International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Design and Optimisation of Piezoelectric Materials for Harnessing Ambient Mechanical Energy

Mr. Raghav Vasudev

Student, Welham Boys School

Abstract:
The ability of some materials to undergo deformation in response to the application of an electric field and, conversely, to generate an electric charge when exposed to mechanical forces is referred to as piezoelectricity. The bidirectional interaction between mechanical and electrical energy renders piezoelectric materials very adaptable for many applications, including sensors, actuators, and energy harvesting. This study focuses on the design and optimization of nano-structured piezoelectric cylindrical rods for harvesting ambient mechanical energy. Using finite element modeling in COMSOL Multiphysics, the research investigates the behavior of various piezoelectric substance, under varying conditions. The performance was analyzed based on eigenfrequencies, deflection patterns, and voltage output across different lengths of the cylindrical rod. Results demonstrated that material selection and structural configuration critically influence the energy harvesting efficiency. Barium Titanate exhibited high voltage output but limited elasticity, while PVDF showed promising flexibility and environmental resilience. The findings support the potential of piezoelectric energy harvesters for powering wireless electronic devices by capturing mechanical vibrations from ambient environments.

Keywords: piezoelectric, mechanical, energy, cylinder, vibrations.

1. INTRODUCTION

The rising global demand for sustainable and decentralized energy solutions has heightened research into ambient energy gathering systems. Among the diverse processes available, piezoelectric energy harvesting has emerged as a highly promising technique for absorbing mechanical energy from the environment—such as vibrations, movements, and mechanical stresses—and transforming it directly into usable electrical energy. This approach possesses significant potential for energizing small electronic devices, wireless sensor networks, wearable technologies, and Internet of Things (IoT) components, thus diminishing reliance on traditional batteries and external power sources. Piezoelectric materials, defined by their inherent capacity to produce electric charges when subjected to mechanical deformation, are fundamental to this technology. The efficacy of energy conversion is significantly influenced by the material's intrinsic qualities, structural design, and operational environment. Conventional piezoceramics, provide elevated energy densities but exhibit brittleness and reduced flexibility, whereas polymer-based piezoelectrics, like polyvinylidene fluoride (PVDF), afford flexibility at the expense of diminished piezoelectric coefficients. Researchers are actively investigating composite materials, doping methods, innovative production techniques, and microstructural optimizations to improve performance. The design and optimization of piezoelectric materials for ambient mechanical energy harvesting necessitate a multidisciplinary approach integrating materials science, mechanical engineering, and electronics. Essential factors, including piezoelectric coefficients, mechanical flexibility, dielectric properties, frequency response, and durability, must be carefully optimized to enhance energy output in practical applications. Moreover, aspects like as miniaturization, scalability, and environmental sustainability are essential in material development.

This study aims to build and optimize a piezoelectric structure, namely a nano-scale hollow cylinder, to maximize the output voltage generated by ambient mechanical vibrations. The study employs finite element modeling and simulation techniques to evaluate the performance of several piezoelectric materials for the purpose of selecting the best suitable alternative for applications that include the effective collection of energy

2. RELATED STUDIES

A. A. Girde et al. (2024) The energy generated from conventional sources is limited and non-renewable. Moreover, urbanization has markedly increased energy consumption. It is essential to generate energy from sources that are sustainable. India's population is experiencing substantial expansion. In 2024, it has reached 140 crores, leading to heightened energy use. Mechanical stress is exerted on the roadways, especially at the speed increases. The mechanical stress arises from the vibrations of vehicles traversing the speed bump, resulting in the generation of electricity. By making it easier to generate renewable energy from moving vehicles, it helps advance sustainable development. The exploitation of piezoelectric cells is an exemplary way for producing renewable energy. Piezoelectric cells are technologies that generate electric charge when subjected to mechanical strain. To transform mechanical energy into electrical energy, piezoelectric cells are placed under the speed breaker. Street lighting, traffic signals, and other such uses may make use of the generated power.

Mohamed Ismail, N. M., & Loganathan, N. A. (2024). Noise is pervasive in the automotive sector and urban settings, including traffic, train stations, and markets. Nevertheless, it may be converted into an advantageous form by the use of advanced materials. The rapid growth of urban regions and enterprises has resulted in significant amounts of potentially harmful garbage being released into the sky. Auditory noise is a kind of danger. Some of the components is a piezoelectric material. Sound-induced vibrations may produce strain, thus generating electrical energy. The objective of this study was to harness electrical energy from harmful noises produced by manufacturers. The computational model was effectively recreated, demonstrating significant agreement between the empirical and calculated spectrum sound patterns. Electrical energy was generated by systematic experimenting using piezoelectric detectors. Augmenting the quantity of sensors may improve energy production, since this material is cost-effective. The research results demonstrated that a sound level of 90 dB produced more than two volts utilizing an individual piezoelectric detector.

Roshan Zameer Ahmed et al. (2023) This work introduces a distinctive piezoelectric energy-capturing device, enhanced using various circuitry elements such as operational boosters and volt quadruplers. Piezoelectric transmitters are electroacoustic instruments that convert electrical charges generated by certain mechanical motions, such as sound, into energy. Traditional energy resources are progressively diminishing, resulting in an escalating energy deficit driven by need. In contrast, the field of acoustic capture of energy remains mostly unexplored, particularly in enclosed environments. The device primarily relies on piezoelectric devices to transform surplus vibrations into electrical energy. Furthermore, the suggested technique seeks to mitigate the risk of noise-induced trauma, which may lead to detrimental long-term effects. It also facilitates a transformative trajectory, offering sustainable energy collection alternatives and improving acoustics inside confined spaces. In our experiments, we attained a voltage of around 12 V for a concert setup with noise levels between 70 and 90 dB, surpassing the existing data. These findings improved the system's effectiveness by six percent, and its versatility was increased fourfold. This innovative energy harvesting technique might enhance acoustic conditioning in confined spaces.

Clementi, Giacomo et al. (2022) A viable approach to power these electronics is the transformation of mechanical power into electrical power using electro-active substances. Although most electro-active materials used for mechanical energy harvesting are either toxic or incompatible with living organisms, piezoelectric materials are among the most promising and widely used. The extensive collection of electronic devices referred to as the Web of Things requires small, autonomous, and ecologically friendly sources of energy. Biologically compatible and environmentally friendly piezoelectric materials for energy harvesting are the focus of this research. With an emphasis on piezoelectric constants and achievable power, we catalog and examine the unique characteristics of every substance class. By reviewing and outlining current research, this study intends to make it easier and faster to choose the best piezoelectric components for individual mechanical energy harvesting purposes.

Hui Fang (2017) The piezoelectric device's audibility is measured between thirty-five and hundred dB. Human speech at fifty to one hundred dB is considered to be in the background in most urban areas. In order to harness the energy generated by sound waves, this study outlines the properties of piezoelectric materials. One use for the Q220-A4-503YB piezoelectric type is as an energy converter. Both the voltage and power provided by this kind of piezoelectric material have been shown to be better. Throughout the pertinent frequency range, the observed results of the piezoelectric transducer, regardless of the additional circuitry, have shown a high agreement with the expected predictions of theory. A Villard voltage multiplier, a Dickson voltage multiplier, and a rectifier with a full wave are all three separate kinds of harnessing circuits that are connected to the piezoelectric transducer's results. The sound wave energy harvester that has been presented displays exceptional performance and has the potential to make wireless signal networks more efficient by replacing the troublesome battery. The results of the investigation suggest that the piezoelectric transducer that was connected to the Villard voltage multiplier demonstrated the highest possible level of performance.

3. OBJECTIVES

- To design a nano-piezoelectric hollow cylindrical rod structure for mechanical energy harnessing.
- To compare the voltage output and mechanical behavior of different materials to determine the optimal choice for practical applications.

4. METHODOLOGY

A Nanostructured rod design mostly made of a piezoelectric substance is being built in this effort. The piezoelectric cylindrical shape becomes curved as a consequence of the rod's deformation.

As the piezoelectric surfaces were deformed, charges of electricity were created. Electrodes are inserted into the outside and interior of the Hollow cylinder rod and linked to an outer electrical circuit. Experimental reasons may be served by attaching a load with resistivity to the voltage that is produced. The piezoelectric dynamic equations are articulated in stress-charge form, used in this work to extract the resultant voltage from the fabricated device. As shown in Fig 1(a), the "Computer" and "Solution" (COMSOL) assessment form is used to generate the mesh framework, whereas Figure 1(b) shows the hollow piezoelectric design.

$$T = c^E S - e^t E \quad \textbf{(1)}$$

$$D = eS + \epsilon^S E \quad \textbf{(2)}$$

In this context, the elastic modulus matrices, piezoelectric bonding matrices, and electronic conductivity coefficient matrices are all used, as are the strain, stress, electro expulsion, and electric field vectors, and denoted as T, S, D, and E, correspondingly c^E , e, ε^S. Variables at an unchanged electric field and stress are denoted by the Upper index E and S, accordingly, while the transpose is denoted by the Upper index t. The electric displacement D is used in the next formula to estimate the produced values in piezoelectric substances,

$$= \oiint_{\Psi} D d\Psi \quad \textbf{(3)}$$

The surface of the piezoelectric substances' useful electrode is represented by Ψ. Although electrodes may be made of any metal, the most common ones used to detect charges and voltages are aluminum or copper. With the current running over the circuit and voltage over the RL (Resistive Load) defined as (V_{output} = IRL) and (I = dQ/dt), we get the final voltage V.

An energy harvester's principal function is to convert mechanical and thermal energy into usable electrical power. Pressure, vibration and wind are among the vibration sources that could be used in Piezoelectric Harvesters. The concentration, charge constant, Young's modulus, design voltage and constant, of the energy harvester are the primary factors that dictate the flow rate of the device. Enhancing energy output from Piezoelectric Harvesters is possible via the use of different configuration architectures. A cylindrical hollow device used to extract power from waves is shown in Fig 2(a). The outer layer is subjected to force or vibration, and the voltage output is measured by electrodes mounted across the Upper and lower layers. An illustration of the exact components that are required for a piezoelectric energy harvesting system may be seen in Fig 2(b). The power that is extracted from PEH is transformed into straight current once it is sent into the circuit that charges the batteries. Several gadgets, such as devices for, mobile charging, and smart lighting and Weather observation receive electrical energy from the lithium-ion battery, which is supplied by the battery charging circuit. An extra perk of the suggested system is that it may be attached to a person's shoes, making it easier to run a smart health monitoring system.

Modeling of Piezoelectric Harvesters

A Hollow cylinder rod was modelled as an energy harvester using the framework dynamics and piezoelectric modules of 'Computer' and 'Solution'(COMSOL). All four types of analysis— time-dependent, eigenfrequency, stationary, and customized—are covered in these classes. Equations are developed for each investigation by applying appropriate boundaries to the existing model. We used Barium Titanate, Lead Zirconate Titanate- 4, Lead Zirconate Titanate - 5H, and polyvinylidene difluoride as piezoelectric materials for our simulations. After designing the nano hollow cylindrical framework, the next step was to choose the best materials to build it with. Electrical connectors are often made of aluminum, both the inside and the outside. In the middle of the two electrodes, there is a small, hollow cylinder made of piezoelectric materials. The experimental piezoelectric materials and their characteristics are detailed in Table 1.

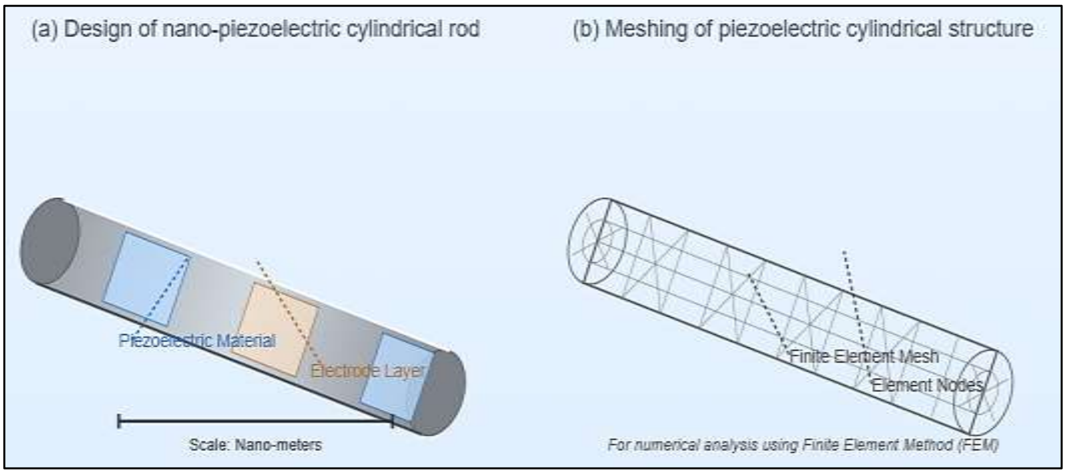


Figure-1: (a) Geometric configuration of the piezoelectric Nanorod. (b) Finite element discretization of the piezoelectric cylindrical domain.

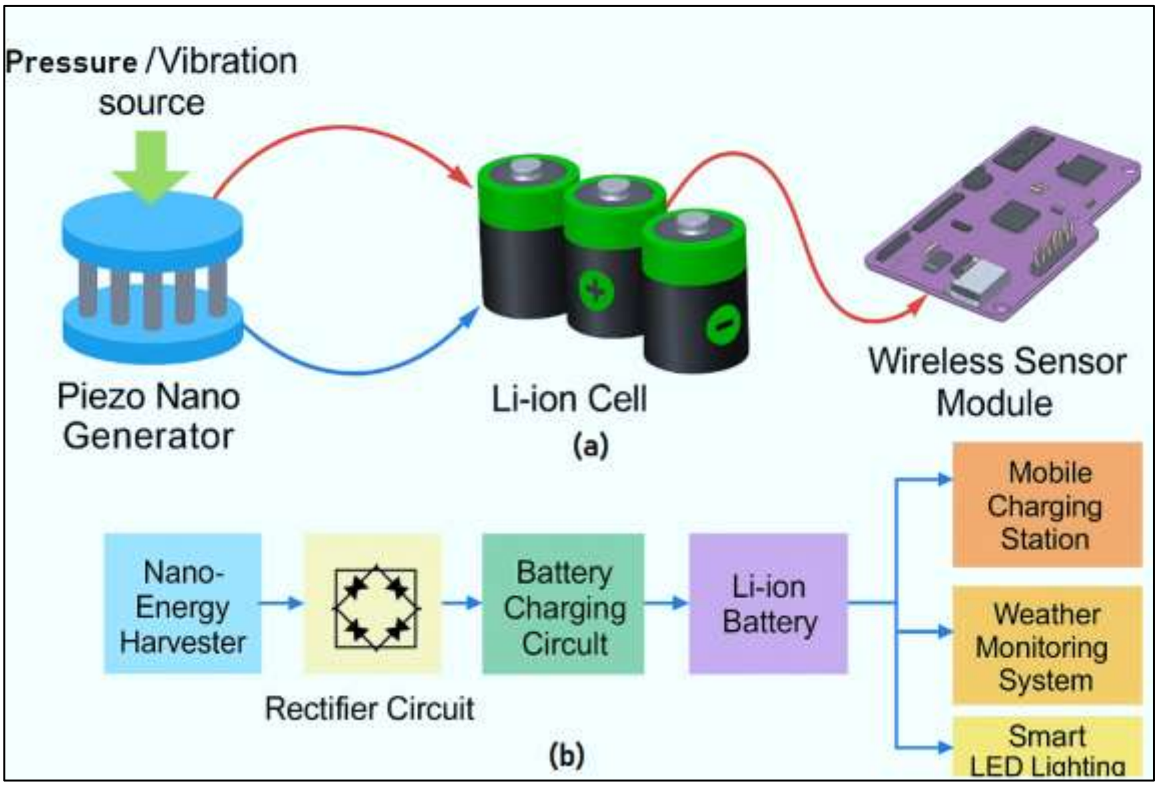


Figure-2: (a) Nanoenergy production based on piezoelectric principles (b) Schematic showing the process of PEH.

For the natural frequency evaluation, the structural mechanics module was utilized. For a range of beam lengths and materials, the generated model calculates the thirty-six natural frequency. The type of mode shapes that correspond to the initial six natural frequency are shown in Fig 3. Table 2 presents the comparison of length and frequency for the nano cylindrical form. The resulting model consists of 13,890 elements and requires around 24 seconds to solve, featuring 62,850 degrees of freedom.

International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Table-1: PMs (Piezoelectric materials) used in simulations and their properties

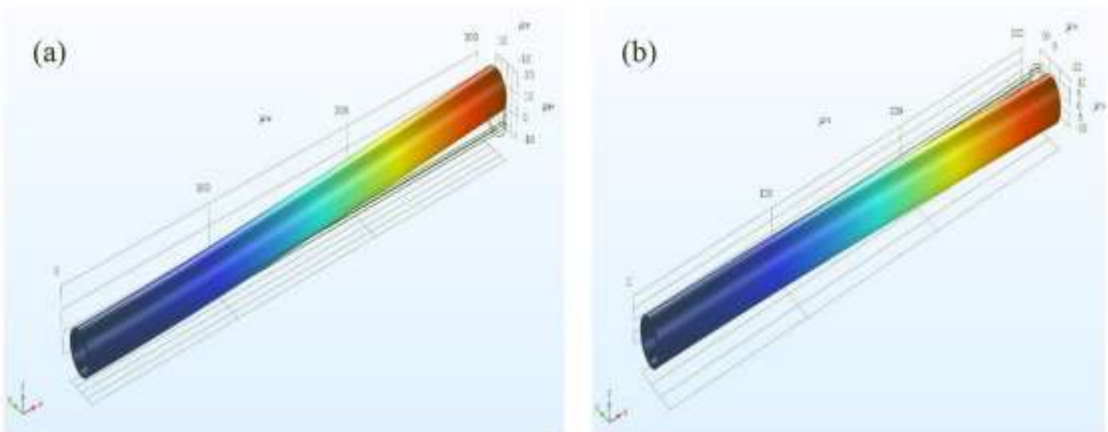
PMs	Volumetric mass density (kg/m3)	Poisson coefficient	Gigapascals (GPa)
BaTiO3	5700	0.29	80
Lead Zirconate Titanate- 4	7500	0.30	64
Lead Zirconate Titanate- 5H	7500	0.34	65
Polyvinylidene difluoride	1780	0.35	4

Numerical Analysis of Piezoelectric Behavior in a Hollow Cylindrical Structure

The PMs were used to build the whole structural module. Fig 4(a) shows the built model's bending curve. A piezo hollow cylinder rod made of many piezoelectric materials is modeled using finite element methods in the simulation. The polarization of prospective through the entire length of the nano energy harvester is shown in Fig 4(b). Throughout the building process, the whole structure was framed with one set boundary and the other allowed to bend. In order to conduct deflection evaluation, the source electrode—the top part of the hollow cylindrical rod—was subjected to pressure, but the base was provided by the bottom interior layer.

5. RESULTS

The relationship between natural frequency and beam length is seen in Fig 5. BaTiO3, Lead Zirconate Titanate- 4, Lead Zirconate Titanate- 5H, and Polyvinylidene difluoride were among the PMs whose natural frequencies were computed and shown using computational methods. Between Fifty and three hundred µm, the beam length was changed. The current computer facility's memory constraints prevent an additional adjustment of the duration during the simulation. When comparing the three materials, the graphs show that Polyvinylidene difluoride and BaTiO3 have the greatest natural frequencies, followed by Lead Zirconate Titanate- 4 and Lead Zirconate Titanate- 5H.



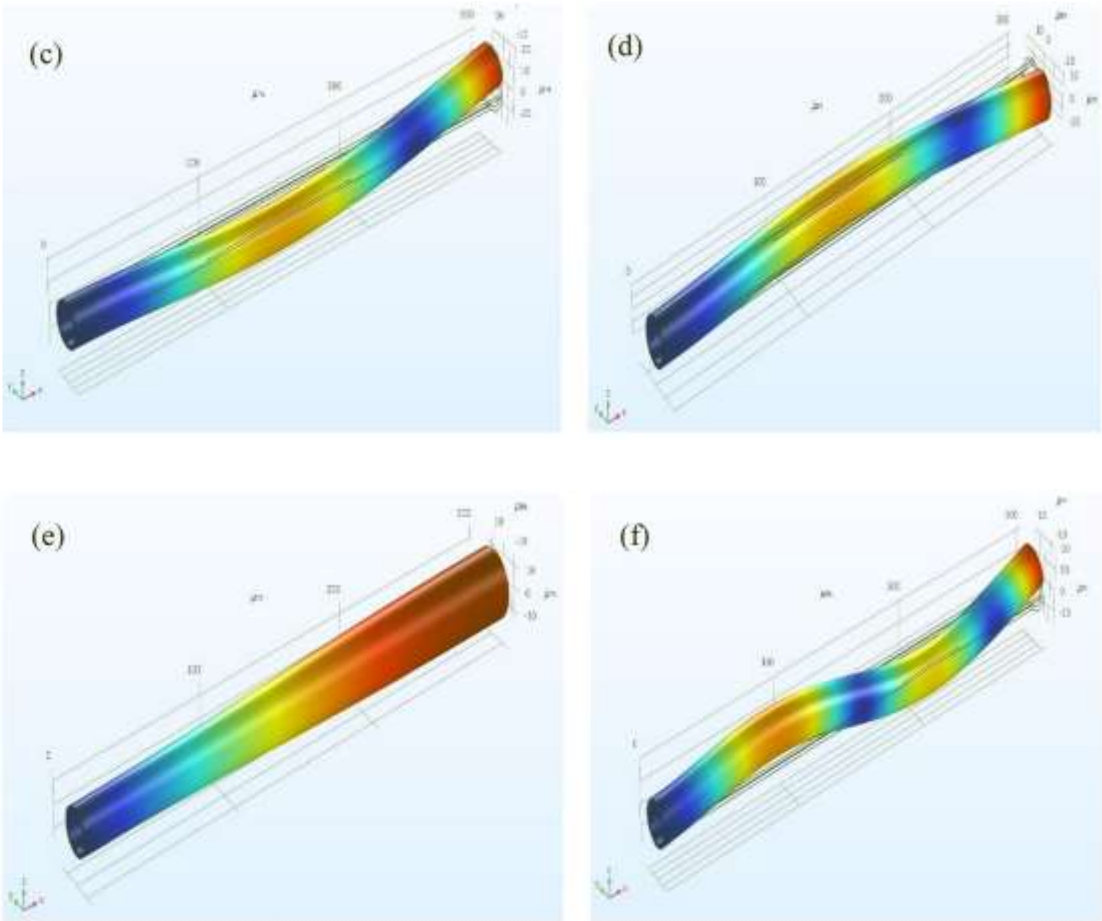


Figure-3: Various stimulation frequencies reveal the mode morphologies of a 300-micrometer-long piezoelectric hollow cylindrical rod based on Polyvinylidene Fluoride

The computed deflection of the piezoelectric activator at different lengths ranging from fifty to three hundred µm is shown in Fig-6. Simulation outcomes show the deflection for several PMs, including Polyvinylidene difluoride, Lead Zirconate Titanate- 4, and BaTiO3. At two hundred and fifty micro meters, the graph shows that the maximum voltage for BaTiO3 was around 3.0911 V.

Table-2: Efficient frequency comparison of nano hollow energy harvesters

Dimensions (µm)	**Various substances Eigenfrequencies (Hertz)**			
	Polyvinylidene difluoride	Lead Zirconate Titanate- 5H	Lead Zirconate Titanate- 4	BaTiO3
50	1450.7	3419.00	3951.9	5344.3
100	415.82	977.03	1137.9	1513.7
150	190.4	446.70	521.35	690.90
200	108,141	259,010.00	296,380	392,280
250	412,941	166,440.00	190,620	252,140
300	48,413	115,840.00	132,730	175,520

Power harvester designs may also benefit from Polyvinylidene difluoride's exceptional flexibility and durability to harsh conditions. This affirms Barium Titanate's viability as a prospective piezoelectric material for micro actuator development compared to alternative piezoelectric substances; nonetheless, it is constrained by its lack of elasticity. The correlation involving micro actuator & voltage lengths is shown in Fig. 6. To get the most out of the nanoscale cylindrical structure, it's important to choose the right size. The graph clearly shows that the bend of the tiny actuator grows with length. There is no additional gain in bending with increasing length beyond the saturation level.

In this article, the authors introduced a cylindrical PEH. The finite element method in 'computer and solution 'Multiphysics was used for the simulation and modeling phases of the study. The results of the simulation show that the harvester can capture the energy that the cylindrical rod produces in different motion modes. Predicting the power harvester's voltage of sortie is within the capabilities of the built system. Using a Natural frequency assessment, we looked at how different lengths of tiny rods generated electrical energy.

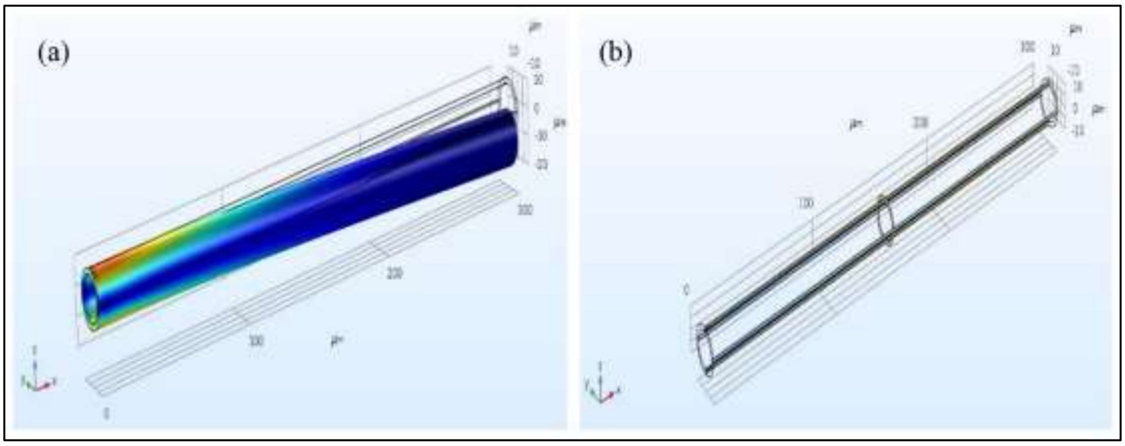


Figure-4: (a) Deflection pattern observed in the micro sensor, (b) distribution of potential within the micro sensor.

International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

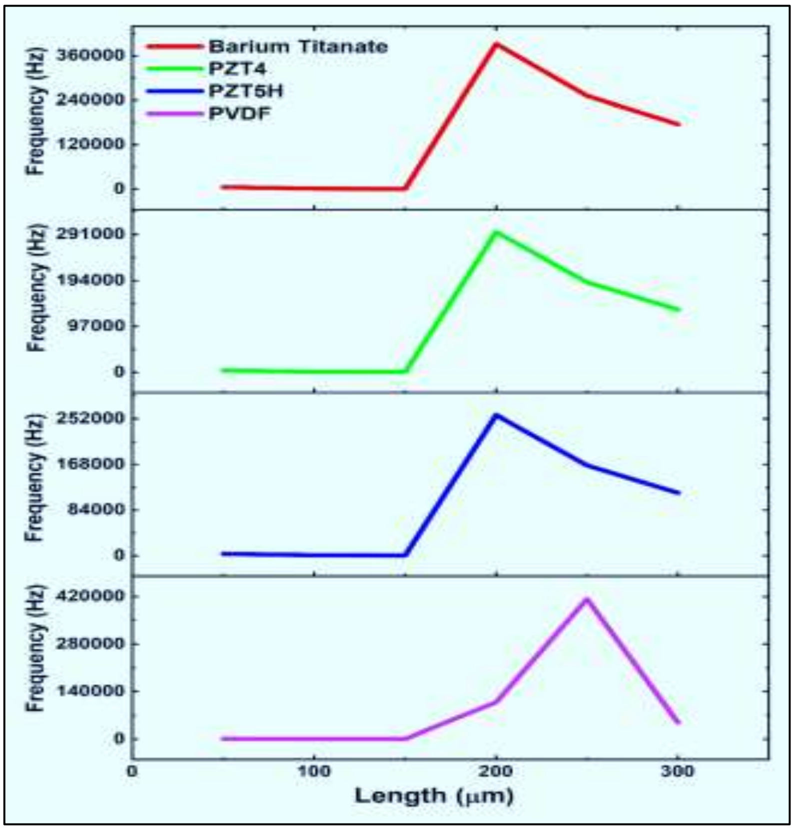


Figure-5: The modeled PEH's frequency versus voltage

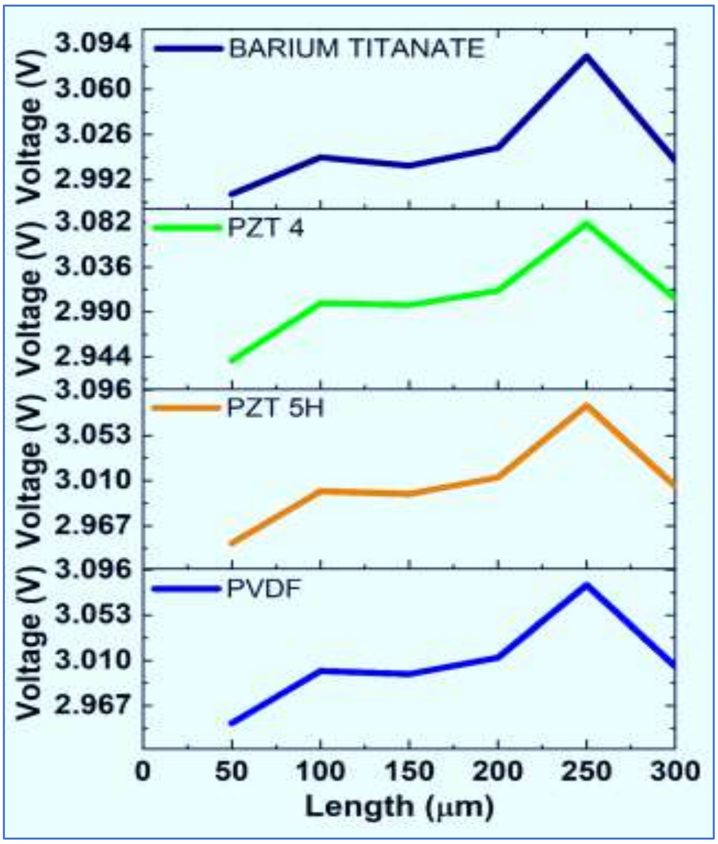


Figure-6: Voltage as a function of the length of the modeled piezoelectric energy harvester.

The simulation findings showed that different PMs had different natural frequencies and different output voltages. Optimizing the energy harvester's effectiveness by adjusting the output voltage and Natural frequency, which are made possible through changing the substance. It was possible to determine the eigenfrequency at which the greatest output voltage could be produced by comparing the natural frequencies of different materials of similar length. More bending allows for a larger transformation from vibrational force to electrical energy, or inversely.

6. CONCLUSION

This study effectively illustrated the design, modeling, and simulation of a nanoscale piezoelectric cylindrical rod aimed at gathering ambient mechanical energy. Finite element research demonstrated that material selection substantially influences energy harvesting efficiency, with Barium Titanate yielding the highest voltage output and PVDF exhibiting enhanced flexibility and durability. The findings provide credence to the practicality of using PEH (Piezoelectric Energy Harvesters) in environmentally friendly technology contexts, particularly for energizing wireless electronic gadgets. Future endeavors will concentrate on optimizing the structural and material configuration to augment output voltage and broaden the spectrum of viable applications. Future work includes framework and design enhancements to the Piezoelectric Energy Harvesters harvester process to boost the output voltage suitable for moderately powerful cordless electronic device charging.

REFERENCES

1. A. Girde, A. A. Farsole, H. P. Deshmukh, M. P. Umate, N. A. Rai, S. S. Lanjewar, M. S. Bhagat (2024) “Harnessing piezoelectric sensors for electricity generation from speed breaker” IOP Conf. Series: Earth and Environmental Science 1409 (2024) 012036. doi:10.1088/1755-1315/1409/1/012036.
2. Abdulmunam, R. T., Taha, L. Y., and Ivey, P. C. Modelling of Low Power Electrostatic Wind Energy Harvester for Macro-Scale Applications. International Journal of Information and Electronics Engineering, 2012. 2(6): p. 912-918.
3. Beker, L., Kulah, H., and Muhtaroglu, A. Piezoelectric Cantilever Prototype for Energy Harvesting in Computing Applications. IEEE Energy Aware Computing (ICEAC), international Conference on Istanbul, 2011. p. 1-4.
4. Camila, G. G., Vitor, R. F., Michael, J. B., Samuel, D. S., and Vicente, L. J. Energy Harvesting Using Piezoelectric and Electromagnetic Transducers. Proceedings of the 9th Brazilian Conference on Dynamics Control and their Applications 2010. p. 1166-1171.
5. Clementi, Giacomo & Cottone, Francesco & Di Michele, Alessandro & Gammaitoni, Luca & Mattarelli, Maurizio & Perna, Gabriele & López-Suárez, Miquel & Baglio, Salvo & Trigona, Carlo & Neri, Igor. (2022). Review on Innovative Piezoelectric Materials for Mechanical Energy Harvesting. Energies. 15. 6227. 10.3390/en15176227.
6. David Berdy, F., Srisungsitthisunti, P., Jung, B., and Peroulis, D. Low-Frequency Meandering Piezoelectric Vibration Energy Harvester. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2012. 59(5): p.846-858.
7. Gaur, A. M., and D. S. Rana. 2014. “Modelling and Eigen Frequency Analysis of Piezoelectric Cantilever Beam.” International Journal of Engineering Sciences 3 (7): 52–9

8. Hui Fang, Liew & Hassan, S.I.s & Abd Rahim, Rosemizi & Isa, Muzamir & Ismail, Baharuddin. (2017). Exploring Piezoelectric for Sound Wave as Energy Harvester. Energy Procedia. 105. 459-466. 10.1016/j.egypro.2017.03.341.
9. Mitcheson, P. D., Green, T. C., Yeatman, E. M., and Holmes, A. S. Power processing circuits for electromagnetic, electrostatic and piezoelectric inertial energy scavengers. Microsystem Technology, 2007. 13(11): p. 1629–1635.
10. Mohamed Ismail, N. M., & Loganathan, N. A. (2024). An Insight into Harvesting Sustainable Electrical Energy from Sound Hazards Using Piezoelectric Materials. Engineering Proceedings, 61(1), 22. https://doi.org/10.3390/engproc2024061022
11. Niell, G., Elvin, G., and Elvin, A. Vibrational Energy Harvesting From Human Gait. IEEE/ASME Trans. On Mechatronics, 2013. 18(2): p. 637-644.
12. Özdemir, A. E. 2019. "Circuit Topology for Piezoelectric Transducers in a Piezoelectric Energy Harvester." IET Renewable Power Generation 13 (12): 2105–10, https://doi.org/10.1049/iet-rpg.2018.6106.
13. Roshan Zameer Ahmed, Rajendra Prasad P, Mohan Kumar M, Nischith Raj K G, Prajwal Hegde, P Ganesh (2023) "Piezoelectric system on harnessing sound energy in closed environment" AIP Publishing. Volume 35, Issue 11. https://pubs.aip.org/aip/pof/article-abstract/35/11/117115/2920946/Piezoelectric-system-on-harnessing-sound-energy-in?redirectedFrom=fulltext
14. Roundy, S., Leland, ES., Baker, J., Carleton, E., Reilly, E., and Lai, E. Improving power output for vibration-based energy scavengers, IEEE Pervasive Computing, 2005. 4(1): p. 28–36.
15. RummanHuq, T., and Sheldon Williamson, S. Comprehensive Comparative Analysis of Piezoelectric Energy Harvesting Circuits for Battery Charging Applications. 39th Annual Conference of the IEEE industrial Electronics Society, IECON 2013. p.6698-6702.
16. Soo Kim, H., Hyong Kim, J., and Kim, J. A Review of Piezoelectric Energy Harvesting Based on Vibration. International Journal of Precision Engineering and Manufacturing, 2011. 12(6): p. 1129-1141.
17. Steven, R., Anton, H., and Sodano, A. A Review of Power Harvesting Using Piezoelectric Materials. IOP Publishing, Smart Material Structure, 2007. 16(3): p. 1-21.
18. Sudevalayam, S., and Kulkarni, P. Energy Harvesting Sensor Nodes: Survey and Implications. IEEE Communications Surveys and Tutorials, 2011. 13(3): p. 443-461.
19. Taufik, T., Thornton, J., and Taufik. M. Small-Scale Wind Energy Harvesting Using Piezoelectric Converter. IEEE Conference on Power Engineering and Renewable Energy, Bali, Indonesia, 2012. p.1-5.
20. Wischke, M., Masur, M., and Woias, P. A Hybrid Generator for Vibration Energy Harvesting Applications. IEEE International Solid –State Sensors, Actuators and Microsystems Conference, Transducers, 2009. p. 521-524.