Automatika

Journal for Control, Measurement, Electronics, Computing and Communications

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/taut20

Experimental study on the piezo-based energy harvester utilizing the ambient vibrations for smart applications

K. S. Jaibhavani & S. Visalakshi

To cite this article: K. S. Jaibhavani & S. Visalakshi (2024) Experimental study on the piezo-based energy harvester utilizing the ambient vibrations for smart applications, Automatika, 65:3, 1013-1024, DOI: 10.1080/00051144.2024.2318167

To link to this article: https://doi.org/10.1080/00051144.2024.2318167

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

Published online: 19 Mar 2024.

Submit your article to this journal

Article views: 549

View related articles

View Crossmark data

Citing articles: 3 View citing articles

Full Terms & Conditions of access and use can be found at https://www.tandfonline.com/action/journalInformation?journalCode=taut20

AUTOMATIKA
2024, VOL. 65, NO. 3, 1013–1024
https://doi.org/10.1080/00051144.2024.2318167

OPEN ACCESS
Check for updates

Experimental study on the piezo-based energy harvester utilizing the ambient vibrations for smart applications

K. S. Jaibhavani and S. Visalakshi

Department of Electronics and Instrumentation Engineering, SRM Valliammai Engineering College, Chengalpet, India

ABSTRACT
The proposed energy harvester has novel construction, its performance evaluated through frequency response, force response and power harvested under an optimum load, is presented. This harvester is more suitable for low power applications like IoT devices, Wireless sensor nodes and biomedical implants. The suggested harvester has two sections namely truncated cone and rectangular beam section (TCRB). The analytical model is formulated and natural frequencies are obtained using FEA tool. Simulations for natural frequencies and associated comprehensive parameters are done along with distribution of stress across the piezo patch. The tapered radius ratio of the truncated cone is analysed to obtain the optimal value. The simulated model is fabricated and verified experimentally. The result is compared with uniform cantilever beam harvester. The voltage produced by a TCRB harvester is 56.76 % higher than the harvester with a homogeneous rectangular cantilever beam. The rectangular harvester has a resonant frequency of 52.8 Hz, while the TCRB harvester has 39.4 Hz. Also, the TCRB type piezoelectric vibration energy harvester with optimum taper radius ratio provides greater power, than uniform and trapezoidal cantilever beams. The obtained experimental results match the simulation results, ascertains the validity of the proposed harvester.

ARTICLE HISTORY
Received 2 November 2023
Accepted 2 January 2024

KEYWORDS
Piezoelectric; tapered cone; vibration; natural frequency; energy harvester

1. Introduction

In recent years, several applications with lower power supply requirements have been pursued, including tiny electronic instruments, distributed wireless sensor nodes and embedded sensor nodes, powering automated guided vehicles, and operating security systems in residential areas. Batteries are inappropriate for wireless sensor nodes or implanted device applications because they have a limited lifetime and may require maintenance and replacement. By harvesting ambient energy, a completely autonomous system can be achieved for these low-power applications. This enables the development of "deploy and forget" sensor nodes that do not require maintenance or replacement after installation and can operate for several years. Energy harvesting [1] is the process of converting waste energy into long-term electrical energy. Energy harvesting is also called power or energy scavenging, transforming available ambient energy from the environment into useful energy. Light, heat, mechanical vibration, electromagnetic radiation, and chemical energy from microbial reactions are considered energy sources that can be collected [2]. The power density of outdoor solar energy is 15 mW/cm^3, which is two times higher than the orders of magnitude of other energy sources. On the other hand, solar energy is unsuitable for usage indoors, because its power density diminishes between 10 and 20 μW/cm^3. The most appealing alternatives are mechanical vibrations with a power density of about 300 μWatts/cm^3 and airflow with a power density of 360 μWatts/cm^3. In addition to mechanical motions, the stray magnetic fields created by alternating current equipment and flowing through the earth, pavement, and the majority of metals, including lead, can be used to generate electricity. This is possible because of the flow of alternating current through these materials. Among these techniques, piezoelectric ones offer advantages, and these materials are not as susceptible to environmental circumstances as solar panels are as they use mechanical energy to provoke electricity [3]. They can also be made very thin, which makes them easy to add to a system with wireless sensor units that demand low power. Because of this, many studies have used piezoelectric materials to collect vibrations from the environment [4–6]. Because of this, there have been several investigations in which piezoelectric materials have been utilized to collect vibrations from the surrounding environment [7]. Thus the piezoelectric energy harvester with different host structures has gained more importance in the research field [8]. They can be made quite thin [9], which allows easy integration into the PVEH structure along with sensor nodes that need to be powered [4–6]. For the meso scale, a review of piezoelectric energy harvesters employing

CONTACT K. S. Jaibhavani ksjaibhavani@gmail.com Department of Electronics and Instrumentation Engineering, SRM Valliammai Engineering College, Chengalpet, Tamil Nadu, India

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

Table 1. Different energy sources and its potential power densities.

Energy Source	Potential power density
Solar – in an outdoor environment	~ 10's mW/cm^2
Solar – in an indoor environment	~ 10's μW/cm^2
Vibrations due to Machineries	~ 100's μW/cm^3
Human Movements	~ 10's μW/cm^3 to1000's μW/cm^3
Thermoelectric	~ 10's μW/cm^2
RF waves	~ 100's μW/cm^3
Airflow	~ 100's μW/cm^3
Acoustic noise	~ 10's μW/cm^3

low-profile transducers is offered, as well as the outcomes of several energy harvesting devices are given [10]. Regarding the Nano-Scale PVEH, many observations proposed by several researchers are presented in the literature. Zinc Oxide Nano Rods (ZnO NRs) research was first done by Wang and Song [11]. They grew ZnO NRs on Sapphire substrate using vapour liquid solid deposition where gold nanoparticles were deposited on the tip of the rods. Theoretical calculations show that the energy density of piezoelectric devices is three hundred to five hundred per cent surpassing electrostatic and electromagnetic devices. Ambient sources available and the associated density for the potential power that can be harvested are presented in Table 1 Pierre and Jacques Curie developed the piezoelectric phenomenon in thenineteenth century. It's the capacity of several materials, particularly crystals and some specific ceramics, to create an electric potential energy in reaction to the experienced mechanical stress. A piezoelectric material, when subjected to stress, will undergo an alteration in its atomic architecture, which will result in the formation of dipole moments. This applied strain is directly proportional to the electrical polarization. This is called the direct piezoelectric effect, and it happens when the force on the piezoelectric material causes it to make electricity. So, if a periodic force (tension or compression) is put on the material, the output will be an alternating current(AC) voltage. On the other hand, if the piezoelectric material is electrically polarized, the inverse piezoelectric effect happens and the material lengthens or shortens when an electric voltage is applied. The direct and inverse piezoelectric effect is shown in Figure 1.

Piezoelectric-based energy harvesters usually work either in 33 mode or 31 mode, as shown in Figure 2. When operating in 33 mode the force applied direction and the poling direction are the same and thus experience a compression in piezo material where the electrodes are placed on the top surface and bottom surface. [1] In the case of 31 mode, the direction of force applied and poling direction is at right angles that are perpendicular to each other. This coupling mode is commonly used because the beam that experienced lateral stress is easily coupled to the beam and the piezo material is patched on the surface of the beam.

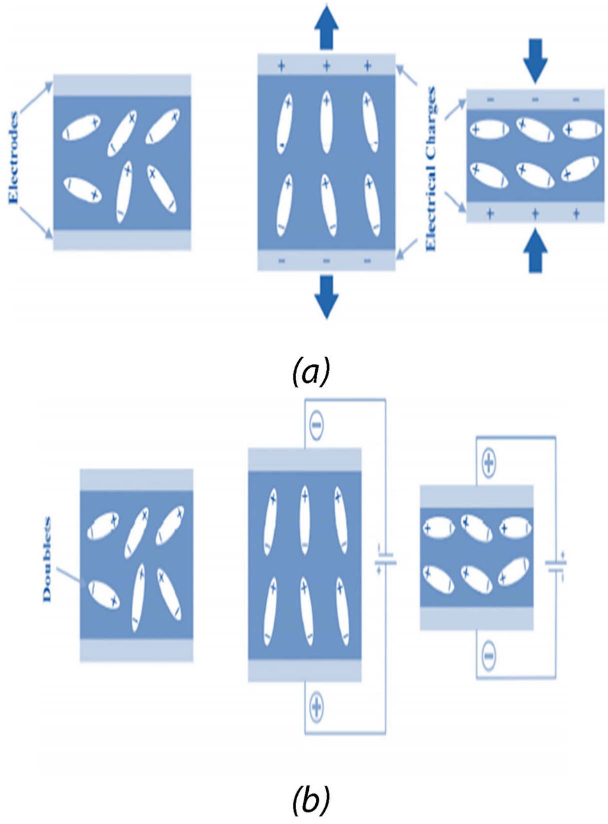


Figure 1. (a) Direct piezo effect (b) Inverse piezo effect.

Piezoelectric-type Vibration Energy Harvester (PVEH) is a promising solution for power supply problems due to (i) Maximum energy storage density [12] (ii) Low-frequency excitation (iii) Easy integration with MEMS technology [10] (iv) It is not subjected to electromagnetic interference (v) low cost and resilience. The vital factors to be considered while designing an optimum PVEH are the materials to be used, operating modes, design configuration and shape of the harvester. Harvester's performance can be improved by appropriate investigation and analysis of the following factors: (i) Material selection (ii) Input frequency operating mode range (iii) Design configuration. Regarding the design configuration, the bridge, diaphragm and cantilever types are followed in PVEH. The two edges are clamped in the case of bridge configuration [13]. The force at the free end of the bridge experiences dislocation of the beam which is clamped between rigid supports at the two ends. The membrane begins to vibrate when a central force is applied. With a cantilever [14], one end is fixed and the other is left free, when a mechanical force is activated at the free end of the beam – cantilever, a strain is developed near the fixed end. Various vibrations in the ambience which vibrate at different frequencies are discussed in [15].

Numerical modelling and analytical models of cantilever beams with tapered cavities have been proposed with the conclusion that by modifying the proposed

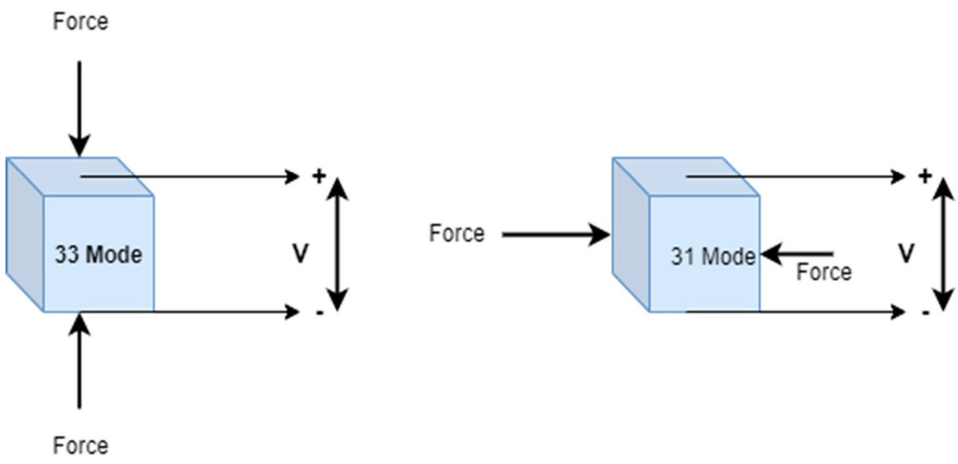


Figure 2. Modes of piezo electric material 31 and 33 mode.

coupling shortly, a more efficient model can be developed so that the first two resonant frequencies are in a wide range of energy collection frequencies. It leads to high performance [16]. formulation and simulation of analysis using Euler Bernoulli beam theory with Bessel functions was developed by [17]. According to the results of the experimental tests and simulation, the energy harvester can be well-worn in an extended frequency range. Finally, stated that an analytical analysis of the stiffness impact as well as a standard design approach should be completed shortly. [18] investigated a piezoelectric vibration energy harvester with varying structural geometry. They used COMSOL Multiphysics to investigate the impact of structural parameter variations on harvester voltage/power. They developed an analytical method based on the Euler-Bernoulli beam theory, which is solved using Bessel functions, and then according to the Rayleigh-Ritz method, it is assumed that the semi-analytic deviation determines the natural frequency of the bond [18]. Irregular cross-sections of the trapezoidal cantilevers with a cylindrical gap and trapezoidal cantilevers with a trapezoidal gap have been developed. Small changes have been made to the cross-section to improve the cantilever strain and its distribution. Compared to the conventional trapezoidal beam, the modelled beam generated more electric energy and it has high power density [19]. In [20], a simulation of a meander-styled piezo-based energy harvester for low-frequency range using Ansys is presented. PZT, Polyvinylidene fluoride-PVDF [21], and MFC- Macro-Fibre Composite [22] are the most frequently used materials in piezoelectric-type electrical power generation.

A PVEH comprises a piezoelectric component with a certain shape, the tweaked geometrical structure of the PVEHs, and an electrical circuit placed externally for processing harvested electricity. The efficiency and power density of vibration-based power harvesters are substantially frequency-dependent because the best operating conditions are at their highest vibration amplitude when they are at their resonance [23], Figure 3 describes the various vibration sources and the building blocks of piezo-based vibration energy harvester.

A wide range of piezoelectric materials are available [24], some are naturally occurring like quartz and some are synthesized piezoelectric materials like Barium Titanate and Lead Zirconate Titanate popularly known as PZT. PZT is one of the most commonly used piezoelectric materials. Harvesting energy through wearable shoes is done in [25] using the lead zirconate ceramic coated with UV resin to withstand a periodic compression of about 60 kgs.

The constitutive equations for a piezoelectric material are given by

$$\delta = \frac{\sigma}{Y} + d \cdot E \tag{1}$$

$$D = \varepsilon \cdot E + d \cdot \sigma \tag{2}$$

where the mechanical strain is denoted as δ, the mechanical stress is denoted σ, Young's modulus of the material is given by Y, the coefficient of strain of the piezoelectric is given by d, E is the electric field, the electrical displacement termed as the charge density mentioned as D and the piezoelectric material dielectric constant is given as ϵ.

2. Description of the proposed piezo electric vibration energy harvester (PVEH)

In this work, a new kind of PVEH with a truncated cone-like structure is proposed along with a rectangular cantilever beam (TCRB) to evaluate its operation. The proposed method is the first one with such a structural difference. The suggested truncated cone with rectangular cantilever beam PVEH is analytically modelled and solved, and the effective high power is then experimentally verified. The work's technical uniqueness and contributions are summarised as follows:

(1) To increase the PVEH power at ambient frequencies, a new geometric structure has been created. This

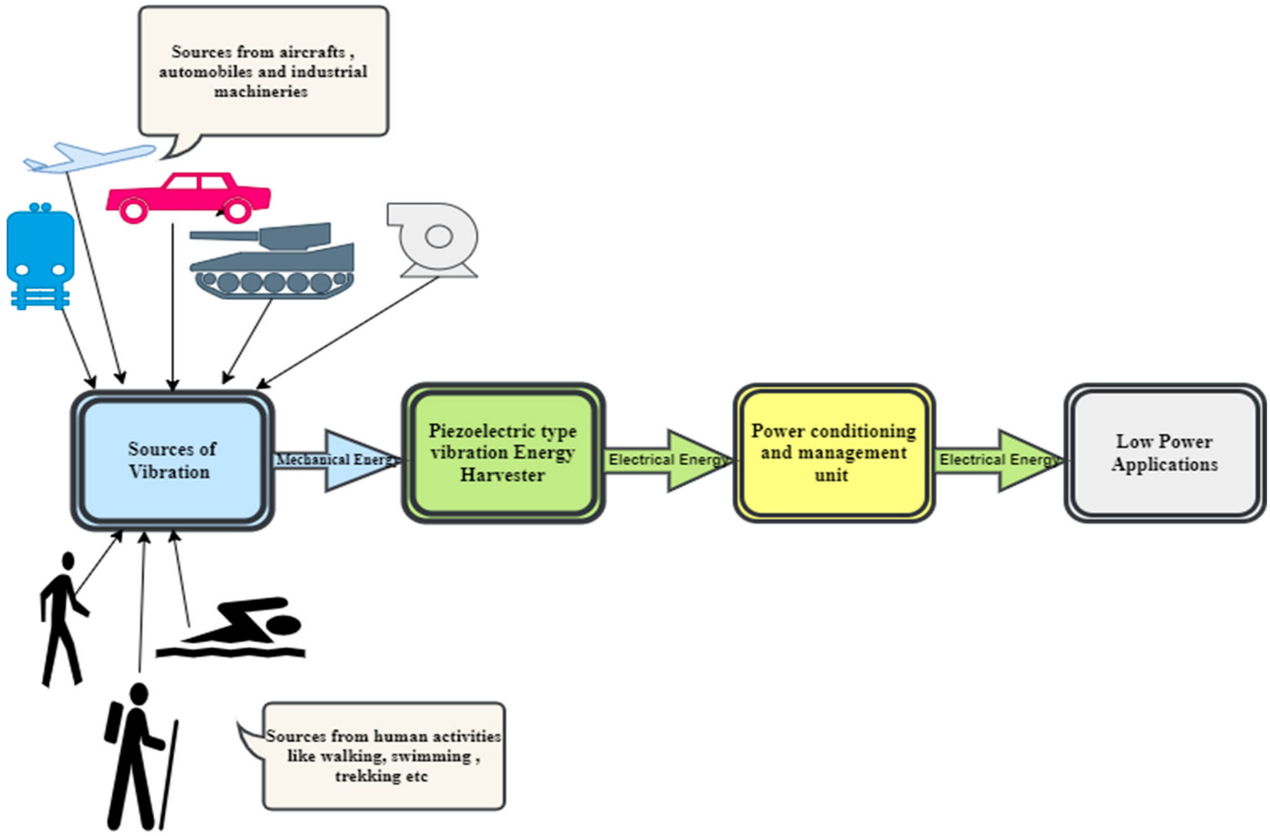


Figure 3. Building blocks of the vibration-based Piezoelectric energy harvester with different sources.

Table 2. Truncated cone with rectangular beam-type PVEH dimensions and piezo patch dimensions.

Tapered Cone Section	Rectangular section	Attached Patch
Radius 1 = 16 mm (R_1)	Width = 100 mm (L_4-L_1)	Width = 15 mm (Wp)
Length = 60 mm (L_1)	Depth = 30 mm (B_b)	Depth = 0.5 mm(B_p)
Radius 2 = 7 mm (R_2)	Height = 10 mm	Height = 15 mm (L_p)

Table 3. Dimensions for the compared uniform cantilever beam type PVEH and its piezo patch.

Uniform Cantilever beam	Attached Patch
Width = 160 mm	Width = 15 mm
Depth = 30 mm	Depth = 0.5 mm
Height = 20 mm	Height = 15 mm

structure is composed of two sections: one section is a truncated cone, and the other half is a rectangular beam. The originality of this work is the demonstration that a truncated cone rectangular cantilever beam PVEH produces more power for the same input force and vibration given at the tip of the beam compared to various structures. This idea is regarded as the original contribution made by the work.

(2) An analytical model of the truncated cone with a rectangular beam structure is developed and the analysis of the associated comprehensive parameters is simulated. It is understood that the TCRB type PVEH with optimal taper radius ratio provides great power at a very low frequency of vibration and the same was verified experimentally by fabricating the harvester in aluminium material.

The graphical view of the proposed energy harvester with a truncated cone-like structure along with the rectangular beam is shown in Figure 4 (TCRB). The proposed harvester design boosts the output power and the voltage in ambient frequency ranges Tables 2–4.

The TCRB-type PVEH consists of a truncated cone section that begins at the fixed end and has a length of L_1. This is then followed by a rectangular cantilever beam section, as shown in Figure 4. The length of the beam section that is a rectangle is (L_4-L_1). The piezo patch is placed about a distance of L_2 (length from fixed end to the start of the piezo patch) to L_3(length from the fixed end to the end of the piezo patch) on the rectangular beam. The length, width and thickness of the piezo patch are L_p, W_p and T_p, respectively. The vibration exciter is responsible for evaluating the harvester's overall performance. The output power of any piezoelectric vibration energy harvester will be greater if it operates at its natural frequency, which can be well established by the material and dimension selection.

The maximum power is attained by operating the TCRCB PVEH at its natural frequency, equation (3) gives the maximum power P_{max}

$$P_{max} = \frac{mR^2\omega_n^3}{4\zeta} \tag{3}$$

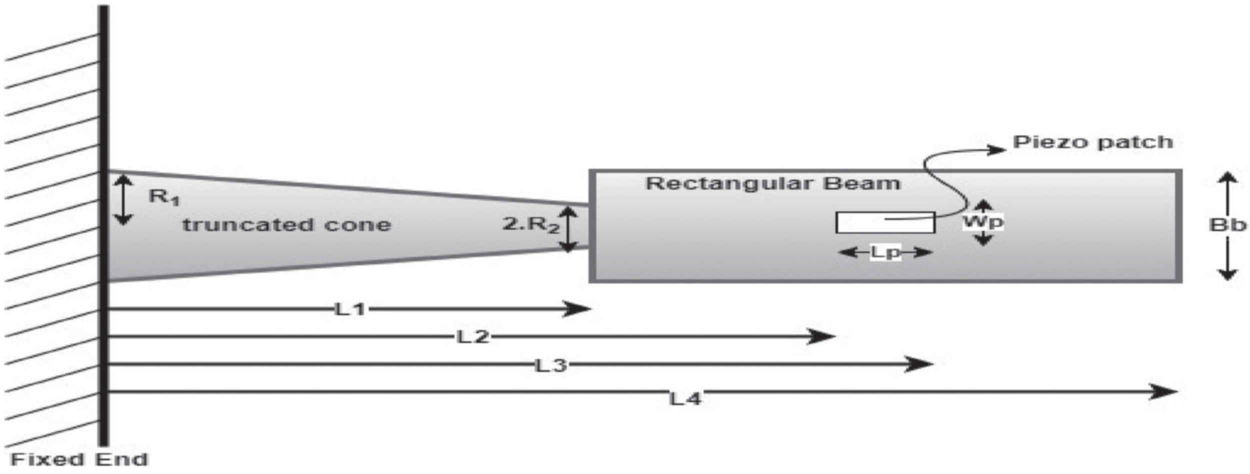


Figure 4. Geometrical structure of the truncated cone with rectangular cantilever beam (TCRB).

Table 4. TCRB, Uniform cantilever beam and Piezo patch materials and their properties.

Beam/Piezopatch	Material	Density (kg/m^3)	Young's modulus (GPa)	Piezoelectric coefficient $g31$ ($10^{-3}\times$ Vm/N)	Piezoelectric constant (C/m^2)
TCRB	Aluminium	2700	70	–	–
Uniform cantilever beam	Aluminium	2700	70	–	–
Piezopatch	PZT – 5A	7750	61	−11	−5.7

The average power produced by the TCRCB energy harvester is determined by

$$R_L = \frac{1}{\omega_n.C_v} \quad (4)$$

$$P_{avg} = \frac{V_{rms}^2}{R_L} \quad (5)$$

$$V_{rms} = \frac{V_{PVEH}}{\sqrt{2}} \quad (6)$$

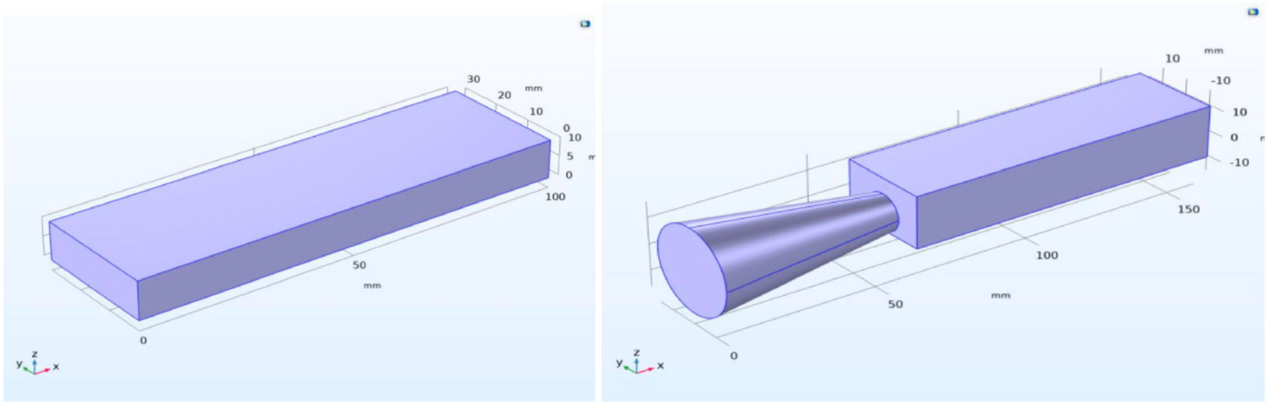
$$I_{rms} = \frac{V_{rms}}{R_L} \quad (7)$$

ω_n is the natural frequency (Hz), Cv is the capacitance of piezoelectric material (nF), P_{avg} is the average power, V_{rms} is the RMS voltage, V_{PVEH} is the open circuit voltage, I_{rms} is the current and R_L is the load resistance.

3. TCRB harvester numerical analysis and discussions

COMSOL Multiphysics was used to do the numerical analysis of the TCRB energy harvesters [28–30]. Table 1 provides the coordinates for the geometric dimensions, as well as the material parameters, of the beam and piezo patch. The fields of physics that were utilized in numerical analysis were solid mechanics, electrostatics, and electrical circuits. One end of the beam was constrained by the boundary conditions, while the other end was free. Figure 4 shows the first four bending modes and the corresponding stress distribution. The natural frequency at the first mode is 38 Hz and TCRB PVEH is allowed to operate at this frequency value for better output. Many mesh sizes were analysed, and it was determined that the typical triangular mesh yields the best results at the smallest time step and the lowest frequency steps of about 0.20 Hz. Eigen frequency analysis was used to determine the primary mode eigen frequency of TCRB energy harvesters. According to the stress analysis results, the TCRB experiences the most stress in the Rectangular section, as illustrated in Figure 4. The piezoelectric patch element is placed on this top rectangular surface of section II, 30 mm from the beam's base. The proposed piezo-based TCRB harvester is allowed to oscillate at resonance using the vibration exciter of varied amplitude to extract maximum power.

Table 5 illustrates the first mode frequency produced from a simulated model. A frequency sweep [16] from 20 to 65 Hz was used to obtain the response of output voltage vs frequency for the suggested harvesters. Figures 5 and 6 show the numerical outcomes of this simulation. The results of the numerical simulation show that the TCRB harvester with the piezoelectric patch produces an output voltage of about 65.3 volts, which is greater than the harvester of the uniform cantilever beam type, which produces an output voltage of 40 volts at frequencies of 38.3 and 59.7 Hz, respectively. Figure 7 shows the numerical simulation of the force voltage characteristics of the TCRB and uniform cantilever beam. Figures 8 and 9 show the numerical simulation results of Input force and voltage and Input force and the harvested power for TCRB-type harvester compared with uniform cantilever beam-type harvester.



(a) (b)

Figure 5. Simulated structure of the truncated cone with rectangular cantilever beam (TCRB).

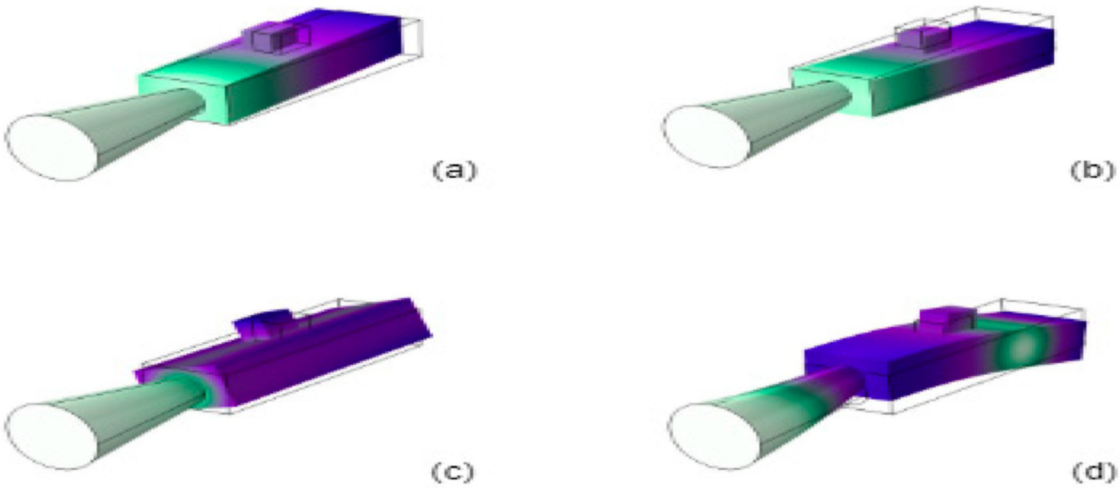


Figure 6. The first four bending modes and the corresponding stress distribution (a) first mode-38.3 Hz (b) second mode-46.4 Hz (c) third mode-54.2 Hz (d) fourth mode-69.7 Hz.

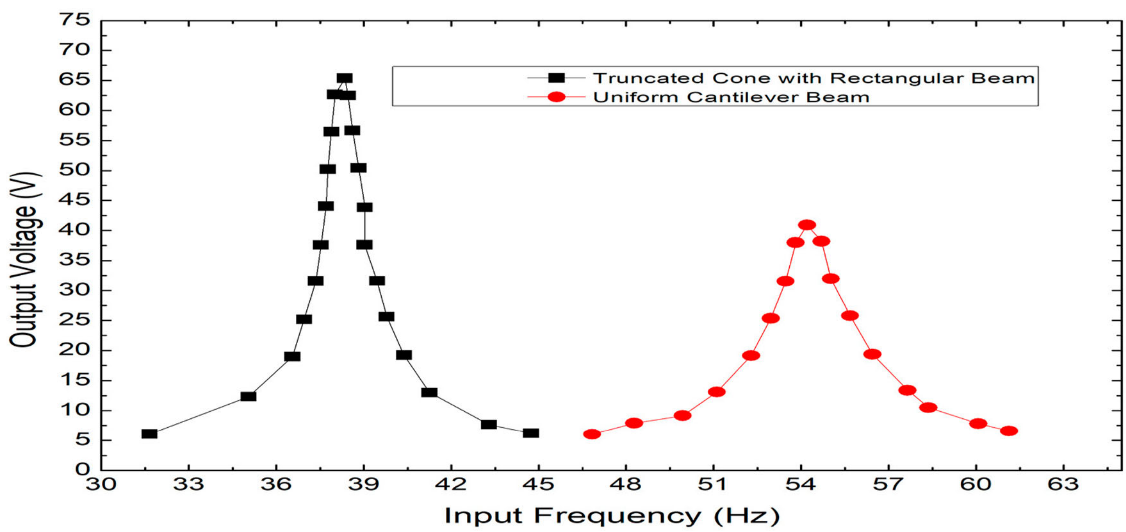


Figure 7. Simulation results input frequency vs. Output voltage for the TCRB-type harvester compared with the uniform cantilever beam-type harvester.

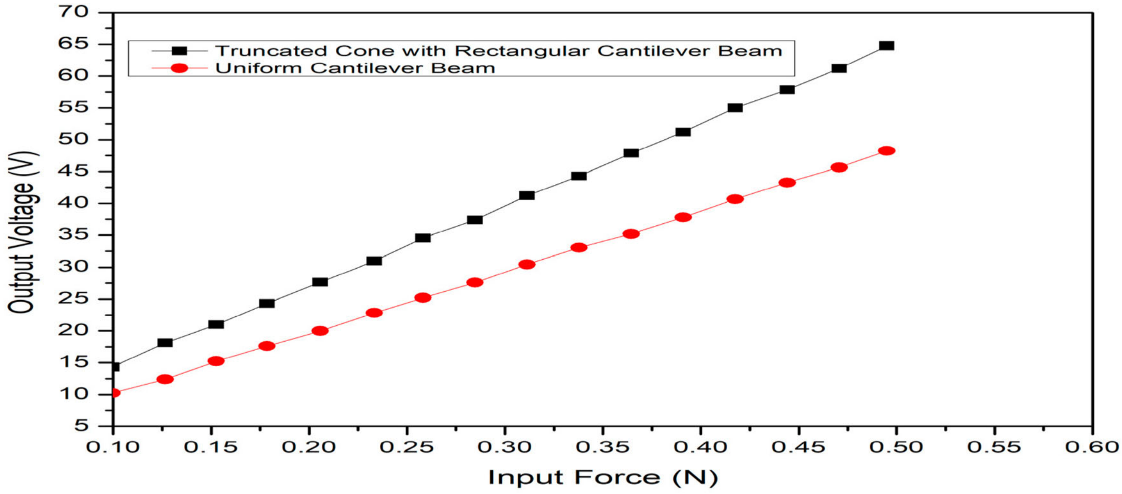


Figure 8. Simulation results input force vs. output voltage for the TCRB-type harvester compared with the uniform cantilever beam-type harvester.

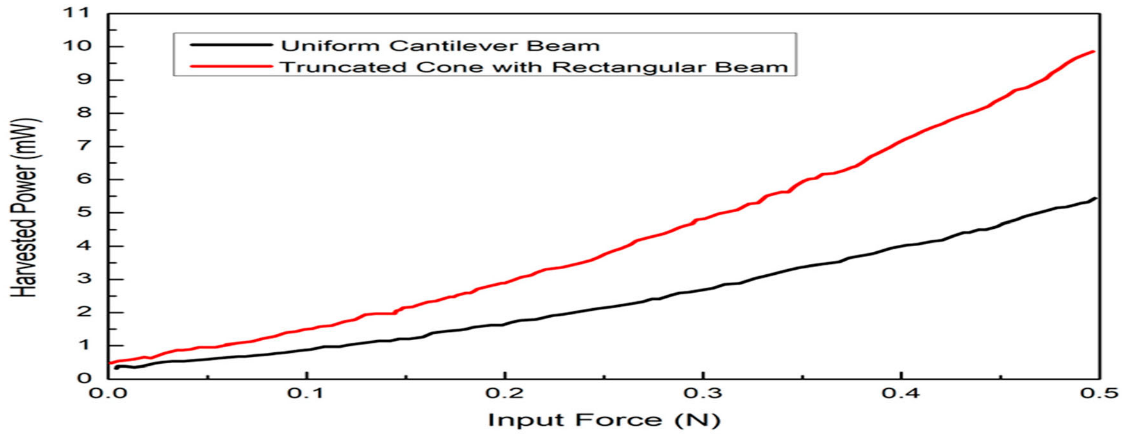


Figure 9. Simulation results input force vs. harvested power for the TCRB-type harvester compared with the uniform cantilever beam-type harvester.

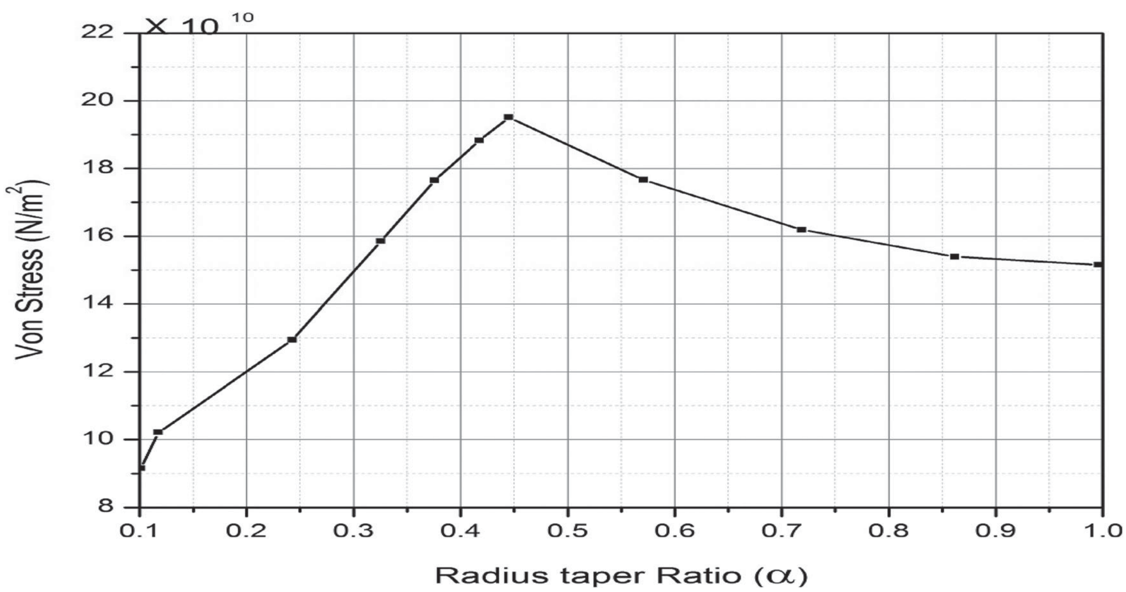


Figure 10. Influence of the taper radius ratio on the von stress.

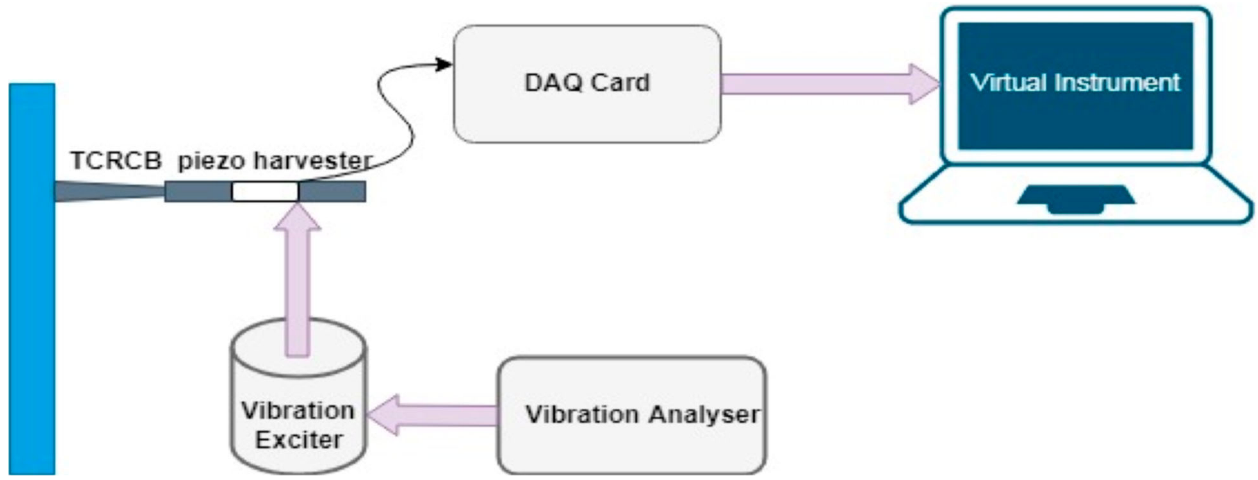


Figure 11. Experimental setup–graphical representation.

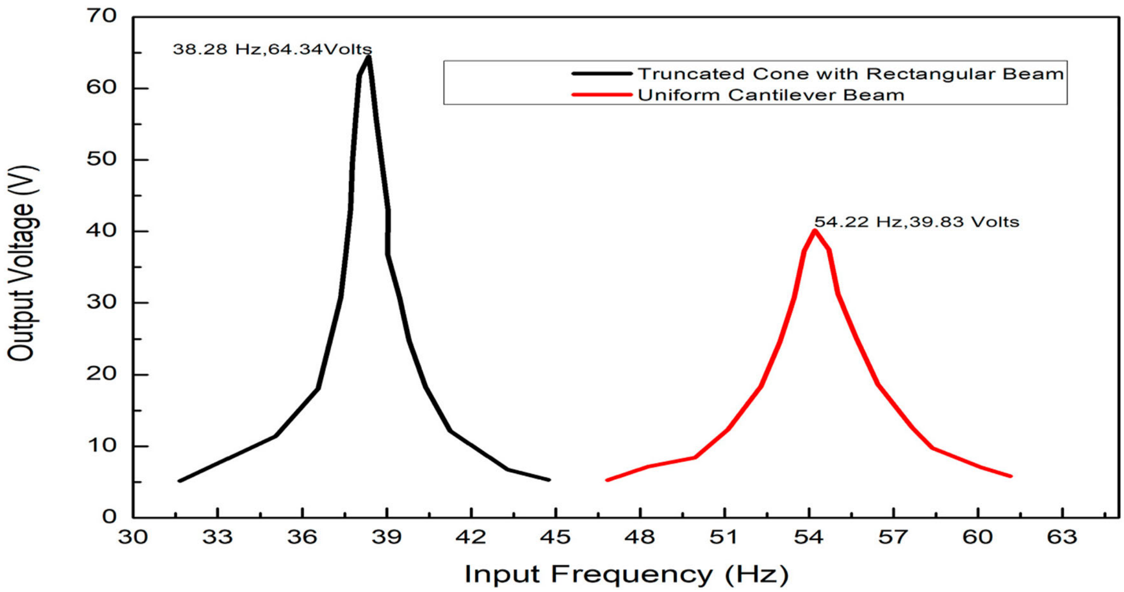


Figure 12. Experimental results input frequency vs. output voltage for the TCRB-type harvester compared with the uniform cantilever beam-type harvester (Experimental).

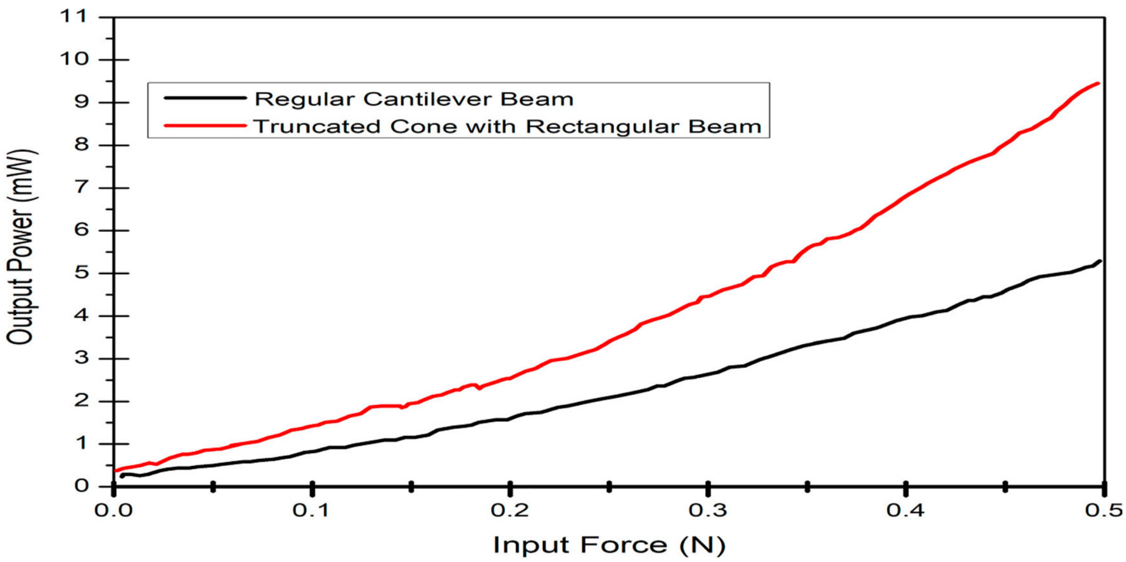


Figure 13. Experimental results Input Force vs. output power for the TCRCB-type harvester compared with the uniform cantilever beam-type harvester (Experimental).

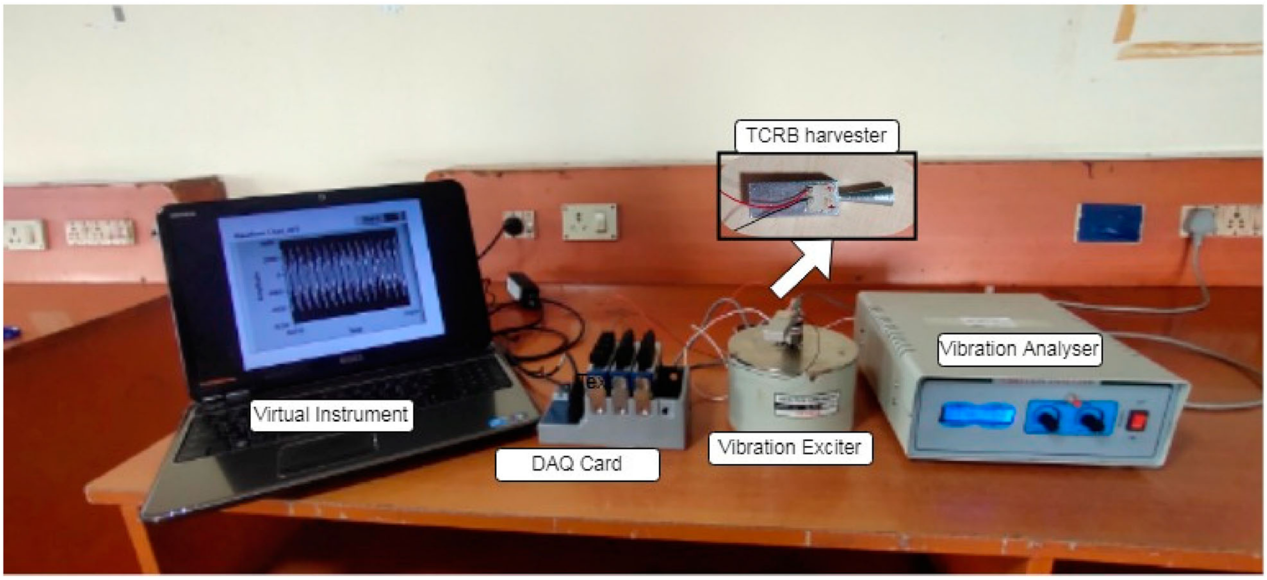


Figure 14. Photograph of the experimental setup of the TCRB piezoelectric vibration energy harvester.

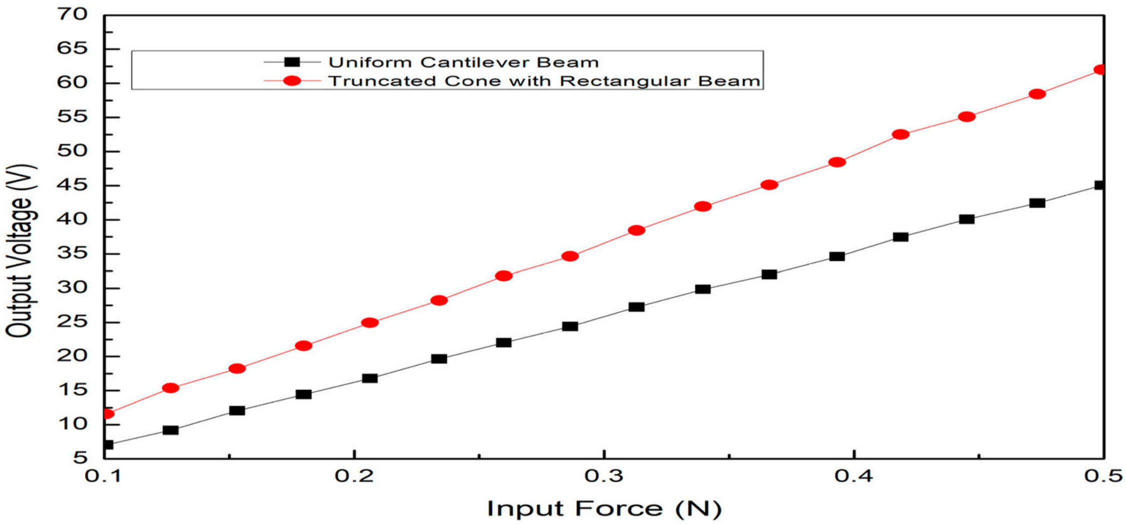


Figure 15. Input force vs. Output voltage for the TCRCB-type PVEH and the Uniform cantilever beam-type PVEH (Experimental).

The influences of radius ratio on the stress distribution, fundamental modes and natural frequencies on the TCRB harvester are analysed using COMSOL simulation for different radius taper ratio values 0.2,0.3, 0.4,0.43, 0.5, 0.6, 0.8, and 1. The radius taper ratio (α) enhances the average distribution of stress throughout the piezoelectric material and, as a result, the harvested output voltage produced by the piezoelectric material also improves.

Figure 10 shows the results of the parametric analysis of the TCRB-type PVEH using simulation for different values of truncated cone taper radius ratio. The equation (8) gives the taper radius ratio.

$$\alpha = R_2/R_1 \tag{8}$$

The optimal radius taper ratio $\alpha = 0.43$ for the TCRCB harvester, which generates higher voltage and power by experiencing the maximum stress over the piezoelectric layer.

4. TCRCB experimental results evaluation and discussions

Figure 11 depicts the experimental setup for the TCRB-type PVEH harvester. The TCRB structure is fabricated using the aluminium material. The piezo patch is

Table 5. Comparative study first mode frequencies and open circuit voltage.

	Experimental Analysis		Numerical Analysis	
PVEH beam structure	Frequency (Hz)	Voltage (Volts)	Frequency (Hz)	Voltage (Volts)
Uniform cantilever beam structure	55.2 Hz	40 V	59.7 Hz	40.5 V
TCRCB structure	39.4 Hz	65 V	38.3 Hz	65.3 V

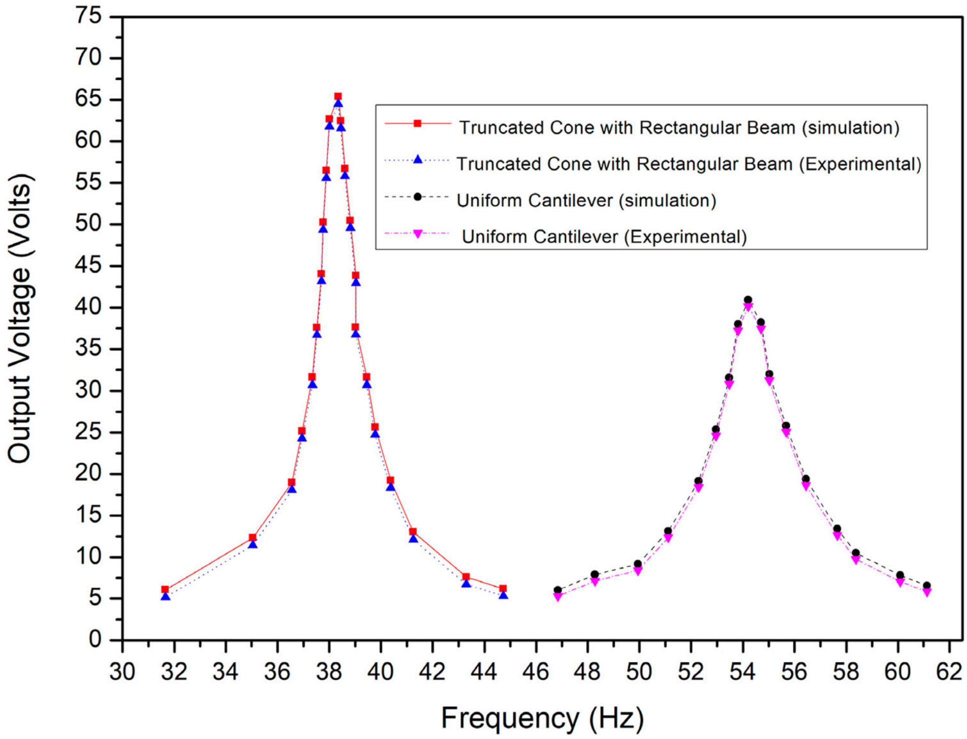


Figure 16. Frequency vss voltage (rms) performance evaluation of the TCRB-type PVEH and the uniform cantilever-type PVEH both experimental and simulation.

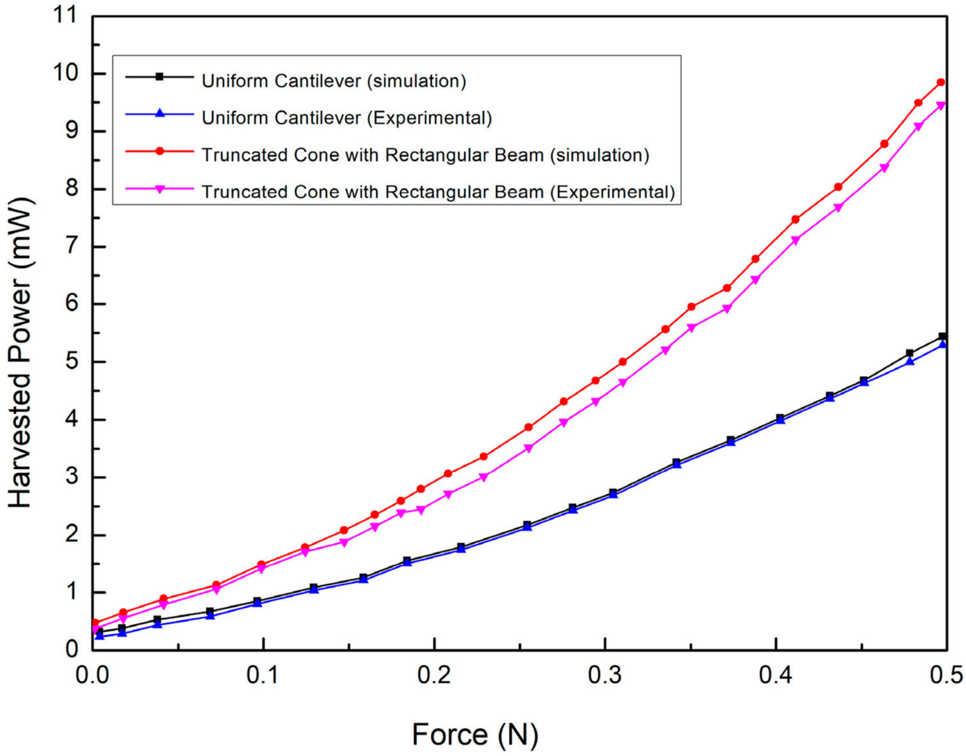


Figure 17. Force vs. Harvested power performance evaluation of the TCRB-type PVEH and the uniform cantilever-type PVEH both experimental and simulation.

bonded on the surface of the TCRB-type PVEH using a standard epoxy resin, Araldite. The vibration exciter is operated from a vibration analyser and the output from the piezo patch bonded on the TCRB-type PVEH is acquired using a data acquisition card (NI 9219). LabVIEW-based virtual instrument is developed to display the harvested energy.

As seen in equation (9), the optimal load resistance varies with driving frequency. As a consequence, within the studied frequency range, the best resistances are

6.37 M (at 10 Hz) to 1.27 M. (at 50 Hz). External rectifier circuits are required since piezoelectric alternating current is rarely used in actual energy harvesting systems [26]. In their most basic configuration, these rectification circuits frequently use discrete components and have an input impedance of less than one megaohm [27].

$$R_{IdealLoad} = \frac{1}{2 \times \pi \times f \times C} \tag{9}$$

Rectification circuits can function successfully within this impedance range and frequency range. The experimental frequency response for the TCRB type harvester is produced by rolling the vibrating frequency ranging between 0 and 100 Hz. Figure 12 illustrates the performance parameters of the TCRB harvester experimental compared with the uniform cantilever beam when vibrating the frequency is at its first resonance. Figures 13 and 15 show a comparison of the performance of a TCRB harvester with a uniform cantilever beam-type harvester in terms of resonance frequency, output voltage, and harvested power Figure 14. Figure 15 depicts the input force output voltage characteristics of TCRB-type PVEH compared with uniform cantilever beam.

When comparing harvesters for this study, it was discovered that TCRB harvesters had higher voltages and powers than those of the uniform cantilever ones. The TCRB-type PVEH produces nearly 38.58 per cent, more voltage than the uniform rectangular-type PVEH. Also compared to the Tapered Section with Rectangular Cavity Beam the TCRB produces 25 per cent more voltage.

The relative frequency error between modelling and experiment findings for the TCRCB harvester was less than 1.6 per cent.

The optimal load resistance is determined by the host harvesting structure's inherent frequency and internal capacitance. The findings, presented in equation 8, indicate that the harvester's power produced an optimal load for a variable input force.

The TCRCB energy harvester gives more power compared to uniform rectangular-type PVEH, and the results obtained from simulation and experimentation are close in agreement. Figure 16 reveals the frequency output voltage characteristics and Figure 17 reveals the relationship between force power characteristics in both simulation and experimental.

5. Conclusions

To harvest more power at very low ambient frequencies, a unique geometric construction called a truncated cone-like structure is proposed along with a rectangular beam (TCRB). The proposed harvester has been designed, simulated, and built, and its functionality has been tested in the actual world. COMSOL Multiphysics is used to conduct the simulations and comprehensive parametric analysis of the suggested harvesters. The influence of truncated cone radius tapering ratio on comprehensive parameters, such as stress distribution, natural frequencies and mode shapes along the length of a truncated cone rectangular cantilever beam, has been thoroughly addressed. To substantiate the preciseness of the results obtained from the developed model, a prototype of the suggested harvester has been fabricated. According to the findings, a TCRB harvester generates a maximum voltage that is higher than that produced by a harvester with a uniform rectangular cantilever beam. The simulation outcomes are in excellent agreement with the experimental data and are greater than the output gathered from a rectangular cantilever beam with a piezoelectric patch. The truncated cone with rectangular cantilever beam type piezoelectric vibration energy harvesters described here is simple to manufacture and offer a greater power of about 9.5 milliWatts in ambient vibration range. This power is enough to drive any sensor or any biomedical implant. Thus the energy can be utilized to power wireless sensor nodes.

Acknowledgement

This work was supported by SRM Valliammai Engineering College

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

[1] Harb A. Energy harvesting: state-of-the-art. Renew Energy. 2011;36:2641–2654. doi:10.1016/j.renene.2010.06.014
[2] Vullers RJ, van Schaijk R, Doms I, et al. Micropower energy harvesting. Solid-State Electron 2009;53(7): 684–693. doi:10.1016/j.sse.2008.12.011
[3] Uchino K, Ishii T. Energy flow analysis in piezoelectric energy harvesting systems. Ferroelectrics. 2010;400: 305–320. doi:10.1080/00150193.2010.505852
[4] Asthana P, Khanna G. An autonomous piezoelectric energy harvesting system for smart sensor nodes in IoT applications. Appl Phys A Mater Sci Process. 2021;127:1–11. doi:10.1007/s00339-021-04976-x
[5] Rubes O, Chalupa J, Ksica F, et al. Development and experimental validation of self-powered wireless vibration sensor node using vibration energy harvester. Mech Syst Signal Process. 2021;160:107890. doi:10.1016/j.ymssp.2021.107890
[6] Kim JH, Cho JY, Jhun JP, et al. Development of a hybrid type smart pen piezoelectric energy harvester for an IoT platform. Energy. 2021;222:119845. doi:10.1016/j.energy.2021.119845
[7] Liu Y, Khanbareh H, Halim MA, et al. Piezoelectric energy harvesting for self-powered wearable upper limb applications. Nano Sel. 2021;2:1–21.

[8] Sodano HA, Inman DJ, Park G. A review of power harvesting from vibration using piezoelectric materials. Shock Vibr Dig. 2004;36:197–205. doi:10.1177/0583102404043275
[9] Pillatsch P, Xiao B, Shashoua N, et al. Degradation of bimorph piezoelectric bending beams in energy harvesting applications. Smart Mater Struct 2017;26: 035046, doi:10.1088/1361-665X/aa5a5d
[10] Priya S. Advances in energy harvesting using low profile piezoelectric transducers. J Electroceram. 2007;19(1): 167–184. doi:10.1007/s10832-007-9043-4
[11] Wang ZL, Song J. Piezoelectric nanogenerators based on zinc oxide nanowire arrays. Science. 2006;312(5771): 242–246. doi:10.1126/science.1124005
[12] Jeon YB, Sood R, Jeong JH, et al. MEMS power generator with transverse mode thin film PZT. Sens Actuators A. 2005;122(1):16–22. doi:10.1016/j.sna.2004.12.032
[13] Gafforelli G, Corigliano A, Xu R, et al. Experimental verification of a bridge-shaped, nonlinear vibration energy harvester. Appl Phys Lett. 2012;105(20):203901, doi:10.1063/1.4902116
[14] Park JC, Park JY, Lee YP. Modeling and Characterization of Piezoelectric d_33 -Mode MEMS Energy Harvester. J Micro Electr Mech Syst. 2010;19(5):1215–1222. doi:10.1109/JMEMS.2010.2067431
[15] Beeby SP, Tudor MJ, White NM. Energy harvesting vibration sources for Microsystems applications. Meas Sci Technol. 2006;17(12):R175, doi:10.1088/0957-0233/17/12/R01
[16] Raju SS, Choi SB, Umapathy M, et al. An effective energy harvesting in low frequency using a piezo-patch cantilever beam with tapered rectangular cavities. Sens Actuators A. 2019;297.
[17] Ramalingam U, Gandhi U, Mangalanathan U, et al. A new piezoelectric energy harvester using two beams with tapered cavity for high power and wide broadband. Int J Mech Sci. 2018;142.
[18] Srinivasulu Raju S, Umapathy M, Uma G. Design and analysis of high-output piezoelectric energy harvester using non-uniform beam. J Mech Adv Mater Struct. 2018;27:1–10.
[19] Čeponis A, Mažeika D, Bakanauskas V. Trapezoidal cantilevers with irregular cross-sections for energy harvesting systems. Int J Appl Sci. 2017;7:134.
[20] Berdy DF, Jung B, Rhoads JF, et al. Wide-bandwidth, meandering vibration energy harvester with distributed circuit board inertial mass. Sens Actuators A 2012;188: 148–157. doi:10.1016/j.sna.2012.01.043
[21] Anton SR, Sodano HA. A review of power harvesting using piezoelectric materials (2003–2006). Smart Mater Struct 2007;16:1–21. doi:10.1088/0964-1726/16/3/R01
[22] Sodano HA, Inman DJ, Park G. Comparison of piezoelectric energy harvesting devices for recharging batteries. J Intell Mater Syst Struct 2005;16(10):799–807. doi:10.1177/1045389X05056681
[23] Usharani R, Uma G, Umapathy M, et al. Design of high output broadband piezoelectric energy harvester. J Mech Sci Technol 2017;31:3131–3142. doi:10.1007/s12206-017-0603-5
[24] Elahi H, Munir K, Eugeni M, et al. Energy harvesting towards self-powered IoT devices. Energies. 2020;13(21):5528, doi:10.3390/en13215528
[25] Jeong SY, Xu LL, Ryu CH, et al. Wearable shoe-mounted piezoelectric energy harvester for a self-powered wireless communication system. Energies. 2022;15(1):237. doi:10.3390/en15010237
[26] Zabek D, Pullins R, Pearson M, et al. Piezoelectric-silicone structure for vibration energy harvesting: experimental testing and modelling. Smart Mater Struct. 2021;30(3):035002, doi:10.1088/1361-665X/abd964
[27] Liao Y, Liang J. Maximum power, optimal load, and impedance analysis of piezoelectric vibration energy harvesters. Smart Mater Struct. 2018;27(7):075053, doi:10.1088/1361-665X/aaca56
[28] Chen CT, Islam RA, Priya S. Electric energy generator. IEEE Trans Ultrason Ferroelectr Freq Control. 2006;53(3):656–661. doi:10.1109/TUFFC.2006.1610576
[29] Mohamed K, Elgamal H, Kouritem SA. An experimental validation of a new shape optimization technique for piezoelectric harvesting cantilever beams. Alexandria Eng J. 2021;60(1):1751–1766. doi:10.1016/j.aej.2020.11.024
[30] Homayouni-Amlashi A, Mohand-Ousaid A, Rakotondrabe M. Analytical modelling and optimization of a piezoelectric cantilever energy harvester with in-span attachment. Micromachines (Basel). 2020;11(6):591, doi:10.3390/mi11060591