ENHANCING THE PERFORMANCE OF PIEZOELECTRIC ENERGY HARVESTER USING CORRUGATED BEAM DESIGN

Firdaus Husaini Mohd Nordin, Azni N. Wahid*

Department of Mechatronics,
Kulliyyah of Engineering,
International Islamic University Malaysia.

azni@iium.edu.my

Article history

Received: 17 Dec 2024

Received in revised form: 30 Dec 2024

Accepted: 30 Dec 2024

Published online: 31 Dec 2024

*Corresponding author: azni@iium.edu.my

ABSTRACT

Piezoelectric materials generate electric charges in response to applied mechanical stress, making them widely used in mechanical energy harvesters to convert mechanical vibration into electrical energy. Despite their promise, energy harvesters typically generate only a few milliwatts of power. This research improves the voltage output of a piezoelectric energy harvester by replacing a conventional flat cantilevered piezoelectric beam with a corrugated cantilevered beam. The relationship between the number of curves in the corrugated beam and the voltage generated was investigated. The system consists of a corrugated beam covered with a polyvinylidene fluoride (PVDF) film with varying numbers of curves, while maintaining a constant total volume. Simulation results using COMSOL indicate that increasing the number of curves increases the Von Misses Stress generated and therefore enhances voltage generation. Experimental studies show an improved voltage generation of 20.2% for four-curve corrugated beam and 18.2% for two-curve corrugated beam relative to straight piezoelectric beam, respectively. Compared to conventional designs, the corrugated beam's higher stiffness and pre-stressed curves result in increased voltage output.

Keywords: *piezoelectric, energy harvester, corrugated beam*

1.0 INTRODUCTION

With the increasing demand for sustainable and self-powered systems, energy harvesting has emerged as a promising solution to capture ambient energy from the environment and convert it into usable electrical energy. Among various energy harvesting technologies, piezoelectric energy harvesters (PEHs) have gained significant attention due to their ability to efficiently convert mechanical energy such as vibrations into electrical energy through the direct piezoelectric effect. Piezoelectric materials generate electrical charge when subjected to mechanical stress or strain, making them ideal for applications in vibration-based energy harvesting systems. These systems are particularly attractive for powering low-power devices such as wireless sensor networks, medical implants, and wearable electronics, where frequent battery replacements are impractical or undesirable [1-6]. Piezoelectric energy harvesters offer several advantages, including compact design, high energy density, and ease of integration with existing mechanical systems. The performance of a piezoelectric energy harvester is largely influenced by its structural design, material properties, and operating conditions. Cantilever beam structures are the most common design due to their simplicity and efficiency under low-frequency vibrations. However, conventional cantilever beams often suffer from limited energy output and narrow bandwidth. To address these limitations, advanced designs have been explored to enhance stress concentration, increase stiffness, and broaden the operational frequency range.

2.0 RELATED WORKS

The shape and structure of piezoelectric devices play a crucial role in determining their energy harvesting efficiency, mechanical performance, and adaptability to various applications. Different designs have been developed to optimize energy output under varying load conditions and vibration frequencies. Kim et al. developed a piezoelectric energy harvester using a parallel cantilever beam structure with attached piezoelectric film [7]. By leveraging multiple degrees of freedom (DOFs) in the vibrating system, the harvester achieved multiple peaks in a wide frequency bandwidth. Their proposed two-DOF system utilized both rotational and translational displacements, leading to enhanced bandwidth and voltage output compared to SDOF systems [7]. Seon-Jun et al. further demonstrated that modifying physical parameters, such as the radius of a rotational device, could tune natural frequencies and optimize output power. Their study showed that increasing the radius of the reel decreased the natural frequency and increased the harvested power [8]. Min-Ho et al. introduced a hybrid cantilever beam consisting of a flexible beam and a piezoelectric-covered cantilever. The flexible beam induced additional bending motion, effectively controlling the system's resonance frequency and enhancing energy generation [9]. Kim et al in their work studies corrugated cantilever beam energy harvester using different number of curves but with the same overall size (length). They found that the more curve used while maintaining the same overall projected length, the higher output voltage is produced [10].

Cymbal is another type of energy harvester design developed using circular piezoelectric disc placed between metal end caps to handle higher loads. Tuan Putera and Kok utilized array configurations of Piezoelectric Cymbal Transducer (PCT) with conditioning circuit for roadway energy harvesting [11]. Kim et al. proposed a cymbal-structured piezoelectric device, which consists of two metal cymbal-shaped endcaps and a piezoelectric disk in between. The endcaps improve the durability of the piezoelectric disk under high loads and act as mechanical transformers. By converting part of the axial stress into radial and tangential stresses, the structure amplifies the piezoelectric coefficients $d31$ and $d33$. The cymbal structure can generate higher power output (up to 100 μW), however, it suffers from energy losses and high resonant frequencies, which limit its performance [12]. Bernat et al in their work added an inner contact column that focuses the load from the cymbal caps onto the centre of the piezoelectric membrane, enhancing its deformation and energy generation. Results show that a more focused inner contact column significantly increases energy production, achieving up to ten times the output of traditional cymbal designs [13].

This research investigates the voltage generated by a piezoelectric corrugated cantilevered beam with varying numbers of curves. To ensure a fair comparison, the volume of the piezoelectric beam is kept constant i.e. the overall projected beam length is different for all case studied. The performance of the corrugated beams is compared to that of a conventional straight cantilever beam. PVDF thin film is chosen as the piezoelectric material due to its flexibility. Three beam designs are considered in this study: a straight beam, a 2-curve beam, and a 4-curve beam. The output voltage, natural frequencies, and Von Mises stress of the beams are first analyzed through simulations using COMSOL software. Experimental studies are then conducted to validate the simulation results.

3.0 SIMULATION STUDIES

3.1 Derivation of natural frequency for corrugated beam

To deduce the relationship for the natural frequency of a corrugated beam, the expression of the flexural rigidity of the corrugated beam in the longitudinal direction given by Briassoulis is expressed as [14]:

$$D_x = \frac{b(Et^3)}{12s(1-v^2)} \tag{1}$$

where *v* is Poisson's ratio, *t* is the thickness of the plate and *E* is the Young's modulus of the plate. For a typical vibrating system composed of a single cantilevered beam and a mass, the natural frequency of the fundamental mode can be simply obtained from

$$\omega_n = \sqrt{\frac{EI}{ML^4}} \tag{2}$$

where *I* is the area moment of inertia, and *M* is the mass. Here, *EI* represents the rigidity of the beam and can be replaced by D_x for the corrugated beam. Therefore, the natural frequency of the corrugated cantilevered beam can be found as:

$$\omega_n = \sqrt{\frac{D_x}{ML^4}} \tag{3}$$

Substituting equation (1) into equation (3) yields:

$$\omega_n = \sqrt{\frac{bEt^3}{12s(1-v^2)}\,\frac{1}{ML^4}} \tag{4}$$

From equation (4), it is known that the natural frequency of the fundamental mode is proportional to the square root of the ratio of b to s as expressed by:

$$\omega_n \propto \sqrt{\frac{b}{s}} \tag{5}$$

Equation (5) shows that the natural frequency of the system depends on the geometry of the wrinkles, s. In other words, the natural frequency can be reduced by increasing the length of wrinkles, s, and decreasing its projected length, b (shown in Figure 1).

Table 1: Dimensions of cantilever beam used (all dimensions in mm)

Beam Model	Length	Width	Thickness	Arclength, s	Projected length, b
Straight				0	0
2-curve	220	20	1	100	63.6
3-curve				50	31.8

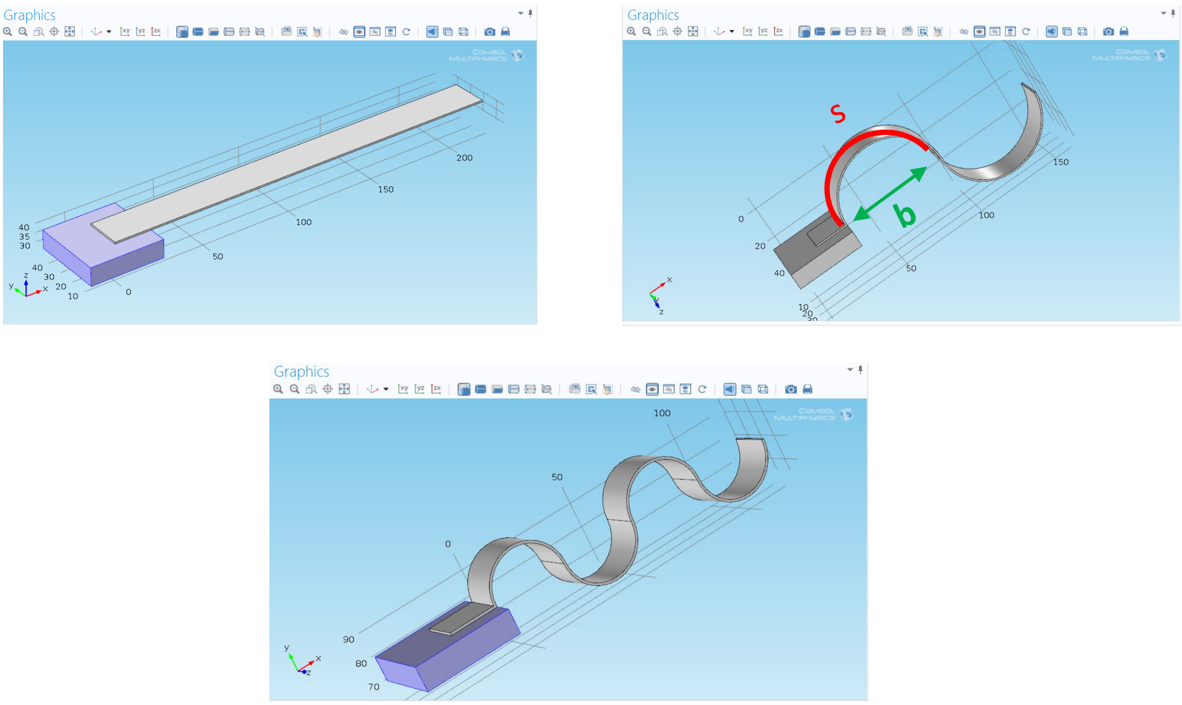

Figure 1: Model of the a) straight b) 2-curves and c) 4-curves cantilevered beam in COMSOL

PERINTIS eJournal

PERINTIS eJournal, **2024**, Vol. 14, No. 2, pp. 39-47

Three cantilevered piezoelectric beam models were simulated using COMSOL Multiphysics; a straight beam, a two-curve corrugated beam, and a four-curve corrugated beam. One crucial aspect of this study is to make the volume of piezoelectric material used to be the same for all models. The simulations analyzed the natural frequency, Von Mises stress, and voltage generation for each design. All models used aluminum as the base material, with a PVDF piezoelectric layer covering the upper surface. The beam dimensions are listed in Table 1. The beam models used in the study are shown in Figure 1.

For the first study in COMSOL, the natural frequencies of each beam model were analyzed. Determining the natural frequency is crucial because it represents the point at which the beam experiences maximum vibration, leading to the highest stress and, consequently, the highest voltage generation from the piezoelectric material. As shown in Table 2, the straight cantilever beam exhibited the lowest natural frequency, followed by the two-curve and four-curve corrugated beam models. The effect of increasing the number of curves increases the natural frequency of the beam, however it still falls in the lower frequency range (<50Hz). This trend is attributed to the increased stiffness of the corrugated beams compared to the straight beam. The results align with the theoretical predictions for corrugated beams, as derived in Equation (4).

Table 2: Results of simulation studies using COMSOL

Beam model	Natural Frequency (Hz)	Electric Potential (V)
Straight beam	21.066	0.85
2-curve beam	29.269	1.79
4-curve beam	35.162	7.376

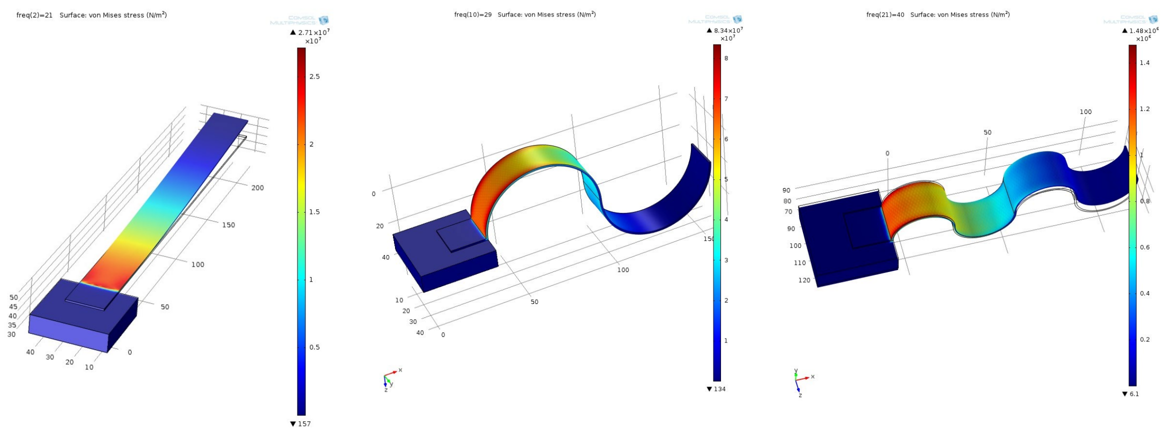

Figure 2 Illustration of Von mises stress developed

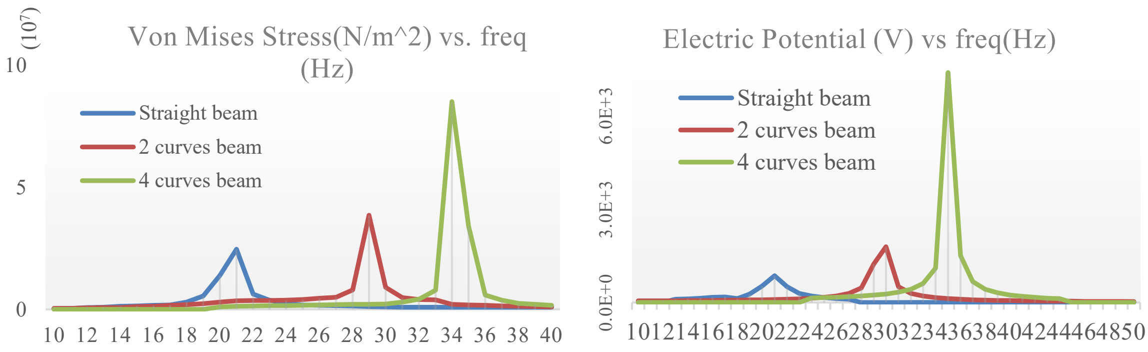

Figure 3. Simulation results. a) Von mises stress and b) Electric potential produced

From Figure 3(a), it is evident that the magnitude of von Mises stress is higher for the four-curve beam compared to the two-curve beam. This increase is attributed to the greater number of curves, which enhance the beam's stiffness. Higher stiffness improves the beam's resistance to deformation under applied forces, resulting in elevated stress levels during vibration. Additionally, the curved sections act as stress concentrators, leading to localized deformation that amplifies the overall stress. Since the charge generated by the piezoelectric material is directly proportional to the stress, the beam with more curves produces a higher voltage output. This confirms the simulation results for magnitude of electrical potential generated as shown in Figure 3(b). It is important to note that the values obtained from simulation studies are not the primary focus. Rather, the emphasis is on analyzing the trends and gaining insights into the underlying behavior of the corrugated piezoelectric beam harvester.

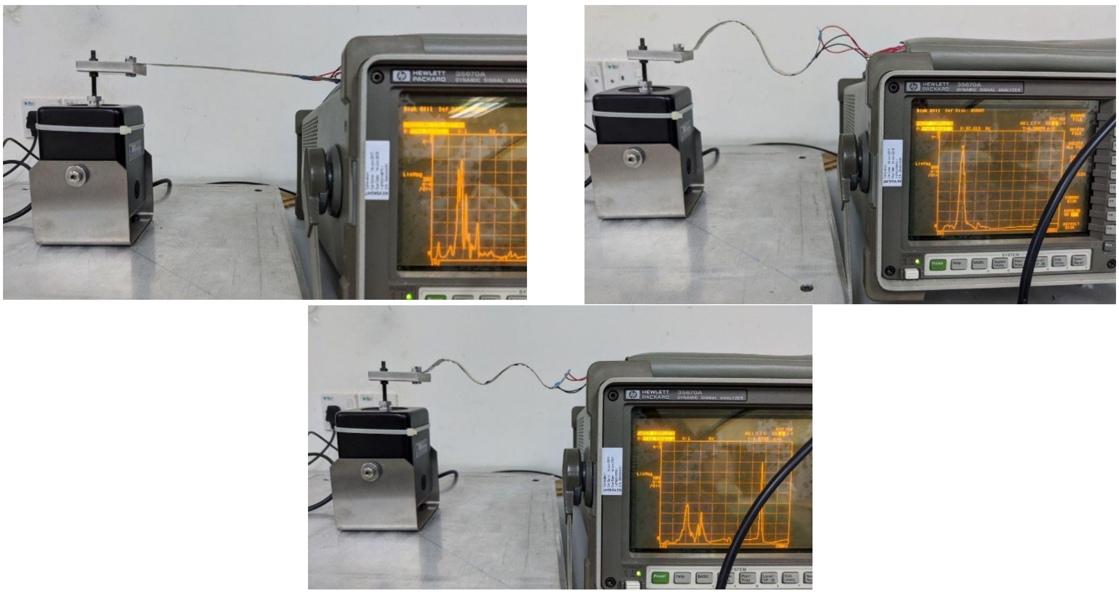

Figure 4: Experimental setup for straight, two-curve and four-curve piezoelectric beam (graph on DSA does not represent the final result)

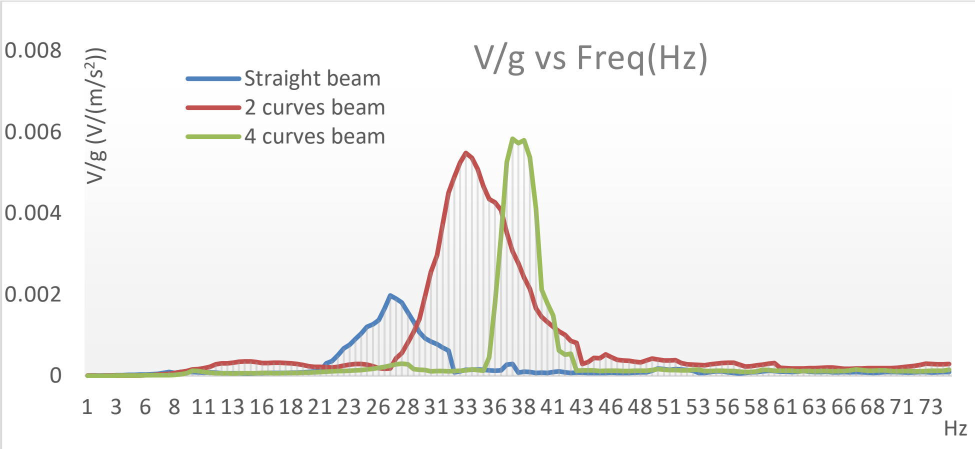

Figure 5: Voltage generation from experimental studies

4.0 EXPERIMENTAL STUDIES

In this study, aluminum cantilever beam is used as the base material, with PVDF piezoelectric layer covering the upper surface of the beam. Each beam is clamped onto an electrodynamic shaker which vibrates at a designated frequency range. The excitation frequency range is chosen such that it covers the first natural frequency of respective beams, found from simulation studies. Due to the vibration, stress will be generated and therefore electrical charge will be produced by the beam in which the output voltage was measured using HP dynamic signal analyzer (DSA). Figure 4 illustrates the experimental setup.

The experimental results presented in Figure 5 illustrate the transfer function of voltage generated per acceleration from the shaker for the three beam designs: straight, two-curve, and four-curve beams. The trend observed in the experiment aligns well with the simulation results i.e. the four-curve beam produces the highest voltage output, followed by the two-curve beam and finally the straight beam. Specifically, the four-curve beam generates 20.1% more voltage compared to the straight beam, while the two-curve beam produces 18.2% more voltage than the straight beam. The lower output obtained for the 4-curve beam may have been affected by the placement of the wire terminals, which likely hindered the vibration at the beam's free end. In terms of resonance, the values obtain experimentally seem to agree well with values obtained from simulation studies i.e. 27 Hz, 33 Hz and 38 Hz for the three beams, respectively. The results validate that introducing curvature into the beam structure effectively improves energy harvesting performance.

5.0 CONCLUSION

This research investigated the relationship between the number of curves in a corrugated cantilevered beam and the resulting voltage generation. Both simulation and experimental results demonstrate that the corrugated beam design significantly enhances voltage output compared to a conventional straight piezoelectric cantilever beam. The improved performance can be attributed to the increased stiffness and higher stress concentration in the corrugated beam, which amplifies the deformation of the piezoelectric material and, consequently, the voltage generation. This study highlights the potential of corrugated beam structures for enhancing the efficiency of piezoelectric energy harvesters by leveraging their unique geometric properties to optimize energy conversion.

REFERENCES

[1] Shirvanimoghaddam, M., Shirvanimoghaddam, K., Abolhasani, M.M., Farhangi, M., Barsari, V.Z., Liu, H., Dohler, M. and Naebe, M., (2019). Towards a green and self-powered Internet of Things using piezoelectric energy harvesting. *Ieee Access*, *7*, 94533-94556.

[2] Won, S. S., Seo, H., Kawahara, M., Glinsek, S., Lee, J., Kim, Y., ... & Kim, S. H. (2019). Flexible vibrational energy harvesting devices using strain-engineered perovskite piezoelectric thin films. *Nano Energy*, *55*, 182-192.

[3] Ali, F., Raza, W., Li, X., Gul, H., & Kim, K. H. (2019). Piezoelectric energy harvesters for biomedical applications. *Nano Energy*, *57*, 879-902.

[4] Sun, Y., Chen, J., Li, X., Lu, Y., Zhang, S., & Cheng, Z. (2019). Flexible piezoelectric energy harvester/sensor with high voltage output over wide temperature range. *Nano Energy*, *61*, 337-345.

[5] Hu, D., Yao, M., Fan, Y., Ma, C., Fan, M., & Liu, M. (2019). Strategies to achieve high performance piezoelectric nanogenerators. *Nano energy*, *55*, 288-304.

[6] Brunelli, D., Benini, L., Moser, C., & Thiele, L. (2008, March). An efficient solar energy harvester for wireless sensor nodes. *Proceedings of the conference on Design, automation and test in Europe*, 104-109.

[7] Kim, I. H., Jung, H. J., Lee, B. M., & Jang, S. J. (2011). Broadband energy-harvesting using a two degree-of-freedom vibrating body. *Applied Physics Letters*, *98*(21).

[8] Jang, S. J., Kim, I. H., Jung, H. J., & Lee, Y. P. (2011). A tunable rotational energy harvester for low frequency vibration. *Applied Physics Letters*, *99*(13).

[9] Seo, M. H., Choi, D. H., Kim, I. H., Jung, H. J., & Yoon, J. B. (2012). Multi-resonant energy harvester exploiting high-mode resonances frequency down-shifted by a flexible body beam. *Applied Physics Letters*, *101*(12).

[10] Kim, I. H., Jin, S., Jang, S. J., & Jung, H. J. (2014). A performance-enhanced energy harvester for low frequency vibration utilizing a corrugated cantilevered beam. *Smart Materials and Structures*, *23*(3), 037002.

[11] Tuan Nurul Afiqah binti Tuan Putera, & BC Kok. (2021). Design Analysis of Piezoelectric

[12] Kok, B. C. (2021). Design Analysis of Piezoelectric Cymbal Transducer (PCT) Array for Roadway Energy Harvesting System. *Evolution in Electrical and Electronic Engineering*, *2*(1), 186-195.

[13] Kim, H. W., Batra, A., Priya, S., Uchino, K., Markley, D., Newnham, R. E., & Hofmann, H. F. (2004). Energy harvesting using a piezoelectric "cymbal" transducer in dynamic environment. *Japanese Journal of Applied Physics*, *43*(9R), 6178.

[14] Bernat-Maso, E., Martínez, B., Mercedes, L., & Mendizábal, V. (2023). Energy harvester based on low cost piezoelectric membrane for road traffic application. *Microsystem Technologies*, *29*(7), 985-998.

[15] Briassoulis, D., Waaijenberg, D., Gratraud, J., & Von Elsner, B. (1997). Mechanical properties of covering materials for greenhouses part 2: quality assessment. *Journal of Agricultural Engineering Research*, *67*(3), 171-217.