COMPREHENSIVE STUDY OF MECHANICAL ENERGY HARVESTING BY VIBRATION SENSOR

S.G. Agrahari[1*], G.D. Agrahari[2] and D.S. Dhote[3]
[1,2,3]Shri Brijlal Biyani Science College Amravati, Maharastra, India
[1*]sheetalgagrahari@gmail.com, [2]gddagrahari@gmail.com, [3]dr.deepak.dhote@gmail.com

ABSTRACT

Piezoelectric effect can be used to convert mechanical energy present in environment into electrical energy to power wireless sensor nodes. Sensor is a simple electrode in the form of cantilever beam of which dimensions are decided and optimized to obtain desired results. This electrode is designed and most accurate material is chosen in order to continue with FEA simulation. When density of piezoelectric material is very high energy obtained per unit volume is also high. In this work simulation is carried out on electrodes to sense the vibrations in the environment for the frequencies of 60 Hz to 200 Hz. Material which is used in electrode is Si, SiO_2, PZT(5A) for structural layer, insulation and piezoelectric layer for energy harvesting. Piezoelectric electrode gives highest energy conversion at resonant frequency which also depends on its design and dimensions. Figure of merit improves with smaller dimensions and better potential output.

Keywords: *MEMS, energy harvester, FEA analysis, frequency response of sensor, design and optimization.*

1. Introduction

The energy harvesters using vibration sensors have received increasing attention to power micro implantable and portable electric system due its simple configuration, good conversion efficiency and compatibility with latest MEMS technology-based circuits. This vibration sensor is in the form of cantilever beam that can generate maximum energy output only when the frequency of vibration matches with ambient vibration frequencies. Drastic change in energy conversion is observed as cantilever beam vibrates at the frequency slightly different than the resonant frequency. Hence, resonant frequency needs to be matched well with environment frequency for operation of energy harvester. In finite element analysis simulation, we obtain outputs still due to convenience and simplicity theoretical formula is always preferred for design. Mass ratio and covering area of proof mass are limited due to the fabrication process, thus big frequency error may occur using this formula, and lead to the resonant frequency usually not actually close to practical results. In order to crosscheck if the desired value is obtained (Jin-Hui, 2015).

Material Selection and Design formulae

For sensing vibration, the sensor i.e., electrode for energy harvester needs to be produced using most accurate material. The spontaneous polarization also changes with temperature enabling pyroelectricity. In addition, there is a special class of materials in which the spontaneous polarization can be permanently reoriented between crystal orientation defined states by applying an electric field (Jing-Qui, 2015). This is the key parameter that distinguishes strictly polar materials from ferroelectric materials such as (PZT) (i.e., Zinc oxide, quartz, Aluminum nitride) (Abid 2015). Silicon becomes most desirable substrate due to its mechanical properties like high Young`s modulus, Poisson ratio, Bulk modulus and density. Silicon can be integrated in electronics for signal transduction on same substrate. High melting point at 1400°C which is about twice as high as that of aluminum. Hence during material deposition silicon has benefits.

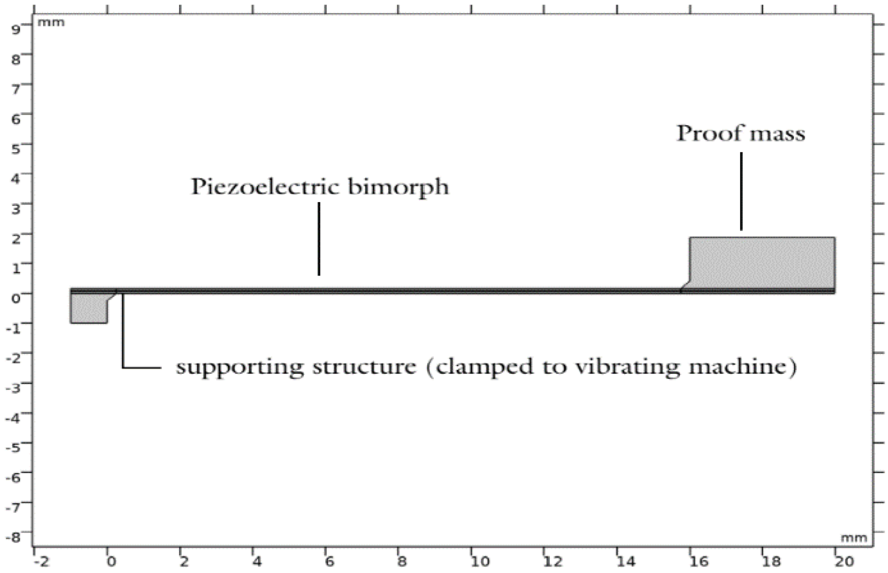


Fig. 1. Cantilever beam with proof mass

a. Formulae for Theoretical analysis and Design of electrode

The deflection of the membrane centre (d) is measured with the applied pressure (P) across the membrane. Then, the pressure-deflection behaviour of a circular membrane is expressed by

$$P=\frac{4\sigma^0 t}{a^2}d+\frac{8Yt}{3(1-y)a^4}d^4 \qquad (1)$$

where P is the applied pressure, d is the centre deflection, *a* is the radius, t is the thickness, Y is Young`s modulus, $\sigma_0$ is Poisson`s ratio, *v* is strain. The resonant frequency of cantilever is calculated using formula as

$$f_n=\frac{1}{2\pi}\sqrt{\frac{k_{eq}}{m_{eq}}}=\frac{1}{2\pi}\sqrt{\frac{3YI/L_c^3}{(33/140)m_c+m_p}}$$
$$=\frac{1}{2\pi}\sqrt{\frac{3Yb_ct_c^3/12L_c^3}{(33/140)L_cb_ct_c\rho_c+L_pb_pt_p\rho_p}}$$

(2)

where L_c and L_p length of cantilever and proof mass. b_c and b_p are width of cantilever and proofmass. m_c and m_p are proof mass and cantilever mass. t_c and t_p are thickness of cantilever and proofmass.ρ_c and ρ_p are density of cantilever and proofmass (Jin-Hui, 2015).

b. Equations in Analysis

Energy harvester sensor that is designed is consisting of two layers 650 µm long and 2.4 µm in thickness separated by a thin layer of insulation 0.001 µm thickness. One end of geometry is clamped and fixed while other end is having a proof mass made of nickel mounted on the other end. This formation is ensuring that same value of voltage is induced on the electrodes that are in the exterior of beam, even though opposite sign of stress is observed in above and below structures of the neutral layer. After formation of geometry in 2D physics and equations for analysis need to be specified. Physics that are included in simulation are solid mechanics, electrostatics and electrical circuit.

$$-\rho\omega\mathbf{u}=\nabla.S+\mathbf{F}ve^{i\Phi} \qquad (3)$$

is the equation for Solid Mechanics. Here ω is angular frequency, S is surface charge density, v is velocity, i is imaginary constant, ρ is permittivity, Φ is flux density, F is force.

$$\nabla.\mathbf{D}=\rho_v \qquad (3)$$

$$\mathbf{E}=-\nabla V \qquad (4)$$

are Maxwell`s equations. D is electric flied density, E is electric field, V is electric potential at a point in electric field. Hence, are the equations for physics of electrostatics involved in analysis.

2. Result and Analysis

Geometry of cantilever beam sensor is designed and all the dimensions are in micrometres. The parameters for analysis process are shown in table 2. In order to proceed with analysis, we need to give acceleration , resistance load value and out of plane dimension thickness.

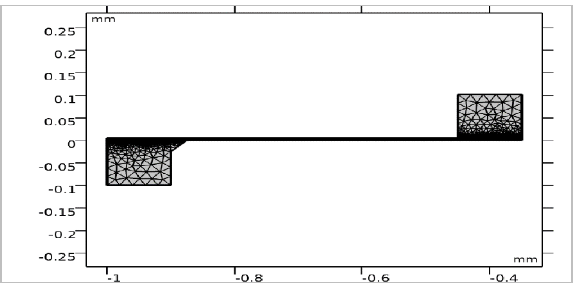
Table-1. Parameter's prerequisite in Analysis

Parameters 1			
Name	**Expression**	**Value**	**Description**
acc	1	1	Acceleration (g)
R_load	12[kohm]	12000 Ω	Load resistance
w_plate	14[mm]	0.014 m	Out of plane dimension

Mesh statistics are necessary to make finite element analysis (FEA) of device. FEA helps us to analyse all the elements of this device by considering analysis for each different element in the mesh. Table 3 helps to understand values of different quantities in Mesh. These mesh statistics are constant for all the device geometries and dimensions.

Table 2. Mesh Statistics for FEA

Mesh statistics	
Description	**Value**
Minimum element quality	0.1718
Average element quality	0.9051
Triangle	106518
Edge element	14915
Vertex element	25



Energy harvester sensor that is designed is consisting of two layers 3400 µm long and 10 µm in thickness separated by a thin layer of insulation 0.001 µm thickness. One end of geometry is clamped and fixed while other end is having a proof mass made of nickel mounted on the other end. This formation is ensuring that same value of voltage is induced on the electrodes that are in the exterior of beam, even though opposite sign of stress is observed in above and below structures of the neutral layer. After formation of geometry in 2D physics and equations for analysis need to be specified.

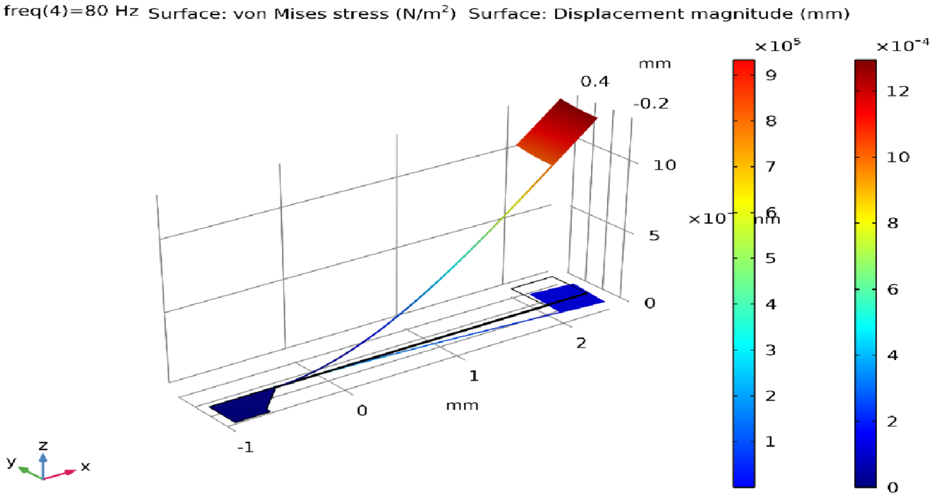


Fig.2 von Mises's stress (N/m^2) Surface: Displacement magnitude (mm)

Hence on running computation in COMSOL we get results for von Mises stress (N/m^2) as 9 x 10^5 N/m^2 and surface displacement magnitude (mm) of 1.2 nm. Electric potential that is obtained is 7 mV for this geometry with dimensions 3400µm x 20 µm.

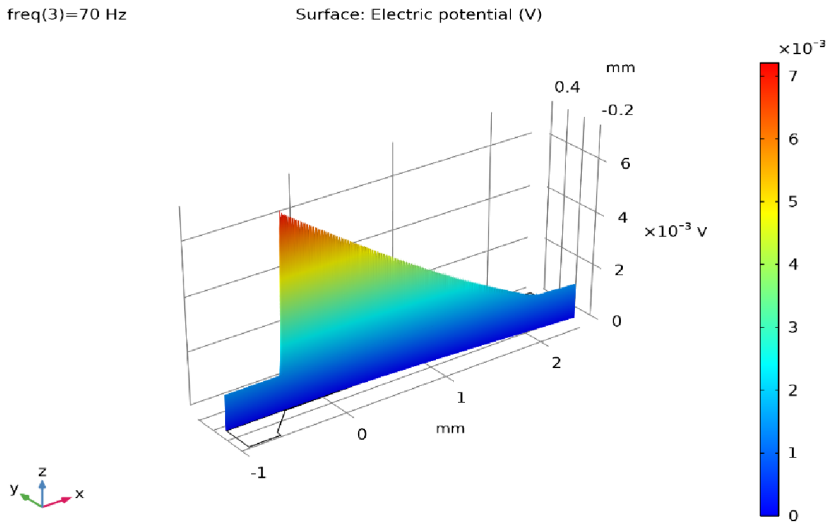


Fig.3 . *Electric potential (V)*

Figure 3. shows electric potential pattern developed inside the piezoelectric layer of cantilever beam. This pattern is considered better if maximum weight of pattern lies near to red. Figure 4. shows the input mechanical power and the power harvested (in mW) as well as the harvested power from the device as a function of the electrical load resistance at an acceleration of 1 g oscillating at 70 Hz. The electrical load is 12 kΩ.

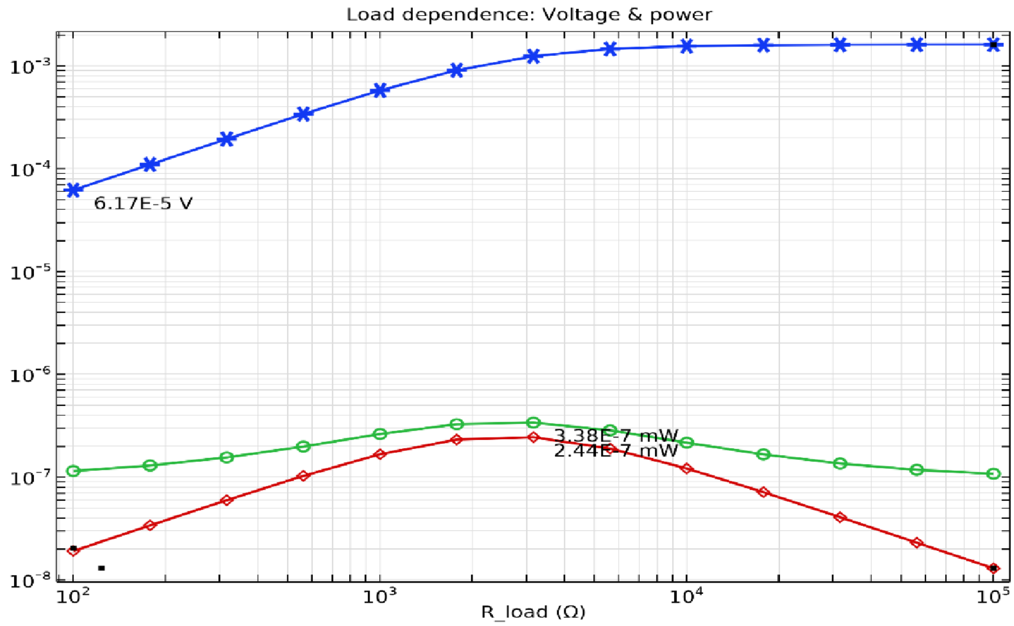


Fig.4. Load Dependence due to voltage and power

Table-3 Comparison of different energy harvesters on basis of figure of merit

Sr. No.	**Dimensions**	**V (mV)**	**Frequency (Hz)**	**FOM (V/m m^3.g)**
1	650µm x 5µm	0.55	120	169.23
2	3400µm x 20µm	7.00	70	103
3	3200µm x 20µm	7.216	80	112.75
4	2800µm x 20µm	2.9612	120	52.85

3. Conclusion

Material chosen for piezoelectric layer during analysis was PZT (5A), silicon for structural layer. Geometry is considered clamped at one end which causes more stress during deflection of cantilever beam, better deflection gives higher potential output. The dimension of 650µm x 5µm has highest FOM 169.23 while dimension 3400µm x 20µm has better potential of 7 mV. When space is concern smaller dimensions can be considered while voltage output is required bigger dimensions are useful. However, to run wireless sensor nodes the required amount of potential needs to be generated with help of an array.

References

1. ZHANG, J.-, MA, S.-, & QIN, L.-. (2015). Analysis of frequency characteristics of mems piezoelectric cantilever beam based energy harvester. Symposium on Piezoelectricity, Acoustic Waves, and Device Applications, 193–197.
2. Sojan, S., & Kulkarni, R. K. (2016). A Comprehensive Review of Energy Harvesting Techniques and its Potential Applications. International Journal of Computer Applications, 139(3), 14–19.
3. S, S., Swain, A. K., & Mahapatra, K. (2012). Design and Analysis of Five Port Router for Network on Chip. Asia Pacific Conferrence on Post Graduate Research in Microelectronics and Electronics, 51–55.
4. Qiu, J., Wen, Y., Li, P., & Chen, H. (2015). Design and optimization of a tunable magnetoelectric and electromagnetic hybrid vibration-based generator for wireless sensor networks. IEEE Transactions on Magnetics, 51(11).
5. Agrahari, S. (2017). Design of MEMS Energy Harvester with Interdigitated Electrodes for Railway Tunnel Health Monitoring. National Conference Recent Innovations in Science and Engineering (NC-RISE 17), 5(9), 1–9.
6. Lionel, W. Y. L., Chunlian, O., & Yuandong, G. (2018). Inexhaustible battery: An energy harvester basedbattery for IoT applications. IEEE International Conference on Nano/Micro Engineered and Molecular Systems, 22–26.
7. Levent Degertekin, F. (2017). Microscale systems based on ultrasonic mems - cmos integration. Transducers 2017, Kaohsiung, TAIWAN, 397–401.