2018 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON)

A Novel Structure for Piezoelectric Based MEMS Energy Harvester

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***Abstract*— A novel structure has been designed to be used as piezoelectric Micro Electro Mechanical Systems (MEMS) energy harvester. A deep investigation has been made for the selection of the piezoelectric material and also for the design of the structure. Finally, the structure of a 'Jaw Harp' is used and 'Rochelle Salt' is applied as the piezoelectric material. Numerous simulations and analytical calculations have been performed in the process of optimizing the device performance by varying its various parameters. Towards the end, a very appreciable result have been achieved. A remarkable output electric potential of 0.12 V has been generated by the harvester on application of 1 Nm^{-2} pressure at the free vibrating end of the device.**

Keywords—energy harvester, jaw harp, MEMS, piezoelectric, rochelle salt

I. INTRODUCTION

Energy is everywhere surrounding us in various forms. Most of them are natural and some of them are because of various abiotic activities. As for some examples, wind energy, solar energy, the thermal energy, and mechanical energy. But the problem lies in the fact that the energy found in these are in such minute quantities that they can hardly be used for any viable purposes. In fact, until the recent development in modern high-end technologies, it was very difficult to capture these kind of energies for any viable applications. [1-2].

Energy Harvesting is considered to be the method of capturing very less amount of energy from one or more available natural energy sources, acquiring them and storing for later use in the applications like WSN (Wireless Sensor Network). In other words, an energy harvesting system is an electromechanical device that can provide power to various sensors and control circuitry for intermittent duty applications [2-3].

The main advantages of energy harvesting is that it is inexhaustible, free and less prone to maintenance. Energy harvesting can be applied to a wireless node which is placed to a remote site where a power plug or a battery is either unreliable or unavailable, a wireless node running on energy harvesting is a self-powered electronic system whose efficiency can be increased by means of using multiple energy sources which will significantly improve the reliability of the system also [1-3].

In the last decade, it is seen that MEMS technology has been widely used for energy harvesting application in various ways. As reported in [4-5], it is seen to be implemented for IoT (Internet of Things) which is ruling the world right now. The IoT requires for smart, integrated, miniaturised and wireless nodes running with low energy batteries which used to be exhausted after a certain period. Therefore, much researches are going on to make them self-powered standalone devices.

RF MEMS as reported in [6] can provide better efficiency in converting solar energy to charge as compared to photovoltaic cells.

The MEMS energy harvesters generate voltage in the range of mV and hence cannot be implemented for more power consuming devices. Therefore, array of such devices can be implemented, as seen in [7] for power conditioning circuits.

II. ARCHITECTURE OF THE PROPOSED MODEL

The architecture of the proposed model is shown Fig. 1 below. It has the structure of a 'Jaw Harp' which is a traditional musical instrument in the region of North-East India. It is an instrument which produces a musical sound because of very high vibration when a small force is applied to it. Since, a piezoelectric energy harvester needs to produce a large stress on application of a small amount of force, this particular structure is one of the best fit to serve the purpose.

The overall width of the proposed structure is 230µm, with first 155µm as movable part which can deflect in both upward and downward directions and the remaining part is defined as the fixed constraints. The overall depth is 10µm and also the overall height is 10µm. For better deflection the height of the main deflecting part is restricted to 2µm only.

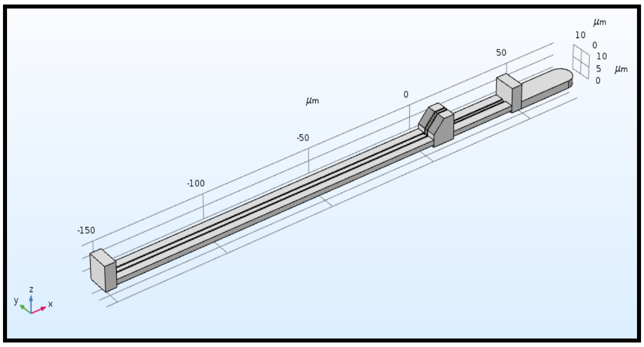

Fig. 1: Architecture of the proposed model

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III. WORKING PRINCIPLES

When the material parameters, the geometrical dimensions, and the external forces are known, the displacement of the beam can be found out. Once, the displacement is found, the stress can be calculated from it and finally from the stress, the electric potential developed in the structure can be calculated.

The architecture of the proposed model is similar to that of a rectangular cantilever and therefore its governing equations can be derived from it.

A. Deflection

For a rectangular cantilever beam structure (shown in Fig. 2), let the width, thickness and length be 'b', 'h' and 'L' respectively. Let 'F' be the force acting on the free end of the cantilever beam. For compensating the loading force 'F', a supporting force 'F_o' is produced at the clamped end in the opposite direction of the loading force. Meanwhile, a restrictive bending moment 'm_o' is produced at the clamped end of the beam to counteract the effect of bending moment caused by the loading force 'F'.

At the free end, the force moment 'FL' is in the downward direction, which as a result generates a balancing restrictive bending moment 'm_o' at the clamped end equal to 'FL' but is in upward direction.

From Fig. 2 at the position 'x', the bending moment at the left is $(-m_o+F_o x)$ and the bending moment at the right is $-F.(L-x)$. The bending moment on the left is equal to the bending moment on the right, i.e. $M(x)=-F.(L-x)$. The differential equation for the displacement function 'w(x)' is given by:

$$-EIw''(x)=-F.(L-x) \quad (1)$$

where, E and I are the Young's modulus and moment of inertia of the beam respectively. The boundary conditions are:

$$w(0) = 0,\ w'(0) = 0 \text{ and } w''(L) = 0 \quad (2)$$

Using Equation (1) and (2), we have:

$$w(x) = (F(3L-x)x^2)/6EI = (2F(3L-x)x^2)/(Ebh^3) \quad (3)$$

The maximum displacement at the free end of the beam that is at x = L is given by:

$$w_{max}= w(L) = (FL^3)/3EI = (4FL^3)/(Ebh^3) \quad (4)$$

The Eqn. (4) is the required equation for the analytical calculations for maximum displacement produced in the proposed model on application of the applied pressure [1] [3].

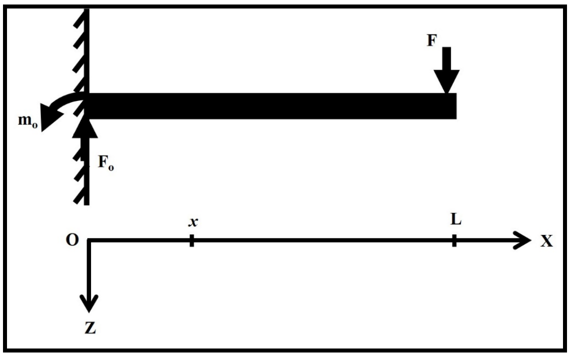

Fig. 2: Cantilever beam subjected to a force at the free end [3]

B. Stress

A miniaturized beam of a rectangular shape is shown in Fig. 3. The length 'L' is comparatively very large than the width 'b' and thickness 'h' of the beam. The length of the beam is taken along X-axis of a co-ordinate system considering its origin at the centre. If some force is acting perpendicularly in the middle of the beam, the top of the beam is compressed and the bottom of the beam is stretched (as shown in Fig. 4). There will also be a neutral plane along the middle of the cross section of the beam.

According to Hooke's Law, the stress in the layer at 'z' is given by:

$$T_{XX}(z) = Ez/r \quad (5)$$

Where r is the radius of curvature. When the beam is bent, the displacement of its central plane is a function of position, which is known as the displacement function 'w(x)'. As in mathematical concept, the absolute value of the second derivative of a curve w(x) will give the reciprocal of the radius of curvature of the curve w(x), which can be expressed as:

$$1/r = |w''(x)| \quad (6)$$

Equating equations (5) and (6) we have :

$$|T(x,z)| = Ez|w''(x)| \quad (7)$$

As shown in Fig. 4, for the bending up condition, we have $w''(x) < 0$. In the elemental section, for a layer with $z > 0$, it will be stretched, i.e. $T > 0$, and vice versa. Therefore, the algebraic relation for equation (7) is:

$$T(x,z) = -Ezw''(x) \quad (8)$$

Using Eq. (8), the stress on the top surface of the beam (at $z = -h/2$) is given by:

$$T(x) = -E(h/2)\, w''(x) = (Fh(L-x))/2I = (6F(L-x))/(bh^2) \quad (9)$$

The stress is maximum at x=0 and decreases linearly to zero at x=L. Using Eq. (9), the maximum stress is given by [1][3]:

$$T_{max} = FhL/2I = 6FL/(bh^2) \quad (10)$$

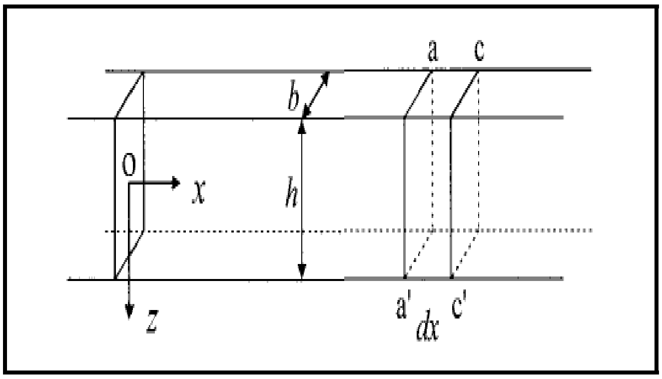

Fig. 3: An elemental section of the beam [3]

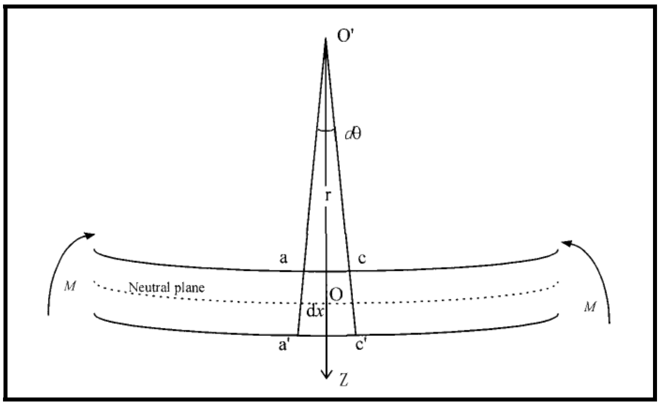

Fig. 4: Bending of the beam under bending moment [3]

C. Electric Potential

Piezoelectric material has used in the proposed work for the generation of electric potential on application of applied force or pressure. Piezoelectric materials are those where electric moments are created and aligned in a specific direction on application of mechanical strain, resulting as a electric dipole on application of mechanical strain, which is called the 'direct piezoelectric effect'. If deformation is created on the surface of the material on application of electric current, it is called 'inverse piezoelectric effect.

If we consider a simple one-dimensional case, a very simple equation can be used for the calculation of charge developed in the piezoelectric material and is given by:

$$q = (d_{33}\, T_{max}\, bh^2)/6L \qquad (11)$$

where q is the charge developed, d_{33} is a material property called the Piezoelectric Constant, and T_{max} is the maximum stress.

IV. Results

For the modelling and simulation of the proposed structure, COMSOL Multiphysics (v5.3) is used which is based on Finite Element Method (FEM) analysis of structures and the following simulation results has been obtained. The analytical values are also calculated and placed in the tables below along with the simulation results.

The applied pressure is varied from 0 N/m^2 to 1 N/m^2 with a step size of 0.1 and the following results have been obtained:

A. Displacement Occured

TABLE I. Analytical and Simulated Results for Displacement

S.L. No.	Applied Pressure (N/m^2)	Total Displacement (µm)	
		Analytical	***Simulated***
1	0	0.000000	0.000000
2	0.1	0.000140	0.000119
3	0.2	0.000280	0.000238
4	0.3	0.000420	0.000356
5	0.4	0.000560	0.000475
6	0.5	0.000700	0.000594
7	0.6	0.000840	0.000713
8	0.7	0.000979	0.000832
9	0.8	0.001119	0.000950
10	0.9	0.001259	0.001070
11	1.0	0.001399	0.001190

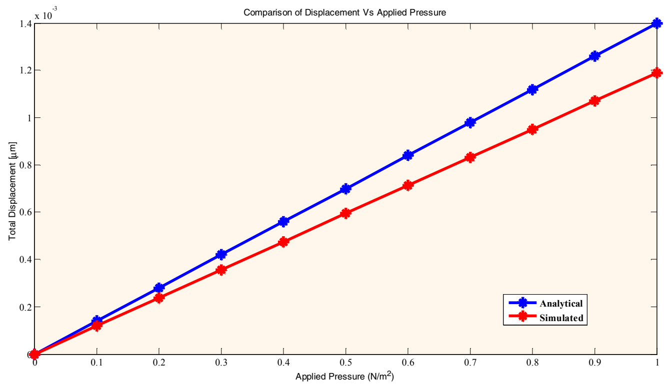

Fig. 5: Comparison of Displacement Occured Vs Applied Pressure

B. Stress Developed

TABLE II. Analytical and Simulated Results for Stress

S.L. No.	Applied Pressure (N/m^2)	Stress (N/m^2)	
		Analytical	***Simulated***
1	0	0	0
2	0.1	183.75	190
3	0.2	367.50	380
4	0.3	551.25	569
5	0.4	735.00	759
6	0.5	918.75	949
7	0.6	1102.50	1140
8	0.7	1286.25	1330
9	0.8	1470.00	1520
10	0.9	1653.75	1710
11	1.0	1837.50	1900

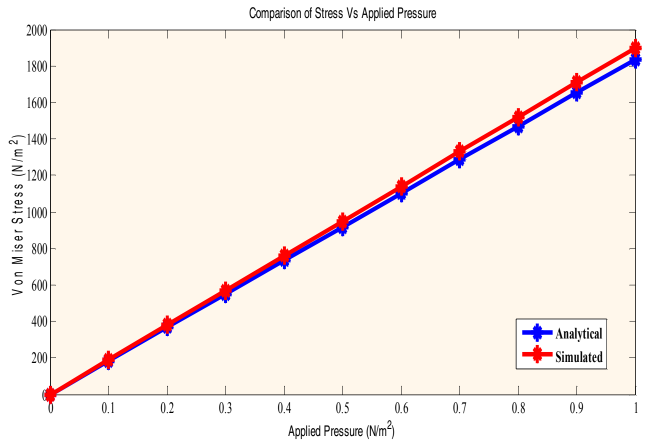

Fig. 6: Comparison of Stress Developed Vs Applied Pressure

C. Electric Potential Generated

TABLE III. ANALYTICAL AND SIMULATED RESULTS FOR ELECTRIC POTENTIAL

S.L. No.	Applied Pressure (N/m2)	Electric Potential (V)	
		Analytical	***Simulated***
1	0	0.000000	0.00
2	0.1	0.009923	0.01
3	0.2	0.019845	0.02
4	0.3	0.029768	0.04
5	0.4	0.039690	0.05
6	0.5	0.049613	0.06
7	0.6	0.059535	0.07
8	0.7	0.069458	0.08
9	0.8	0.079380	0.10
10	0.9	0.089303	0.11
11	1.0	0.099225	0.12

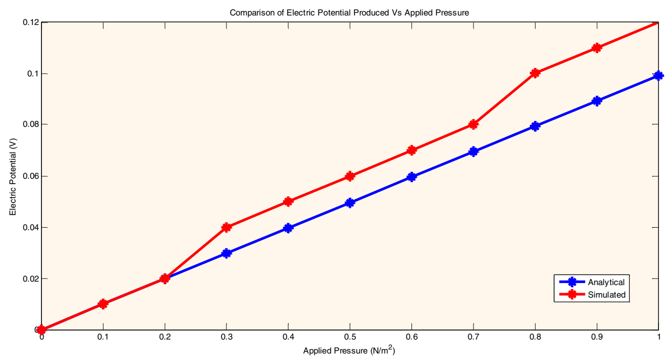

Fig. 7: Comparison of Electric Potential Generated Vs Applied Pressure

V. CONCLUSIONS

From the graphs shown above, it is clear that both the analytical and simulated results for the model are very close to each other which in turn verifies the project. Using Rochelle Salt as the Piezoelectric material and 150 µm as the length of the free vibrating end of the structure, electric potential in the range of ~ mV has been obtained. On varying the applied pressure from 0.1 to 1.0 Nm^{-2} a voltage range of 0.01 to 0.12 V has been generated as the output which can be used to power wireless nodes in a wireless sensor networks (WSN).

ACKNOWLEDGMENT

We do hereby like to acknowledge the help and support that have been received from all the faculty members of Dept. of ECE, RGU for their kind support and guidance. We would also like to thank them for allowing us to use the lab facilities for carrying out the simulation works.

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