STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 11, Special Issue 9, 2023
DOI (Journal): 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Performance Analysis of a Three-DOF Piezoelectric Vibration Energy Harvester

Jalalu Guntur[1], S Srinivasulu Raju [2], M Srikanth[3], J Likhitha[4], D Lekhana[5]

Abstract

Mechanical vibration energy can be transformed into electrical energy by a vibration energy harvester, which can then be stored in the battery for later use. It can convert vibrational motions like walking, leaping, running, etc. into pure renewable energy. This can turn previously squandered energy into energy that can be used to recharge wireless sensors and portable electronics. If these gadgets are used widely, they can produce a lot of green energy and contribute to environmental protection. The majority of MEMS energy harvesters are made to collect energy solely in one direction. A new three-Degree of freedom (DOF) MEMS piezoelectric vibration harvester solution is proposed in this work. A core silicon mass in the shape of a H is sustained by two pairs of T-beams on either side of the device. The mass is fixed on both sides along four sets of folded beams that oscillate in the X direction. The mass can vibrate in both the Y and Z axes thanks to two sets of straight rays. Along the beam surfaces, the piezoelectric material is already placed. It can transform the beams' vibrational energy into electrical energy voltage that flows via the rectifier circuit to recharge the battery. A more effective energy harvesting outcome is achieved by the device's ability to capture vibrational energy along all three axes. Using the COMSOL Multiphysics® programme, it is both developed and simulated. It is proposed that MEMS energy harvesters be mounted to shoes, tyres, or other vibrating surfaces from which it harvests energy from motion while moving while traveling, running, and walking.

Keywords: cantilever beam, piezoelectric, stress, deflection, non-traditional geometry

INTRODUCTION

Mechanical vibration energy can be transformed into electric energy and stored in a battery for future usage using a vibration energy harvester. Walking, jumping, running, and other vibrational motions can generate clean, renewable energy. This can transform energy that would otherwise be wasted into energy that can be used to recharge movable electronics. It provides a clean, sustainable energy source for use in the future. If such a vibration energy harvester can be included into a variety of applications, such as shoes, bridges, and other items, it can recycle a significant quantity of green energy and contribute to environmental protection. Energy harvesting is one of the interesting topics for researchers in recent years because it converts the waste energy of the environment into useful energy. Due to the fact that these energy harvesting devices can actually absorb the excessive vibration energy of the surfaces, it may also aid in stabilizing the road and bridge surfaces. In order to extend the time between recharges, the energy captured can be used to power implanted biomedical equipment (such as pacemakers) and portable electronics. In order to enable them to be partially or entirely self-powered, it can

***Author for Correspondence**
S Srinivasulu Raju

[1,2]Assistant Professor, Department of Electronics and Instrumentation Engineering, VR Siddhartha Engineering College, Vijayawada, Andhra Pradesh, India
[3]Assistant Professor, Department of Electronics and Communication Engineering, Bapatla Engineering College, Bapatla, Andhra Pradesh, India
[4,5]student, Department of Electronics and Instrumentation Engineering, VR Siddhartha Engineering College, Vijayawada, Andhra Pradesh, India.

Received Date: September 07, 2023
Accepted Date: September 17, 2023
Published Date: September 28, 2023

Citation: Jalalu Guntur, S Srinivasulu Raju, M Srikanth, J Likhitha, D Lekhana. Performance Analysis of a Three-DOF Piezoelectric Vibration Energy Harvester. Journal of Polymer & Composites. 2023; 11(Special Issue 9): S10–S18.

also be utilized for standalone and isolated equipment like wireless sensor networks and security cameras to monitor forest wildfires. Due to their tiny size, low cost, and great efficiency, MEMS (Microelectromechanical Systems) technology is particularly ideal for energy harvesting applications. There have been described electrostatic [1]–[3], electromagnetic [4–5], and piezoelectric transducer-based MEMS vibration energy harvesting devices.

An electrostatic transducer-based 3-degree-of-freedom MEMS energy harvester that uses ultrasonic waves to create electrical energy is described in [1]. To detect the ultrasonic vibrations, the system uses seismic mass coupled to a collection of flextures. A collection of in-plane and out-of-plane variable comb storage capacitors are charged using the energy that was captured. The use of capacitor transducers in another MEMS vibration energy harvester is documented in [2]. To enable straightforward post-CMOS modular construction, electroplated nickel is used as a structural layer. [3] reports the development of an SOI-MEMS electrostatic vibration energy harvester. According to simulation data, the device can produce a extreme harvest power of 5.891 W at a 2 kHz excitation frequency. Two magnetic MEMS vibrational energy harvesters are described in [4]–[5]. Permanent macro magnets are used by electromagnetic energy harvesters to convert energy. There is no need for additional operating power because power is produced by the comparative undertaking of the coils and magnetic field. Vibrational energy is transformed into electrical energy using piezoelectric energy harvesters. When a piezoelectric material experiences stress from vibration, the resulting electrical voltage differential between the material's two surfaces can be used to charge batteries. A MEMS vibration energy harvester using piezoelectric cantilevers that resemble AFM and are linked to a rotating gear is disclosed in [6,7]. An oscillating mass powers the gear. The use of a Zinc oxide (ZnO) piezoelectric cantilever in a MEMS vibration energy harvester for mechanical to electrical transduction is reported in [8]. For optimum energy conversion efficiency, MEMS piezoelectric vibration energy harvester devices with various cantilever structures are simulated in [9]10]. Two three-axis piezoelectric vibration energy harvesters that are capable of collecting energy along all X, Y, and Z axes were reported in [11] and [12]. In [12], four L-shaped bulk-PZT/Si beams that may bend in the X, Y, and Z directions are coupled to the seismic mass. In the transverse piezoelectric mode, a collection of divided anodes on the PZT arms capture mechanical energy. An out-of-plane proof mass is used by the energy harvester in [13] to cause movement along the Z-axis in response to both in-plane and out-of-plane vibrations. The PZT piezoelectric thin films have the ability to harvest the stress that results from out-of-plane bending.

In this paper, a 3-DoF piezoelectric MEMS vibrational energy harvester is suggested. It is connected to two seismic masses via two sets of T-shaped beams and four sets of folded beams. The seismic masses' mass centres are outside the beam plane because they are substantially thicker than the beams. On the underside of the T-shape beams are pre-deposited piezoelectric films with top/bottom metal electrodes. The induced stress inside T-shape beams can be detected by the piezoelectric films in order to produce voltage output if the external vibration is in the Z direction, which causes the beams to bend up and down. The inertial force induces a net torque when there is an external vibration in the X or Y direction, causing the T-shaped beam at one end to bend up and the T-shaped beam at the other end to bend down. Piezoelectric films can once more sense the stress inside T-shaped beams to produce a voltage difference between the surfaces of the beams' top and bottom. As a result, the tool may collect vibrational energy along all three axes of freedom. An AC voltage signal is what is generated. The vibration energy is transformed into electrical energy and kept for future usage by using a rectifying circuit to turn it into DC voltage to power portable gadgets or a battery. The piezoelectric energy harvester's vibrational modes are simulated using COMSOL simulation, and the associated resonance frequencies are then determined. To convert vibration energy for the generation of green energy, the gadget can be inserted into shoes, placed beneath the surface of the road, or fastened to a person.

VIBRATION ENERGY HARVESTER DESIGN

Figure 1 depicts the suggested vibration energy harvester. The technology is composed of silicon on glass. Silicon-glass anodic bonding is used to join the silicon structure and glass substrate. The glass substrate is not depicted in Figure 1 since we are interested in the silicon structure's vibrational modes.

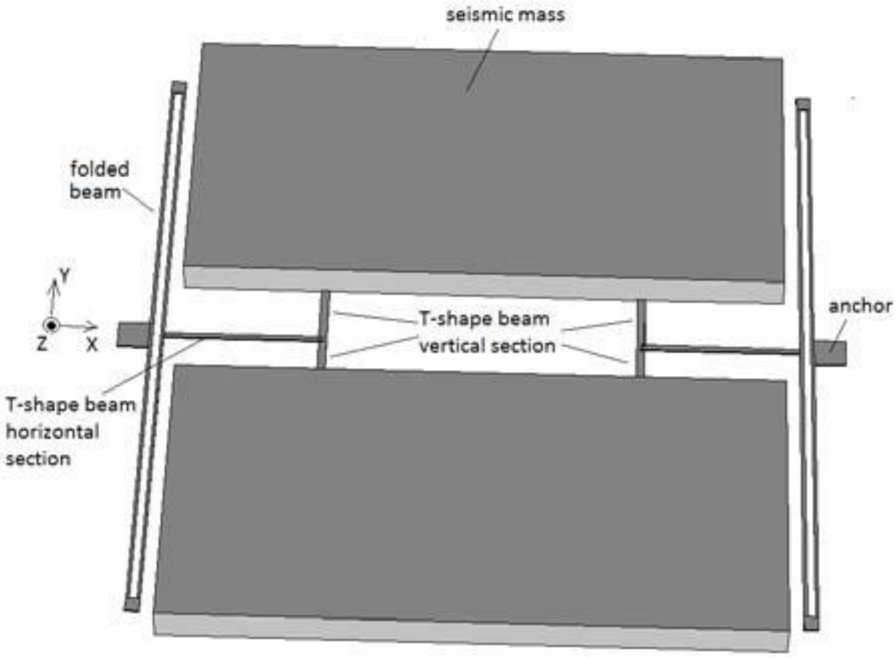

Figure 1. Structure diagram of MEMS vibration energy harvester.

The device structure is comprised of two seismic masses adjourned by two sets of T-shaped beams and four sets of doubled beams, as shown in Figure 1. The folded beams' one end is secured to the substrate with anchors. Before silicon-glass bonding, piezoelectric thin films with top/bottom metal electrodes (not seen in the picture) are pre-placed on the lowest surface of the T-shape beams. The seismic masses have a mass center that is above the plane of the beams because they are significantly thicker than the beams. When in-plane vibration is detected, this imbalance is purposefully created to cause out-of-plane movement of both T-shape beams. The inertial force acting on the seismic masses produces a net torque when there is vibration in the device plane along the X or Y axes, which causes one T-shaped beam to bend up and the other T-shaped beam to bend down, respectively. Additionally, if the vibration is in the Z direction, the T-shape beams vibrate in the same way. Therefore, the T-shape beams vibrate outside of the device plane whether the vibration is inside or outside of the device plane. Due to the produced stress inside the T-shape beams, the pre-deposited piezoelectric films on the bottom surface of the beams produce a voltage differential between its top and bottom surfaces. The battery is charged using the generated voltage, which goes via a rectifying circuit to capture the vibration energy and store it as electrical energy for later use.

The device's resonance frequency is a crucial factor in vibration energy harvesters. The device's resonant frequency should be created to competition the frequency range of the vibration that will be captured in order to increase the effectiveness of energy harvesting. Frequency for routine motions like walking and running is typically under 100 Hz. Two T-shaped beams and four folded beams make up the planned energy harvester. Each folded beam section has dimensions of Wfb, Lfb, and tb, respectively. The horizontal segment of the T-shape beam has the following dimensions: Wtb1, Ltb1, and tb. Each vertical portion of the T-shape beam has dimensions of Wtb2, Ltb2, and tb, correspondingly. One seismic mass has the following dimensions: Wm, Lm, and tm, respectively. Silicon has a density of and a Young's modulus of E. We will individually calculate the energy harvester's resonance frequencies along the X, Y, and Z directions. Both four folded beams and four sections of T-shaped beams contribute to vibration in the X direction, and they are both connected in series. The parallel connections between the four folded beams. Four folded beams with a combined spring constant of

$$K_{fb\_xtot} = 2EW_{fb}^{3} \cdot t_{b} / L_{fb}^{3} \tag{1}$$

T-shaped beams in four vertical sections are joined in parallel. The overall spring constant of four vertical T-shape beam sections is

$$K_{tb2\_xtot} = 4EW_{tb2}^3 \cdot t_b / L_{tb2}^3 \tag{2}$$

The four folding beams and the four vertical T-shaped beam sections are linked together in succession. The apparatus's overall spring constant in the X direction is

$$K_{X\_tot} = \frac{K_{fb\_xtot} \cdot K_{tb2\_xtot}}{K_{fb\_xtot} + K_{tb2\_xtot}} \tag{3}$$

The total mass of two seismic masses is

$$M = 2\rho W_m L_m t_m \tag{4}$$

When the energy harvester is modelled as a basic spring-mass system without taking into account the mass of the piezoelectric films and its top/bottom electrodes, its resonance frequency along the X direction is

$$f_x = \frac{1}{2\pi}\sqrt{\frac{K_{X\_tot}}{M}} \tag{5}$$

Only two horizontal T-shape beam portions that are connected in parallel contribute to vibration in the Y direction. The energy harvester's overall spring constant in the Y-direction is

$$K_{Y\_tot} = 2EW_{tb1}^3 \cdot t_b / L_{tb1}^3 \tag{6}$$

The resonant frequency of the energy harvester along Y-direction is

$$f_y = \frac{1}{2\pi}\sqrt{\frac{K_{Y\_tot}}{M}} \tag{7}$$

All four folded beams and the two T-shaped beams contribute to the vibration in the Z direction. Four folded beams have a total spring constant in the Z direction of

$$K_{fb\_ztot} = 2EW_{fb} \cdot t_b^3 / L_{fb}^3 \tag{8}$$

The total spring constant of two horizontal sections of T-shape beams along Z direction is

$$K_{tb1\_ztot} = 2EW_{tb1} \cdot t_b^3 / L_{tb1}^3 \tag{9}$$

The total spring constant of four vertical sections of T-shape beams along Z direction is

$$K_{tb2\_ztot} = 4EW_{tb2} \cdot t_b^3 / L_{tb2}^3 \tag{10}$$

The four folded beams, two horizontal T-shaped beam sections, four vertical T-shaped beam sections, and four folded beams are all connected in series to allow for vibration along the Z-direction. The energy harvester's overall spring constant in the Z-direction is

$$K_{Z\_tot} = \frac{1}{(1/K_{fb\_ztot} + 1/K_{tb1\_ztot} + 1/K_{tb2\_ztot})} \tag{11}$$

The resonant frequencies of the energy harvester along Z-direction is

$$f_z = \frac{1}{2\pi}\sqrt{\frac{K_{Z\_tot}}{M}} \tag{12}$$

The resonant frequencies of the energy harvester along the X, Y, and Z directions can be roughly estimated using the formulae above. They do, however, have a simplified spring-mass model that could lead to some mistakes. The gadget also exhibits rotational and tilting movement while in operation since the seismic masses and the mass centre of the beams are not in the same plane. The lateral vibrations will include the rotation/tilting and affect the resonance frequencies. The energy harvester's true resonance frequencies should be approximated using COMSOL FEM (Finite Element Method) simulation for more accuracy.

COMSOL Multiphysics

The vibration energy harvester's top 6 vibration modes are simulated using COMSOL Multiphysics. We used the Solid Mechanics module in the COMSOL simulation, and the device's Eigenfrequency investigation was carried out. We also noticed that the T-shaped beams shake and spin in the Z orientations in response to vibrations along the X, Y, and Z directions. The piezoelectric films on the bottom surface of the T-shape beams sense the stress caused by this out-of-plane vibration and rotation and produce electricity as a result. In order to transform mechanical vibration energy into electric energy, the energy harvester works as follows. The design parameters of the piezoelectric energy harvester device is listed in Table 1.

Table 1. Design parameters of the energy harvester

Components	**Design parameters**
Folded beams (4 sections)	Beam width W_{fb}=50µm Beam length L_{fb}=5000µm Beam thickness $_{tb}$=30µm
Horizontal sections of T-shape beams (2 sections)	Beam width W_{tb1}=3000µm Beam length L_{tb1}=90µm Beam thickness t_b=30µm
Vertical sections of T-shape beams (4 sections)	Beam width W_{tb2}=200µm Beam length L_{tb2}=1000µm Beam thickness t_{b2}=30µm
Seismic masses (2 masses)	Mass width W_m=7800µm Mass length L_m=4200µm Mass thickness t_m=500µm

Single-crystalline silicon is the substance that makes up the structure of vibration energy harvesting devices. All of the mechanical and electrical properties of the material have already been established, and it was chosen from the built-in material library in COMSOL. The piezoelectric thin film is not modelled because our focus is on identifying the vibrational modes and resonance frequencies of the silicon structure. For the same stress input, different piezoelectric materials produce different voltages. A excellent material for piezoelectric film is PZT-5H. Figure 2 displays the energy harvester's mesh model.

SIMULATION RESULTS AND DISCUSSION

Design and simulation of the piezoelectric vibration energy harvesting device are done in COMSOL. The device's first six vibrational modes and accompanying resonance frequencies are extracted via modal simulation. Figure 3 depicts the first vibrational mode, which has a resonance frequency of f1=15.57514Hz. This is the mode in reaction to vibration in the Y direction, as can be seen. The seismic masses tilt about the X axis as a result of the inertial force since their mass centres are not in the same plane as the beams'. The T-shaped beams tilt as a result, and the resulting tension causes the piezoelectric films to produce voltage.

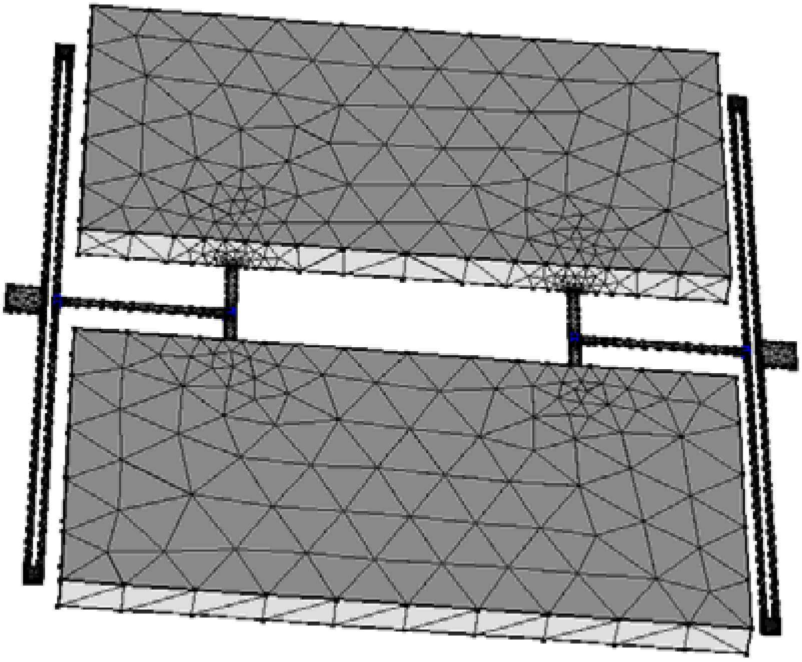

Figure 2. COMSOL meshed model of the MEMS vibration energy harvester.

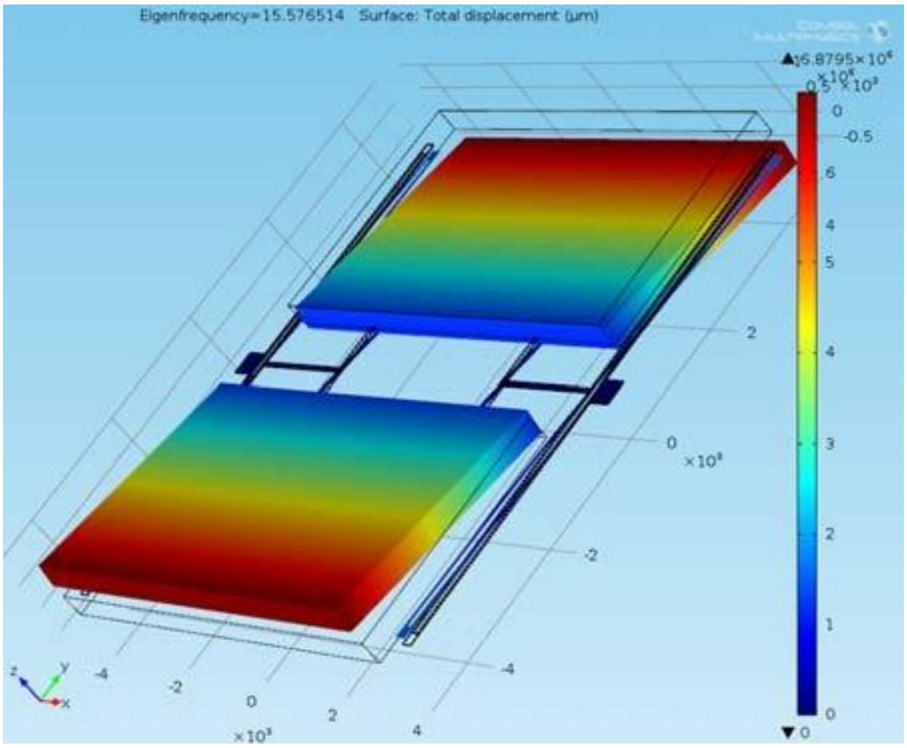

Figure 3. First vibration mode: for vibration along Y- direction (resonant frequency f_y = 15.57514Hz).

Figure 4 displays the COMSOL simulation results for the energy harvester's second vibration mode. The associated resonance frequency is f2=21.473948Hz. This is the mode of vibration that results from input vibration travelling in the Z direction. In this mode, both seismic masses oscillate upward and downward along the Z axis. As a result, the folded beams as well as both T-shaped beam portions bend upward and downward, moving the beams out of plane. The piezoelectric coatings on the bottom surface of the T-shape beams produce voltage as a result of the tension this creates inside the beams.

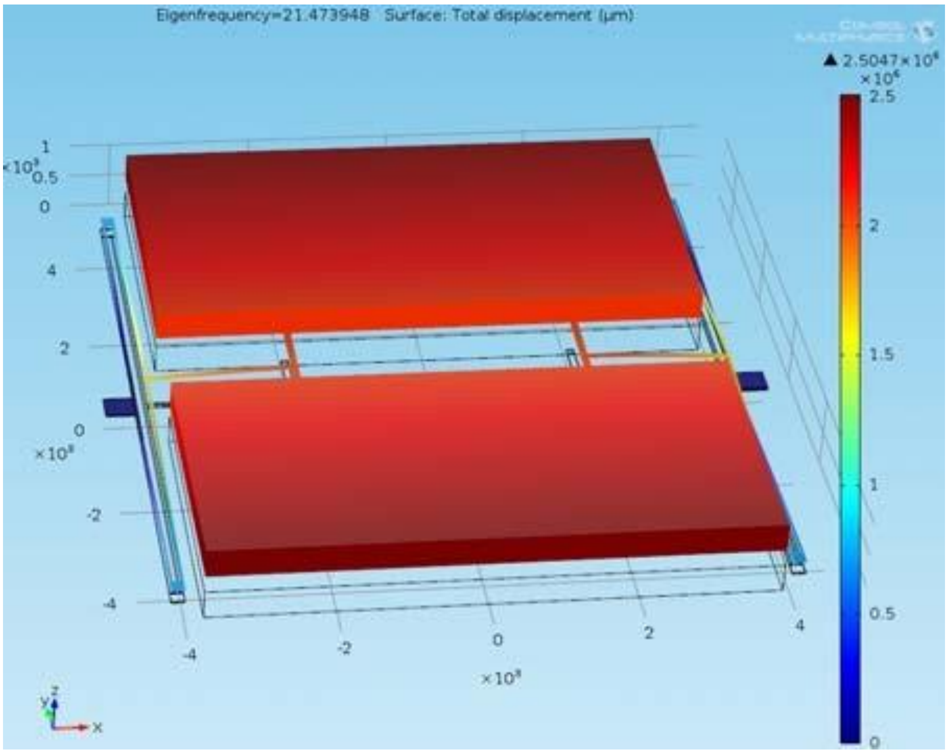

Figure 4. Second vibration mode: for vibration along Z-direction (resonant frequency f_z = 21.473948Hz)

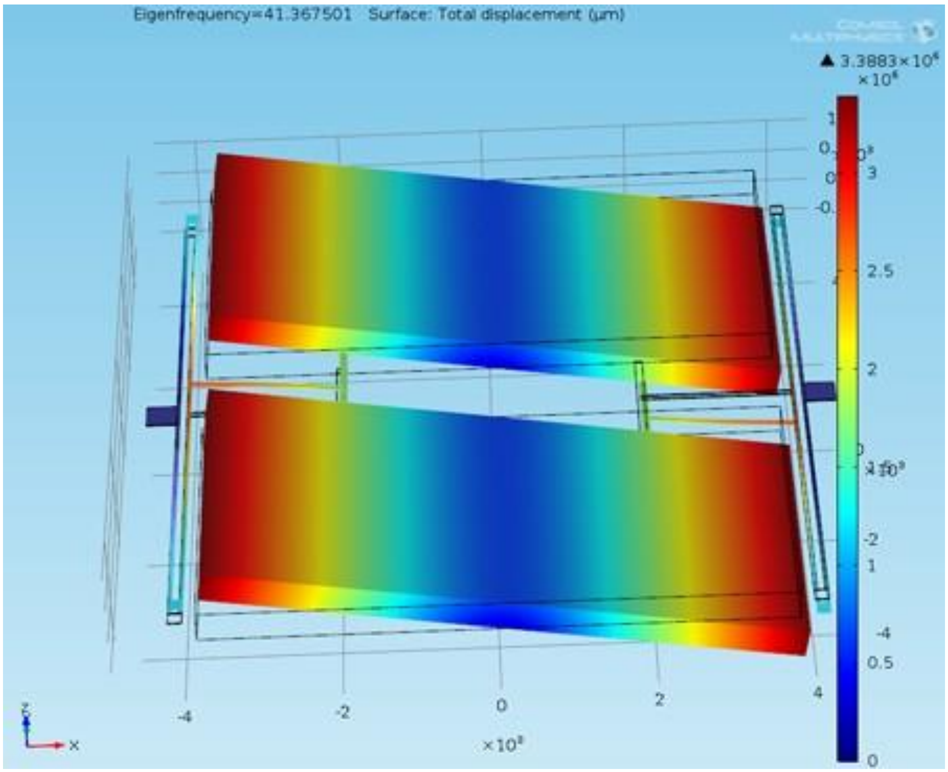

Figure 5. Third vibration mode: for vibration along X-direction (resonant frequency f_x = 41.367501Hz).

Figure 5 displays the COMSOL simulation results for the energy harvester's third vibration mode. The associated resonance frequency is f3=41.367501Hz. The vibration mode in response to an input vibration in the X direction is shown here. The seismic masses rotate as a result of the inertial force they encounter, which produces a net torque. The seismic masses' left and right halves tilt upward and downward in a Y direction. As a result, one T-shaped beam bends upward while the other bends downward. T-shape beams' internal stress is induced by the out-of-plane bending, which causes the piezoelectric films to produce voltage between their top and bottom surfaces.

The higher vibrational modes' COMSOL simulation results are also achieved. However, they result in higher order energy harvester vibrations that twist several beams and the masses. As a result, they are not listed here because they are not the energy harvester's operational modes. According to the COMSOL simulation, we can observe that vibrations in the X, Y, and Z directions all result in the T-shape beams vibrating out of plane. As a result, the beam material will experience internal stress, which will cause the piezoelectric films on its bottom surface to produce voltage output. The rectifier circuit will transform the output AC voltage into DC voltage, which can then be utilised to charge batteries or portable electronics. This allows for the collection and storage of the vibrational energy from the environment for later use. It is more efficient than energy harvesters that are just sensitive in one direction since it can collect vibrational energy from all three degrees of freedom. The first three vibrational modes' resonant frequencies are all under 50 Hz, which is an excellent match for the common frequencies of daily movement. The technology might be used to generate energy from human motions like walking, leaping, or working out. The device can be very compact and readily inserted inside the sole of shoes thanks to MEMS technology, as demonstrated in Figure 6. The energy of the shoe's vibration can be captured and stored in rechargeable batteries for use later on when individuals walk, run, or exercise. The energy harvester gadget can be used to recharge the backup battery of mobile electronics such as digital cameras, smartphones, and other small electronics. This generates "green" energy and provides a practical method for users to "on-the-go" recharge their mobile batteries. Every day, people go for walks, runs, and workouts. A significant amount of clean energy might be produced if such MEMS energy harvesters were integrated into every pair of shoes.

Figure 6. Shoe with vibration energy harvester inserted in its sole.

CONCLUSIONS

A MEMS energy harvester that can collect energy along all three DoFs (Degrees of Freedom) has been investigated in this work. The energy harvester senses the input vibration using inertial sensing technology and transforms it into electrical energy that can be stored for use in the future. The device's seismic masses and beams are various thicknesses. This imbalance causes the in-plane vibration from the input vibration to result in an inertial force that causes a net torque and causes the T-shape beams to move out of their normal position. T-shape beams will bend in the same direction along the Z axis as the input vibration. The T-shape beams' piezoelectric films on the bottom surface sense internal tension and produce voltage output. The rectifier circuit transforms the generated AC voltage into DC voltage, which is then used to charge batteries or portable electronic devices. The proposed device produces more energy gathering in all directions than an energy harvester that is just responsive to one direction.

Its vibrational modes are simulated using COMSOL Multiphysics, and the associated resonance frequencies were identified. The working vibration modes in the X, Y, and Z axes have resonance frequencies of fx=41.367501Hz, fy=15.57514Hz, and fz=21.473948Hz, respectively, according to the results of the COMSOL simulation. It is particularly well suited to be placed under the sole of shoes, tires, road surfaces, bridges, or other locations with regular vibrations due to its small size. Where such energy was previously lost through vibrations, it can now be harvested.

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. 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.
7. 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 Conference on Micro Electro Mechanical Systems (MEMS), 2014, pp. 429-432.
8. S. Srinivasulu Raju, M. Umapathy and G. Uma, "Cantilever piezoelectric energy harvester with multiple cavities", Smart Mater. Struct., vol. 24, pp. 115023, 2015.
9. 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.
10. 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.
11. 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.
12. 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
13. 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.