Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 2 (2024)

Design and Modal Analysis of Swastik-Shaped Flexible Piezoelectric Biomechanical Energy Harvester

Namrata Saxena[1], Mamta Devi Sharma[2], Ritu Sharma[3*], C. Periasamy[4]

[1, 2, 3, 4] *Department of Electronics & Communication Engineering, Malaviya National Institute of Technology Jaipur, Rajasthan, India*

Abstract:- There is a lot of energy generated by the physiological activities inside the human body which gets wasted. In the recent times energy harvesting from these physiological activities is one of the major research area. In this work a swastik-shaped flexible piezoelectric biomechanical energy harvester (PBEH) is designed to harvest energy from the human body. The structure consists of squared-shaped seismic mass at the center of the four L-shaped beams forming a swastik using Polydimethylsiloxane (PDMS) as a flexible substrate and zinc oxide (ZnO) as the piezoelectric material and gold (Au) for the top and bottom electrode materials outperformed in terms of lower resonance frequency of 90 Hz which makes the device suitable for human body energy harvesting application. The designed PBEH can be attached as a band on any part of the human body for the harvesting of energy.

Keywords: *Biomechanical energy harvester, flexible substrate, L-shaped beams, modal analysis, Polydimethylsiloxane (PDMS).*

1. Introduction

With the development in the area of micro electro mechanical systems (MEMS) fabrication technologies the prerequisite power and the size of the transistors are decreased to nanowatt and nanometer range respectively. This advancement aids the growth of numerous wireless electronic devices for various applications like implantable medical devices, etc. that improves the quality and the lifespan of human life to an appreciable limit. These implantable gadgets are utilized in the field of medical science to detect several biological aspects such as temperature, blood pressure, heart rate, movements, etc. The detection of these parameters are done using implantable medical instruments like pacemakers, sensors, stimulators [1-3]. With the help of these devices the diagnosis of diseases in different parts of the body such as brain, heart, limbs, etc. can be easily done. For instance, the irregularity in the heart beat occurs due to heart blockage can be corrected using cardiac pacemakers. Though, these medical instruments provide aid to attain improved human life although have several challenges in their fabrication [4-6]. The major constraint in the development of these implantable devices is their light weight and compact size in order to reduce its consequences on the human body [7-9]. Recently, batteries are the foremost alternative to serve as the power source for implantable medical instruments. The implementation of batteries in the implantable medical devices is very challenging task due to its fabrication complexities and short lifespan. For instance, the battery used in the pacemakers for the generation of pulses requires replacement after every 2-4 years [10-12]. To overcome this problem a novel research domain is explored by the researchers i.e., based on the harvesting of energy generated from the physical activities of the human body. To fulfill this task the energy within or outside the human body would be directly used to power these in-vivo medical equipments. Recently, several researchers are exploring methods for human energy harvesting generated from muscle contractions, glucose oxidation, mechanical energy in the form of pulses and vibrations [13-15]. This mechanical energy from the human body can be converted using different conversion mechanisms such as piezoelectric, electromagnetic and electrostatic. However, all the methods are capable of converting mechanical energy into useful form but piezoelectric mechanism outperforms the other methods because of its innate property of transforming mechanical form of energy into electrical signals [16-17]. To harvest small mechanical vibrations from the human body the energy scavengers manufactured using conventional solid and inflexible substrates are unsuitable. Consequently, there is a need of thin, lightweight and flexible substrate material. Generally, polymer based materials are used to develop thin and flexible substrate such as PE (polyethylene), PI (polyimide), PDMS (Polydimethylsiloxane) and PET (polyethylene terephthalate) which is compatible with human body energy harvesting. For the piezoelectric type of nanogenerators the material like $BaTiO_3$, ZnO, PVDF (polyvinylidene difluoride), etc. are used as piezoelectric layer [18-21].

The main aim of the proposed work is to design, develop and modal analysis of the piezoelectric biomechanical energy harvester (PBEH) that generates electric energy by capturing energy from physiological activities of human body. This PBEH is designed using FEM simulator with PDMS as the flexible substrate, ZnO as the piezoelectric material and gold (Au) as the electrode material. The eigen mode analysis is performed to compute the resonance frequency of the PBEH out of all the obtained eigen modes.

2. Mathematical Modeling of Piezoelectric Biomechanical Energy Harvester

The PBEH designed in this work could be analyzed as a mass-spring -damper arrangement which yields optimum electric energy whilst the resonance frequency of the PBEH equalizes with the frequency of mechanical vibrations inside the human body, or else there would be drop in the achieved electric energy. The PBEH consists of four L-shaped beams and a square-shaped seismic-mass.

The mathematical equation for the determination of resonance frequency (f) of flexible PBEH is mentioned in Eq. (1) [5-8, 21]

$$\mathrm{f} = \frac{1}{2\pi}\sqrt{\frac{\mathrm{k}}{\mathrm{m_t}}} \tag{1}$$

where, k and m_t represents the spring-constant and the total mass of the PBEH.

The total mass is the addition of $m_{sm}$and m_{eff}which represents the mass of the proof-mass and the effective mass of the L-shaped beam respectively.

$$m_{eff} = \frac{33}{140}m_b \tag{2}$$

where, the beam-mass is represented as m_b.

Thus, the total mass of the PBEH is obtained as

$$m_t = m_{eff} + m_{sm} \tag{3}$$

The spring-constant (k) of the L-shaped beam is given as in Eq. (4)

$$k = 4\left(\frac{Ewt^3}{l^3}\right) \tag{4}$$

where, E is the Young's modulus, and w, t, and l denotes the width, thickness and length of the beam respectively.

The final expression for obtaining the resonance frequency of the proposed swastik-shaped flexible PBEH is given in Eq. (5)

$$f = \frac{1}{\pi}\sqrt{\frac{Ewt^3}{m_t\, l^3}} \tag{5}$$

3. Design Parameters of Piezoelectric Biomechanical Energy Harvester

In the proposed work, a swastik-shaped flexible PBEH is designed for human body vibrational energy harvesting application. The energy harvester is in fixed-guided configuration comprises of four flexible L-shaped beams connected to all the four sides of the square-shaped proof-mass. In this PBEH, the two boundary conditions are applied. The mechanical condition is applied by defining that the one-end of the L-shaped beam is fixed and the other-end to which the proof-mass is connected is free to vibrate which is defined as the guided-end. The electrical boundary condition is applied by connecting terminal potential to the top gold electrode and ground potential to the bottom electrode. The material properties of the flexible substrate material PDMS, piezoelectric material ZnO and the electrodes material gold is listed in Table I.

Table I. Material properties of flexible substrate (PDMS), piezoelectric material (ZnO), and Electrode material (Gold)

Properties	Materials		
	PDMS	ZnO	Gold
Density (kg/m^3)	970	5680	19300
Young's Modulus (E) (Pa)	750×10^3	210×10^9	70×10^9
Poisson's Ratio (υ)	0.49	0.35	0.44
Relative Permittivity (ξ^T)	2.75	{8.5446, 8.5446, 10.204}	6.9

where (ξ^T) is 3×3 relative permittivity matrix in stress-charge form

A. Design parameters of square-shaped proof-mass

The main purpose of this work is to design a flexible PBEH that has the resonance frequency below 100Hz so as to utilize it for the energy harvesting from low frequency mechanical vibrations from the human body. From Eq. (5), it is noticed that the desired low frequency range i.e., below 100 Hz would be obtained by connected a mass generally referred as the proof-mass to the four L-shaped beams. To accomplish this task a square-shaped proof-mass with thickness of 2000 μm, length and width of 6000 μm is coupled at the guided-end of the four L-shaped beams as shown in Fig. 1.

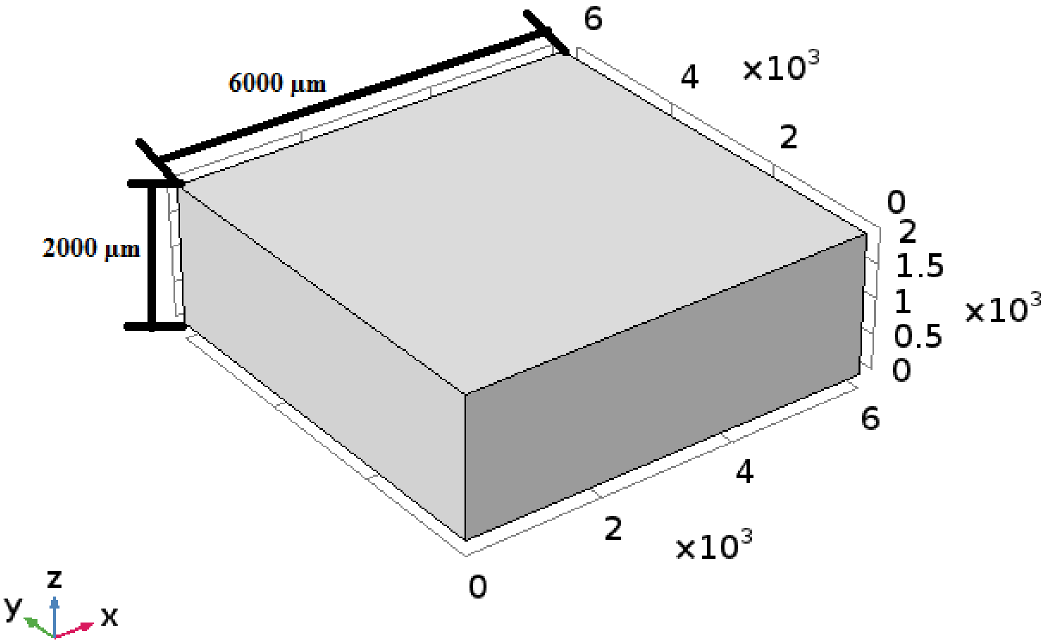

Fig. 1 Dimensional representation of the square-shaped seismic-mass

---

B. Design Parameters of L-shaped Flexible Beam

From Eq. (4) and (5) it is clearly observed that the geometrical dimensions of the beam are the deciding factors for achieving the harvester's resonance frequency. The beam curling would occur if the length of the beam is bigger beyond a certain limit and if the thickness is increased too much then the resonance frequency would increase and if it is reduced below the certain value then it would not bear the load of the attached proof-mass. The width of the PBEH beam also needs to be optimized so that the device would resonate in low frequency range and does not become bulky. The thickness of the flexible PDMS layer of the beam is 2000 µm, length of the shorter arm is 6000 µm, length of the longer arm is 10000 µm, thickness of the piezoelectric layer of ZnO is 2 µm and the top and bottom gold (Au) electrode is 1 µm. The geometrical view of the swastik-shaped flexible L-shaped beam PBEH is shown in Fig. 2.

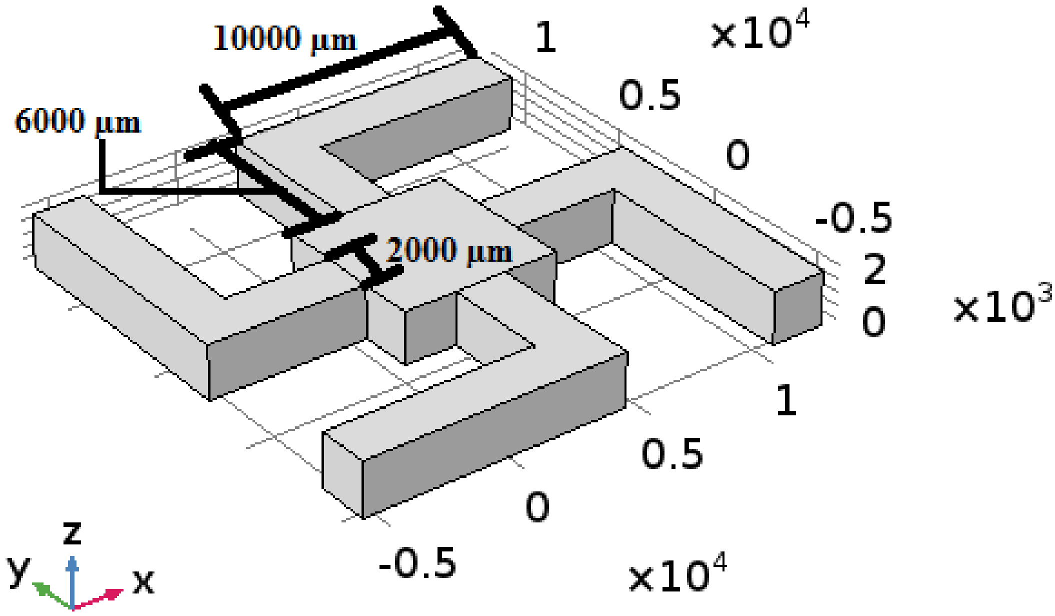

Fig. 2 Geometrical view of Swastik-shaped flexible L-beam PBEH

4. Result and Discussion

The resonance frequency of the swastik-shaped flexible PBEH is obtained using eigen-mode analysis in the COMSOL Multiphysics® software. In order to validate the simulated resonance frequency its comparison with the analytically calculated resonance frequency is also performed. From this comparison it is observed that the resonance frequency is in good agreement with each other.

A. Modal Analysis

For the exact determination of the resonance frequency of the flexible PBEH the four eigen modes have been obtained. Fig. 3 demonstrates all the four eigen modes i.e., 90.078Hz, 155.33Hz, 224.19Hz and 316.45Hz respectively. Among all these modes the first eigen mode is treated as the resonance frequency of the flexible PBEH because this shape of deformation is apt for energy harvesting application and the maximum energy is generated in first eigenmode. The obtained resonance frequency of the swastik-shaped PBEH is 90.078Hz which is less than 100Hz and thus suitable for harvesting energy from the physical actions of human body.

The comparison between analytical and simulated resonance frequency is tabulated in Table II.

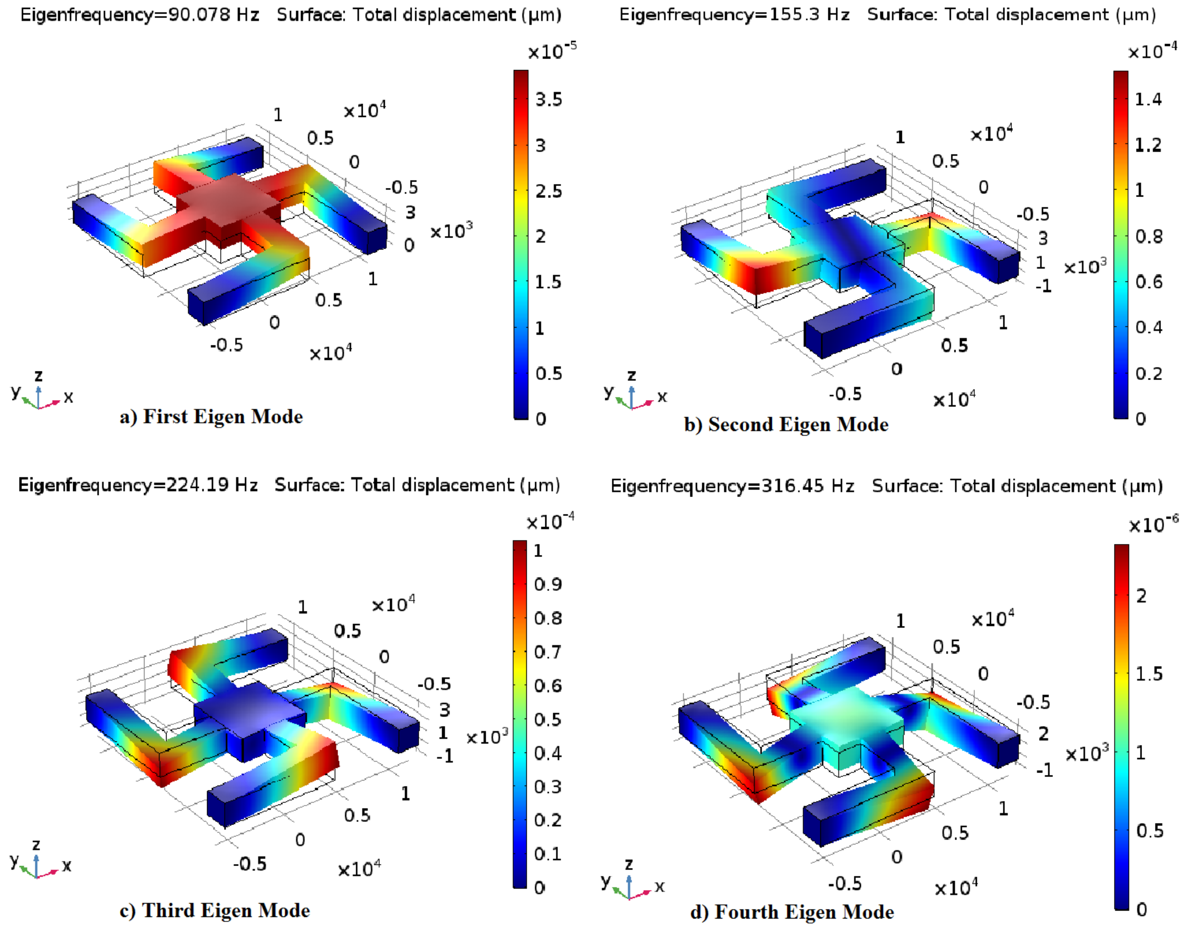

Fig. 3 First four eigen-modes of Swastik-shaped Flexible PBEH

Table II. Comparison between analytically Computed And simulated resonance frequency

Parameter	
$\mathbf{k_b}$ $(\mathbf{kg/s^2})$	91.81
$f_{rq\_simulation}$ (Hz)	90.078
$\mathbf{f_{rq\_analytical}}$ (Hz)	90.00
Error (%)	0.086

5. Conclusions

The swastik-shaped flexible L-beam PBEH is designed and analyzed. The eigen-mode analysis is performed to determine the resonance frequency of the PBEH among all the different eigen-modes. The proposed flexible piezoelectric energy harvester resonates at the frequency of around 90Hz and thus makes the device suitable for human body energy harvesting application.

Acknowledgments

The authors wish to appreciatively recognize SERB (Power Grant), New Delhi for imparting financial aid to this project.

References

[1] G.-T. Hwang, D. Im, S.E. Lee, J. Lee, M. Koo, S.Y. Park, S. Kim, K. Yang, S.J. Kim, K. Lee, K.J. Lee, "In vivo silicon-based flexible radio frequency integrated circuits monolithically encapsulated with biocompatible liquid crystal polymers", ACS Nano 7 (2013) 4545–4553.

[2] B. Condon, and D. Hadley, "Cardiac pacing systems and implantable cardiac defibrillators (ICDs): a radiological perspective of equipment, anatomy and complications", Clin. Radiol. 59 (2004) 1145

[3] J.S. Perlmutter and J.W. Mink, "Deep brain stimulation, Annu. Rev. Neurosci. 29 (2006) 229–257.

[4] A. Cheng, L.G. Tereshchenko, Evolutionary innovations in cardiac pacing, J. Electrocardiol. 44 (2011) 611–615.

[5] N. Saxena, R. Sharma, K.K. Sharma, V. Sharma, (2020). Design and Performance Analysis of Different Structures for Low-Frequency Piezoelectric Energy Harvester. In: Nath, V., Mandal, J. (eds) Nanoelectronics, Circuits and Communication Systems. NCCS 2018. Lecture Notes in Electrical Engineering, vol 642. Springer, Singapore.

[6] N. Saxena, V. Sharma, R. Sharma, K. K. Sharma, S. Gupta, "Design, modeling, and frequency domain analysis with parametric variation for fixed-guided vibrational piezoelectric energy harvesters", Microprocessors and Microsystems,2022, 95, 10692

[7] N. Saxena, V. Sharma, R.Sharma, et al. Design, parametric analysis and comparison of fixed-guided two beam and four beam vibrational piezoelectric energy harvesters. Microsystem Technologies 28, 1203–1212 (2022).

[8] N. Saxena, V. Sharma, R. Sharma, K.K. Sharma, S. Chaudhary, (2020). Design and Performance Analysis of Different Structures of MEMS PVDF-Based Low-Frequency Piezoelectric Energy Harvester. In: Kalam, A., Niazi, K., Soni, A., Siddiqui, S., Mundra, A. (eds) Intelligent Computing Techniques for Smart Energy Systems. Lecture Notes in Electrical Engineering, vol 607. Springer, Singapore.

[9] F.W. Horlbeck, F. Mellert, J. Kreuz, G. Nickenig and J.O. Schwab, "Real-world data on the lifespan of implantable cardioverter-defibrillators depending on manufacturers and the amount of ventricular pacing, J. Cardiovasc. Electrophysiol. 23 (2012) 1336–1342.

[10] V.S. Mallela, V. Ilankumaran, N.S. Rao, Trends in cardiac pacemaker batteries, Indian Pacing Electrophysiol. J. 4 (2004) 201–212.

[11] A. Zurbuchen, A. Pfenniger, A. Stahel, C.T. Stoeck, S. Vandenberghe, V.M. Koch, and R. Vogel, Energy harvesting from the beating heart by a mass imbalance oscillation generator, Ann. Biomed. Eng. 41 (2013) 131–141.

[12] S.R. Platt, S. Farritor, H. Haider, On low-frequency electric power generation with PZT ceramics, IEEE/ASME Trans. Mechatron. 10 (2005) 240–252.

[13] G. Tang, J.-Q. Liu, B. Yang, J.-B. Luo, H.-S. Liu, Y.-G. Li, C.-S. Yang, V.-D. Dao, K. Tanaka and S. Sugiyama, "Piezoelectric MEMS low-level vibration energy harvester with PMN-PT single crystal cantilever", ELECTRONICS LETTERS 21st June 2012 Vol. 48 No. 13.

[14] Marco Laurenti, Denis Perrone, Alessio Verna, Candido F. Pirri and Alessandro Chiolerio, "Development of a Flexible Lead-Free Piezoelectric Transducer for Health Monitoring in the Space Environment", 2015, 6, 1729 - 1744.

[15] Yi Xin, Hongshuai Sun, Hongying Tian, Chao Guo, Xiang Li, Shuhong Wang & Cheng Wang, "The use of polyvinylidene fluoride (PVDF) films as sensors for vibration measurement: A brief review", 2016, 502 (1), 28 - 42.

[16] N. Saxena, R. Sharma, M. D. Sharma and C. Periasamy, "Design and Eigen Mode Analysis of Flexible Two-Beam Piezoelectric Biomechanical Energy Harvester," 2023 3rd International Conference on Emerging Frontiers in Electrical and Electronic Technologies (ICEFEET), Patna, India, 2023, pp. 1-5.

[17] Le Van Minh, Motoaki Hara, and Hiroki Kuwano, " Lead-Free (K,Na)NbO_3 Impact-Induced-Oscillation Microenergy Harvester", Journal Of Microelectromechanical Systems, 2015, 24 (6), 1887 - 1895.

[18] Alperen Toprak and Onur Tigli, "MEMS Scale PVDF-TrFE-Based Piezoelectric Energy Harvesters", Journal Of Microelectromechanical Systems, 2015, 24(6), 1989 - 1997.

[19] N. Saxena, M. D. Sharma, R. Sharma and C. Periasamy, "Effect of Substrate Material on the Resonance Frequency of Array-Shaped Flexible Piezoelectric Biomechanical Energy Harvester," 2023 International Conference on Next Generation Electronics (NEleX), Vellore, India, 2023, pp. 1-4.

[20] Sunija Sukumaran, Samir Chatbouri, Didier Rouxel, Etienne Tisserand, Fre´de´ric Thiebaud and Tarak Ben Zineb, "Recent advances in flexible PVDF based piezoelectric polymer devices for energy harvesting applications", Journal of Intelligent Material Systems and Structures 2020, 1 - 35.

[21] N. Saxena, V. Sharma, R. Sharma, et al. Design, Modeling and Parametric Analysis of Piezoelectric Energy Scavenger on Silicon Substrate as a Vibration Sensor. Silicon 14, 3765–3774 (2022).