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VIBRATION POWERED PIEZOELECTRIC GENERATOR USING FINITE ELEMENT METHOD

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Abstract - Energy harvesting is a renewable and green power generation and is key technology of future having wide application in wireless Sensors, NEMS, MEMS, UAV, medical implant devices, health monitoring and many more (1). Approach used in this model is simple based on basic piezoelectric, beam theory. We applied this model to predict the power generated from a bimorph cantilever beam with harmonic oscillations using PZT as a piezoelectric material to supply output power to wireless sensor node. The model used to develop a genetic algorithm for optimization of an energy harvester design. The existing designs meet all engineering constraints and can be utilized for other applications as well. These results are validated to a certain degree with finite element analysis.

Keywords – Energy harvesting, Vibration, Genetic Algorithm, FEM, Mathematical model.

I. INTRODUCTION

Energy harvesting (also known as power harvesting or energy scavenging) is the process by which energy is derived from external sources e.g., solar power, thermal energy, wind energy, salinity gradients, citation needed and kinetic energy, captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks [1]. Vibrational energy harvesting has been an attractive technique for potential power generation for wireless and low power devices. Among all the energy harvesting devices, piezoelectric has attracted lot of researcher interest for its simplicity. pressure), automotive(pressure, celerometer), and industrial (pressure, mass air flow) applications. It has been proposed that the piezoelectric technique is the most efficient way of harvesting vibration energy by Roundy [2]. The major application of this technology is in sensors which include sensors for medical (blood pressure), automotive (pressure, accelerometer), and industrial (pressure, mass air flow) applications.

II. MEMS POWER GENERATION BASED ON A PIEZOELECTRIC DIAPHRAGM

The energy converter consists of a piezoelectric diaphragm arranged as a spring–mass-system. Fig. 1[3] depicts the schematic design. An inertial mass is attached to the piezoelectric diaphragm which forms the mechanical spring and concurrently converts mechanical energy into electrical energy as a result of the transverse piezoelectric effect. A mechanical strain within the piezoelectric layer results in a charge asymmetry generating a voltage between the electrode and the counter-electrode.

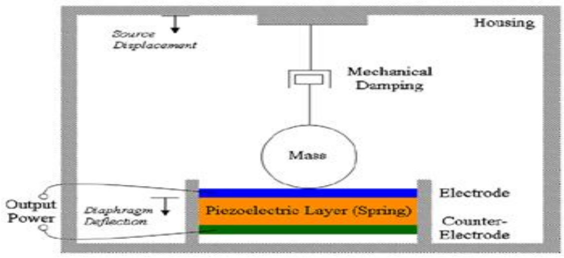


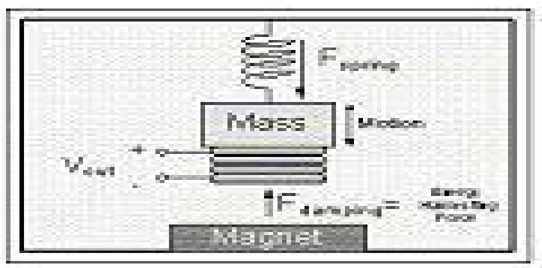
Fig – 1 Schematic design of energy converte

III. IBRATIONAL ENERGY EXTRACTION METHODS

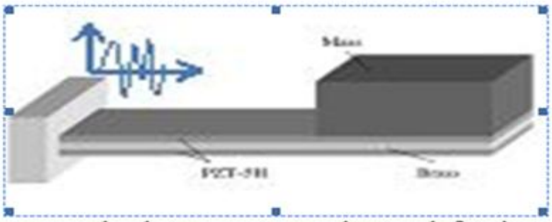
There are three possible devices shown in figure [4] below that can transform ambient vibrations into electrical energy:

- Variable capacitor (electrostatic fields).

- Electromagnetic inductor (electro-magnetic fields)



- Piezoelectric transducer (straining a piezoelectric material).



These three methods are commonly used for inertial sensors (i.e. accelerometers) as well as for actuators. The best transducers systems should be those that can maximize the coupling between the kinetic energy of the source and the conversion mechanism dependently entirely upon the characteristics of the environmental vibrations.

IV. MATHEMATICAL MODELING

The Euler-Bernoulli method is used to model the cantilever beam. A simple transverse mode type bimorph piezoelectric generator model based on Euler–Bernoulli beam theory with the assumption of the piezoelectric layer thickness in comparison to the length of the beam is very thin and the electrical field between the upper surface and lower surface of the piezoelectric layer is uniform. The linear constitutive equations for a piezoelectric material [5] have been employed in terms of the piezoelectric coefficient e_{31}, the permittivity $Є_{33}$, and the electric field applied across the thickness of the layer E_z.

$$D_z=e_{31}\,\sigma_{33}+Є_{33}E_z \quad (1)$$

Where D_z piezoelectric displacement. The stress σ in z-direction is zero as we assume the piezoelectric layer thickness in comparison to the length of the beam can be considered very thin.

To model the deformation of the piezoelectric cantilever design, an elastic cantilever beam under a concentrated load is considered.

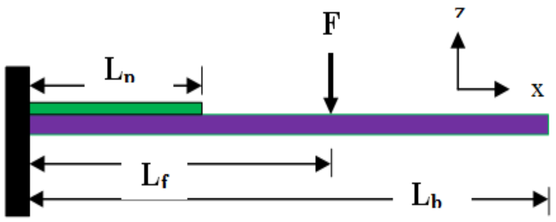


Fig- 5: Cantilever Beam with attached PZT sensor

The Euler-Bernoulli method is used to model the cantilever beam, its equation is.

$$\rho a\,\frac{\partial^2 u(x,t)}{\partial x^2}+E\,I\,\frac{\partial^4 u(x,t)}{\partial x^4}=F(t) \quad (2)$$

Applying the boundary conditions, the general mode shape equation for a cantilever beam is:

$$X_i(x)=\cosh(\beta_i x)-\cos(\beta_i x)-\frac{\sinh(\beta_i L_b)-\sin(\beta_i L_b)}{\cosh(\beta_i L_b)+\cos(\beta_i L_b)}\left(\sinh(\beta_i x)-\sin(\beta_i x)\right) \quad (3)$$

Where L_b is the beam length. Power is written as:

$$P=\frac{\omega^2 b^2 t_{sh}^{\ 2}\ e_{31}^{\ 2}\ \theta^2}{4\left(1+bL_b\epsilon_{33}\frac{\omega R}{t_p}\right)^2}\,R \quad (4)$$

Where θ is angle of deflection.

V. DESIGN OF RESONATOR

To model the deformation of the piezoelectric cantilever design, an elastic cantilever beam under a concentrated load is considered. This model assumes a single isentropic material, even though the actual structure consists of a piezoelectric bimorph. A schematic of the system is shown in Figure 6 [6].

Fig – 6: Elastic cantilever beam under a concentrated load at the end.

As a result, the following governing equations provide the displacement and angle of displacement as functions of *x*.

$$\textit{Deflection}\qquad u(x)=\frac{W}{6EI}(x-L_b)^3-\frac{WL^2}{2EI}x+\frac{WL^3}{6EI}$$

$$\textit{Angle of Deflection}\qquad \theta(x)=\frac{W}{2EI}(x-L_b)^2-\frac{WL^3}{2EI}$$

VI. PIEZOELECTRIC POWER GENERATOR

The vibration-to-electricity energy converter is described by a two-layer bending element (bimorph) mounted as a cantilever beam with a proof mass placed at the free end, as shown in Figure 7.

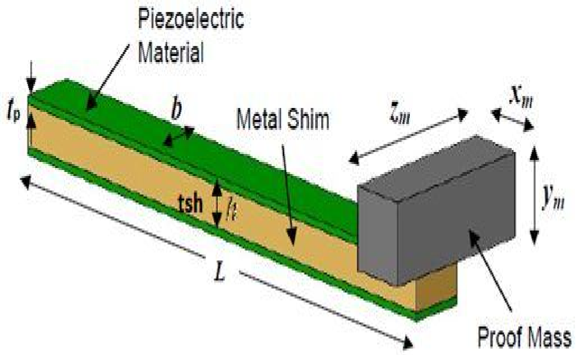


Fig-7: Piezoelectric power generator with bimorph Cantilever

The time-averaged power generated by a bimorph piezoelectric cantilever design is modelled by Equation 4, where *b* is the width of the beam, t_{sh} is the height of the metal shim, θ is the angle of displacement, *L* is the beam length, and t_p is the thickness of the piezoelectric layer. From this equation, it is found that the output power is dependent on the excitation frequency, *ω*, and the external resistance, *R*. A final observation of interest is that power increases when the piezoelectric material thickness is large and metal shim thickness is small. However, this model was developed under the assumption that the piezoelectric material thickness is much smaller than the shim thickness. The genetic algorithm written in MATLAB is compared to hand-derived calculations to prove the accuracy of the code.

VII. ANALYSIS AND RESULTS

The genetic algorithm developed for this investigation finds the optimum design based on two different criteria. The first maximizes output power and minimize total volume while satisfying all the other design constraints.

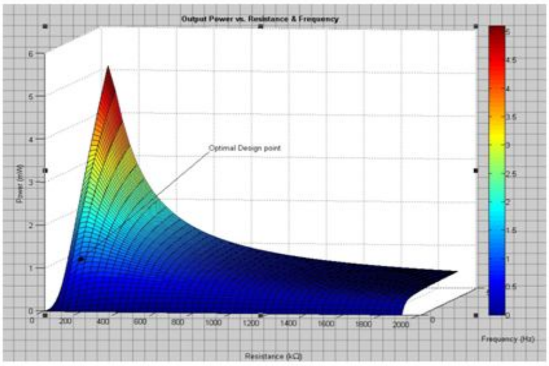


Fig - 8: Design obtained from Genetic algorithm

Figure 8 reveals that power increases when frequency increases and resistance decreases. This observation is confirmed by examining Equation 4, in which power is directly related to frequency and inversely related to resistance. Two analyses are performed to validate the theoretical models. The first is a static analysis to determine displacement, angle of displacement, and stress. The second includes a frequency analysis to determine the natural frequency of the cantilever-proof mass system. For a cantilever beam maximum deflection appears at the free end is 4.551 µm shown in figure 9. Although the maximum displacement is not exactly the value determined theoretically, it is within one order of magnitude and therefore considered reasonably accurate. It should be noted that the **Maximum Stress** According to the theory developed previously, it is expected that the maximum stress is located at the fixed end. Figure 10(b) confirms this assertion and states the maximum stress is 9.2 MPa. This value is relatively close to the theoretically derived value of 9.61 MPa displacement taken is at the free end of the beam, not the corner of the proof mass.

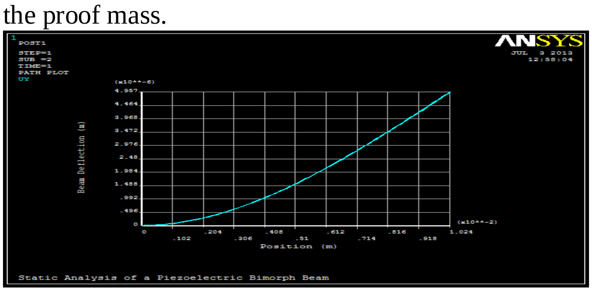


Figure 9: Deflection along beam length

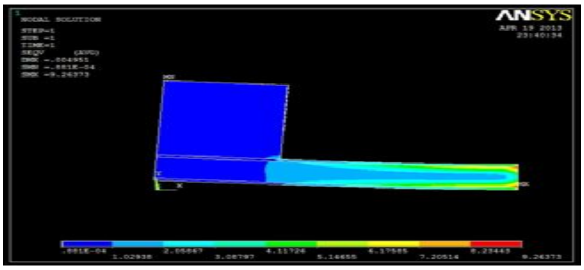


Fig 10a - Stress Distribution using Static FEA

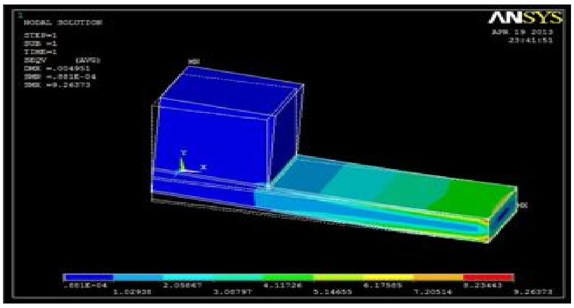


Fig 10b - Stress Distribution using Static FEA

As the strain is maximum at the support end instead of free end hence the voltage generated is 3.4 Volt which is the maximum at the fixed support end as we used the bimorph structure the voltage becomes doubles. The output voltage will be taken from the top faced of the by using electrode connected to top piezoelectric layer and the bottom layer is ground having zero voltage. The figure 11 shows the generated output voltage is

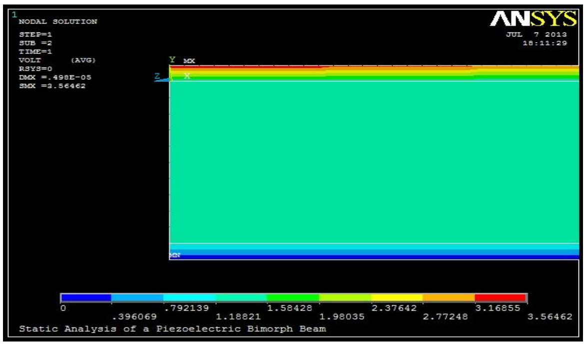


Fig 11: Output Voltage Generated

VIII. DISCUSSION AND CONCLUSION

The results from both the theoretically driven genetic algorithm and finite element analyses are provided in Table.

Design	GA	FEM	% Difference
Max Displacement	4.82µm	4.96 µm	- 2.82 %
Max Stress	9.61 Mpa	9.2 Mpa	+ 1.26 %
Natural Frequency	101.55 Hz	112.43 Hz	- 9.67 %
Output Voltage	3.91 v	3.56 v	+8.91%

Both methods provide results that do not deviate by more than 9 %. Therefore the simplified analytical model and alternative finite element simulation methods must be indicative of the actual energy harvesting system.

Through this analysis, the proposed design produce maximizes output power 1.02 mW at a natural frequency of 101.5 Hz and total volume of 15,869.00 mm^3. The existing designs meet all engineering constraints and can be utilized for other applications as well. These results are validated to a certain degree with finite element analysis. Although all calculations agree to within ±9% recommendations have been made to create theoretical models and design that more accurately

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