Modelling, Fabrication and Characterization of a Piezoelectric Vibration Energy Harvester

Prasanta Kumar Samal,
Indian Institute of Science, Bangalore

Premanjan Sethy,
Indian Institute of Science, Bangalore

Pramod Kumar Malik,
Indian Institute of Science, Bangalore

Dr. Rudra Pratap
Indian Institute of Science, Bangalore

Abstract

In the immediate surroundings of our daily life, we can find a lot of places where the energy in the form of vibration is being wasted. Therefore, we have enormous opportunities to utilize the same. Piezoelectric character of matter enables us to convert this mechanical vibration energy into electrical energy which can be stored and used to power other device, instead of being wasted. This work is done to realize both actuator and sensor in a cantilever beam based on piezoelectricity. The sensor part is called vibration energy harvester. The numerical analyses were performed for the cantilever beam using the commercial package ANSYS and MATLAB. The cantilever beam is realized by taking a plate and fixing its one end between two massive plates. Two PZT patches were glued to the beam on its two faces. Experiments were performed using data acquisition system (DAQ) and LABVIEW software for actuating and sensing the vibration of the cantilever beam.

1. Introduction

There are so many technologies have been developed in energy harvesting, such as solar, wind, geothermal, and hydraulic power plants or farms. Since vibration exists everywhere, such as the vibration of floor and wall, machines, pumps, vehicle chassis, railway train or tracks, and human motions, etc. it becomes a good alternative energy source and receives more and more attention in recent years.

The process of converting the wasting vibration energy into useful one is known as vibration energy harvesting. When piezoelectric materials are used for conversion, this is termed as piezoelectric vibration energy harvesting. And also the present world scenario is such that, the big things are becoming bigger and bigger and small things are becoming smaller and smaller. An alternative for batteries for small machineries is to create energy while working. Using piezoelectric materials (e.g., PZT) is one way we can accomplish this. This is another application of piezoelectric transducer. Transducer is a device which converts one form of energy into other. In electromechanical system, the electrical energy is converted into mechanical energy and vice versa. They are of two types one is actuator, and another is sensor. When the electrical energy is converted into mechanical one to excite any structure, is called actuation. And when the mechanical vibration energy is converted into and represented in terms of electrical energy, is called sensing.

Piezoelectricity is the property of certain materials called piezoelectric materials. By virtue of which if the material is subjected to mechanical stress it generates charge distribution and thus there is voltage difference between two electrodes. This is known as direct piezoelectric effect. The reverse piezoelectric effect causes mechanical strain on the material by the application of electrical voltage. When an AC voltage is applied, it will cause it to vibrate and thus generate mechanical or pressure waves at the same frequency of applied AC voltage. This reverse piezoelectric effect is usually used as actuator which converts electrical energy into mechanical energy. Similarly, the direct piezoelectric effect can be used in sensing the mechanical displacements by measuring electrical voltage produced due to the resulting mechanical stress. Both actuators and sensors are the transducers which convert one form of energy into another [1].

A significant number of journal papers and conference proceedings develop accurate models and discuss the numerous applications of the field in great detail.

The piezoelectric effect was first mentioned in 1817 by the French mineralogist Rene Just Hauy[1]. It was first demonstrated by Pierre and Jacques Curie in 1880. Their experiments led them to elaborate the early theory of piezoelectricity. This theory was complemented by the further work of G.Lippman[2], W.G.Hankel[3], Lord Kelvin and W. Voigt (beginning of 20th century).

Harvesting vibration energy from civil structures such as tall buildings, communication towers, and long-span bridges were dealt [2-4]. Harvesting power in regenerative vehicle suspensions [5-9]. Harvesting Bike Vibrations Energy [10]. Power-generating floor has been developed by Research & Development Center of JR East Group [11]. Energy harvesting potential from railway tracks [12-15]. Power generation from road bump vibrations [16]. Vibration energy harvesting using piezoelectric Materials [17-20].

As expected from any relatively new technology, the research in this field has been mostly in design and development. Numerous products have been designed and developed within research organizations and universities. However, only a few have been realized as commercially viable products. This paper includes not only design, and development, but also conducting experiments validating its intended function.

[1] First observation of the presence of electric charges on the surface of a stressed tourmaline crystal
[2] Mathematical deduction of the inverse piezoelectric effect, confirmed experimentally by P. & J. Curie: 1881
[3] W.G.Hankel introduced the term piezoelectricity

First, the piezoelectric constitutive relations and the corresponding matrices are defined in section ‘‘Fundamentals of Piezoelectric Materials.’’ Then, finite element analyses and their results are shown in section ‘‘Numerical Analysis.’’ In section ‘‘Fabrication and Setup”, the procedure followed in realizing the device and the experimental setup is discussed. Experimental procedure and the results are plotted in section ‘‘experimental result.’’ The concluding discussion including future research directions are presented in section ‘‘conclusion.’’

2. Fundamentals of Piezoelectric Materials

Piezoelectricity is the coupling between electrical voltage and mechanical stress. It is the property of the material by which electricity is produced by the application of pressure and vice versa.

Piezoelectric Relations: The electrical behavior at constant stress or of an unstressed medium under the influence of an electric field is defined by two quantities, the field strength (E), and the dielectric displacement (D). Their relationship is:

$$\boldsymbol{D} = \boldsymbol{\varepsilon}^{\sigma}\boldsymbol{E} \qquad (2.1)$$

Here ‘ε^{σ}’ is the permittivity at constant stress or of the (unstressed) medium.

The mechanical behaviour of the same medium at zero electric field strength is defined by two mechanical quantities, the stress applied (σ), and the strain (ϵ). Their relationship is:

$$\boldsymbol{\epsilon} = \boldsymbol{S}^{E}\boldsymbol{\sigma} \qquad (2.2)$$

Here ‘S^{E}’ denotes the compliance of the medium (at zero electric field).

Piezoelectricity involves the interaction between the electrical and mechanical behavior of the medium. To a good approximation this interaction can be described by linear relations between two electrical and mechanical variables (σ and E):

$$\boldsymbol{\epsilon} = \boldsymbol{S}^{E}\boldsymbol{\sigma} + \boldsymbol{d}^{T}\boldsymbol{E} \qquad (2.3)$$

$$\boldsymbol{D} = \boldsymbol{d}\boldsymbol{\sigma} + \boldsymbol{\varepsilon}^{\sigma}\boldsymbol{E} \qquad (2.4)$$

These two equations are known as the strain form of piezoelectric equations. The second set of piezoelectric equations (stress form) can be obtained from the first set (strain form) as follows:

$$\boldsymbol{\epsilon} = \boldsymbol{C}^{E-1}\boldsymbol{\sigma} + \boldsymbol{d}^{T}\boldsymbol{E}$$

$$\boldsymbol{C}^{E-1}\boldsymbol{\sigma} = \boldsymbol{\epsilon} - \boldsymbol{d}^{T}\boldsymbol{E}$$

$$\boldsymbol{\sigma} = \boldsymbol{C}^{E}\boldsymbol{\epsilon} - \boldsymbol{C}^{E}\boldsymbol{d}^{T}\boldsymbol{E} = \boldsymbol{C}^{E}\boldsymbol{\epsilon} - \boldsymbol{e}\boldsymbol{E}$$

Where, $\boldsymbol{e} = \boldsymbol{C}^{E}\boldsymbol{d}^{T}$ = piezoelectric stress matrix, $\boldsymbol{C}^{E}$ is the stiffness matrix which is the inverse matrix of compliance matrix $\boldsymbol{S}^{E}$ and thus

$$\boldsymbol{e} = \boldsymbol{C}^{E}\boldsymbol{d}^{T}$$

$$\begin{aligned} e^T &= (C^E d^T)^T \\ &= (d^T)^T (C^E)^T \\ &= d(C^E)^T \\ &= dC^E \end{aligned}$$

As 'C^E' is a symmetric tensor. Substituting $\sigma = C^E \epsilon - eE$ in equation 2.4, we have

$$\begin{aligned} D &= d\sigma + \varepsilon^\sigma E \\ &= d(C^E \epsilon - eE) + \varepsilon^\sigma E \\ &= dC^E \epsilon + (\varepsilon^\sigma - de)\,E \\ &= e^T \epsilon + \varepsilon^\epsilon E \end{aligned}$$

Where, 'ε^ϵ'$= (\varepsilon^\sigma - de)$ = permittivity at constant strain (clamped permittivity).

Thus the stress form of piezoelectric equations is:

$$\sigma = C^E \epsilon - eE \qquad (2.5)$$

$$D = e^T \epsilon + \varepsilon^\epsilon E \qquad (2.6)$$

Piezoelectric Matrices: Piezoelectric materials are transversely isotropic. Transversely isotropic materials are a special class of orthotropic materials having the same properties in one plane (e.g. the x-y plane) and different properties in its normal direction (e.g. the z-axis). Such materials are described by 5 independent elastic constants, instead of 9 for fully orthotropic materials.

The only 5 independent elastic constants are: c_{11}, c_{33}, c_{44}, c_{12} and c_{13}.

Here we use the notation 'c' instead of 'c^E' for convenience. We have

$$c_{22} = c_{11},\ c_{55} = c_{44},\ c_{66} = 2(c_{11} - c_{12}),\ c_{23} = c_{13},$$

and other coefficients are zero. So we have 'c' matrix

$$[C] = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(c_{11} - c_{12}) \end{bmatrix}$$

As per equations (2.3) and (2.4), the piezoelectric matrix (d_{3X6}) is the coupling between mechanical stress (σ_{6X1}) and electric field strength (E_{3X1}). The only 3 independent piezoelectric coefficients are: d_{33}, d_{31} and d_{15}.We have

$$d_{32} = d_{31} \text{ and } d_{24} = d_{15},$$

and other coefficients are zero. So we have 'd' matrix

$$[d] = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix}$$

3. Numerical Analysis

Modal and Harmonic analysis were performed in order to determine the fundamental frequencies and its frequency response, using finite element calculation in ANSYS. For the analyses, the physical dimensions of the beam are given in the Table3.1, and its properties are given in the Table 3.2.

Table3.1: Physical dimension of system

Material	Length (mm)	Width (mm)	Thickness (mm)
Aluminum	150	25	1

Table3.2: Properties of Beam Material

Material	Elasticity (E) in GPa	Poisson's Ratio (υ)	Density (ρ) Kg/m^3
Aluminum	70	0.33	2800

Figure 3.1 through 3.4 show the four fundamental mode shapes of the cantilever beam and its corresponding natural frequencies. The frequency response of the system was obtained from harmonic analysis as shown in Figure 3.5. This correlates the modal analysis showing the spikes at corresponding natural frequencies.

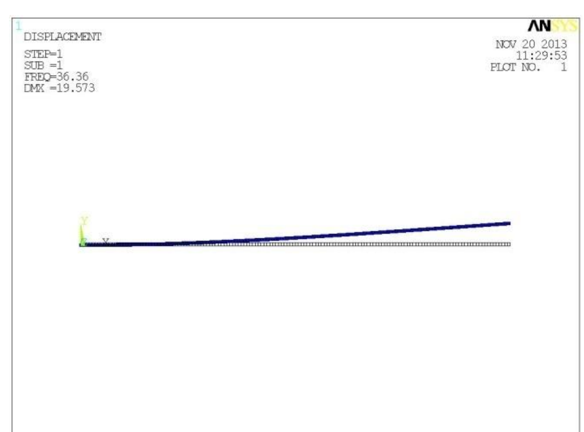

Figure 3.1: First Mode

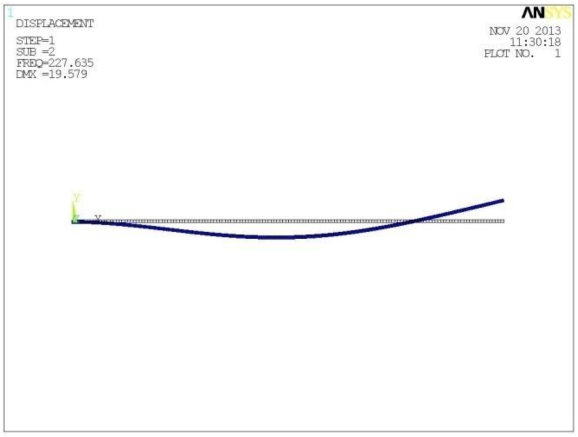

Figure 3.2: Second Mode

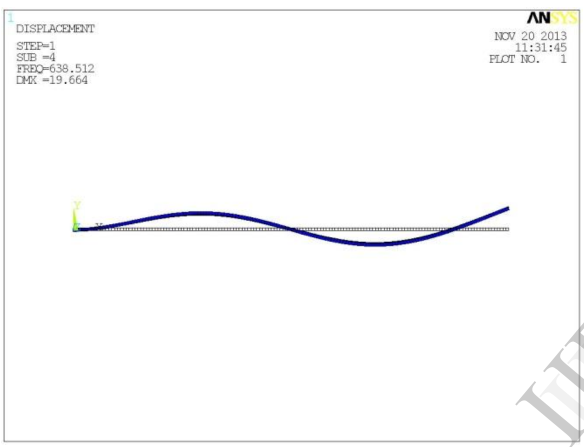

Figure 3.3: Third Mode

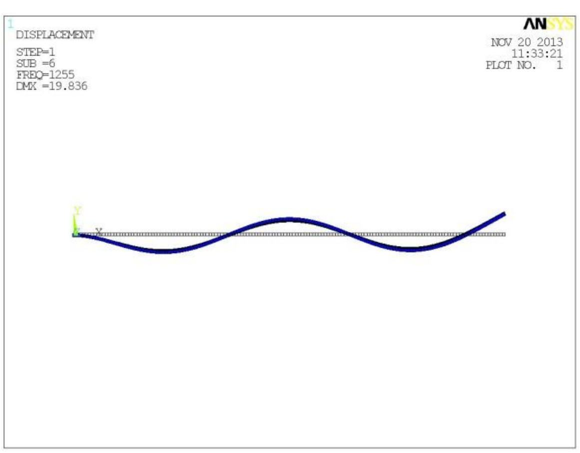

Figure 3.4: Fourth Mode

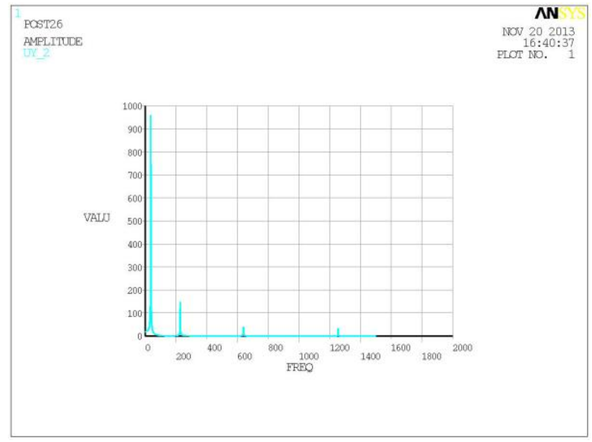

Figure 3.5: Frequency Response of the System

4. Fabrication and Setup

The simplest structure, "a cantilever beam" is realized by taking an aluminium plate as per dimensions. Two PZT patches, as the piezoelectric material, for actuation and sensing of its vibration, were collected. The PZT patches were glued to the beam on both the flat faces of the plate. The plate with two patches glued to it was fixed between two massive plates to realize the fixed condition of cantilever beam as shown in Figure 4.1.

In the actuation mode, when the AC voltage is applied, the (actuating) PZT patch deforms and thus the beam starts vibrating. Similarly the other (sensing) PZT patch deforms due to the vibration of the beam, and thus produces electric field between the electrodes as sensing signal. This is the application of piezoelectricity in actuation and sensing of the vibration of a beam.

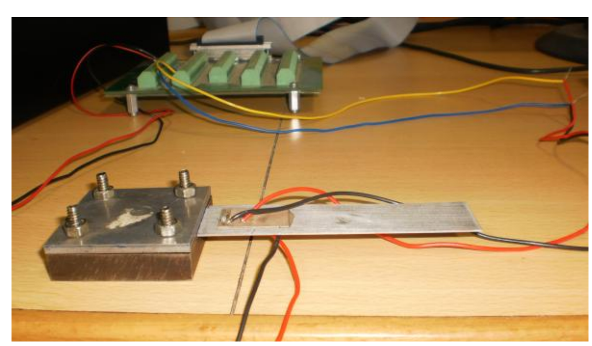

Figure 4.1: Actual Setup

5. Experimental Result

The vibration of the beam was actuated and sensed by using DAQ and the LabVIEW software. This acts as a transducer, the application of piezoelectric effect.

The beam was successfully actuated in different conditions and also corresponding vibrations were sensed. A LabVIEW VI was written for both acquiring and generating analog voltage. By running the VI the DAQ generates the voltage in the specific channel out of the two output channels available for the device. From the corresponding pins of the connector block, two wires were connected to the two electrodes of the actuating PZT patch. This AC voltage creates vibration of the beam according to the wave form of the signal. The generated voltage can be amplified using an Amplifier if the generated voltage is not sufficient to actuate the beam. Due to the vibration of the beam, electrical voltage difference is produced between the two electrodes of the sensing PZT patch. This voltage is now acquired by the acquiring part of the VI. Both the signals were seen on the graph indicators as well as stored in the measurement files. These measurement files were plotted in MATLAB.

Following are some of the plots in different conditions of actuation and corresponding sensing signals:

Figure 5.1 shows the actuation (Blue) and sensing (Green) of the beam vibration; initially no actuation i.e., noise, then it was continuously actuated at 58 V for around 700 milliseconds and the corresponding sensing voltage was 2.2 V. Then the beam was manually excited by just taping the beam as shown it is done for twice. Thus there was only noise in actuation part, and spikes were there in sensing part. Similarly, Figure 5.2 shows actuation and sensing of the beam (initially noise, excited first with high and then with low amplitudes.

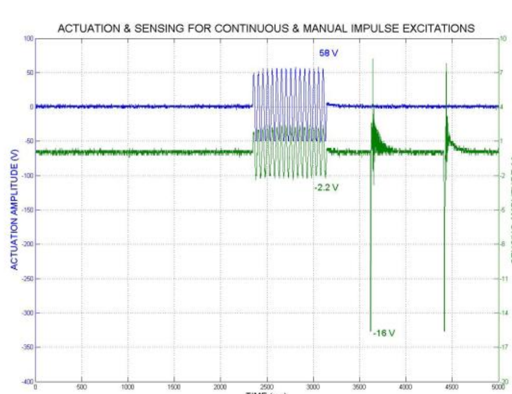

Figure 5.1: Actuation and sensing (noise, continuous sinusoidal signal and manual pulses)

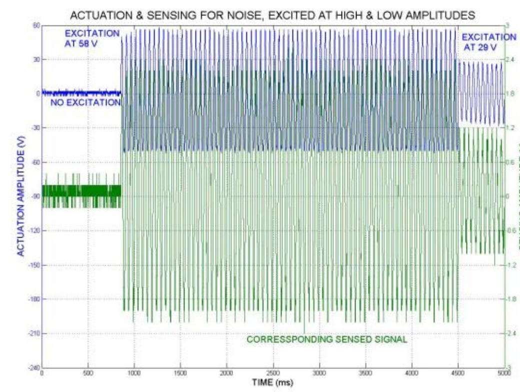

Figure 5.2: Actuation and sensing (noise, excited with first high and then low amplitudes)

6. Conclusion

The simplest system for testing the vibration energy harvesting has been successfully fabricated. Its numerical analyses were performed by finite element calculation using ANSYS. The first four fundamental frequencies were determined to be 36.36 Hz, 227.635 Hz, 638.512 Hz, and 1255 Hz respectively. The frequency response for the same was obtained and correlated. Experiments of the system have been performed using data acquisition system and plotted in MATLAB. The system was actuated at various frequencies with various amplitudes. It is concluded that the vibration energy can be harvested by the use of simple structures like beams, frames, plates, etc. with piezoelectric patches glued to them. The energy developed can be utilized in some useful power requirements specifically in small power requirements.

7. References

[1] Prasanta Kumar Samal, (June 2011), ME Thesis on “Fabrication and Characterization of Piezoelectric Micromachined Ultrasonic Transducer (PMUT) For Liquid Level Sensing.” Department of Mechanical Engineering, IISc, Bangalore.

[2] Kareem A, Kijewski T and Tamura Y (1999), “Mitigation of motions of tall buildings with specific examples of recent applications.” Wind and Structures 2(3): 201–251.

[3] Schwartz TA (2001), “When bad things happen to good buildings.” Architecture Week, 25. April 2001.

[4] Scott R (2001), "In the Wake of Tacoma: Suspension Bridges and the Quest for Aerodynamic Stability. Reston", VA: ASCE Press.

[5] Goldner RB, Zerigian P and Hull JR (2001) A preliminary study of energy recovery in vehicles by using regenerative magnetic shock absorbers. SAE paper #2001-01-2071.

[6] Martins I, Esteves J, Marques GD, et al. (2006) Permanent magnets linear actuators applicability in automobile active 1428 Journal of Intelligent Material Systems and Structures 24(11) suspensions. IEEE Transactions on Vehicular Technology 55(1): 86–94.

[7] Zheng X, Yu F and Zhang Y (2008) A novel energy regenerative active suspension for vehicles. Journal of Shanghai Jiaotong University (Science) 13(2): 184–188.

[8] Zuo L, Tang X and Zhang P (2010) Electricity-Generating Shock Absorbers, United States Patent Application 31/368,846, Filed 07/2010.

[9] Zuo L and Zhang P (2011) Energy, ride comfort, and road handling of regenerative vehicle suspensions. In: 2011

[10] E. Minazara, D. Vasic and F. Costa (2012) Piezoelectric Generator Harvesting Bike Vibrations Energy to Supply Portable Devices, SATIE (CNRS UMR 8029), PRES UNIVERSUD, ENS Cachan, 61 av. du Président Wilson 94230 Cachan France Université de Cergy-Pontoise 5031 IUFM Paris 12

[11] East Japan Railway Company (2008) Demonstration experiment of the ''Power-Generating Floor'' at Tokyo station.

[12] Bowness D, Lock AC, Powrie W, et al. (2007) Monitoring the dynamic displacements of railway track. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 221(1): 13–22.

[13] Igwemezie J (2007) Understanding stresses in rails. Interface: The Journal of Wheel/Rail Interaction.

[14] Penamalli GR (2011) Structural health monitoring and energy harvesting for railroad. Master Thesis, State University of New York at Stony Brook, Stony Brook, NY.

[15] Phillips KJ (2011) Simulation and control system of a railroad track power harvesting device. Master Thesis, University of Nebraska-Lincoln, Lincoln, NE.

[16] Chandler D (2009) More power from bumps in the road-MIT students develop energy-harvesting shock absorbers. MIT News.

[17] P. Muralt, A.Kholkin, M.Kohli, T.Maeder, "Piezoelectric Actuation of PZT Thin Film Diaphragms at Static and Resonant Conditions", Sensors and Actuators A, vol. 53, pp. 398-404, 1996.

[18] Henry A. Sodano and Daniel J. Inman (2004) A Review of Power Harvesting from Vibration using Piezoelectric Materials *LA-UR-03-5397, The Shock and Vibration Digest, 36(3), 197-205*

[19] Wei Wang, Tongqing Yang, Xurui Chen, and Xi Yao, Vibration Energy Harvesting Using a Piezoelectric Circular Diaphragm Array, IEEE Transactions on Ultrasonics, Ferroelectrics, and Fr 2022 equency Control, vol. 59, no. 9, September 2012

[20] Lei Zuo and Xiudong Tang (2013) Large-scale vibration energy harvesting, Journal of Intelligent Material Systems and Structures 24(11) 1405–1430