Analysis of Piezoelectric Heterogeneous Bimorph Energy Harvesters

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Abstract— Piezoelectric materials have been known for the conversion of electrical energy into mechanical energy and mechanical energy to electrical energy. The property of the piezoelectric materials in converting the mechanical energy into electrical energy has paved a wat for their vast applications in sensors and actuators. This paper presents the study and modeling of the piezoelectric heterogeneous bimorphs made of PZT-5A and structural steel for harvesting of electrical power from mechanical power. These bimorphs can potentially be used as the replacements for the battery and power supplies in the milliwatt range. The following paper presents the theoretical analysis heterogeneous bimorph and its several factors such as efficiency, dependence of voltage and power on the efficiency, analysis of the dependence of load on voltage and power generated along with the frequency, acceleration dependence on the voltage and power. There by later on an application each of the developed models in the fields such as vibrating machinery in the industries and use of the modeled weight beams such in the case of bending platforms such as treadmill sand conveyor belts will be discussed as an applications.

Keywords—Piezoelectricmaterials, piezoelectricity, power generation, piezeoceramics, piezoelectric heterogenoeus bimorphs, PZT ceramics.

I. INTRODUCTION

Piezoelectric crystals are known to convert the mechanical energy to electrical energy an electrical energy to mechanical energy. The mechanical stresses applied to the piezoelectric materials distort the internal dipole moments which in-turn generate the voltages that are directly proportional to the applied stress.[1] As these materials exhibit the above properties they are used in applications such as sensors and actuators. They were initially used in development of sonar's. [5] The piezoelectric sensors and actuators are widely available and widely used in modern world. The factor that these crystals convert mechanical energy to electrical energy makes these materials useful in electricity generation. These have poor source characteristics that are they yield high voltage, low current and high impedance. This happens to be true at low frequency and low output power. The recent inventions show that PZT (Lead Zirconate Titanate) and flexible PVDF films to embed them into the shoes to generate the electricity. [2]

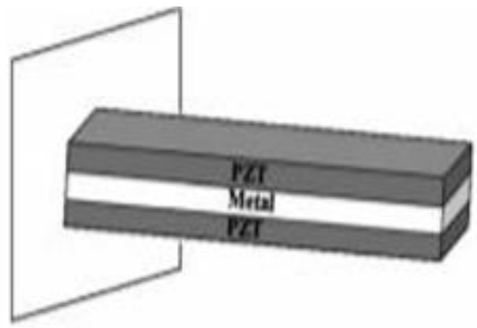

Figure 1: Piezoelectric Bimorph

The energy harvesters are the centers for the power source for the sensors and actuators. The piezoelectric energy harvesters generate the power in milliwatt and microwatt range which are suitable and indeed they can replace the conventional batteries for low power applications and also serve as the continuous power sources. [3] [14] Replacement of the batteries may become in the inaccessible locations, thus integrating a harvester can potentially solve the problem of replacement of the batteries and thereby solve the problem of procuring costly less bulky batteries [9]. Typical sensing environments have the available energy in the form of mechanical vibrations. The method to convert the mechanical energy to electrical energy is based on the piezoelectric, electrostatic, electromechanical principles. Piezoelectric harvesters are smaller, lighter and have as much as three times higher energy densities compared to electromagnetic and electrostatic counterparts. [4] Moreover, they provide the necessary voltages directly without the need of a separate voltage source as required in electro-static conversion process. For the frequencies below 100Hz, the piezoelectric energy harvesters are the best suitable ones. [10] Efforts to increase the power generated by the piezoelectric bimorphs have been carried out by the researchers and it is witnessed that triangular bimorphs generate more power when compared to the rectangular bimorphs.[11] The electromechanical coupling factor, the proof mass and quality factor greatly influence the amount of power generated.[12].

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II. RELATED WORK

Out of many papers those we referred here are some of them which we found to be helpful for our project

- The paper 'On Low-Frequency Electric Power Generation with PZT Ceramics' by Stephen R. Platt, Shane Farritor, and Hani Haider, presents a theoretical analysis of piezoelectric power generation that is verified with simulation and experimental results. Several important considerations in designing such generators are explored, including parameter identification, load-matching, form-factors, efficiency, longevity, energy conversion and energy storage. [1]

- In the paper 'Modeling and analysis of a bimorph piezoelectric cantilever beam for voltage generation' by J. Ajitsaria, S Y Choe, D Shen and D J Kim, the modeling of piezoelectric bending beam for replacement of battery for the supply of low power in microwatts of power for sensors and actuators. [2]

- In the paper 'Determination of maximum power transfer conditions of bimorph piezoelectric energy harvesters' by

- Mahmoud Al Ahamad, A M Elshurafa, K N Salama and H N

- Alshareef, a method to find the maximum power transfer conditions in bimorph piezoelectric- based harvesters is proposed. Explicitly, derivation of a closed form expression that relates the load resistance to the mechanical parameters describing the bimorph based on the electromechanical, single degree of freedom, analogy. [6]

- In the paper, 'Performance Enhancement of Piezoelectric Energy Harvesters Using Multilayer and Multistep Beam Configurations' by Rammohan Sriramdas, Sanketh Chiplunkar, Ramya M.Cuduvally, and Rudra Pratap, the focus was made on enhancing the performance of piezoelectric harvesters through a multilayer and, in particular, a multistep configuration. Partial coverage of piezoelectric material in steps along the length of a cantilever beam results in a multistep piezoelectric energy harvester. A discussion for obtaining an approximate deformation curve for the beam with multiple steps in a computationally efficient manner. [7]

III. THEORY

Piezoelectric bimorphs have in the proposed model have 2 piezoelectric beams separated by a metal that is structural steel in this case. When the mechanical load is applied to the model, the strain generated induces the voltage thus leads to conversion from mechanical domain to electrical domain conversion. [13] Modeling piezoelectric bimorph harvesters using an electric circuit based on the electromechanical analogy is shown in Figure2. Left side of the network represents the mechanical domain and the right side of the network represents the electrical domain. Lm models the mass of the harvester, Ck models the inverse of stiffness, Rb models the mechanical damping, Zin models the input impedance of the harvester. [2]

A. Electrical Equivalent circuit.

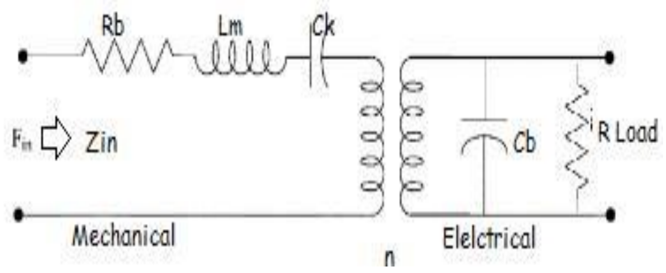

Figure 2: Electrical Equivalent system for the Piezoelectric Bimorph left side being mechanical domain and right side being electrical domain

$$\sigma in = RbS' + nV \quad (1)$$

σin models the input vibrations to the harvester. V being the voltage at the secondary of transformer.

$$V = iR \quad (2)$$

Substituting the equation 2 in equation 1, we get

$$\sigma in = RbS' + niR \quad (3)$$

The current generated because of mechanical stress is evaluated at zero electric field, is given by

$$i = awled31cpS' = \alpha S' \quad (4)$$

where a is a constant, that is, 1 or 2, depending on the wiring of the harvester, w is the width of the piezoelectric material, le is the length of the electrode in the piezoelectric harvester, d31 is the piezoelectric strain coefficient, cp is the Young's Modulus of the piezoelectric material.

Hence, substituting Eq. (4) into Eq. (3),

$$\sigma in = (Rb + n\alpha R)\, S' \quad (5)$$

Equation (5) provides important insight regarding the transfer of impedances in electromechanical analogy networks.

By relying on power system theory, the equivalent load resistance should be carried to the primary side and hold a new value of n^2R. However, Eq. (5) explicitly indicates that the load resistance will be carried to the primary side with a scaling factor equal to n. This finding is one of the important contributions of this communication.

Now, the optimum corresponding mechanical power delivered to the electrical domain, PML, assuming maximum power transfer is

$$PML = (n\alpha R/(Rb + n\alpha R)^2)\, \sigma in^2 \quad (6)$$

The electrical power, PEL, delivered to the load R can be computed as

$$PEL = iR^2R \quad (7)$$

Where iR is the current passing through the load, and it can be calculated using the current divider rule in terms of the applied mechanical strain rate as

$$iR = i/(1+jwCbR) \quad (8)$$

Where w is the radial frequency, Cb is the capacitance of the piezoelectric bender, and j is the complex number. Therefore,

$$iR = \alpha\, S'/(1+jwCbR) \quad (9)$$

Solving Eq. (5) for S_ and substituting the result into Eq. (10) yield

$$iR = [\ \alpha /(1+jwCbR)]\ [\sigma in/(Rb + n\alpha R)] \quad (11)$$

Consequently, the power delivered to the load now becomes

$$PEL = [\ \alpha /(1+jwCbR)]\ [\sigma in/(Rb + n\alpha R)] \quad (12)$$

For maximum power transfer, we take the derivative of Eq. (11) with respect to R and equate it to zero. After solving, the optimum resistance, Ropt, is found to be

$$Ropt = abs(\ Rb/[n\alpha+jwCb\ (Rb + 2n\alpha)]) \quad (13)$$

And the maximum power is obtained by substituting the value of Ropt as derived in Eq. (12) into Eq. (11). Now we turn the attention to Rb, which represents the electrical analogy of the mechanical damping; Rb can be expressed as follows:

$$Rb = k1k2bm \quad (14)$$

Where bm is the damping coefficient, k1 is a constant that relates stress to force, and k2 is a constant that relates strain to deflection.

Now the resonant frequency can be derived as follows

To find the resonant frequency Cb should be transferred to the primary side using the factor nα, and the input impedance is obtained as

$$Zin = Rb + jwLm + (1/jwCk) + (n\alpha/jwCb) \quad (15)$$

At resonance, the imaginary part of the impedance goes to zero. Hence, we write

$$jwLm-(j/wCk)-(jn\alpha/wCb)=0 \quad (16)$$

Finally, the resonant frequency is obtained as

$$wn=(1/Lm(1/Ck+ n\alpha/Cb))^{1/2} \quad (17)$$

B. Mechanical Equivalent circuit

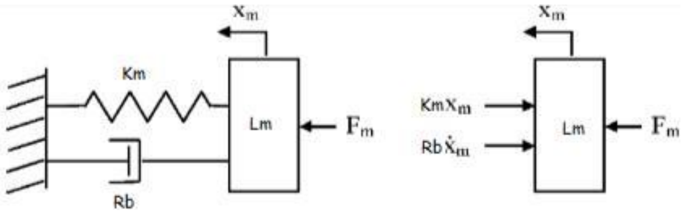

Figure 3 : Mechanical Equivalent circuit for bimorph.

$$Fm=Lmxm'' +Rbxm' +Kmxm \quad (18)$$

$$Fm/xm =(sMm+Bm+Km/s)$$

$$=(jwMm+Bm+Km/jw) \quad (19)$$

The above circuit in figure 3 shows the mechanical equivalent circuit. Here Lm corresponds to Mass and xm being displacement, xm′ being the velocity and xm″ being the acceleration. Rb is the mechanical damping coefficient. [2]

IV. MODEL DESIGN AND SIMULATION

We have designed and discussed about 2 models of piezoelectric heterogeneous bimorphs. One is the piezoelectric cantilever and other is piezoelectric weight-beam. The design was done using COMSOL multiphysics software. The analysis of these models is as follows.

A. Model 1- Piezoelectric Cantilever

We have used 2 materials PZT 5-A as Piezoelectric material and structural steel as the metal sandwiched between the 2 layers of PZT-5A. as shown in figure 4.

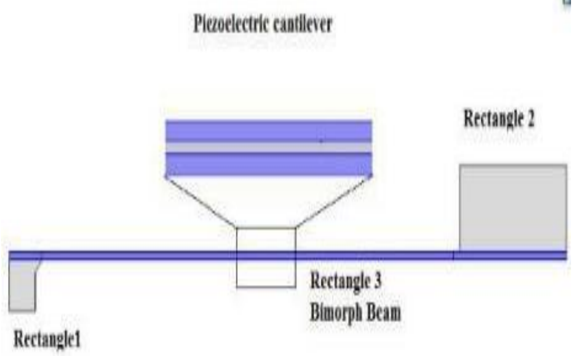

Figure 4: Piezoelectric cantilever structure.

Lead Zirconate Titanate is an intermetallic inorganic compound with the chemical formula Pb[Zr x Ti 1-x]O 3 (0x1). Also called PZT, it is a ceramic perovskite material that shows a marked piezoelectric effect, meaning that the compound changes shape when an electric field is applied and vice versa. Thus this compound can be used to generate the power when the stress is applied upon it, thereby helping in energy harvesting. The coupling between the structural and electrical domains can be expressed in the form of a connection between the material stress and its permittivity at constant stress or as a coupling between the material strain and its permittivity at constant strain. [8]

Steel derives its mechanical properties from a combination of chemical composition, heat treatment and manufacturing processes. While the major constituent of steel is iron, the addition of very small quantities of other elements can have a marked effect upon the properties of the steel.[9] The use of structural steel in this model is because of the main reason that it serves as the strengthening axis to the piezoelectric material that is PZT-5A there by not allowing the easy damage.

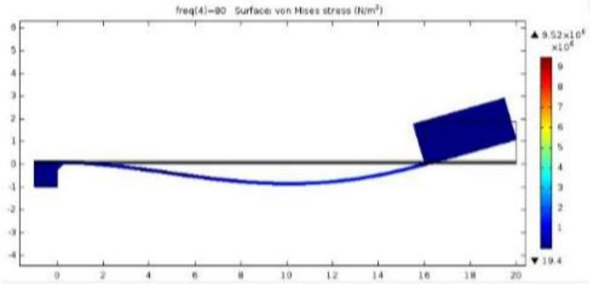

Figure 5: Piezoelectric Cantilever When the Stress Is Applied

The vibration mode of the piezoelectric cantilever is as shown in figure 5. The piezoelectric cantilever has one fixed constraint thus it vibrates as shown in the figure above.

B. Model 2- Piezoelectric Weightbeam

The Design procedure for piezoelectric weight-beam is similar to that of the procedure for piezoelectric cantilever beam except that in the geometrical design.

The piezoelectric weight-beam is as shown in the figure 6.

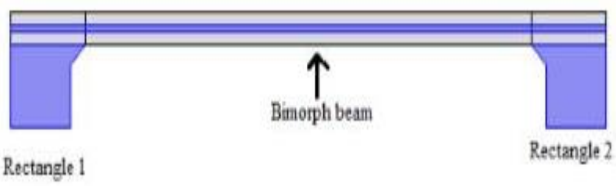

Figure 6: Piezoelectric Weightbeam Structure.

As the piezoelectric weight beam has 2 fixed ends, the vibration mode of this model is as follows. It vibrates as shown in the figure 7.

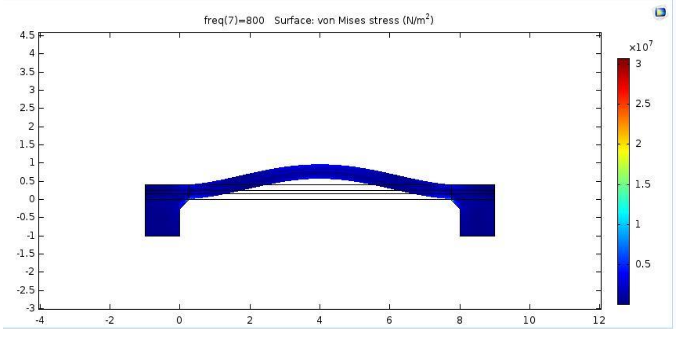

Figure 7: Piezoelectric Weightbeam when the stress is applied

V. RESULTS AND DISCUSSIONS

The following are the results of the simulation obtained for the piezoelectric cantilever beam Figure 8, Figure 9, Figure 10 show the plots of the results.

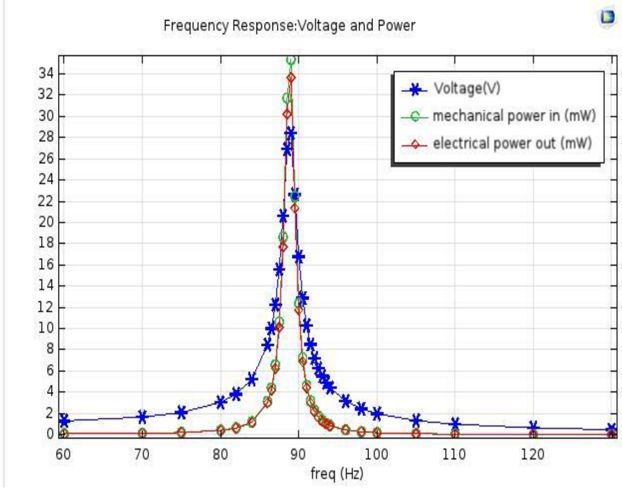

Figure 8: Frequency response Voltage and Power for piezoelectic Cantilever.

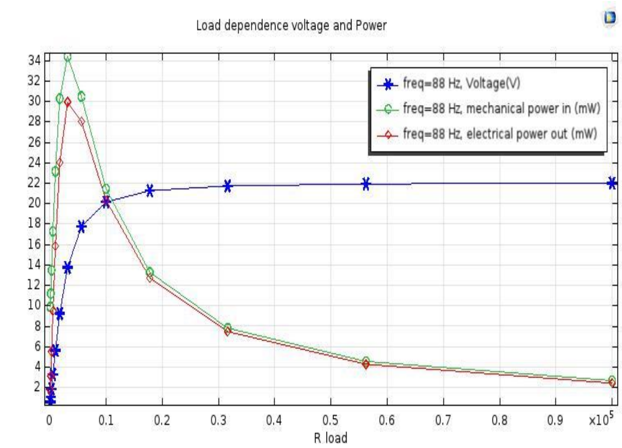

Figure 9: Load dependence on Voltage and Power for piezoelectic Cantilever.

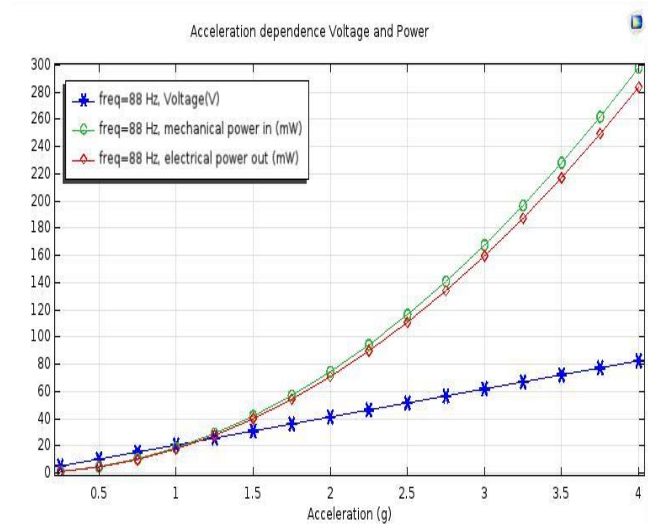

Figure 10: Accleration dependence on Voltage and Power for piezoelectic Cantilever.

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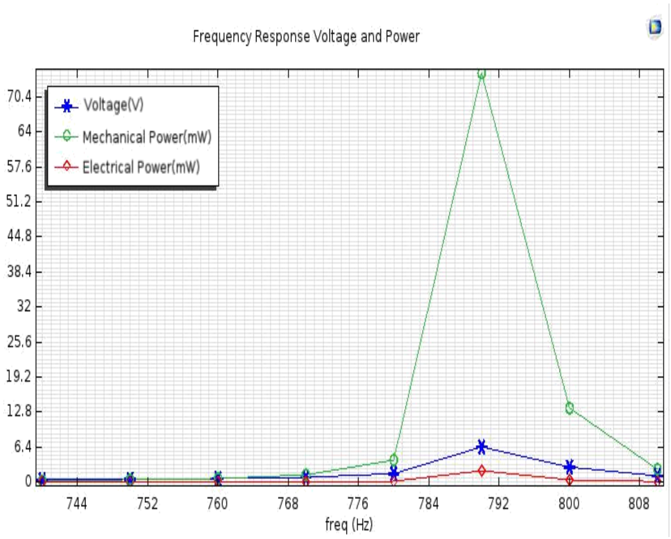

Figure 11: Frequency response Voltage and Power for piezoelectic Weightbeam

The following figures viz Figure 11, Figure 12, Figure 13 were the output plots obtained for the piezoelectric weight beam.

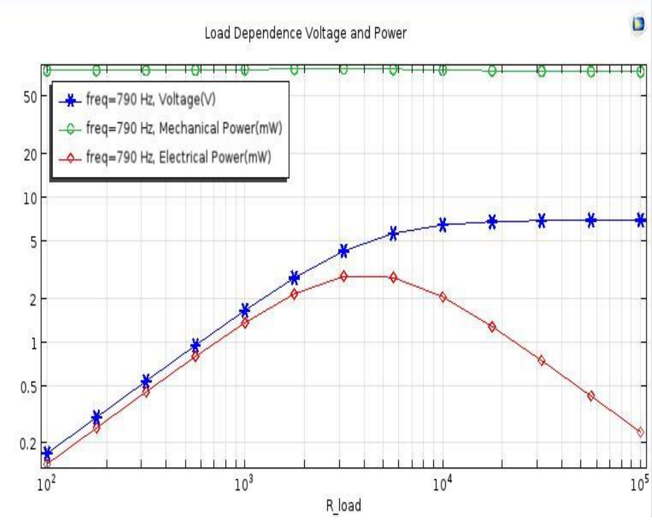

Figure 12: Load dependence on Voltage and Power for piezoelectic Weightbeam

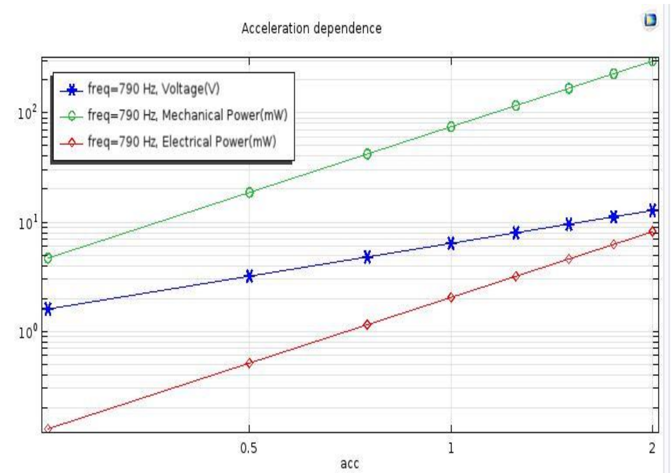

Figure 13: Acceleration Dependence on Voltage and Power for piezoelectic Weightbeam

The electromechanical coupling factor, k, is an indicator of the effectiveness with which a piezoelectric material converts electrical energy into mechanical energy, or converts mechanical energy into electrical energy. k values quoted in ceramic suppliers' specifications typically are theoretical maximum values. At low input frequencies, a typical piezoelectric ceramic can convert 30- 75% of the energy.

Parameters	PZT-Cantilever beam	PZT-Weight beam
Length of Bimorph(mm)	210	254
PZT Material	PZT-5A	PZT-5A
Out of plane dimension (mm)	14	14
Acceleration	1	1
R_{load} (Kohm)	12	12
Voltage (V)	28	6.4
Electrical power (mW)	34	2

Table 1 : Comparison Between 2 Developed Models.

VI. APPLICATIONS

Coming to applications, we find the application of the Piezoelectric cantilever in the vibrating machinery where the vibrating environment can cause this cantilever to vibrate and thus it can lead to generation of electricity. Application fields of the piezoelectric cantilevers can be vibrating machines, turbines and so on.

Coming to application of piezoelectric weightbeam, we can use this in the platforms like base of treadmills and conveyor belts where there will be continuous and constant vibrations there by generating the power.

VII. CONCLUSION AND FUTURE SCOPE

One method of performing power harvesting is to use PZT materials that can convert the ambient vibration energy surrounding them into electrical energy. This electrical energy can then be used to power other devices or stored for later use. The need for power harvesting devices is caused by the use of batteries as power supplies for wireless electronics. We have developed a model to predict the amount of power capable of being generated through the vibration of a cantilever beam with attached PZT elements. The derivation of the model has been provided with boundary conditions. The verification of the model was performed on a bimorph PZT bender and the piezoelectric weight beam, indicating that the models are robust and can be applied to a variety of different mechanical conditions. The models developed provide a design tool for developing power harvesting systems by assisting in determining the size and extent of vibration needed to produce the desired level of power generation. Efforts to improve the power generated by a bimorph have also been made and it was found that the dimensions of the piezoelectric harvester decide its output power. Apart from the shape of the bimorph, it is noticed that the electromechanical coupling factor (ke), the proof mass, and the quality factor of the device greatly influence the generated power.

REFERENCES

[1]. 'Low-Frequency Electric Power Generation With PZT Ceramics', Stephen R. Platt, Shane Farritor, and Hani Haider, IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 10, NO. 2, APRIL 2005.

[2]. H. A. C. Tilmans, "Equivalent circuit representation of electromechanical transducers: I. Lumped paramter systems," J. Micromech. Microeng.

[3]. S. Roundy and P. Wright, "A piezoelectric vibration based generator for wireless electronics," Smart Mater. Struct. 13, 1131 (2004).

[4]. "Modeling and analysis of a bimorph piezoelectric cantilever beam for voltage generation' , J Ajitsaria, S Y Choe, D Shen and D J Kim, Published 14 February 2007.

[5]. 'Determination of maximum power transfer conditions of bimorph piezoelectric energy harvesters', Mahmoud Al Ahmad, A. M. Elshurafa, K. N. Salama, and H. N. Alshareef.

[6]. 'Performance Enhancement of Piezoelectric Energy Harvesters Using Multilayer and Multistep Beam Configurations', Rammohan Sriramdas,

[7]. Sanketh Chiplunkar, Ramya M. Cuduvally, and Rudra Pratap, IEEE SENSORS JOURNAL, VOL. 15, NO. 6, JUNE 2015.

[8]. https://www.americanpiezo.com/blog/top-uses-of piezoelectricity-in-everydayapplications

[9]. R. Meadows, Electric Network Analysis (Burns & Oates, 1972).

[10]. M. El-Hami et al., "Design and fabrication of a new vibration-based electromechanical power generator," Sens. Actuators, A 92, 335–342 (2001).

[11]. S. Roundy, P. Wright, and J. Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes," Comput. Commun. 26, 1131– 1144 (2003).

[12]. C. Williams et al., "Development of an electromagnetic micro-generator," IEEE Proc.: Circuits Devices Syst. 148, 337–342 (2001).

[13]. N. Stephen, "On energy harvesting from ambient vibration," J. Sound Vib.293, 409–425 (2006).

[14]. Beeby, M. Tudor, and N. White, "Energy harvesting vibration sources for Microsystems applications," Meas. Sci. Technol. 17, R175 (2006).
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