Modelling and Analysis of Novel Shape Vibrational Piezoelectric Energy Harvester

S. Srinivasulu Raju[1], D. Bhanuchandra Rao[2], U. Nagamaneswara Rao[3], K. Durga Prasad[2], P. Vamsi Sagar[4], R. Swapna[5], S. Hariprasad[6*]

[1]Department of EIE, VR Siddhartha Engineering College, Vijayawada,Andhra Pradesh -520007, India

[2]Department of Mechanical Engineering, Aditya Institute of Technology and Management, Tekkali-532201, Srikakulam, Andhra Pradesh, India

[3]Department of Mechanical Engineering, Aditya University, Surampalem-533437, Andhra Pradesh, India
[4]Department of Mathematics, Aditya University , Surampalem, Kakinada-533437, Andhra Pradesh, India
[5]Department of Physics, Avanthi Institute of Engineering and Technology, Tagarapuvalsa, 531162, Vizianagaram, India.

[6]Department of Physics, Basic Science & Humanities, Aditya Institute of Technology and Management, Tekkali-532201, Srikakulam, Andhra Pradesh, India

Abstract: This paper presents a novel approach for a Micro-Electro Mechanical Systems (MEMS) based piezoelectric vibratory motion harvesting device with three degrees of freedom (DOF). The H-shaped core silicon mass is supported by two pairs of T-shaped cantilever beams positioned on both sides of the device. The mass is securely attached to four sets of folded beams that oscillate exclusively along the X axes. The mass can oscillate in both the Y and Z directions due to two sets of linear rays. The piezoelectric material has already been positioned on the surfaces of the beam. The device has the ability to convert the vibratory motion energy of the beams into electrical energy, which is then converted into voltage and travels via the rectifier circuit to recharge the battery. The device's capacity to capture vibrational energy in all three dimensions leads to a more efficient energy harvesting result. The COMSOL Multiphasic® application is utilized for both development and simulation purposes. It is suggested that MEMS based energy harvesting device can be attached to shoes, tires, or any other oscillating surfaces to extract energy from the movement generated during travel, jogging, and walking.

Keywords: *Vibratory motion, MEMs based piezoelectric, T type cantilever beam, Energy harvesting, COMSOL*

1. INTRODUCTION:

A vibratory motion energy harvesting device can transform mechanical vibrations into electrical energy, which can then be restored in a battery for the future utilization. Vibrational activities such as running, jumping, and walking can provide clean and renewable energy. Through this process, the energy that would otherwise be squandered can be transformed into energy to replenish portable electronic devices. It provides a renewable energy source that can be utilized in the future. By integrating a vibration energy harvester, such as the one depicted, into diverse products such as footwear, bridges, and other objects, a substantial amount of renewable energy can be harnessed and contribute to environmental preservation. Energy harvesting has gained significant attention in recent years due to its ability to convert environmental waste energy into usable energy. These energy harvesting systems may effectively absorb the excessive vibratory motion energy of the surfaces, so contributing to the stabilization of road and bridge surfaces. The collected energy can be utilized to operate biomedical implants (such as pace-making devices) and portable sized electronics, thereby extending the duration between recharging intervals. Additionally, it can be utilized for autonomous and segregated devices such as sensor based wireless networks and security cameras to oversee forest wildfires, enabling them to operate with some or whole reliance on their own power sources. With its small size, lower cost, and greater efficiency, MEMS based technology is ideal for energy harvesting applications. From MEMS vibration energy harvesting systems that use electrostatic, electromagnetic, and piezoelectric transducers.

Fowler et al., [1] studied that the MEMS based energy harvesting device that utilizes ultrasonic motion waves to generate electrical energy. This harvester is based on an electrostatic transducer and is capable of achieving 3 degrees of freedom. The device employs a seismic loaded mass attached to a set of flexures to detect ultrasonic vibratory motion. A set of variable comb storage capacitors, both in-plane and out-of-plane, are charged utilizing the captured energy. The utilization of capacitor transducers in a different MEMS based vibratory motion energy harvester is recorded in [2]. Structural layer that was formed by Electroplating of nickel is utilized as a to facilitate the direct and uncomplicated assembly of components after the complementary metal-oxide-semiconductor (CMOS) process. Sidek et al., reported that the creation of a silicon-on-insulator microelectromechanical system (SOI-MEMS) device that can convert mechanical vibrations into electrical energy using electrostatic principles [3]. Based on modeling data, the device is capable of generating an exceptionally high harvest power of 5.891 W when subjected to an excitation frequency of 2 kHz. The Raju et al. [4] and Han et al. [5] studied and a description on utilization of permanent macro magnets by the electromagnetic energy harvesting device to convert into energy. Additional operating power is unnecessary as the coils and magnetic field work together to generate power. Piezoelectric energy harvesters convert vibrational energy into electrical energy. Piezoelectric materials generate an electrical voltage difference between their surfaces when subjected to vibration-induced stress, which can be used to charge batteries [6]. Janphuang et al., [7] studied a microelectromechanical system MEMS based vibratory motion energy harvester. This device utilizes piezoelectric cantilevers that have a similar structure to atomic force microscopy (AFM) and are connected to a spinning gear. A vibrating mass drives the gear. Srinivasulu Raju et al., [8] describes the utilization of a Zinc oxide (ZnO) piezoelectric cantilever in a MEMS vibration energy harvester for the purpose of transforming mechanical type of energy into electrical energy. Simulations were performed on energy harvesting devices that are working on MEMS based piezoelectric vibratory type with various cantilever designs to attain the maximum efficiency in energy conversion [9, 10]. Two three-axis piezoelectric vibration energy harvesters which could capture energy along the X, Y, and Z channels. Four L-shaped bulk-PZT/Si beams, capable of bending in the X, Y, and Z axes, are connected to the seismic mass in [11, 13]. In the transverse piezoelectric mode, a group of segmented anodes on the PZT arms harness mechanical energy. The energy harvester in reference [14] movement along the Z-axis in response to vibrations occurring both in the plane and out of the plane. PZT piezoelectric thin films has the capability to capture the strain generated by bending in a direction perpendicular to the surface [15].

This research proposes a 3-DoF piezoelectric MEMS vibrational energy harvester. The structure is linked to two seismic loaded masses using two series of T-shaped beams and four series of folding type beams. The mass centers of the seismic masses are located outside the plane of the beam due to their significantly greater thickness compared to the beams. The T-shaped beams have pre-deposited piezoelectric films on their undersides, which are equipped with top and bottom metal electrodes. Piezoelectric films may detect the induced stress within T-shape beams and provide a voltage output when the external vibration occurs in the Z direction, resulting in the bending of the beams in an up and down motion. When there is an external vibration in the X or Y direction, the inertial force generates a net torque. This torque causes the T-shaped beam at one end to bend upwards and the T-shaped beam at the other end to bend downwards. Piezoelectric films have the ability to detect stress within T-shaped beams and generate a voltage differential between the top and bottom surfaces of the beams. Consequently, the tool has the capability to gather vibrational energy in all three degrees of freedom. A sinusoidal voltage signal is generated. Mechanical vibrations are converted into electrical energy that was restored for future use by employing a rectifying circuit for converting it into direct current (DC) voltage, which can then be used to power portable devices or charge a battery. The vibrational modes of the piezoelectric energy harvester are simulated using COMSOL simulation, and subsequently, the corresponding resonance frequencies are obtained. In order to harness vibration energy for the production of environmentally friendly energy, the device can be incorporated into footwear, positioned beneath the road's surface, or attached to an individual.

2. HARVESTER DESIGN

In Fig. 1, the suggested vibration energy harvester was depicted in which the silicon has been placed onto a glass substrate. Anodic bonding method was employed to to connect the silicon structure and glass substrate.

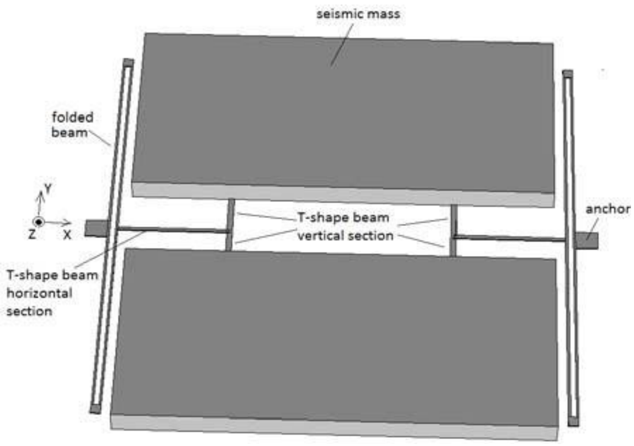

Figure 1: Proposed MEMS based vibrational energy harvester

The proposed structure contains of two seismic loaded masses connected by two series of T-shaped beams and 4 series of doubled beams, as shown in Fig. 1. Anchors are used to secure one end of the folded beams to the substrate. Prior to the silicon-glass bonding process, piezoelectric thin films, which have metal electrodes on the top and bottom (not visible in the picture), are positioned beforehand on the bottom surface of the T-shaped beams. The seismic masses possess a mass center positioned beyond the plane of the beams due to their considerable thickness in comparison to the beams. When the detection of in-plane vibration occurs, intentional imbalance is introduced to induce out-of-plane motion in both T-shaped beams. The seismic masses experience an inertial force that generates a resultant torque when there is vibration in the device plane along the X or Y axes. This torque forces one T-shaped beam to bend upwards and the other T-shaped beam to bend downwards, correspondingly. Moreover, when the vibration occurs on the Z axis, the T-shaped beams exhibit corresponding vibrations. Hence, the T-shaped beams exhibit vibrations that occur both within and outside the plane of the device. The stress generated within the T-shaped beams results in the production of a voltage between the top and bottom faces of the beams, due to the presence of pre-deposited piezoelectric films on the bottom surface. The battery is charged by harnessing the generated voltage, which is directed through a rectifying circuit to capture and store the vibration energy as electrical energy for future utilization.

The resonance frequency of the device is a critical determinant in vibration energy harvesters. The resonance frequency of the expedient would be adjusted to match the frequency array of the acquired vibration in order to enhance the efficiency of energy harvesting. The frequency of everyday motions such as walking and running is often below 100 Hz. The projected energy harvester consists of two T-shaped beams and four folded beams. The dimensions of each folded beam segment are Wfb, Lfb, and tb, respectively. The T-shaped beam's horizontal portion is characterized by the parameters Wtb1, Ltb1, and tb. The dimensions of apiece perpendicular slice of the T-shaped beam are Wtb2, Ltb2, and tb, correspondingly. The seismic mass is characterized by its dimensions: width (Wm), length (Lm), and thickness (tm). Silicon has a density and a Young's modulus of E. The energy harvester's resonance frequencies will be calculated independently for the X, Y, and Z axes. Vibration in the X-direction is produced by a combination of four folded beams and four T-shaped beam sections, which are linked in series with each other. All four of the folded beams run in tandem with one another. When all four beams are folded, their total spring constant is

$$K_{fb\_xtot} = 2EW_{fb}^3 . t_b / L_{fb}^3 \qquad \text{(i)}$$

All four vertical sections of the T-shaped beams are joined to one another in parallel. When all four vertical T-shaped beam sections are considered together, the overall spring constant is

$$K_{tb2\_xtot} = 4EW_{tb2}^3 . t_b / L_{tb2}^3 \qquad \text{(ii)}$$

The four parts of the beam that can be collapsed and the four parts of the beam that form a vertical T are linked in a sequential fashion. In the X-axis, the device's total spring constant is

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 1 (2025)

$$K_{X\_tot} = \frac{K_{fb\_xtot} \cdot K_{tb2\_xtot}}{K_{fb\_xtot} + K_{tb2\_xtot}} \qquad \text{(iii)}$$

The total mass is

$$M = 2\rho W_m L_m t_m \qquad \text{(iv)}$$

The resonant frequency of harvester, when modeled as a simple spring-mass system without considering the mass of the piezoelectric films and its electrodes, is

$$f_x = \frac{1}{2\pi}\sqrt{\frac{K_{X\_tot}}{M}} \qquad \text{(v)}$$

Only two parallel T-shaped beam segments contribute to vibration in the Y direction. The energy harvester's total constant of spring in the Y-direction is

$$K_{Y\_tot} = 2EW_{tb1}^3 . t_b / L_{tb1}^3 \qquad \text{(vi)}$$

The resonant frequency is

$$f_y = \frac{1}{2\pi}\sqrt{\frac{K_{Y\_tot}}{M}} \qquad \text{(vii)}$$

In Z direction, the vibration of beam is affected by total spring constant of the four folded beams and the two T-shaped beams.

$$K_{fb\_ztot} = 2EW_{fb} . t_b^3 / L_{fb}^3 \qquad \text{(viii)}$$

In the Z-direction, the overall spring constant of beam having vertical sections is

$$K_{tb1\_ztot} = 2EW_{tb1} . t_b^3 / L_{tb1}^3 \qquad \text{(ix)}$$

$$K_{tb2\_ztot} = 4EW_{tb2} . t_b^3 / L_{tb2}^3 \qquad \text{(x)}$$

The four folded beams, consisting of two horizontal T-shaped beam sections, four vertical T-shaped beam sections, and four folded beams, are interconnected in a series configuration to facilitate vibration in the Z-direction. The energy harvester's total spring constant in the Z-axis is

$$K_{z\_tot} = \frac{1}{(1/K_{fb_{ztot}} + K_{tb1_{ztot}} + K_{tb2\_ztot})} \qquad \text{(xi)}$$

The proposed harvester vibrating in direction of Z and its resonant frequency is

$$f_z = \frac{1}{2\pi}\sqrt{\frac{K_{Z\_tot}}{M}} \qquad \text{(xii)}$$

The calculations provided above can be used to provide a preliminary approximation of the resonant frequencies of the proposed harvester in the directions of X, Y, and Z. Nevertheless, they possess a streamlined spring-mass model that may result in some errors. The gadget demonstrates both rotational and tilting motion during operation due to the misalignment of the seismic masses and the center of mass of the beams. The lateral vibrations will encompass rotational and tilting movements, hence influencing the resonance frequencies. To achieve greater accuracy, it is recommended to use COMSOL FEM simulation to estimate the actual resonance frequencies of the energy harvester.

3. COMSOL MULTIPHYSICS SOFTWARE

The six vibrational modes of the energy harvester proposed in this article is simulated using COMSOL Multiphysics. The COMSOL simulation utilized the Solid Mechanics module to investigate the Eigenfrequency of the device. Additionally, we observed that the T-shaped beams exhibit oscillations and rotations in the Z axis when subjected to vibrations in directions of X, Y, and Z. The piezoelectric patch located on the lower surface of the T-shaped beams detect the strain induced by the vibration and rotation occurring outside of the plane, and subsequently generate electrical energy. The energy harvester operates by converting mechanical vibration energy into electrical energy. The design specifications of the piezoelectric energy harvesting device are provided in Table 1.

Table 1: Parameters considered for energy harvester

Modules	Parameter values (Width, Length, Thickness)
Folded beams	W_{fb}=50µm L_{fb}=5000µm Beam $_{tb}$=30µm
T-shape beams horizontal sections	W_{tb1}=3000µm L_{tb1}=90µm t_b=30µm
T-shape beams vertical sections	W_{tb2}=200µm L_{tb2}=1000µm t_{b2}=30µm
Masses	W_m=7800µm L_m=4200µm t_m=500µm

The structure of vibration energy harvesting devices is composed of single-crystalline silicon. The material's mechanical and electrical properties have been determined and certain from the pre-existing material library in COMSOL. The omission of the piezoelectric thin film in our analysis is deliberate, as our primary objective is to ascertain the vibration modes and resonance frequencies of the silicon base. Different piezoelectric materials yield varying voltages in response to the same applied stress. An optimal choice for a piezoelectric film is PZT-5H. Fig. 2 depicts the mesh model of the proposed structure harvester.

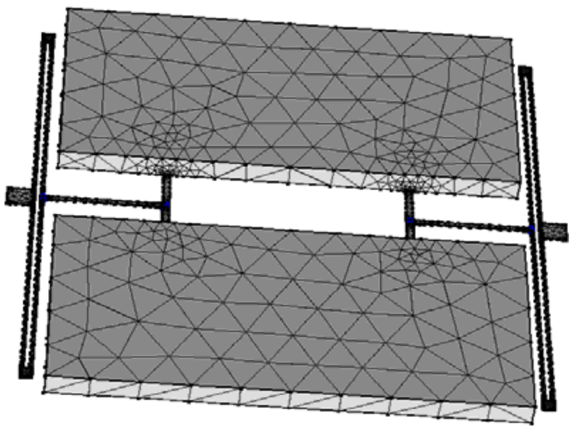

Figure 2: Meshed model of proposed harvester

4. RESULTS AND DISCUSSIONS

The COMSOL software is utilized for the design and modeling of the piezoelectric vibration energy harvesting device. The simulation modal is used to extract the first six vibration modes of device, together with their corresponding resonance frequencies. Figure 3 illustrates the initial vibrational mode, characterized by a resonance frequency of f1=15.57514Hz. This represents the vibration response in the Y direction, as seen. The seismic masses rotate about the X axis due to the inertial force since their centers of mass are not in the same plane as the beams. The T-shaped beams undergo tilting, which induces stress and subsequently leads to the generation of voltage by the piezoelectric films.

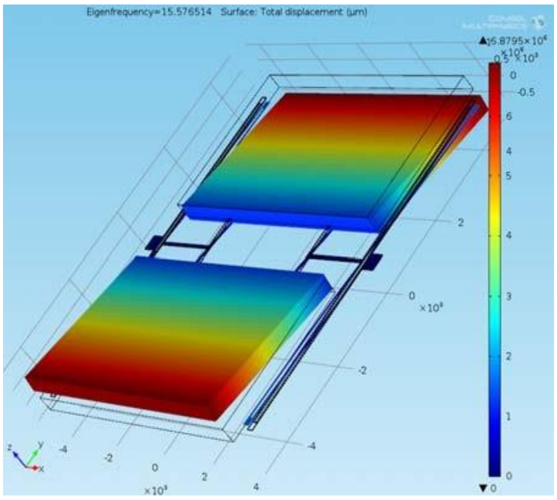

Figure 3: First resonant mode for proposed harvester

The 2nd vibrational mode of energy harvester as shown in Fig. 4, showcasing the simulation results obtained using COMSOL. The resonance frequency that is linked to this is f2=22.4384 Hz. This vibration mode that occurs when input vibration propagates in the Z direction. During this mode, both masses undergo oscillations in both the upward and downward directions along the Z axis. Consequently, the folded beams, along with both sections of the T-shaped beam, experience upward and downward bending, causing the beams to move out of alignment.

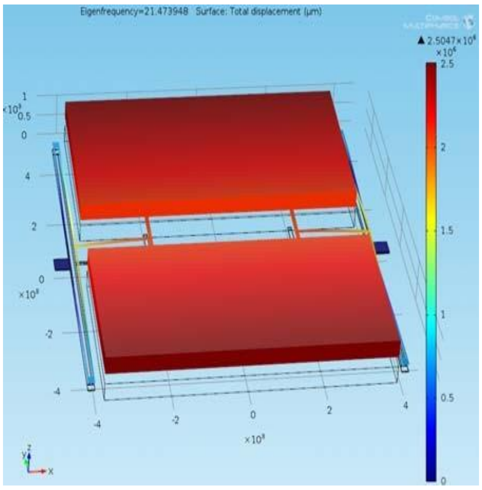

Figure 4: Second resonant mode for proposed harvester

The application of piezoelectric coatings on the lower surface of the T-shaped beams generates electricity due to the tensile stress induced within the beams.

The simulation results for the 3rd vibrational mode of proposed harvester as shown in Fig. 5. The resonance frequency that is linked to this is f3=41.367501Hz. The vibrational mode corresponding to an input vibration in the directional X is depicted here. The seismic masses undergo rotational motion because to the inertial force they experience, resulting in a net force. The masses right and left halves exhibit upward and downward tilting in the Y direction. Consequently, one T-shaped beam exhibits upward bending while the other displays downward bending. The internal stress in T-shape beams is generated by the bending that occurs out of the plane, resulting in the production of voltage between the top and bottom sides of piezoelectric films.

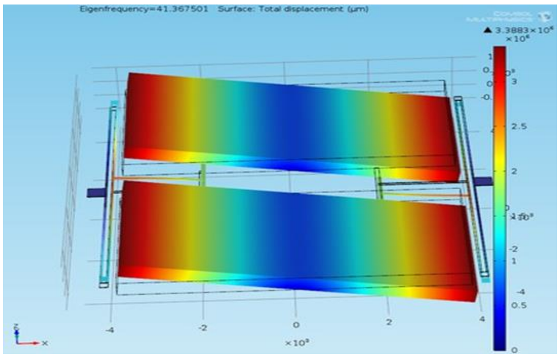

Figure 5: Third resonant mode for proposed harvester

Results for the higher vibrational modes in the COMSOL simulation are also obtained. Consequently, they are excluded from this list as they do not fall under the energy harvester's working modes. Based on the COMSOL simulation, it is evident that vibrations in all the three directions cause the proposed T-shape structure to vibrate in a direction perpendicular to their plane. Consequently, the beam material will undergo internal stress, leading to the generation of voltage output by the piezoelectric films on its lower surface. This enables the gathering and retention of vibrational energy from the surroundings for future utilization. It exhibits superior efficiency compared to energy harvesters that are only sensitive in one direction, as it is capable of collecting vibrational energy from all three degrees of freedom. The resonance frequencies of the initial vibration modes are all below 50 Hz, making them highly compatible with the typical frequencies associated with everyday motion. The device could potentially harness the kinetic energy produced by human movements such as exercising, walking and jumping in order to generate power. The device can be highly compact and easily put into the sole of shoes due to the utilization of MEMS technology, as exemplified in Fig. 6. The kinetic energy generated by the shoe's vibration can be harnessed and stored in rechargeable batteries for subsequent utilization during activities such as walking, running, or exercising. The energy harvesting device is capable of replenishing the auxiliary battery of portable electronic devices, including digital cameras, smartphones, and other compact electronics. Renewable energy is generated by this technology, which also provides a practical way for customers to charge their mobile batteries while they are on the go. On a daily basis, individuals engage in walking, jogging, and exercising. Integrating MEMS energy harvesters into every pair of shoes might provide a substantial amount of clean energy.

Figure 6: Application of the vibrational energy harvester

5. CONCLUSIONS AND FUTURE WORK

This study explores a MEMS based energy harvester capable of collecting energy across all three Degrees of Freedom (DoFs). The energy harvester utilizes inertial sensing technology to detect and convert input vibrations into electrical energy, which can then be stored for future use. The proposed beams with masses have different thicknesses. The asymmetry leads to the generation of a force, resulting in a remaining torque and displacement of the T-shaped beams from their equilibrium position due to the in-plane vibration. T-shaped beams will exhibit deflection in the same direction as the input vibration along the Z-axis. The piezoelectric patches located on the bottommost superficial of the T-shaped beams detect internal stress and generate voltage as an output. The electronic circuits transform the AC voltage into DC voltage, which is then utilized for the purpose of charging batteries or powering portable electronic devices. The suggested device exhibits superior omnidirectional energy harvesting capabilities compared to a unidirectional energy harvester. The vibrational modes of the system were pretend using COMSOL Multiphysics, and the corresponding resonance frequencies were determined. The resonance frequencies of the employed vibration modes in the X, Y, and Z axes are f_x=42.37501 Hz, f_y=16.7514 Hz, and f_z=22.4348 Hz, as determined by the COMSOL simulation. Due to its compact size, this material is very suitable for use beneath the soles of tires, shoes, road surfaces, and any other areas that experience frequent vibrations. The energy that was previously dissipated through vibrations can now be captured and utilized. In the future, stress modelling will be employed to ascertain the utmost stress induced by input vibrations along the X, Y, and Z axes within T-shaped beams. To ascertain the precise voltage output resulting from the input vibrations, we will additionally perform a piezoelectric simulation.

ACKNOWLEDGEMENTS:

The authors are thankful to the Director, Aditya Institute of Technology and Management (AITAM), Tekkali, Andhra Pradesh for the constant support and encouragement.

REFERENCES:

[1] A.G. Fowler, S.O.R. Moheimani, S.A. Behrens, "3-DoF MEMS ultrasonic energy harvester", *IEEE Sensors Journal*, 2012, pp. 1-4.

[2] S. Srinivasulu Raju, M. Umapathy and G. Uma, "Piezoelectric energy harvesting with single and multiple condensed cavities", *Journal of Ferroelectrics*, vol. 507, pp. 29-42, 2017.

[3] O. Sidek, M.A. Khalid, M.Z. Ishak, M.A. Miskam, "Design and simulation of SOI-MEMS electrostatic vibration energy harvester for micro power generation", *2011 International Conference on Electrical, Control and Computer Engineering (INECCE)*, 2011, pp. 207-212.

[4] S. S. Raju, M. Umapathy, and G. Uma, Design and analysis of high output piezoelectric energy harvester using non uniform beam, Mech. Adv. Mater. Struct., vol. 27, no. 3, pp. 218–227, 2020. DOI: 10.1080/15376494.2018.1472341.

[5] M. Han, Q. Yuan, X. Sun, H. Zhang, "Design and Fabrication of Integrated Magnetic MEMS Energy Harvester for Low Frequency Applications", *Journal of Microelectromechanical Systems*, 2014, Vol. 23,Issue 1, pp. 204-212.

[6] P. Durga Prasad, Mani Satthiyaraju, A. Radhamanohar, Ali Akbari-Fakhrabadi, Viviana Meruane, S. Hari Prasad, Arun Thirumurugan. Flexible piezoelectric, triboelectric and hybrid nanogenerators. In Advances in Flexible and Printed Electronics: Materials, fabrication, and applications 2023 (pp. 12-1). Bristol, UK: IOP Publishing.

[7] S. Srinivasulu Raju, Seung-Bok. Choi, M. Umapathy and G. Uma, "An effective energy harvesting in low frequency using a piezo-patch cantilever beam with tapered rectangular cavities", *Sensor and Actuator A: physical*, vol. 297, pp. 111522, 2019.

[8] P. Janphuang, R. Lockhart, D. Briand, N.F. de Rooij, N.F., "On the optimization and performances of a compact piezoelectric impact MEMS energy harvester", *2014 IEEE 27th International Conferenceon Micro Electro Mechanical Systems (MEMS)*, 2014, pp. 429-432.

[9] S. Srinivasulu Raju, M. Umapathy and G. Uma, "Cantilever piezoelectric energy harvester with multiple cavities", *Smart Mater. Struct.*, vol. 24, pp. 115023, 2015.

[10] A.A.M. Ralib, A.N. Nordin, H. Salleh, "Simulation of a MEMS piezoelectric energy harvester", *2010 Symposium on Design Test Integration and Packaging of MEMS/MOEMS (DTIP)*, 2010, pp. 177-181.

[11] O. Sidek, S. Saadon, "Vibration-based MEMS Piezoelectric Energy Harvester for Power Optimization", *2013 UKSim 15th International Conference on Computer Modelling and Simulation (UKSim)*, 2013, pp. 241-246.

[12] S. Srinivasulu Raju, M. Srikanth, T. Niranjan, P. A. Sai and S. K. Mohinuddin, "Design and Development of MEMS based Piezoelectric Energy Harvester," *2022 10th International Conference on Emerging Trends in Engineering and Technology - Signal and Information Processing (ICETET-SIP-22)*, 2022, pp. 1-6, doi: 10.1109/ICETET-SIP-2254415.2022.9791635.

[13] Raju SS, Umapathy M, Uma G. High-output piezoelectric energy harvester using tapered beam with cavity. Journal of Intelligent Material Systems and Structures. 2018;29(5):800-815. doi:10.1177/1045389X17721044

[14] C-F. Hung, T-K. Chung, P-C. Yeh, C-C. Chen, C-M. Wang, S-H. Lin, "A miniature mechanical-piezoelectric-configured three-axis vibrational energy harvester", IEEE Sensors Journal, 2015, Vol. 15, Issue 10, pp. 5601-5615.

[15] Sampatirao, H., Satthiyaraju, M., Pabba, D. P., Ram, N., Pabba, N. K., Kaarthik, J., ... & Thirumurugan, A. Nanoengineering low-dimensional materials for energy harvesting. In Nano-Engineering at Functional Interfaces for Multi-Disciplinary Applications, 2025, pp. 283-310.