simulate the resonance frequency and maximum displacement of the cantilevers as shown in figure 3. The potential developed at the electrodes is also obtained. Before starting, a few constraints are added to the structure. The Poly-Si base is fixed and made incapable of movement. The lower and upper Al electrodes are assigned ground and floating potential respectively. A force is then applied as a surface load on the Ni layer and the displacement and potential are plotted for different dimensions of the cantilever.

MATERIAL	LENGTH (µm)	WIDTH (µm)	THICKNESS (µm)
Silicon	200 – 500; 600 – 1500	50; 100	1
Silicon Dioxide	200 – 500; 600 – 1500	50; 100	0.1
Aluminium	200 – 500; 600 – 1500	50; 100	1
Zinc Oxide	200 – 500; 600 – 1500	50; 100	2, 3, 4
Nickel	20 – 50; 60 – 150	50; 100	10

Table 3: Device dimension for simulation

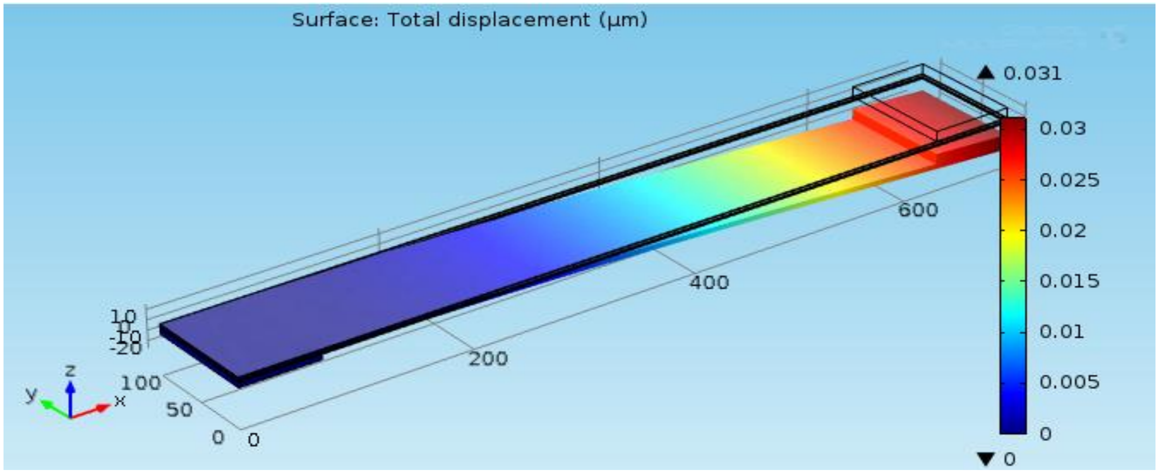

Figure 3:3D model of simulation

Maximizing the energy harvested from vibrations of a vehicle due to the unevenness on the road surface would require an analysis of the road profile. Assuming a car running with a maximum speed of 180kmph and a sinusoidal road profile with a wavelength of 1cm, we get a frequency of vibration to be up to 5 KHz depending on speed of the vehicle. Taking into account the rotation of the tyre as well as the position of the energy harvesting device, this frequency reduces down to 125Hz. As a result, the proposed MEMS sensor positioned inside a car tyre would attain mild vibrations at a frequency of 5 kHz and a magnified vibration at a frequency of 125Hz.

Based on the results obtained during vibration analysis simulation, an array of cantilevers is intended to be developed to best suit the vehicular example given. The device would have maximum dimensions of 5000 μm x 5000 μm x 25 μm with cantilevers of length varying from 400 μm to 1500 μm with 800 μm and 900 μm used twice each, packed on the two sides of the device as shown in figure 4. Eigen frequency analysis of individual cantilever yields that a resonance frequency of all the cantilever lies within the range of 1 kHz to 150 kHz. Integrating the two frequency ranges, frequency analysis for a frequency range of 10Hz to 30 KHz was performed.

Simulations were performed on individual cantilevers. A range of frequencies of car tyre vibration can hence, be utilized and converted in electric charge to power remote electronic sensor units. Advantages achieved would be lesser dependency on batteries, lesser complexity due to unnecessary wiring and longer lifetime. Since the cantilevers would be acting in series to each other, the voltage generated would also be the sum of each individual energy harvester.

4. Results:

The results obtained have been displayed in graphical form below. Inferences that can be made are as follows. The voltage generated is proportional to the length of the cantilever beam. This is due to the fact that maximum displacement at the end of the beam increases with increase in length, leading to greater voltage levels. Also, as the voltage directly depends on the distance between the metal electrodes, the cantilever with piezoelectric material thickness 4 μm shows a higher trend line than the one with 2 μm, as shown in chart 1 and 2.

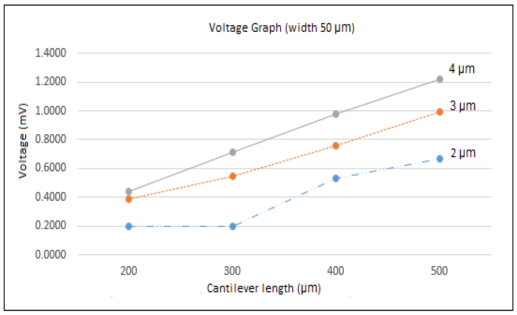

Chart 1: Voltage v/s cantilever length for 50 μm width

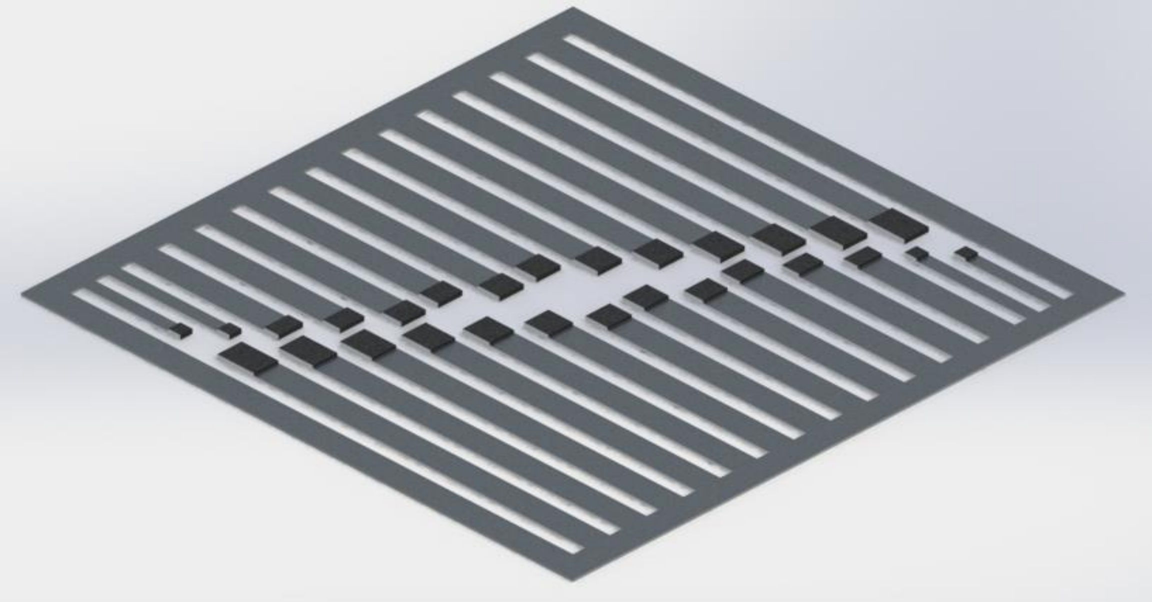

Figure 4: 3D model of cantilever array

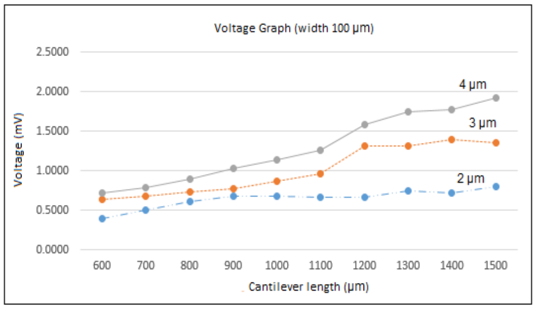

Chart 2: Voltage v/s cantilever length for 100 µm width

In the frequency plots, an indirect relation is observed between length of cantilever and its natural frequency. Also, due to greater rigidity, the beam with largest ZnO thickness shows greatest frequency values as shown in chart 3 and 4.

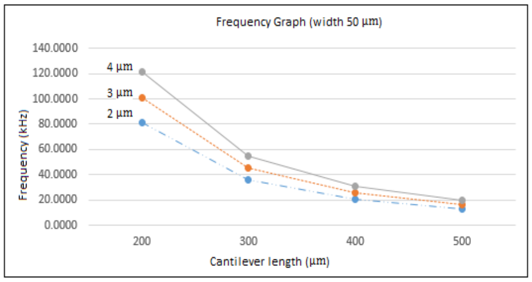

Chart 3: Frequency v/s cantilever length for 50 µm width

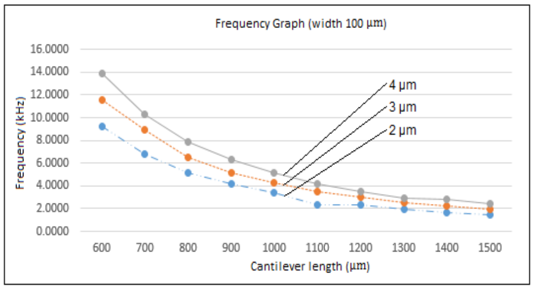

Chart 4: Frequency v/s cantilever length for 100 µm length

The frequency analysis simulation performed on the cantilevers reveals a peak attained at the respective resonance frequency as well as the first overtone, as expected. Chart 5 shows one such result performed on cantilever of length 800 µm.

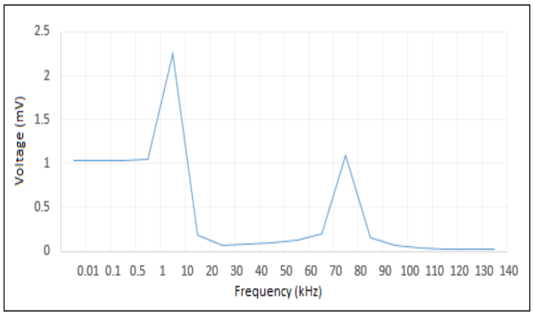

Chart 5: Voltage v/s frequency (cantilever length 800 µm)

Adding the voltages achieved in each of the frequency analysis performed on different cantilever sizes, leads to the voltage output for the array. Chart 6 shows the net array output voltage produced due to vibrations at a range of frequencies between 10Hz to 30 kHz.

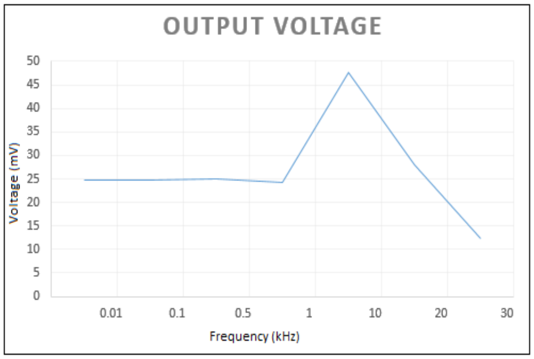

Chart 6: Array output voltage v/s frequency of vibration

As can be inferred from the graphs the net output voltage varies with frequency depending upon which constituent cantilever attains resonance or is near to the resonance frequency at the frequency of vibration under study. Simulation results shows that the device under study is best suited for frequency between the range of 1 kHz – 20 kHz with the peak output voltage being 47.52mV.

5. Conclusions

This paper was written to provide the result of design and simulation of MEMS piezoelectric energy harvesters operating in d_{31} mode. A cantilever structure was designed using Si/SiO_2/Al/ZnO/Ni materials. ZnO was used as the piezoelectric material due to its many advantages. Simulation was done to analyze the resonant frequencies of various dimensions of the cantilever and a graphical representation of results obtained have been shown. An array of cantilevers was designed and a frequency analysis was performed revealing a maximum voltage of 47.52mV attained at a frequency of 10 kHz. The main purpose of the array device, to harness a range of vibration and sustain a harsh environment viz. tyre surface, can be achieved through the proposed design.

6. References

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7. Acknowledgements

We would like to express our gratitude towards the extremely supportive and friendly teachers and teaching assistants at Birla Institute of Technology & Science, Pilani. We are extremely grateful to all the people who have helped during the projects. Omission of credits is deeply regretted.