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Multi-Source Piezoelectric Energy Harvester

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Abstract— **Energy harvester gained a great amount of attention due to the recent advances in wireless technology allowing sensors to be flexible placed in remote locations and operate at very low power for low powered electronic devices; especially when being placed in a remote area, micro scale energy harvesting is preferable. Piezoelectric energy harvesting is a promising technology for extracting the power from environmental vibrations. It generates the electrical power of few orders of amplitudes which is sufficient to drive several autonomous electrical devices. Such vibration-based energy harvester enhances the power output by increase the effective area of force or pressure. When the application area reduces, the performance of the generator drastically reduces. In this line, present work first studies the various factors affecting the amount of power harvested. Simplest model to be started is with a single source piezoelectric energy harvester. To enhance the power harvesting capability of such simplest system over a wide bandwidth range, a multi-source energy harvester system is explained in the present work. Multi-source energy harvester is achieved by increased area by developing a piezoelectric stack with increased number of parallel cantilever beam. Its capability to work over a range of frequency and number of stack for required power output is mathematically predicted. The system uses an appropriate interface circuit, SECE interface which can enhance the power output of the harvester. The continuous beam models based on Euler theory is considered in this thesis which is solved using Finite Element Method. Results are validated with ANSYS solutions. As a next step, the multi-source harvesting problem is considered to know the modeling issues and amount of power harvested. In shock absorber motion of motorbike while driving through the road the effective vibration is utilize to harvest power. Results are satisfactory when compared to operate a piezoelectric stack.**

Keywords - **Energy Harvesting, Multi-Source Piezoelectric Energy Harvesting, SECE interface, Piezoelement stack**

I. INTRODUCTION

Energy harvester gained a great amount of attention due to the recent advances in wireless technology allowing sensors to be flexible placed in remote locations and operate at very low power for low powered electronic devices [6]; especially when being placed in a remote area, micro scale energy harvesting is preferable. Energy harvesting is also described as capture and storage or direct use of ambient energy for human purposes [21]. Piezoelectric crystals can be uses its property to transfer ambient motion (usually vibration) into electrical energy that may be stored and used to power other devices. The phenomenon of the generation of voltage under mechanical stress is known as piezoelectric effect. The output power generated will be effective at the instances that obtain mechanical resonance for the time varying inputs from its generator [3]. By implementing power harvesting devices, portable systems can be developed that do not depend on traditional methods for providing power, such as the battery, which has a limited operating life.

Most piezoelectric electricity sources produce power on the order of milliwatts, too small for system application. Davion et al. [4] pointed that energy source such as solar, vibration, thermal and other potential energy sources, and described the mathematical model of each energy source [27]. This method is that changes the solar cells array from series to parallel or series-parallel mixed way to find out a best array that output the maximum power [24]. This method also can be used in other energy source. Vehicles driving along the highway or city street generate vibration as the vehicle tread encounters the texture of the pavement and the vehicle suspension undulates from variations in height along the roadway [1]. The kinetic energy contained in these movements of vehicle goes unused on a system level; although these processes are part of the physics in creating a comfortable and functional ride in a vehicle and maintaining traction [12]. This energy can effectively and efficiently convert to electrical energy by using the application of piezoelectric effect.

The study aims to develop of a complete, integrated multi-source piezoelectric energy harvest (M-PEH) electromechanical system, which can harvest energy from high frequency ambient source by enhancing the power output using multi-source technique. The ambient low frequency vibration is up-converted to a high resonant frequency one by the periodic impacts between the driving beam and the generating beams. To enhance the power harvesting capability of such simplest system over a wide bandwidth range, increase the available area effect of piezoelectric element. It is done by using multi-source stack.

In this paper, the generation of energy harvesting is take advantage of a piezoelectric cantilever based harvester. For piezoelectric energy harvesting, a composite cantilever beam is the most common way for accumulating vibration energy from host structure. In this study, stack will act as a number of cantilever beams arranged in parallel where piezoelement are mounting over each stack. In order to attain more power piezoelement are arranged in series and parallel connection. Multi-source piezoelectric energy harvester is connected to sece interface circuit which reduces impedance mismatch with respect to other interface circuit and capacitors in this circuit act as temporary storage unit. Solidwork model of the stack is generated and evaluated using fea and validated by ansys. paper follows by overview of piezoelement

II. OVERVIEW OF PIEZOELECTRIC ELEMENT

Piezoelectricity, also called the piezoelectric effect, is the ability of certain materials to generate an alternating current, voltage when subjected to mechanical stress or vibration, or to vibrate when subjected to an AC voltage, or both. The generation of electric field is proportional to the stress. The most common piezoelectric material is quartz. Certain ceramics, Rochelle salts, and various other solids also exhibit this effect.

Vibration-to-electricity conversion is a potential source for self-sustaining wireless sensor network in many environment. Low level vibrations occur in many environments including: large commercial building, industrial environments, automobiles, aircraft, ships, trains, and household appliances. Low level vibration source could generate about 300-800μW/cm³ in such environment. A stress is the function of a piezoelectric device, such as compression from outside forces, impact force. The first application of stress will generate voltage and current (power) within the material, but the stress must be relaxed in order for the material to generate power again. The amplitude and frequency of the signal is directly proportional to the mechanical deformation of the piezoelectric material. The resulting deformation causes a change in the surface charge density of the material so that a voltage appears between the electrode surfaces.

The electrical charges developed by piezo element decay with a time constant that is determined by the dielectric constant and the internal resistance of the element, as well as the input impedance of the interface electronics to which the film is connected. Practically speaking, the lowest frequency measurable with piezo element is in the order of 0.001Hz.

For best performance, the piezoelectric energy harvester should be excited mostly around its resonance frequency, deviation from the resonance frequency significantly reduces the output voltage.

Table 1: List of vibration source with their maximum accelerations and corresponding frequency

Vibration Source	Peak Acceleration (m/s²)	Frequency of Peak (Hz)
Base of a 5 HP 3-axis machine tool	10	70
Door frame just after door closes	3	125
Kitchen blender casing	6.4	120
HVAC vents in office building	0.2-1.5	60
Wooden deck with people walking	1.3	385
Washing machine	0.5	109
Motor bike shock absorber	5	25

The design model should consider the resonant frequency of the piezoelectric element. Select the piezoelement with respect to the frequency available so that it can attain a resonant frequency enable large amount of power output.

Piezoelectric vibration energy harvesters have advantages of high energy density, non-electromagnetic interface and easy integration with MEMS. To enhance the power harvesting capability of such simplest system over a wide bandwidth range, increase the available area effect of piezoelectric element. It is done by using multi-source stack.

An effective source of piezoelectric harvester is vehicle suspensions which produces a large broadband frequency.

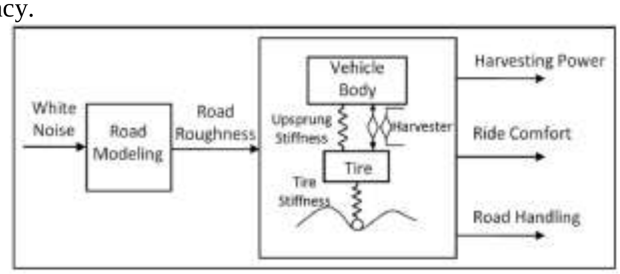


Fig. 2.1: Integrated road-vehicle harvesting model

Fig. 2.1 Explains the possibility of harvesting from vehicle. Harvester from road, pavement already excited, so principle of enhancing can make advantage from the methods. To enhance the power harvesting capability of such simplest system over a wide bandwidth range, increase the available area effect of piezoelectric element. It is done by using multi-source stack.

III. MULTI-SOURCE PIEZOELECTRIC ENERGY HARVESTER

Piezoelement theory: Piezoelectric materials are materials that convert mechanical energy from vibrations, force and pressure into electricity. At present, polycrystalline ceramic is the most common piezoelectric material. Typically, the constitutive equations for a piezoelectric material are given by following equation.

$$\delta = \frac{\sigma}{V} + dE \quad (1)$$

$$D = \varepsilon E + d\sigma \quad (2)$$

where δ is mechanical strain, σ is the mechanical stress, *Y* is the modules of elasticity (Young's Modules), *d* is the piezoelectric strain coefficient, *E* is the electric field, *D* is the electrical displacement (charge density), ε is the dielectric constant of the piezoelectric material. . The open circuit which means that the electrical displacement (D) is zero is defined as:

$$V_{OC} = \frac{-dt}{\varepsilon}\sigma \quad (3)$$

where t is thickness of the piezoelectric material.
Power harvested by a piezoelectric is given by:

$$E = \frac{\sigma_y^{2} k^{2}}{2Y} \quad (4)$$

Maximum energy available is 17.7mJ/cm³. Piezoelectric material has high energy density, high conversion efficiency and other excellent advantageous, this method has been widely used in ambient energy harvesting.

PZT is best for the application purpose. It is investigated the energy storage characteristics of a power harvesting system consisting of a PZT, full-bridge rectifier and a capacitor. Their work discussed the effect of various parameters on the efficiency of the storage circuit. Following their analytic investigation a prototype was developed and stated to have an efficiency of over 35%, more than three times greater than a solar cell.

To improve the robustness and efficiency of an energy harvester, a few studies have been carried out and the harvesters with wider bandwidth have been proposed or built. Three major ways are used to achieve a wider bandwidth for the piezoelectric harvesters which are (1) nonlinear stiffness, (2) bi-stable vibration and (3) multiple harvesters. While this approach has enjoyed great success in many aspects, there are two shortcomings. The first one is the low power area density and the second is the pronounced power reduction at off-resonance. The former is hard to improve due to limitations in the area of devices and the latter requires sophisticated techniques for frequency tuning by developing adjustable stiffness structures or the use of nonlinear techniques. This has motivated a prototype based on the use of multiple piezoelectric oscillators, since such a design allows multi-source deployment of structures to give increased power area density in a confined space. In addition, the overall bandwidth of an array structure can be enlarged by suitably adjusting the resonance of each oscillator.

A properly designed interface circuit plays a key role in the optimization of piezo elements. The applications of piezo element span from toys to military sensors and interfacing to electronics is highly application dependent. In many cases, piezo element can be directly connected to electronic circuits without special interface considerations. However, for those cases where an interface circuit is required, the following 3 steps are recommended:

1. Consider the frequency range and signal amplitude requirements over the desired dynamic range.
2. Choose a proper load resistance to assure the low end operating frequency and to minimize signal loss due to the loading effect.
3. Select a buffer circuit if the signal level is small. if a high value load resistance is needed, a low leakage high impedance buffer amplifier is recommended

Energy harvesting applications makes use of a single piezoelectric harvester or cantilever beam, which is called single source piezoelectric energy harvesting (S-PEH). In reality, S-PEH has some inherent limitations, for example, low power density and narrow operating frequency.

In this paper, new technique called multi-source interface circuit is used. Multi-source said that the cantilever attached with each other in a stack. The equivalent electrical impedance of a nonlinear full-bridge rectifier is difficult to compute in practice, and it cannot be considered a constant because of its intermittent conduction. While cases of serial and parallel connection of multiple piezoelectric elements have been investigated, we still lack a scalable and practical energy harvesting interface for M-PEH.

To optimize the performance of energy harvesting on bridge systems, vibration-based energy harvesting is studied for various bridges under different conditions.

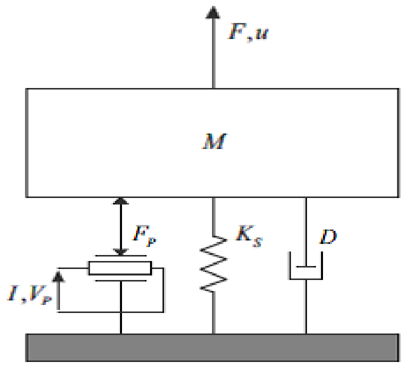


Fig. 3.2: Equivalent model of the cantilever-type piezoelectric energy harvester.

A type of interface simple, low-cost, nonlinear process to improve the efficiency of energy extraction, which is called the Synchronized Switch Harvesting on Inductor (SSHI) technique. Based on SSHI technique, some improved interfaces have been developed to enhance its performance, e.g. Double Synchronized Switch Harvesting (DSSH), Self-Power SSHI(SP-SSHI), SSHI with Magnetic Rectifier (SSHI-MR), Velocity Control SSHI (V-SSHI). Unfortunately, the standard interface and the SSHI interface both encounter the problem of impedance mismatching between the transducer and the load. Therefore, a technique called Synchronous Electric Charge Extraction (SECE), which adds a temporary storage unit to implement load decoupling, has been developed for these interfaces. These techniques can accelerate the charging process and improve the efficiency of energy extraction. However, they all require extra energy to support their active components in fact. While the energy generated from the piezoelectric element is usually low. In short, these above techniques have the same voltage threshold and power consumption due to the use of active components. Several interesting solutions that use mechanical switches instead of these active components in the circuit have been proposed, most of which utilize the motion of the piezoelectric cantilever beam to close mechanical contact and activate the switch control.

IV. SCALABLE SECE INTERFACE FOR M-PEH

The scalable standard interface for M-PEH is derived from the full-wave rectifier bridge circuit, where half of the full-wave rectifier bridge has been replaced by the middle point filtering capacitance pair (C_{f1}, C_{f2}), and the other half has been replaced by pairs of rectifying diodes (D_{n1}, D_{n2}), which corresponds with the number of piezoelectric elements. To obtain the rectified voltage, one output port of each piezoelectric element connects to the middle point of its rectifying diode-pair, and another output port of each piezoelectric element connects with the middle point of the filtering capacitance-pair. Assume that the rectifying diodes are ideal. When the absolute value of the i-th piezoelectric voltage V_p is less than the rectified voltage V_{DC1} (resp. V_{DC2}), the i-th rectifying diode-pair is blocked and the i-th piezoelectric element is in open circuit, causing the piezoelectric voltage V_p to vary with thedisplacement. Conversely, when the absolute value of the piezoelectric voltage V_p equals the rectified voltage V_{DC1} (resp. V_{DC2}),the rectifying diode D_{n1} (resp. D_{n2}) conducts and the current flows from the i-th piezoelectric element to the filtering capacitance C_{f1} (resp. C_{f2}). Multiple piezoelectric elements conducting at the same time can enhance the total charging current. The energy extraction process of the i-th piezoelectric element terminates when its piezoelectric voltage V_p drops to below the rectified voltage V_{DC1} (resp. V_{DC2}), and the current I_p cancels simultaneously Owing to the direct connection between the piezoelectric element and the storage unit, the harvested power of the other interfaces such as scalable standard interface and scalable series- SSHI interface for M-PEH is seriously influenced by the problem of impedance mismatching. But, the fact of impedance mismatching is almost unavoidable even though it has a match initial value. To overcome this difficulty, the scalable SECE interface for M-PEH, which adds an inductor L_i and a switch S_i to each piezoelectric element, has been proposed. Unlike the scalable series-SSHI inter-face, the inductor L_i of the scalable SECE interface is installed between the i^{th} rectifying diode-pair and the filtering capacitance pair, which acts as a temporary storage unit to implement the technique of load decoupling.

The SECE technique divides the energy extraction process into two stages. First, when the local extreme displacement of the i^{th} piezoelectric harvester occurs, the switch S_i is closed for a very short period and the energy in the i^{th} piezoelectric element is transferred to the inductor L_i. Then, the switch S_i opens and the energy stored in the inductor L_i is transferred to the storage capacitance C_{f1} (resp. C_{f2}). Figure 3.7 displays the schematic of the scalable SECE interface for M-PEH.

The governing differential equation of this SDOF system in its linear range is given by (3.1) in which F is the equivalent external excitation force on the mass, and F_p is the restoring force due to the piezoelectric element.

$$M\ddot{u} + D\dot{u} + K_s + F_p = F \qquad (5)$$

The expressions of the harvested power of these scalable M-PEH interfaces are derived as follows. According to the principle of the SECE technique, the harvested power of the

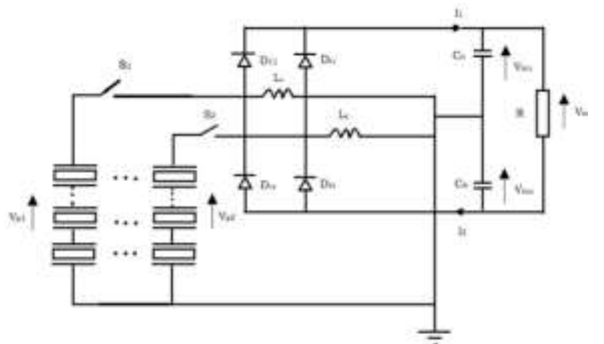


Fig. 3.3: Schematic of the scalable SECE interface for M-PEH.

scalable SECE interface for M-PEH is a function of each peak piezoelectric voltage V_{PMi}, and has no relation theoretically with the load resistance R. Therefore, the expression of the harvested power of the scalable SECE interface for M-PEH can be described by

$$p^{SECE} = \frac{1}{T}\sum_{i=1}^{N}\int_{0}^{T} V_{Pi} I_{Pi}\, dt = \frac{1}{T}\sum_{i=1}^{N} C_{Pi} V_{PMi}^2 \quad (6)$$

$$V_{PMi} = 2\frac{\alpha_i}{C_{Pi}} u_{Mi} \quad (7)$$

$$p^{SECE} = \sum_{i=1}^{N} \frac{2\omega \alpha_i^2 u_{Mi}^2}{\pi C_{Pi}} \quad (8)$$

where, I_{Pi} is the current of the i^{th} piezoelectric element and correspond to the displacement

V. MATHEMATICAL FORMULATIONS

An accurate model of a piezoelectric energy harvester plays a very important role in the study, design and application of the energy harvesting system. The modeling of piezoelectric materials has been studied thoroughly in the last century. The direct and inverse piezoelectric effects can be accurately described through the equations with a piezoelectric stain coefficient or piezoelectric stress coefficient. However, a more accurate model of a piezoelectric composite beam which is the typical formation of a piezoelectric energy harvester is in urgent demand for the study of energy harvesting.

Voltage and power output of single piezoelement very low compared to that required, in order to enhance both voltage and power output a stack is designed in cantilever beam model and piezoelement are arranging series and parallel connections.

Considering the low natural frequency of bridge structures, a cantilever with a single piezoelectric layer is used for the energy harvester in the present study to reduce the stiffness of the cantilever beam and therefore the fundamental natural frequency of the harvester. Apply Newton's second law of motion to the differential element in the *y* direction to obtain

$$\sum F_y = ma_y \Rightarrow V + \frac{\partial V}{\partial x}dx - V - q(x,t)dx = (\rho A x)\frac{\partial^2 v}{\partial t^2} \quad (9)$$

where ρ is the material density and *A* is the cross-sectional area of the element. The quantity *A* represents mass per unit length in the *x* direction.

The consistent mass matrix for a two-dimensional beam element is given by

$$[m^{(e)}] = \rho A \int_0^L [N]^T [N] dx \quad (10)$$

Substitution for the interpolation functions and performing the required integrations gives the mass matrix as

$$[m^{(e)}] = \frac{\rho A L}{420}\begin{bmatrix} 156 & 22L & 54 & -13L \\ 22L & 4L^2 & 13L & -3L^2 \\ 54 & 12L & 156 & -22L \\ -13L & -3L^2 & -22L & 4L^2 \end{bmatrix} \quad (11)$$

and it is to be noted that we have assumed constant cross-sectional area in this development.

VI. RESULTS AND DISCUSSIONS

Single cantilever model in solid works is shown below. Calculation conducted for ABS material which is (i) Good impact resistance with toughness and rigidity (ii) Metal coating have excellent adhesion to ABS (iii) Formed by conventional thermoplastic methods (iv) A light weight plastic

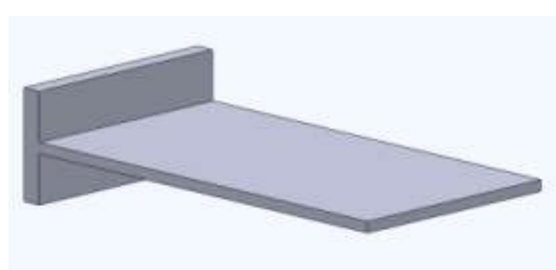


Fig. 5.1: Cantilever beam

Selected material is Acrylonitrile Butadiene Styrene (ABS)

Specifications of single cantilever beam,

Length, l = 90mm
Breadth, b = 58mm
Height, h = 2mm

The table 5.3 shows the properties of the Acrylonitrile Butadiene Styrene (ABS) material

Table 5.1: Properties of ABS

Property	Value
Density, ρ	$1.42 g/cm^3$
Tensile Strength	$40\text{-}50 N/mm^2$
Young's Modulus, E	2.00GPa
Poisson's Ratio	0.42

By applying the equation

$$\frac{\rho AL}{420}\begin{bmatrix}156 & -22L\\ -22L & 4L^2\end{bmatrix}\begin{Bmatrix}\ddot{v}\\ \ddot{\theta}\end{Bmatrix}+\frac{EI}{L^3}\begin{bmatrix}156 & -22L\\ -22L & 4L^2\end{bmatrix}=\begin{Bmatrix}0\\ 0\end{Bmatrix}$$

$$\omega_1 = 4.3\text{Hz}\,;\ \omega_2 = 29.58\text{Hz} \qquad (12)$$

VII. ANALYSIS IN ANSYS

Compared with the traditional analytical modeling, finite element analysis (FEA) is a more tractable approach to predicting he dynamic response of a harvester. The finite element analysis (FEA) simulation was performed using ANSYS.14.5. The finite elements in ANSYS that can be used to model the piezoelectric devices include 2NODE 188 and 3NODE 189 elements the specific descriptions of these elements can be found in the ANSYS theory manual

Table 5.2: ANSYS Analysed Result

SET	FREQUENCY
1	1.629
2	4.6672
3	10.398
4	14.117
5	23.915
6	30.231
7	34.295
8	36.731
9	45.473
10	57.583

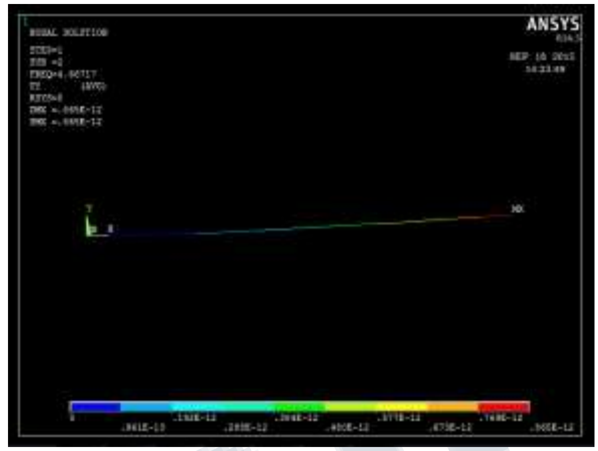


Figure 5.2: Deflection for frequency 4.667Hz

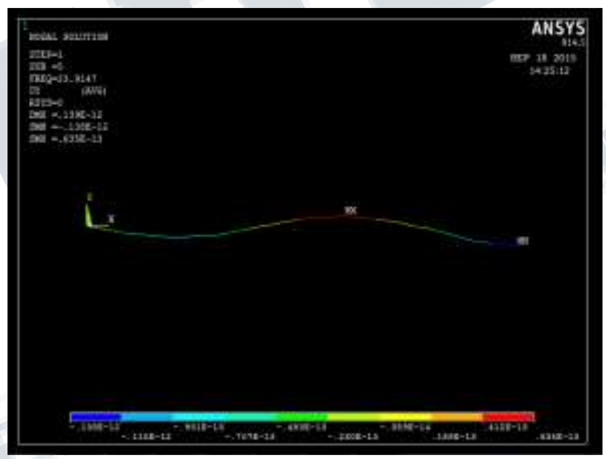


Fig. 5.3: Deflection for frequency 23.914Hz

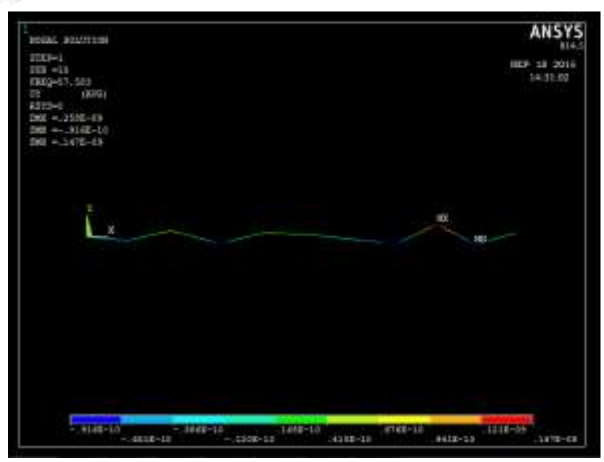
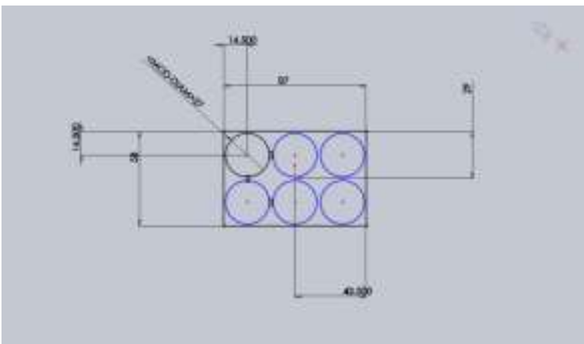


Fig. 5.4: Deflection for frequency 57.583Hz

VIII. SOLIDWORKS MODEL OF THE PIEZOELEMENT STACK

Cantilever beams stack into case and piezoelements are mounting over it. Each stack contains six piezoelement. By considering the performance, features, durability, conformance and aesthetic aspects find an optimized position for the placing the multi-layer piezoelectric energy harvester.



Fig/ 3.8: Single stack of cantilever beam

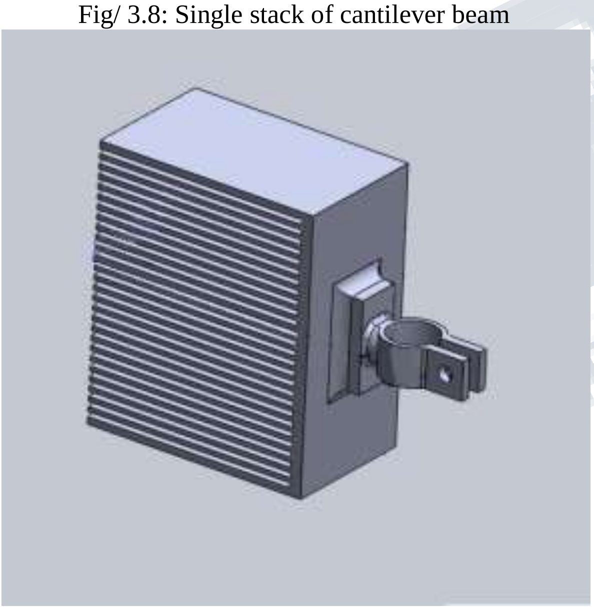


Fig. 3.9: Piezoelement stack

IX. CONCLUSIONS

Harvesting energy from the ambient environment is generally considered to be the best way to power small electronic devices, especially for those installed in irreplaceable and inaccessible locations. Converting mechanical energy to electrical energy using piezoelectric materials seems to be the most promising solution for powering these devices.

In this project, an integrated piezoelectric energy harvester is designed to scavenge enhanced energy. A single piezoelement is not sufficient for the generation of the application. Thus the design of a multi-source piezoelement stack of cantilever beams and combination of series and parallel connections of piezoelements are mounted for obtaining the required voltage and power. Acrylonitrile Butadiene Styrene (ABS) is used for modeling the cantilever beam stack. Synchronous Electric Charge Extraction (SECE) interface is used for enhancing the power output of the piezoelement stack which offers reduction in impedance mismatching. Piezoelectric stack was modeled in SOLIDWORKS.

Analyzed the modal analysis using FEA analysis and validated it with ANSYS software. An experiment was conducted based on single stack of PEH. Analysis gave a sufficient value of power output which can multiply by increasing the number of stacks.

Further work can be carried out by considering integrated circuit of the interface circuit. Study can be conducted based on low frequency input utilization for energy harvesting.

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