

# Acoustic Energy Harvesting Through Multilayer Piezoelectric Harvester Model

M. Sreenivasulu, V. Usha Shree, P. Chandrasekhar Reddy

*Abstract-Low-power requirements of contemporary sensing technology attract research on alternate power sources that can replace batteries. Energy harvesters' function as power sources for sensors and other low-power devices by transducing the ambient energy into usable electrical form. Energy harvesters absorbing the ambient vibrations that have potential to deliver uninterrupted power to sensing nodes installed in remote and vibration rich environments motivate the research in vibrational energy harvesting. Piezoelectric bimorphs have been demonstrating a pre-eminence in converting the mechanical energy in ambient vibrations into electrical energy. Improving the performance of these harvesters is pivotal, as the energy in ambient vibrations is innately low.*

*In this paper, we propose a mechanism namely Multilayer-PEHM (Piezoelectric Energy Harvester Model) which helps in converting the waste or unused energy into the useful energy. Multilayer-PEHM contains the various layer, which is placed one over the other, each layer is placed with specific element according to their properties and size, the size of the layer plays an important part for achieving efficiency. Furthermore, this paper presents an audit of the energy available in a vibrating source and design for effective transfer of the energy to harvesters, secondly, design of vibration energy harvesters with a focus to enhance their performance, and lastly, identification of key performance metrics influencing conversion efficiencies and scaling analysis for these acoustic harvesters. Typical vibration levels in stationary installations such as surfaces of blowers and ducts, and in mobile platforms such as light and heavy transport vehicles, are determined by measuring the acceleration signal. The frequency content in the signal is determined from the Fast Fourier Transform.*

**Keywords:** Acoustic Energy Harvester, Multilayer-PEHM, Piezoelectric Harvester Model, Energy Harvesting.

## I. INTRODUCTION:

Interest in energy harvesting from ambient vibrations has increased several folds in recent years owing to its uniqueness in powering wireless sensor networks without the need for batteries. Relatively longer lifetimes prove to be invaluable for devices operating in remote environments. The feasibility of using micro-electric generators for absorbing ambient vibrations has been observed in past few years, several researchers have reported various architectures of energy harvesters and power management circuits [1].

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However, the ubiquitous configuration for harvesting energy from vibrations uses a CBH (cantilever beam type harvester). Harvester models in the form of unimorph [2] and bimorph [3] piezoelectric beams has been found to be interesting due to its properties. Moreover, several efforts to improve the power generated by a bimorph have been made and during the verification, the observation is made that a triangular bimorph has higher tolerable excitation amplitude than a rectangular bimorph. Moreover, Harvester shape optimization can result in a significant increase in the harvested energy. Apart from the shape of the bimorph, it is also noticed that the proof mass and the quality factor of the device greatly influence the generated power. Several experimental and analytical parametric study was carried out on unimorph beams by identifying optimum piezoelectric thickness for different substrate materials. Recently, increase in the power developed by arranging multiple layers of piezoelectric material on one side of the substrate. Multilayer harvesters have been used with single supply pre-biasing (SSPB) for improving the power generation. In addition to the physical and geometrical parameters, it was observed that the load circuit impedance is an important performance parameter. Maximum power transfer conditions for bimorph harvesters have been derived, however, it has been observed that the power developed by a harvester can be made independent of the load resistance by implementing synchronous electric charge extraction technique, particularly from random vibrations.

## I.1 Equivalent Circuit Models:

Equivalent circuit representation of energy harvesters would facilitate modelling the associated power management circuit with relative ease. Electrical models of piezoelectric ceramics [4] for unloaded and loaded piezoelectric structures were proposed and Analysis of power output and efficiency of conversion for piezoelectric energy harvesting systems was performed. Cheng et al. have proposed equivalent circuit representation for magnetic vibrational energy harvesters [5]. Several researchers have carried out system-level analysis of energy harvesters including the power electronics. Circuit models have been effectively used in determining the power generated from low frequencies. Low-frequency forces exerted on shoes during walking have been studied as a potential source of power for mobile computing. Energy harvesting for wearable electronics from human motion at low frequencies has been successful by using frequency up-conversion technique. Equivalent circuit models provide versatile control for analysing the harvester irrespective of the kind of architecture adopted to harvest energy. Other than cantilever harvesters, compression-based harvesters can also be modelled using equivalent circuits for large-scale energy extraction using piezoelectric materials in applications such as roadways.

## I.2 Improving Energy Transfer

The vibration energy absorbing harvesters placed on a vibrating surface resemble passive dynamic vibration absorbers. The focus in energy harvesting community has been in treating the harvester simultaneously as an energy harvester and a vibration absorber. A dynamic vibration absorber passively absorbs unintended vibrations and a harvester as the absorber not only attenuates the primary source but also converts the energy into reusable electrical form. The system parameters, viz., the frequency ratio and the mass ratio of a system with undamped primary structure and a damped absorber have been determined in closed form. Several researchers have addressed the determination of optimum parameters for systems with light damping in the primary structure. The typical procedure adopted in obtaining the parameters for such systems is the optimization of primary structure response as discussed. The optimum frequency ratio for light to moderately damped primary structure was given in closed form, and procedure for obtaining absorber damping for continuous systems was given. However, for systems with moderate to large primary structure damping, the errors in estimating the optimum parameters using approximate relations become unacceptable. Hence, there is a need for a simple, robust and quick method to determine the optimum system parameters for a generic system.

## I.3 Broadband Vibration Energy Harvesting:

### I.3.1 Nonlinearities for Improving Bandwidth

Several researcher have carried out the experiment through vibration based energy harvester for power improvisation, these harvesters are designed to absorb energy at resonance, and improving bandwidth of energy harvesters is a major challenge. Broadband piezoelectric harvesters using multiple bimorphs with different operating frequencies has been presented, However, the probability that all of the harvesters are active at a given instant is low. Broadband power generation from nonlinear oscillations of a cantilever harvester is studied .The primary objective of studying nonlinear harvesting models is to design wide bandwidth and higher power levels for harvesters. Nonlinearities are introduced by biasing through end magnetic field and by the asymmetric M-shaped configuration. Energy harvesting from bistable structures also has been studied for improving the bandwidth of energy extraction. Additionally, parametric resonant based harvesting is reported where a passive mechanical amplifier before actual harvesting resonator reduces the initiation threshold amplitude of parametric resonant regimes. However, maintaining high-energy orbits, designing for correct harmonics of a stochastic source and determining the performance metrics are major challenges in bistable energy harvesting and furthermore, harvesters with nonlinear stiffness do not have the fundamental advantage over linear ones when excited by white noise.

### I.3.2 Self-tuning and Hybrid Harvesting

Several attempts to improve the power developed by vibration energy harvesters have been made through self-tuning, multimodal coupling, and hybrid harvesting. Resonant frequency tuning by modifying stiffness of the resonator using compressive axial preload has been investigated. Other tuning mechanisms using external load circuit have also been studied. An alternative technique to

tune resonance includes electrical excitation of piezoelectric layers to modify stiffness. Passive self-tuning of resonant frequency from 24 Hz to 49 Hz has been reported using a sliding beam. A semi-active magnetic force tuning technique that consumes energy only during tuning process is proposed. However, a careful audit of the amount of power expended in tuning is necessary. Anton describing self-charging structures has studied multifunctional energy harvesting concepts. Multimodal vibration energy harvesting working on magneto electric transduction using different modes of spiral cantilever from 15 Hz to 70 Hz has been recorded. Hybrid harvesters with combination of multiple domains are gaining impetus owing to their increased power levels. Magneto-mechano-electric generators working on both electromagnetic and piezoelectric principles were studied, where anisotropic single-crystal fiber composite generates the power in response to the external magnetic field variations. Hybrid energy harvesting systems using piezoelectric and electromagnetic mechanisms have been compared and studied have reported power of 0.25 W from the electromagnetic mechanism and 0.25 mW from the piezoelectric mechanism at 35 gn input acceleration and 20 Hz frequency from a multimodal energy harvester. Similarity and duality of electromagnetic and piezoelectric vibration energy harvesters for both efficiency and normalized power have been reported. Yang et al. have reported power levels of 176  $\mu$ W and 0.19  $\mu$ W from piezoelectric and electromagnetic domain respectively. Standalone electromagnetic energy harvester delivering 20 mW at 1 gn acceleration has been reported. A recent study on a piezoelectromagnetic hybrid energy harvester indicates that the performance of the harvester significantly depends on electrical boundary conditions. Hence, a comprehensive study of hybrid energy harvesters is required to determine optimal electrical boundary conditions and efficiency of conversion.

### I.3.3 MEMS Harvesters

Advances in computation technologies have considerably reduced the power requirements of integrated circuits used in sensors and sensor nodes. Hence, although power developed by absorbing ambient vibrations is low, powering sensor nodes by energy harvesting has become a reality in many different environments. Additionally, the associated electronics required for processing the generated power into regulated form is also turning efficient. Recent advances in improving the performance of processing electronics include switching circuits and bias-flip rectifier with shared inductor Integrating harvesters with the sensing node in addition to a power management circuit is possible by incorporating CMOS compatible methods of preparing piezoelectric film on silicon substrate. Several efforts are made to realize piezoelectric and electromagnetic harvesters in MEMS scale. A micro electromagnetic vibration harvester occupying less than 0.15 cm<sup>3</sup> volume made using discrete components and generating 46  $\mu$ W at 52 Hz from 60 mgn acceleration was proposed. The design was extended to include tuning of harvester resonance over a range of 30 Hz from 68 Hz to 98 Hz resulting in power levels ranging from 157  $\mu$ W to 62  $\mu$ W.

Planar configuration of electromagnetic MEMS harvesters has been focused in recent work on scaling laws and power density metrics for electromagnetic energy harvesters proposes an upper limit for peak power as a function of device volume and resonant frequency. Most common piezoelectric materials for MEMS harvesters are Aluminum Nitride (AlN), Zinc Oxide (ZnO), and Lead Zirconate Titanate (PZT). A unique design in which several beams suspend a single mass generates a power of  $66 \mu\text{W}$  for 0.5 gn input at 234 Hz. A  $2 \mu\text{m}$  thick PZT layer was used as the piezoelectric layer. A maximum power of  $40 \mu\text{W}$  was reported at 1.8 kHz for an input amplitude of 180 nm, using  $1 \mu\text{m}$  of PZT layer. Another design reported the use of AlN to generate  $60 \mu\text{W}$  of power from 2 gn input acceleration at 571 Hz. They have further compared the power developed by different end-masses at different pressures and report a power of  $85 \mu\text{W}$  at 1.75 gn acceleration from a vacuum packaged AlN harvester [6]. Moreover, a model was developed to trace the influence of end-mass by defining an effective length and report a power of  $128 \mu\text{W}$  from 1 gn acceleration at 58 Hz. Apart from thin film based micro harvesters, attempts have been made to thin down bulk piezoelectric materials to make micro scale harvesters as top down approach retains the bulk properties have thinned down bulk PZT to  $20 \mu\text{m}$  and bonded to a silicon substrate. Besides, a tungsten end-mass was bonded to the free end of the Si beam and a power level of  $205 \mu\text{W}$  for an input acceleration of 1.5 gn at 154 Hz was achieved. In order to achieve higher energy conversion efficiencies, epitaxial growth, and grain texturing of piezoelectric materials are being developed. Besides, transfer of PZT thin film onto a stainless steel cantilever beam has been shown to result in better power levels due to decreased relative permittivity. Lead-free based Potassium Sodium Niobate (KNN) energy harvesters are observed to be competing with thin film PZT based harvesters. Performance of d31 and d33 based harvesters using AlN at MEMS scale was evaluated and the design of inter-digital electrodes that improves the performance of d33 based harvesters. Fabrication and characterisation of bulk micromachined ZnO (d33based) energy transducer with inter-digital electrodes on a cantilever beam was reported. However, clamped-clamped type of bridge-shaped d33 based nonlinear piezoelectric harvester has been modeled. Additionally, different kinds of topologies were studied to improve the power generated by micro harvesters. They have observed that a micro cantilever coupled with a subsidiary cantilever was able to develop highest power over five different topologies. Material selection criterion for designing bulk piezoelectric harvesters was proposed. A comparison of piezoelectric materials for MEMS applications has been carried out. Moreover, five different figures of merit have been proposed for selecting piezoelectric materials for MEMS harvesters depending on energy conversion capacity of the active material. Although the dimensions of piezoelectric harvesters are different in bulk and MEMS scale, the figures of merit have to be independent of size and thickness of the active material. Hence, there is a need to delineate the contribution of each element of the harvester including end mass and determine the power developed by the harvester irrespective of the size.

#### I.4 Modelling of Piezoelectric Harvesters:

Power harvesters based on the piezoelectric effect are more promising in harnessing energy from ambient vibrations. In this chapter, design of piezoelectric resonators in the form of bimorph, multilayer and multistep harvesters is discussed. The piezoelectric materials used to build these resonators are Lead Zirconate Titanate (PZT) and Polyvinylidene fluoride (PVDF) in  $\beta$ -form. This phase of PVDF is obtained by stretching the  $\alpha$ -form films developed through solvent cast method. Low frequency harvesters can be easily designed with PVDF due to the inherent low elastic modulus. However, modelling of a stepped piezoelectric beam is discussed to design a low frequency resonator using PZT. In comparison to PZT, low cost and ease of production may be especially attractive for PVDF. Despite weak piezoelectric coupling observed in PVDF, methods of improving the performance of these harvesters are proposed using arrays and multilayer configurations. Modelling of harvesters using Newtonian and Hamilton approaches is discussed in subsequent sections. Bimorph harvesters are modelled using Newtonian approach while multilayer harvesters are modelled using extended Hamilton approach. In an effort to improve the power generated by a bimorph, stepped piezoelectric beam and multilayer harvesters are discussed using the Hamilton's principle that is relatively easier for handling composite beams. Additionally, design of a multi-step harvester is proposed that enhances the power generation considerably.

#### I.5 Motivation and Contribution of this research Work

In past two decades, the energy harvesting technologies have been explored in a broader manner by various researcher as an option for conventional power resources for the electronic devices that requires the low power to function. In this paper, we have proposed a mechanism that can extract the sound energy and convert into the electrical. Moreover, the contribution of our researcher work has been given below.

- In this research work, the focus is to develop the acoustic energy harvester through PZT device.
- Differing from the traditional approach, we propose multilayer- PEHM (Piezoelectric Energy Harvesting Model).
- Multilayer – PEHM is six layer placed one over the other based on their properties.
- In order to prove the efficiency of mechanism we evaluated our mechanism by comparing with various existing research work and Multilayer – PEHM outperforms all existing mechanism.

This research work is organized like any standard research work, here first section starts with basic need for energy harvesting and then it discuss the various terminology related to it followed by various issue related to it, last part of the section discuss the motivation and contribution of the research work. Second section discuss the various existing mechanism for energy harvesting along with their shortcoming, third section discuss the proposed mechanism i.e. multilayer- PEHM along with mathematical notation and methodologies. Finally yet importantly, section i.e.



fourth section discuss the evaluation of multilayer- PEHM through comparing with various technique.

## II. RELATED WORK

Energy harvesting technology deals with the extraction of energy from the unused energy in our environment and later converting it into useful purpose, it is one of the interesting phenomena and several researchers have contributed to develop the energy-harvesting model, some of them has been discussed here. [7] The slider mechanism in together with multiple shape memory alloy, which is super elastic ridges along with the movement of the frequency, which is low as well as at the natural frequency, it excites a piezoelectric bimorph and this all is proposed in this. In addition, here in [8] used similar impact mechanism as well as piezoelectric bimorphs pair get impacted by a free slider, which includes in a low frequency harvester. In [9] presented a design, which is novel for a frequency up-conversion device, which consists in together with snap-through mechanism-based multiple piezoelectric cantilever beams working along with proof mass, 4 buckled slender bridges. In [10] recommended impact driven mechanisms as well as in [11] too. There is beam that impacts occasionally on one or more piezoelectric beams in which at the frequency, which is resonant generator beams, are excited by it thus all process happens in the compliant driving beam and this is included in [10]. In [12] from low frequency vibration, by making the use of 2 permanent magnets, spiral piezoelectric beams pair as well as resonator mass, impact driven energy harvester package has been constructed. And also, the noticeable power is achieved by this package.[13] By utilizing the soft spring in together with proof mass which is linked to the beam i.e. tip of a piezoelectric cantilever beam, a mechanism which is having a simple frequency up-conversion. For expanding the piezoelectric energy, harvester applications in order to low efficiency as well as configurations are not applicable in applications, which are practically special as these configurations are proposed by the researchers as in together with the piezoelectric beam harvesters. With proof masses as well as various beams patterns, the several works recommend utilization of piezoelectric beam having shape of zigzag as it. Lower stress level as well as power density, which is higher, is presented by the configuration, which is zigzag. In addition, as compared to the cantilever beams the durability having higher is provided by it. Piezoelectric patches with the ability of being joined to the outside of wavering bodies, for example, vehicles and airplanes, another type of piezoelectric harvester is presented, From the fluids in pressure energy harvesting for e.g. blood pressure / hydraulic pressure, this is recommended by making the use of diaphragm-type piezoelectric transducers . To investigate the applications having high FAPW (Force Amplitude Power Generation) as well as non-resonant and for this, analysts are enabled by the bridge-type piezoelectric harvesters in together with Cymbal-type. By utilizing a harvester, which is having, s-shaped, from the vibration of multi-axis consists. A high -power generator as it is contactless generator was created by utilizing magnetic slabs as well as piezoelectric in together with the harvester having ring shaped energy. [14] From the human gait for the

harvesting of energy here a device, which is nonlinear, piezoelectric is proposed. Here considered the model recommended a potential function, which is non-linear, which is analytical. In past there they utilized some opposite of potential functions, which is same. On an external flame there is harvester positioned basically in harvester consists 2 magnets which are rotatable as well as piezoelectric bimorph cantilever beam in together with a tip magnet. On legs of human, here analysis is done by utilizing various harvesters as well as in 3.21  $\mu\text{W}$ , 18.73  $\mu\text{W}$ , and 23.2  $\mu\text{W}$  shown that maximum average result will be created by utilizing monostable, bi-stable as well as linear harvesters. More to say, in [15] Here utilization of solutions' combination which is requirement for optimization and characterization along with complex dynamic for e.g. chaotic and random vibrations of non-linear harvesters which are multi-stable. Bi-stable piezomagnetic systems have some problems that is high potential well in which limits some harvesters' application to applications having high oscillation amplitude in order to give energy which is sufficient for crossing the potential walls . [16] Piezoelectric beam in together with two external magnets and tip magnet along with unique plan as compared to the classical bi-stable system, which consists in piezoelectric energy harvester that is triple-well nonlinear, have proposed. Over the range of frequency from 15.1 Hz to 32.5 Hz as compared to the classical bi-stable system, it has done under vibration amplitudes which are smaller amount, which is significant of energy can, harvested as well as over the range of frequency between 10 Hz to 35 Hz, theoretical as well as experimental test will be result. Moreover, there is one system, which is based on cantilever beams and magnets that is multi-stable systems, nonlinear energy harvesters' design has been presented by the researchers. In [17] when under the frequency (i.e. resonant) the system gets excited then there harvested a power which is of higher level that is shown here by utilizing nonlinear Coulomb damping.

Moreover it is observed that huge research have been carried out for energy harvesting, through our survey we found that many of the mechanism fails to consider the right kind of material and their configuration this causes the degrade in performance. Hence, in this we have considered Multilayer-PEHM, which is discussed in detail in the next section of the same research work.

## III. PROPOSED WORK

### III.1.1 Bimorph - Dual Layer Piezoelectric Harvesters Preliminaries

Bimorph is nothing but cantilever, which is used for either sensing or actuation, this consist of two layer, it is widely used for the energy harvesting through its sensing ability. In here the bending of the bimorph produces the voltage that can be used for the measuring the acceleration or the displacement. Furthermore, Bimorph have the two distinctive variants based on the poling direction in the layer of piezoelectric, moreover vibrating bimorph imposes parallel combination once the poling is found to be similar and imposes the series combination if the poling is found to be the similar. Below equation represents stress charge form.

$$V_k = E_k^G U_L - g_{mk} G_m \quad (1)$$

$$F_k = g_{kL} U_L + \zeta_{kl}^U G_L \quad (2)$$

In the above equation  $U$  represents the strain and  $V$  represents the stress. In addition  $K$  and  $L$  subscript of the respective notation range from one to size.  $F$  Indicates the displacement (electric) and  $E$  indicates Electric Field, subscript of these two  $F$  and  $L$  range from one to three. In addition  $\zeta^U$  is relative permittivity,  $E^G$  is the stiffness at the electric field (kept as constant).  $g$  Represents the piezoelectric stress coefficient. Equation 1 and Equation 2 minimizes the compact form and this makes it simpler. Moreover, if the poling for the both layer found to be similar then the two electrodes represents the terminals. Any power from bimorph can be measured through considering the potential drop in the load resistance, which is denoted through  $T_N$ . Moreover, bending stresses in bimorph occurs mainly due to the transverse vibrations, the minimization of mm2 symmetry from equation and equation 2 can be represented as given below.

$$V_1 = E_{11}^G U_1 - g_{31} G_3 \quad (3)$$

$$F_3 = g_{31} U_1 + \zeta_{33}^U G_3 \quad (4)$$

In equation 3 and equation 4, number 1 and 3 presents length and thickness, moreover the electrode arrangement gives the equipotential surface for PDF (potential Distribution Function) and denoted by  $\Phi$ .  $d_m$  is the PD (Potential Difference) between the two electrode,  $e$  denotes the layer thickness. Moreover the PD (Potential Difference) is calculated through the below equation i.e. equation 5, this equation is said to be the linear  $\Phi_B = \frac{d_m B}{e}$

Now we calculate the EF (Electric Field) inside the given layer and given in the below equation.

$$\begin{aligned} \bar{G} &= -\nabla_{\Phi} \\ G_3 &= -\frac{d_m}{e} \end{aligned} \quad (5)$$

Equation 6 represents the relative displacement of the beam and given through the below equation.

$$U_1 = -B w_{t,zz} \quad (6)$$

$w_t$  is the displacement with respect to the ground displacement  $w_1$ . Moreover, the relation between the voltage and the relative displacement is given through the equation 7 and equation 8.

$$-e_{11}^G B w_{t,zz} + g_{31} \frac{x}{2e}, \quad V_1 = \quad (7)$$

$$F_3 = -g_{31} B w_{t,xx} - \zeta_{33}^U \frac{x}{2e} \quad (8)$$

Moreover, when the force balance is applied to the differential element of the beam element i.e. equation of motion is given as

$$\frac{\partial^2 \mathcal{O}_d}{\partial z^2} + \bar{\omega} \dot{w}_t = -\bar{\omega} \dot{w}_1 \quad (9)$$

In case if the width of bimorph becomes  $d$ , then the cross section though BM (Bending Moment) is given as

$$\mathcal{O}_d = \int_{-e}^e V_1 d_B f_B \quad (10)$$

Moreover  $V_1$  is substituted from the above equation i.e. equation 7, then the bending moment is depicted through the below equation, using the step function we achieve the two derivatives of bending moment in equation 11 and equation 12.

$$\begin{aligned} \mathcal{O}_b &= \frac{2d e^3}{3} e_{11}^G \frac{\partial^2 w_t}{\partial z^2} \\ &\quad - \frac{1}{2} g_{31} b \text{ex}[J(z) - J(z - N)] \end{aligned} \quad (11)$$

$$\frac{\partial \mathcal{O}_b}{\partial z} = \frac{2d e^3}{3} e_{11}^G \frac{\partial^3 w_t}{\partial z^3} - \frac{1}{2} g_{31} b \text{ex}[\Delta(z) - \Delta(z - N)] \quad (12)$$

$$\begin{aligned} \frac{\partial^2 \mathcal{O}_b}{\partial z^2} &= \frac{2d e^3}{3} e_{11}^G \frac{\partial^4 w_t}{\partial z^4} \\ &\quad - 0.5 e_{31} b \text{ex} \left[ \frac{d\Delta(z)}{dz} \right. \\ &\quad \left. - \frac{d\Delta(z - N)}{dz} \right] \end{aligned} \quad (13)$$

Later in equation 8, substituting equation 11, 12 and 13 along with the variable separation through the  $w_t$  as PSV (Product of spatial variation) and TV (Temporal Variation). Moreover from above equation the partial derivative is converted to differential equations,  $n$  is normal differential equation,  $I$  describes the mode. Equation 13 gives the frequency of the model; this is achieved through invoking the mode with the Mass  $\mathcal{O}_k$ , VDR (Viscous Dumping Ratio) is denoted as  $\zeta_i$  and the electromechanical CC (Coupling Coefficient) as  $I_k$

$$\ddot{t}_m + 2Z_k \Omega_k \dot{t}_m + \Omega_k^2 t_k - \frac{I_k}{\mathcal{O}_k} X_k = \frac{H_k}{\mathcal{O}_k} \quad (14)$$

Where  $\mathcal{O}_k$ ,  $H_k$  and  $I_k$  is computed through the equation 14, 15 and 16 respectively.

$$\mathcal{O}_k = \int_0^1 \bar{\omega} \Phi_k^2 dz \quad (15)$$

$$H_k = -\int_0^1 \bar{\omega} \dot{w}_1 dz \quad (16)$$



$$I_k = 0.5 g_{31} d e \Phi_{k,z}(m) \quad (17)$$

Equation 18 shows the charge  $S$  which is obtained by integrate in the area  $\gamma$

$$S = \int_{\gamma} F_3 dy \quad (18)$$

$$S = -g_{31} b d w_{t,z} - \zeta_{33}^U d m x (2e)^{-1}$$

Differentiating the equation 18 w.r.t time, current flow is achieved in equation 19,  $E_r$  is computed through equation 19

$$\frac{x}{T_m} + G_k \dot{x}_m + E_r \dot{x} = 0. \quad (19)$$

$$E_r = \zeta_{33}^U (2e)^{-1} \quad (20)$$

if it satisfies the condition that if two layers connected parallelly opposite to one another and given potential is same as the LR(Load Resistance) then  $d = d_m$ , through all the above equation we observe Electromechanical CC( coupling coefficient )which is given in equation 21.

$$I_k = g_{31} d e \Phi_{k,z}(m) \quad (21)$$

Similarly, the whole capacitance can be calculated through the summing of each layer and for parallel configuration, the capacitance is computed.

$$E_r = 2 \zeta_{33}^U d_m (2e)^{-1} \quad (22)$$

For  $k$  th mode, the natural frequency is given through below equation i.e. equation 23, here  $a$  is WF (Weighted Frequency) without dimension

$$\Omega_k = a_{Nk}^2 \frac{e}{(3m^2)^{1/2}} \left( \frac{e_{11}}{r} \right)^{1/2} \quad (23)$$

Moreover the beam shape function with  $a_N$  is given in equation 23, Here  $C$  indicates the modal constant. LDE (Linear Difference Equation) is solved through the harmonic response function given below.

$$\Phi(z) = C \left( \cos c_N \frac{z}{N} - \cos aN + \cosh aN \sin aN + \sinh aN \sin cN - \sinh cN z \right) \quad (24)$$

Here  $C$  is the modal constant; moreover, linear differential equation can be solved through the harmonic response function such as:

$$\begin{aligned} H &= H_0 g^{lyv} \\ t &= t_0 g^{lyv} \\ x &= x g^{lyv} \end{aligned} \quad (25)$$

Moreover these harmonic function is substituted in equation 13 and equation 20, after simplifying harmonic displacement are given as

$$t_0 = 1 + \frac{AB(A(1 + M_g^2 - B^2) + 2Z)B + I(B^2(1 + 2AZ) - 1)^{-1} H_0 (\Omega_p^2)^{-1}}{\quad} \quad (26)$$

Similarly, voltage is given in (26) and equation (27) computes the power

$$x_0 = \frac{ABm_g^2 \left( (A(1 + M_g^2 - B^2) + 2Z)B + I(B^2(1 + 2AZ) - 1)H_0I^{-1} \right)}{\quad} \quad (26)$$

Later, equation (26) is increased with respect to the  $R_l$

$$R = x_0^2 (2T_m)^{-1} \quad (27)$$

Equation (28) computes the optimized load resistance with corresponds to the maximum amount of power.

$$T_{opt} = 2\mu \left( e_r \Omega_p (M_g^4 + 4\mu^2)^{1/2} \right)^{-1} \quad (27)$$

In case of negligible coupling factor  $M_g$ , the current on harvester can be considered as the below equation.

$$K \approx \frac{E_r \Omega_p m_g^2 H_0}{2Z I} \quad (29)$$

Moreover, form the above equation it is clear that current on bimorph is not dependent on the load resistance and bimorph can be parallel in for increasing the power.

### III.1.2 Modelling of multilayer Piezoelectric Energy harvesting model (multilayer- PEHM)

In this sub-section of the research work, we design a multilayer Piezoelectric Energy harvesting model (multilayer- PEHM) for the optimal acoustic energy harvesting; in previous section with bimorph, we observe that the mechanism is not sufficient. Hence, in order to maximize the performance we use multi-layer configuration, it has multiple layers of piezoelectric material, here each of these material are placed one over the other. Here our model has six distinctive layers with different material, the detail of the material and their configuration has been discussed in the next section of this research work. Moreover these are configured and designed through the below process.

Let this structure have  $P$  layers, here the layers are placed in a manner where poling direction for neighbouring layer is one opposite to the other. Moreover, the layers are combined in such a manner that each layer contributes for generating power, also parallel configuration has various poling direction and this is mainly considered when focus is on the energy with the respective layer.

In here neutral surface height is achieved by assuming that the elemental beam has to be in absolute bending condition, hence the neutral surface height is given through the below equation i.e. equation 30. Here thickness of layer is denoted as  $v_l$ ,  $e_{11k}$  is young modulus and  $C_k$  denotes the Area.

$$\bar{B} = \sum_{k=1}^p e_{11k} C_k \sum_{l=1}^k v_l - \sum_{k=1}^n C_{11k} C_k \frac{v_1}{2} \left( \sum_{k=1}^p e_{11} C_k \right)^{-1} \quad (30)$$

Similar flexible rigidity of the multilayer beam is given in equation (31),  $e_{11k}$  indicates the modulus kth layer,  $d_k$  indicates the width, stress coefficient of the given layer is denoted by  $g_{31k}$ .



$$GK = \sum_{k=1}^{k=p} d_k e_{11k} \left( \left( \sum_{\ell=1}^{\ell=k} v_{\ell} \right) - \bar{b} \right) \left( \sum_{\ell=1}^{\ell=k-1} v_{\ell} - \bar{b} \right) + \frac{v_k^3}{3} \quad (31)$$

Equation 32 presents the Electromechanical CC (Coupling Coefficient) and denoted as  $J$ , moreover the capacitance of harvester are calculated in equation 33 and denoted as  $\epsilon_r$

$$J = \sum_{k=1}^{k=p} d_k g_{31k} \left( \left( \sum_{\ell=1}^{\ell=k} v_{\ell} - \bar{b} \right) - 0.5 \right) \Phi_{r,z}(n) \quad (32)$$

$$\epsilon_r = \sum_{k=1}^{k=p} d_k n \epsilon_{33}^u (v_k)^{-1} \quad (33)$$

Hence, proposed mechanism Multilayer- PEHM mechanism helps in converting the unused acoustical energy into the useful energy, it is observed that in past the existing model has failed to select the material that can provide the ideal configuration. Moreover, Multilayer- PEHM mechanism might not be the ideal mechanism but it does provide the efficiency that can be considered for the further research. Further, next section proves the efficiency of our mechanism.

#### IV. PERFORMANCE EVALUATION

In this section, we perform the evaluation of proposed model i.e. multilayer Piezoelectric Energy harvesting model; we have performed on the ideal configuration of the system, which is configured with i-7 processor loaded with 8 GB of RAM. Moreover, python is used as the programming language, performance evaluation section is parted into the three section, first section shows the model of our structure, second section shows the various graph plotted, and third section shows the **comparison of various model**.

##### IV.1 Model details and material used

Below figure shows the meshed model for multilayer PZT harvesting model, here Tetrahedral Mesh model has been used and has six distinctive layers. First layer is Silicon layer and the length of material is 700 um, second layer is placed with silicon nitride i.e. Si3N4, silicon nitride has various properties such as low density, high temperature strength, good fracture toughness and oxidation resistance. Apart from all these properties, it has very good fracture toughness and high strength. Here length of Si3N4 is 0.15 um. Third layer is Thermal oxide with length of 0.45um; the main advantage of the thermal oxide is its slow oxidation rate. Third layer is placed with platinum as platinum is one of the densest metal and mainly it is used due to its two main properties i.e. malleable and ductile properties.

Malleable properties is that it can be formed without breaking and it can be deformed without any change in its strength, the length of platinum is 0.15um. Fourth layer is placed with PZT, also known as Piezoelectric Layer uses lead zirconate titanate and has a length of 2um also known as PZT layer. Sixth and last layer is aluminium layer with length of 0.2 um; moreover, aluminium is used for its properties of thermal and electrical conductivity, Ductility and corrosion resistance. Moreover the size of the model is given in three axis scaling i.e. X= 150um, y =150um and z=100um.

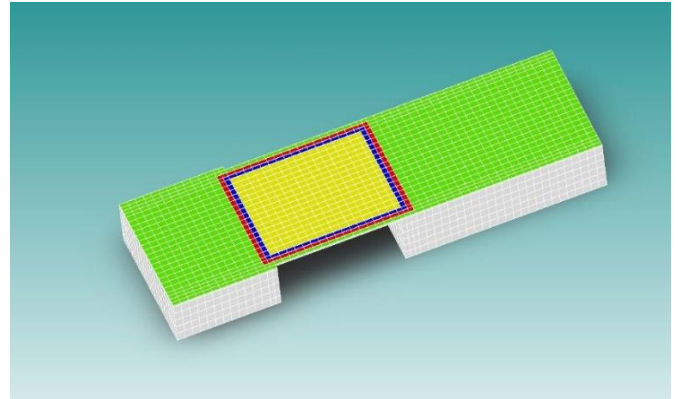


Figure 1: Multilayer PZT harvesting

##### IV.2 Evaluation through graph

In this sub-section of the performance evaluation, we tend to plot different graph to show the evaluation of multilayer-PZTEHM, figure 2 shows the displacement and its measured natural frequency. Here maximum displacement is observed at frequency of 182. Similarly, Figure 3 shows the power observed and its measured natural frequency, here it is observed that maximum power observed is at frequency 182. Figure 4 shows the power vs frequency, here as the power increase, increase in displacement is also observed. Moreover, from these three graph we prove the performance of proposed model.

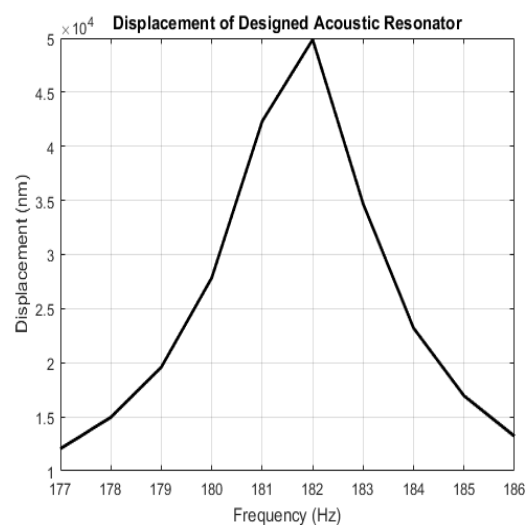


Figure 2: Displacement vs frequency



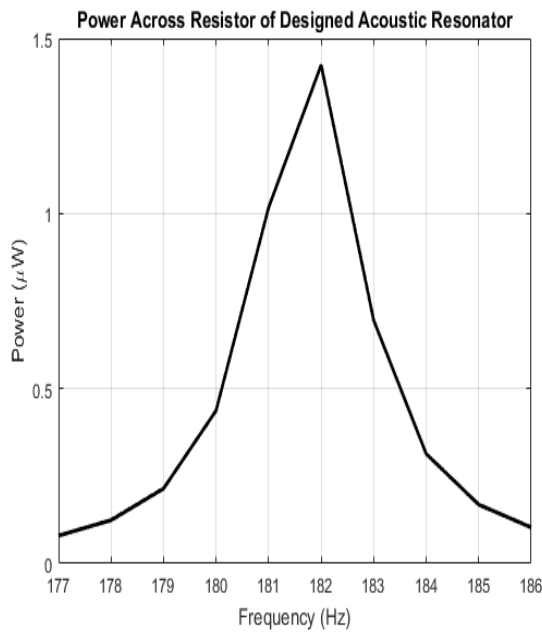


Figure 3: Power vs frequency

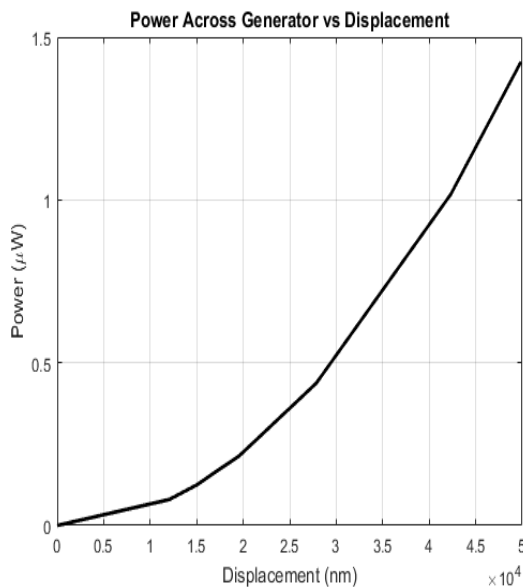


Figure 4: power vs displacement

IV.3 Comparative Evaluation

Furthermore, proposed model is evaluated by comparing the model with other existing model, to prove the efficiency of model we have considered several parameter as considered in the existing paper. Different parameter such as power, power density, Normalise power Density and Volume. In table 1, first column shows the different methodologies, second column presents the power; third column represents the power density, fourth normalised Power Density and Volume. Here in terms of power paper [18] observes the  $0.68\mu W$ , [19] observes  $0.63\mu W$ , [20] observes 1.46, [21] observes 0.80 and existing mechanism [22] observes 1.03 whereas proposed protocol observes the 1.4. Similarly, in terms of power density the value observed by these methods as [18], [19], [20], [21] and existing [22] are 5.66, 0.46, 1.14, 2.35, 9.36 whereas our methodology observes the 9.61. Similarly we observe that the volume is optimized in Multilayer-PEHM mechanism with 0.01456

Table 1 Comparison based on different parameter

Reference Paper	Power( $\mu W$ )	Power Density( $\mu W/mm^3$ )	Normalised Power Density( $\mu W/mm^3/g^2$ )	Volume( $mm^3$ )
[18]	0.68	5.66	5.66	0.12
[19]	0.63	0.46	6.57	1.50
[20]	1.46	1.14	28.50	1.28
[21]	0.80	2.35	0.58	0.34
[22] existing	1.03	9.36	58.5	0.11
proposed	1.4	9.61	99.91	0.01456

V. CONCLUSION

In this research work, we propose a novel acoustic energy harvesting mechanism named as multilayer-PZTEHM, this mechanism uses the multi-layer approach for energy harvesting. The main aim of this mechanism is to harvest acoustic energy in efficient manner. However, it is very important to select the material type, configuration, and layering. Hence, in multilayer approach one layer is placed above other in such a manner along with right configuration that it harvest the adequate amount of acoustic energy. Moreover to evaluate the proposed model the evaluation has been done in three parts first shows the different layer of the model, second part shows the evaluation through the graph plotted i.e. Displacement vs frequency, power vs frequency and power vs displacement, these graphs prove the efficiency of mechanism. Further evaluation is done through comparing the multilayer-PZTEHM along with existing approach. Here we observe that our model observes the Normalised Power Density of 99.91, power density of 9.61, Power of  $1.4\mu W$  that is higher than the other model. Moreover in future work our intention would be to improve the design of acoustic sensor for better energy harvesting.

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