A Review of Piezoelectric Energy Harvesting in Shape and Array Configuration

Nik Ahmad Kamil Zainal Abidin, Norkharziana Mohd Nayan*, Nursabirah Jamel and Azuwa Ali

***Abstract*—This paper provides a general review of the use of piezoelectric energy harvesting, focusing specifically on its application in different shapes and array configuration. Piezoelectric energy harvesting is a technique that takes advantage of the ability of materials to generate an electric field when exposed to mechanical force, a phenomenon known as the direct piezoelectric effect. Piezoelectric transducers can be fabricated in various shapes and materials, making them suitable for a wide range of applications. To maximize the efficiency of piezoelectric devices in applications, a model is required to observe the generated power output. This paper not only discusses different aspects of piezoelectric modelling but also focuses specifically on piezoelectric transducer shape. Furthermore, it compares the performance of an array of piezoelectric transducers with and without ACDC to gain insight into their effectiveness.**

***Index Terms*— AC-DC converter, Array Configuration, Piezoelectric energy harvesting, Piezoelectric transducer shape, Vibration energy**

I. INTRODUCTION

Energy harvesting is also called as power harvesting or energy scavenging [1-3]. With recent advances on wireless and MEMS technology, energy harvesting is highlighted as the alternatives of the conventional battery. Ultra-low power portable electronics and wireless sensors use the conventional batteries as their power sources, but the life of the battery is limited and very short compared to the working life of the devices. As the replacement or recharging of batteries can be inefficient or even impossible, many researchers have focused on exploring energy harvesting technologies as a means of powering portable devices and wireless sensor network systems independently. These efforts seek to provide self-sustaining power sources that can operate without the need for regular maintenance or external power supplies [4-9].

There are three main part of an energy harvesting system that require to extracting energy. First, the energy source is a representation of the energy that will be used to generate electrical power. There are two types of energy that can be extracted: ambient energy, which is present in the surrounding environment and includes things like wind, ambient heat, and sunlight, and external energy, which comes from sources like lightning, vibration, human movement, and heat [10-11]. Second, the device that consists of the material or structure that transforms the energy from the environment into electrical energy. Lastly the load means the device that either stores or uses energy from electrical output.

Renewable energy sources like wind, water, geothermal, and solar have been used for energy conversion for centuries, generating kilowatt (kW) to megawatt (MW) level power. In contrast, piezoelectric energy harvesters are micro energy harvesting technologies that generate milliwatt (mW) to micro-watt (μW) level power from extracting energy from pressure or vibration [12-13]. Piezoelectric energy harvesters work by utilizing the piezoelectric effect, which generates an electric charge in certain materials in response to mechanical stress or pressure. Piezoelectric energy harvesters offer a sustainable source of renewable energy for low-power applications such as sensors, wearables, and Internet of Things (IoT) devices [14-15]. As material science and engineering continue to advance, the efficiency and scalability of piezoelectric energy harvesters are expected to improve, making them a viable option for micro energy harvesting. There are several techniques to increase efficiency for piezoelectric energy harvesting which are non-linearity, double pendulum system, frequency up conversion and circuit management [2].

This paper reports on a study that explores the application of piezoelectric transducers in harvesting vibration kinetic energy, using two common structures - the cantilever beam and the bridge - and two primary materials, PVDF and PZT [16]. The focus of the study is the shape of the piezoelectric transducer, and it evaluates the performance of an array of these transducers, with and without ACDC, in order to provide a comprehensive comparison of their energy-harvesting capabilities. In addition, this paper provides a comprehensive review of different piezoelectric designs and configurations in order to optimize the energy harvesting system's efficiency and output power based on latest publications in the field. Given the limited energy that can be extracted from vibration kinetic energy, the conversion

This manuscript is submitted on 26 December 2023, revised on 15 February 2024, accepted on 10 July 2024 and published on 31 October 2024.
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efficiency of the interface circuit becomes a critical issue. The literature offers numerous solutions to this problem that improve the circuit conversion efficiency for piezoelectric harvesters based on vibration.

Therefore, this paper aims to discuss fundamental study on the shape of piezoelectric transducers and compares the performance of an array of piezoelectric transducers with and without an AC-DC converter as well as recent advancements during the previous few years.

TABLE I. SUMMARY OF PIEZOELECTRIC ENERGY HARVESTERS

Authors (Year)	Types of piezoelectric	Types of harvester structures	Output
Rosario Miceli, et al. (2014) [19]	PZT PVDF	Bridge Cantiliver	0.12 μW (82 kΩ) 5 μW (47 kΩ)
V. K. Wong, et al. (2014) [20]	PZT Bimorph	Cantilever	1.55 V/0.16 mW (15 kΩ)
M. Al Ahmad (2014) [21]	5 layer of PZT thick films	Cantilever	Vpk-to-pk = 0.8 V (10 kΩ), 23 μW
M. A. Ilyas (2015) [22]	PVDF	Cantilever	2.3 μW (2.2 MΩ)
Izhab Muhammad Izrin (2017) [23]	PVDF	Bridge	3V (0.68 MΩ) 13.25 μW
Izhab Muhammad Izrin (2017) [24]	PVDF	Bridge	3.18 V average (0.68 MΩ) 15.36 μW
Z. Z. Ong (2016) [25]	PZT	Cantilever	62.26 μJ 356.94 μJ
Mohammad Adnan Ilyas (2017) [26]	PVDF	Cantilever	4.1V -17 μW 3.2V -12 μW 2.1V -4.9 μW
V. K. Wong, et al. (2016) [27]	PZT	Cantilever	38.89 μJ - 0.1448 μW 52.05 μJ - 0.1731 μW 114.68 μJ - 0.3946 μW
V. K. Wong, et al. (2015) [28]	PZT	Cantilever	Without water layer RMS voltage (mV) = 0.19V With water layer RMS voltage (mV) = 0.10V
Alberto Doria (2019) [29]	PZT	Cantilever	spoon full of water = 2.5 V dry spoon = 1.1 V dry spoon with added mass = 0.9V
Fabio Viola (2013) [30]	PZT PVDF	Cantilever	V22BL = 0.89 μW (47 kΩ) V22B = 0.8 μW (100 kΩ) single pvdf = 4.6 μW (47 kΩ) parallel pvdf = 1.8 μW (68 kΩ)
Lee et al. (2014) [31	PVDF	Cantilever	72.2 μW (470 kΩ)
Muhamad Faizal Yaakub (2017) [32]	PZT PVDF	Cantilever	PVDF= 2.51 μW PZT= 30 μW

II. PIEZOELECTRIC ENERGY HARVESTERS

Vibration energy harvesting can be divided into three types of energy transducers: piezoelectric, electrostatic and electromagnetic. However, among these transducers, piezoelectric has been widely studied due to its high-power density, simple operating mechanism, no heat and easy to manufacture [3,17]. Not only that, piezoelectric materials, such as PZT and PVDF are commonly used due to their ability to transform mechanical strain energy into electrical charge [18]. as PZT and PVDF are commonly used due to their ability to transform mechanical strain energy into electrical charge [18]. Table 1 show summary of piezoelectric energy harvester using PZT and PVDF material.

Fig. 1 provides an electrical equivalent circuit and basic block diagram of a typical piezoelectric energy harvesting system consisting of five main components [3,17,33]: a piezoelectric generator, rectifier, DC-DC converter, energy storage device, and load. To optimize system performance, each block can be designed using different strategies. The piezoelectric generator, or transducer, is a sensor that converts vibration energy into electrical energy. It can be modelled by an AC current source in parallel with a capacitor and a large resistor [34-36]. However, the electrical energy output of the transducer is a strong and irregular function of time, requiring an AC-DC converter to produce a stable DC power source. The rectifier circuit is used to convert the AC signal generated by the transducer into a DC signal that can be stored in an energy storage device, such as a battery or supercapacitor. Before the system is used under load, a voltage regulator is usually operated to ensure a suitable voltage.

Overall, the piezoelectric energy harvesting system is composed of several critical components that must be designed and optimized to maximize system performance. Through proper design and configuration, it is possible to achieve high levels of energy efficiency and output power in piezoelectric energy harvesting systems.

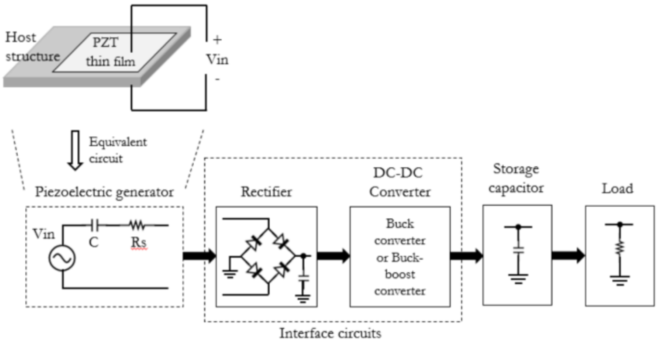


Fig. 1. Five major phases associated with piezoelectric energy harvesting [17].

A. *Working Principles*

Piezoelectric materials are capable of producing charges when subjected to stress, which is known as the direct piezoelectric effect, and they can also deform under the influence of an electrical field, which is referred to as the converse or inverse piezoelectric effect. The direct piezoelectric effect is depicted in Fig. 2, where the piezoelectric material that is subjected to stress generates charges Q on its surfaces, which are then collected by the two electrodes, leading to the creation of a voltage V = Q/C. Here, C represents the capacitance between the electrodes. On the other hand, if a voltage is applied to the electrodes, the piezoelectric material deforms proportionally to the produced stress or strain. Hence, a piezoelectric sensor measures the charges or voltages generated, while the actuator converts the applied voltage into a deformation of the piezoelectric material. The direct piezoelectric effect was discovered in 1880 by the Curie brothers, Jacques and Pierre. In materials that exhibit this phenomenon, a geometric strain is also observed that is proportional to an applied electric field. The converse effect, on the other hand, was predicted by Gabriel Lippmann in 1881, based on thermomechanical considerations, and was soon afterwards verified by the Curies [37].

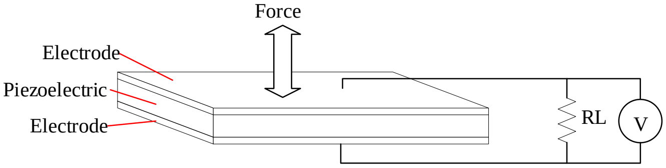


Fig. 2. The direct piezoelectric effect.

Hooke’s law is used to describe the piezoelectric material’s electrical behaviour and is represented as (1):

$$D = \varepsilon E, \tag{1}$$

where D is the electric polarization, ε is the permittivity, and E is the applied electric field strength. In order to describe a system, Hooke’s Law states that (2):

$$S = sT, \tag{2}$$

where S is the strain, s is the compliance, and T is the stress. Equations (1) and (2) are combined to form the following relations (3):

$$\begin{cases} \{S\} = [s^E]\{T\} + [d]\{E\} \\ \{D\} = [d^t]\{T\} + [\varepsilon^T]\{E\} \end{cases} \tag{3}$$

where [d] is the direct piezoelectric coefficient matrix, $[d^t]$ the converse piezoelectric effect, E is the electric field vector, T is the stress vector, and t is the matrix that describes determines the transposition matrix.

A more straightforward approach for describing the direct and converse piezoelectric effect is represented as (4) [29],

$$\begin{cases} D = dT + \varepsilon E \\ S = sT + dE \end{cases} \tag{4}$$

The constitutive equation represents the direct piezoelectric effect (5),

$$D = dT + \varepsilon E \tag{5}$$

where D is the electric polarization (C/m^2), d is a piezoelectric coefficient matrix, T is the stress vector (N/m^2), ε is the electrical permittivity matrix (F/m), and E is the electric field vector (V/m)[38-39]. By convention, the polarization direction of the piezoelectric material is depicted by direction 3, as shown in Fig 3.

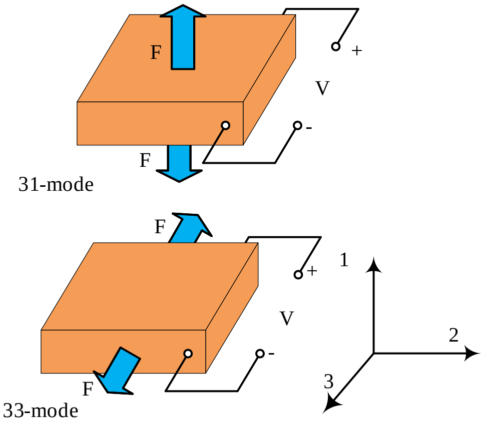


Fig. 3. The direct piezoelectric effect.

Due to the inherent symmetry of piezoelectric materials, directions at right angles to the polar axis are also equivalent and are commonly referred to as the "1" directions. When applying stress to a piezoelectric material, it can be either along the polar axis (3-direction) or at right angles to it (1-direction), resulting in two common configurations for piezoelectric energy harvesting: the 33-mode and 31-mode. In the 33-mode configuration, the piezoelectric material is subjected to compressive stress/strain applied in parallel to the 3-direction, resulting in a voltage generated along the same axis. On the other hand, in the 31-mode configuration, the stress/strain is applied perpendicular to the polar axis, with the generated voltage at a right angle to the applied force.

Understanding the different modes of piezoelectric energy harvesting is critical for optimizing the design and performance of piezoelectric devices. By selecting the appropriate configuration, it is possible to maximize the output power and efficiency of the energy harvesting system.

The transducer’s mechanical-electrical conversion efficiency $E\%$ determines the performance [2], which can be calculated as (6),

$$E\% = \frac{P_{out}}{P_{in}} \times 100 \tag{6}$$

where Pout is the electrical output power, defined as (7),

$$P_{out} = V_p I_p \tag{7}$$

and Pin is the mechanical input power, defined as (8),

$$P_{in} = Fv \tag{8}$$

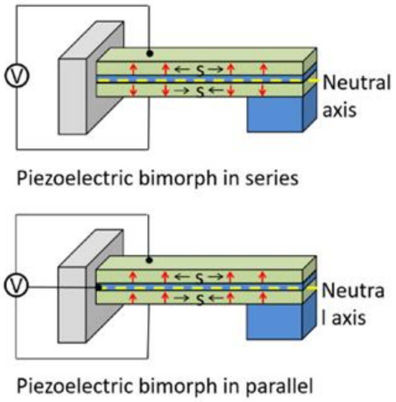
where F is the external mechanical force, v is the speed of the moving object, and I_p is the current supplied by the piezoelectric transducer. Where V_p is the overall voltage generated between the transducer's electrodes.

B. *Piezoelectric Material Configuration*

The cantilever is a highly effective structure for mechanical energy harvesting from vibrations, particularly in piezoelectric energy harvesting. By utilizing a thin layer of piezoelectric ceramics bonded to a non-piezoelectric layer, a large mechanical strain can be generated during vibration, producing electrical charge. Fig. 4(a) illustrates a cantilever constructed using a single active layer of piezoelectric material, also known as a "unimorph." One end of the cantilever is fixed to utilize its flexural mode, and the non-piezoelectric layer acts as a conductor for the produced charge.

In contrast, Fig. 4 (b) shows a bimorph configuration, where two thin layers of piezoelectric ceramic are bonded to the same metal sheet, maximizing the unit's power output. This configuration doubles the energy capacity of PEH without significantly increasing the unit volume, making bimorph piezoelectric cantilevers more commonly used in PEH studies. The top and bottom layers are poled in either the same direction (parallel poling) or opposite directions (series poling) to induce accumulated current or voltage by each layer, respectively.

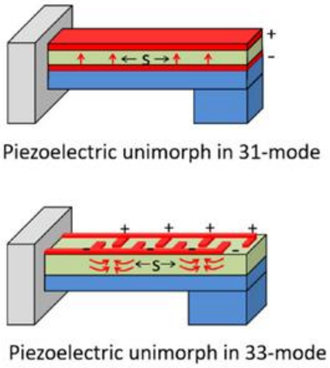
Overall, the cantilever structure provides an effective means for mechanical energy harvesting from vibrations, with the bimorph configuration offering increased energy capacity without a significant increase in unit volume.



(a)

III. SHAPE PIEZOELECTRIC ENERGY HARVESTER

The design of a piezoelectric cantilever that maximizes output power is a crucial challenge in vibration energy harvesting. To achieve this, various prototypes need to be developed, and numerous design processes need to be experimented with extensively to produce an efficient harvester. Khaled Mohamed (2020) conducted a study using COMSOL to investigate the effectiveness of various shapes of cantilever beam for piezoelectric-based energy harvesting. The results showed that the T-shaped cantilever structure produced the highest voltage and power at the lowest natural frequency, compared to other shapes.



(b)

Fig. 4. (a) 31-mode bimorph cantilever in series and parallel connections; and (b) 31-mode and 33-mode unimorph cantilever configuration [40]

Additionally, the T-shaped geometry show in Fig. 5 was found to be the best shape for piezoelectric-based energy harvesting cantilevers, with 3.4 times higher output power compared to the triangular shape. The rectangular-shaped cantilever was also found to be effective due to its simple construction and low stress. The study revealed that the power of the T-shaped cantilever was improved by optimizing resistance from 18 mW at 100 Ω (unoptimized) to 28 mW at 316.3 Ω.

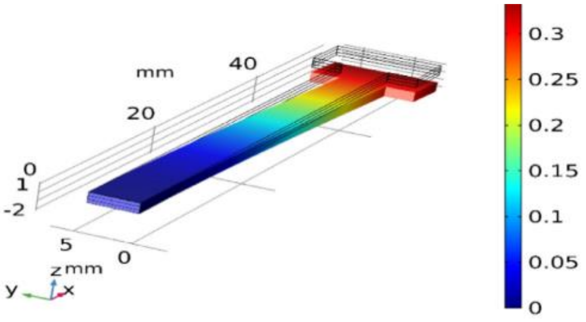


Fig. 5. T-shaped [41]

In Md. Naim Uddin's (2016) study, a T-shaped piezoelectric cantilever beam was designed and analyzed for converting ambient low vibration energy into electrical energy suitable for biomedical devices was show in Fig. 6.

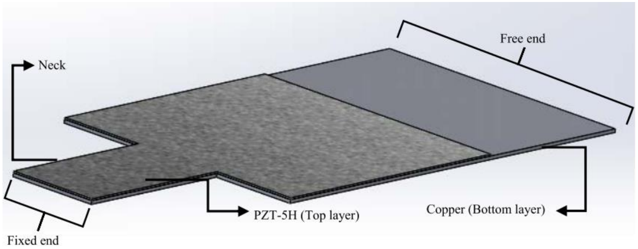
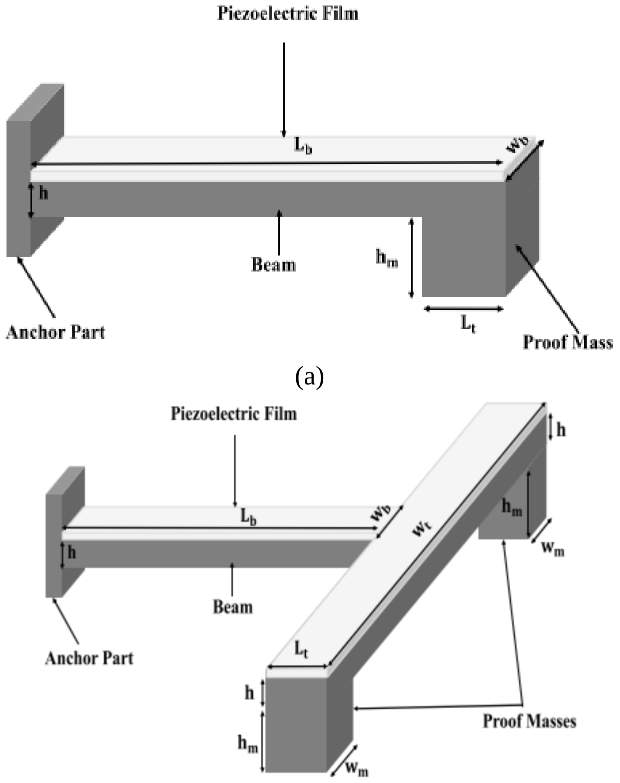


Fig. 6. 3-D representation of T-shaped cantilever beam [42]

The beam was designed with a simplified structure without a proof mass at the free end. Analysis of the beam showed that it had a lower resonant frequency of 229.25 Hz, and produced a maximum stress of amount and a total elastic strain energy of 2.39×10^{8} N m^{-2} and 0.28 mJ, respectively.

In this study, Seyedfakhreddin Nabavi (2018) presented a T-shaped piezoelectric MEMS energy harvester and evaluated its performance through numerical simulations that sow in Fig. 7. The results indicated that the proposed power management system could increase the magnitude of the harvested voltage from 1.5V to 5V. To ensure a stable output voltage level, we utilized a JFET transistor as a voltage limiter. This approach prevented the delivered voltage at the load side from exceeding 4V, even if the harvester produced a higher voltage [43].

In this study, a T-shaped piezoelectric structure with two identical proof masses at the T-segment was proposed and compared to a conventional straight cantilever. The two harvesters were excited by sinusoidal acceleration at their resonant frequencies and the generated voltage was calculated using Frequency Domain Study in COMSOL Multiphysics. The results showed that the T-shaped piezoelectric structure generated a significantly higher voltage of 2.33V, compared to only 0.49V for the conventional cantilever. This is a remarkable 4.75 times increase in harvested voltage, indicating a direct relationship between the voltage and absorbed mechanical strain. Additionally, the T-shaped structure exhibited a much lower resonant frequency than the conventional cantilever, making it a more suitable choice for low-frequency energy harvesting applications.

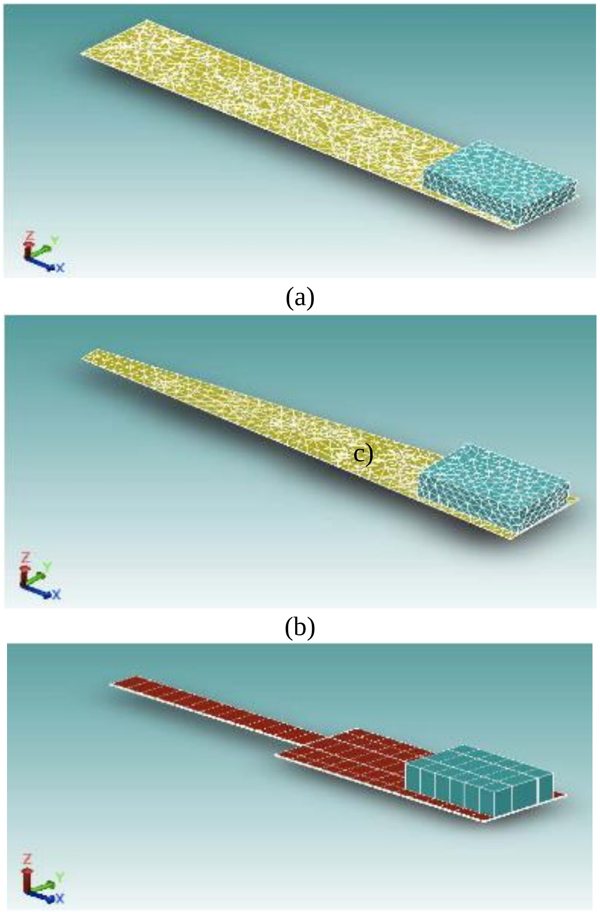


(a)

(b)

Fig. 7. Structural diagrams of (a) the conventional unimorph straight piezoelectric cantilever and (b) our proposed T-shaped structure [44].

The paper presents a novel model for a MEMS-based energy harvester using piezoelectric cantilevers of three different shapes: rectangular, trapezoidal, and T-shaped beams that sow in Fig. 8. Through simulations conducted using the COVENTORWARE2010 approach, we investigate the performance of the harvester under ambient vibration excitation. Our results show that the T-shaped cantilever-based MEMS energy harvester, which operates under an ambient excitation frequency of 11 Hz with a base acceleration of 1g, generates the highest output power of 2.4 μw at a 5kΩ load. This is significantly higher than the output power generated by the other two shapes under the same conditions.



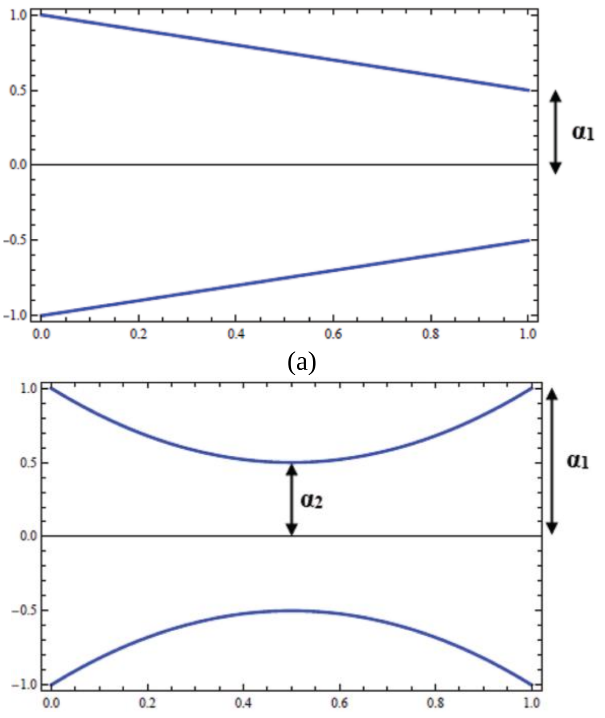
(a)

(b)

(c)

Fig. 8. (a) Rectangular, (b) Trapezoidal, and (c) T-shaped beam [45].

In the paper, Samah Ben Ayed (2013) investigates the effects of linear and quadratic shape variations on the performance of a piezoelectric energy harvester composed of a cantilever beam with piezoelectric and metallic layers in a unimorph design, with a rigid mass attached to its free end. Fig. 9 show geometric variables of the shape function for (a) linear and (b) quadratic configurations. The study aims to design piezoelectric energy harvesters that can generate energy at low frequencies and maximize the harvested energy. The results show that the fundamental natural frequency and mode shape of the beam are strongly affected when the shape is varied. Additionally, the influence of electrical load resistance and shape parameters at resonance on the system's performance is discussed. It is determined that, for specific resistance values, the quadratic shape can produce the highest energy harvested compared to a linear shape, which is 0.009 Ws^4/m^2 at 13 kΩ.



(a)

(b)

Fig. 9. Geometric variables of the shape function for (a) linear and (b) quadratic configurations [46].

In the paper, a high-performance piezoelectric energy harvester (PEH) with a rectangular hole is presented for low-frequency operation show in Fig. 10. The PEH is constructed using a thinned bulk PZT film on flexible phosphor bronze, consisting of a piezoelectric layer, supporting layer, and proof mass to reduce the resonant frequency of the device. The use of thinned bulk PZT thick film as the piezoelectric layer is preferred for its high piezoelectric coefficient, while phosphor bronze is deployed as the supporting layer due to its superior flexibility and durability under high acceleration ambient conditions compared to silicon. Experimental results show that the maximum open-circuit voltage of the PEH is 15.7 V at a low resonant frequency of 34.3 Hz, when the input vibration acceleration is 1.5 g (g ¼ 9.81 m/s2). The maximum output power, output power density, and actual current at the same acceleration are 216.66 µW, 1713.58 µW/cm3, and 170 µA, respectively, when the optimal matched resistance of 60 kΩ is connected.

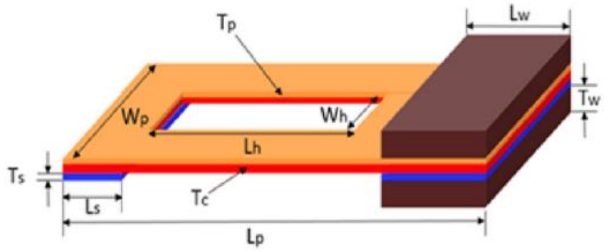


Fig. 10. The schematic of the PEH with a rectangular hole [47].

The study aims to design a broadband energy harvester device using a multi-beam approach and a non-linear trapezoidal geometry approach that show in Fig. 11. The researchers simulated the performance of a composite piezoelectric PZT-PZN polycrystalline ceramic material using COMSOL Multiphysics, and compared the results using a series configuration of a composite bimorph energy harvester vibrating at its 1st fundamental frequency. To demonstrate the effectiveness of the multi-beam approach, a five cantilever multibeam harvester was chosen to show that the individual fundamental modes of the beams can generate power and achieve a broader frequency band. Additionally, the researchers showed that the composite trapezoidal beam design leads to high power density broadband frequency response. The multibeam approach resulted in a broader bandwidth of 18 Hz, generating a power density of 0.0913 mW/cm3, whereas the trapezoidal shape generated 2.3 – 2.5 mW/cm3 with a bandwidth of 4 to 6 Hz.

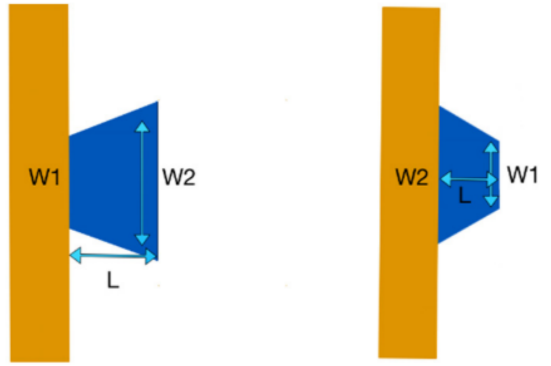


Fig. 11. Bimorph piezoelectric trapezoidal beam [7].

The paper presents a new design for a piezoelectric cantilever structure that is specifically optimized for harvesting energy from the vibration of a human heartbeat show in Fig. 12. The proposed cantilever is ultra-thin at only 14 mm and has compact outer dimensions of 6mm × 6mm. By utilizing a spiral structure, it have been able to reduce the stiffness of the cantilever beam, thereby lowering its resonant frequency. Furthermore, it introduced a proof mass within the spiral structure to further reduce the resonant frequency of the cantilever beam. Our proposed cantilever structure has a resonant frequency of 30.6Hz, which makes it highly suitable for harvesting energy from the human heartbeat. Additionally, the resonant frequency of our 3-turn spiral cantilever beam is 33.18% lower than that of the 2.5-turn spiral cantilever beam and 54.93% lower than that of the 2-turn spiral. Our proposed 3-turn spiral harvester generates a peak output open-circuit voltage of 4V and a peak output power of 5.3 mW at a resonant frequency of 30.6Hz, when subjected to a sinusoidal acceleration of 1g (1g =9.8m/s^2).

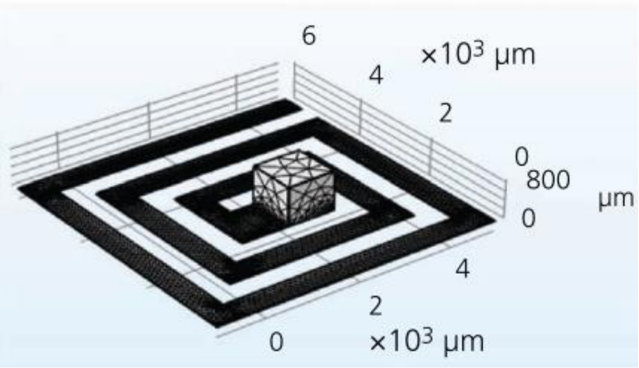


Fig. 12. 3-turn spiral [48]

Piezoelectric wind energy harvesters, which consist of a bluff body and a piezoelectric cantilever beam, are an ideal technology for powering small wireless devices. However, to generate a higher energy output, the beam is designed to undergo large deformations, leading to nonlinearity in the energy harvesters. In this paper, K.F. Wang (2019) a nonlinear model is developed for a piezoelectric wind harvester with varying geometrical parameters, and the energy harvesting performance of different geometries is compared. The study finds that the onset speeds of galloping for trapezoidal and exponential piezoelectric energy harvesters are significantly lower than those of rectangular beams. Additionally, the beam with an exponential shape yields an average power output density of 0.14 W using a 10 MΩ load at a wind speed of 10m/s, which is larger than that of trapezoidal and rectangular beams. Figure 13 show the exponential piezoelectric energy harvesters.

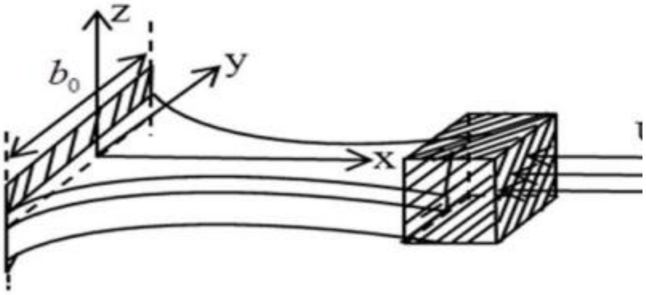


Fig. 13. Exponential piezoelectric energy harvesters [49].

IV. ARRAY PIEZOELECTRIC ENERGY HARVESTERS

An array piezoelectric energy harvester consists of multiple piezoelectric transducers arranged in a specific configuration show in Fig. 14. The transducers work together to harvest energy from mechanical vibrations, with each transducer contributing to the overall power output of the system. The configuration of the array can greatly impact its performance, and various designs have been developed to optimize energy harvesting efficiency. By carefully selecting the number and placement of the transducers, it is possible to maximize the amount of energy that can be harvested from a given vibration source. Additionally, incorporating electronics such as rectifiers and DC-DC converters can further increase the efficiency and usefulness of the energy harvested.

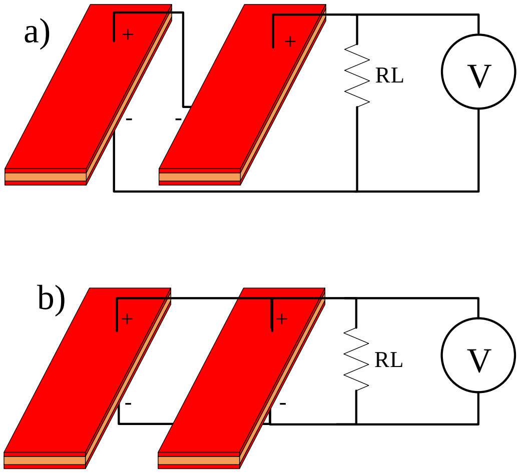


Fig. 14. a) Series and b) parallel configuration using two piezoelectric transducers.

An array piezoelectric energy harvester utilizes multiple piezoelectric transducers to increase the number of electrical nodes. When using two piezoelectric transducers, each transducer generates two voltage elements, V1 and V2, and has corresponding capacitances, Cp1 and Cp2. In most applications, only a single output voltage is required from the energy harvester. This can be achieved by connecting the two piezoelectric transducers either in series to increase the overall voltage, or in parallel to increase the overall current.

In order to carry out a single value of voltage explicitly showing the behaviour of two piezoelectric plates and by restoring the output charge being Q1, Q2 the output charges generated by the piezoelectric plates. Fig. 15 shows the configurations for series (a) and parallel (b) connection. In series connection, the global output charge is equal to each output charge generated by each piezoelectric plates, Q = Q1 = Q2, whereas the global output voltage is the sum of each output voltage, that is (9) ,(10):

$$V = V_1 + V_2 \tag{9}$$

$$V_1 = \frac{Q}{C_{p1}}, V_2 = \frac{Q}{C_{p2}} \tag{10}$$

In terms of electrical current, I flowing through the external load R we have (11),

$$I = \frac{V}{R} = \frac{(V_1 + V_2)}{R} \tag{11}$$

under the assumption of equal piezoelectric materials, that is, $C_{p1} = C_{p2}$ and $V_1 = V_2$ leading to (12):

$$C_p = \frac{C_{p1}}{2} = \frac{C_{p2}}{2} \tag{12}$$

Conversely, in parallel connection the global output charge is the sum of each output charge generated by each piezoelectric plates, $Q = Q_1 + Q_2$, whereas the global output voltage is equal to each output voltage, that is, $V = V_1 = V_2$. By following the same procedure discussed for series connection the total capacitance is, $C_p = C_{p1} + C_{p2}$.

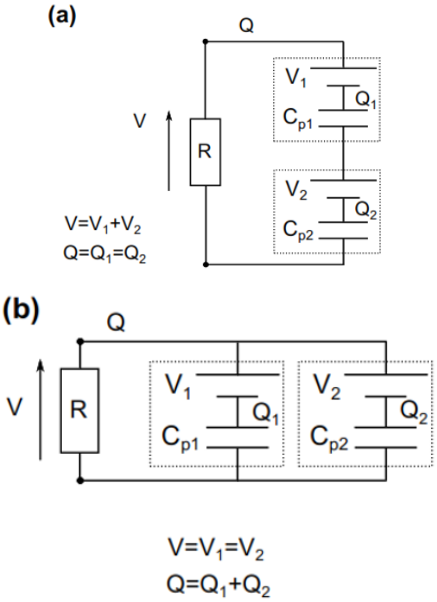


Fig. 15. (a) Series connection of two piezoelectric plates. (b) Parallel connection of two

piezoelectric plates. V and Q represent the global output voltage and output charge, respectively, R is the external load [50].

A. *Inferences from Literature Review Studies*

The study investigates the use of array piezoelectric configurations to optimize the performance of a piezoelectric raindrop energy harvester (PREH) by controlling the timing of energy harvesting events. The study focuses on the impact of different configurations of piezoelectric arrays on the resulting RMS output voltage. The findings indicate that increasing the number of piezoelectric elements connected in series leads to an increase in output voltage. Specifically, the highest RMS voltage of 255.2 mV was achieved with a configuration using six piezoelectric elements. Moreover, the 3S-2P configuration show in Fig. 16 was found to be the most effective among the different configurations for combination array circuits, generating the highest RMS voltage overall.

This study presents a novel soft-push-type piezoelectric energy harvester (PEH) show in Fig. 17 designed for non-resonant operation, which features a multi-array system optimized for maximum power output. The research team also developed a self-powered wireless switch that uses infrared communication, demonstrating the potential for practical applications of the proposed technology. The PEH design incorporates two beams connected in parallel, which reduces the resistive impedance matching to 250 kΩ and enables the device to achieve a power output of 4 mW. By operating at non-resonance, the PEH can effectively harness ambient mechanical energy and convert it into electrical energy.

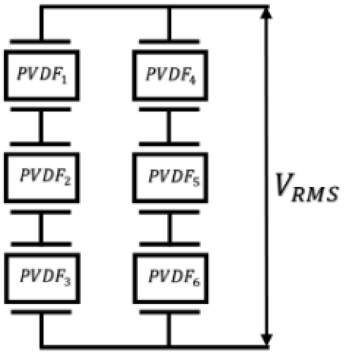


Fig. 16. 3 Series–2 Parallel (3S-2P) [51]

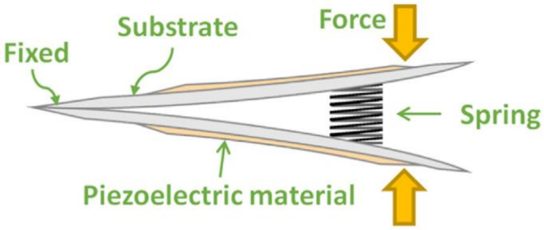


Fig. 17. Design of multi-array PEH of the soft-push-type [33].

This study presents a novel approach to energy harvesting from pavements through a compression-based device that utilizes piezoelectric transducers. The study investigates the selection of component materials based on four technical device requirements that aim to enhance the electric energy output of power-generation pavements. The device design is tested using a 150mm × 150mm prototype, and its electrical output performance is evaluated under typical road loading conditions. The results indicate that the device can generate a maximum output power of 50.41 mW with nine parallel transducers under a loading of 0.7 MPa and 15 Hz. The optimum loading for this condition is 4 kΩ. Similarly, under a loading of 0.2 Mpa and 10 Hz, the device generates a maximum output power of 2.92 mW, and the optimum load is 10 kΩ [52].

The paper presents a novel approach to harvesting energy from a broadband vibration source by using an array of piezoelectric cantilevers. The harvested energy is then used to power an op-amp, which amplifies the signal obtained from a shorter piezoelectric cantilever. Experimental results demonstrate that using four series-connected piezoelectric cantilevers at a frequency of 275 Hz generates an output voltage of 3.2 V, with a corresponding load resistor of 10 kΩ [53].

The study aimed to analyze the use of an array of piezoelectric transducers for raindrop energy harvesting applications. The study investigated the relationship between the number of PVDF piezoelectric transducers connected and the voltage generated. The results of the study indicate that the output voltage increases as the number of PVDF piezoelectric transducers connected increases. The highest voltage generated was observed from a 2 x 3 array parallel-series connection of PVDF piezoelectric transducers, which produced a voltage of 1.87 V compared to 1.25 V from a 2 x 3 array series-parallel connection [54].

The study investigated how different connections of piezoelectric cantilever arrays affect their output. The researchers conducted experiments to determine the optimal load resistance for the arrays by varying the resistance while subjecting them to a specific frequency and acceleration. The results showed that using a single cantilever yielded the best load resistance at 13 kΩ, but when multiple cantilevers were connected in series, the optimal load resistance increased. Conversely, connecting the cantilevers in parallel decreased the load resistance. When the cantilevers were connected in series, the voltage output was higher, while in parallel, the power output was higher. Furthermore, the maximum power output increased from 272 µWin the series configuration to 521µW when two cantilevers were connected in parallel with the same polarity. Fig. 18 show piezoelectric cantilever arrays in a parallel configuration using four piezoelectric elements. These findings are useful for designing more efficient piezoelectric cantilever arrays for various applications.

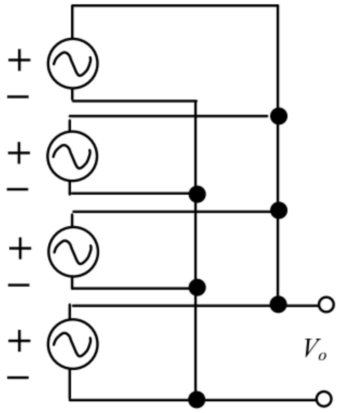


Fig. 18. Piezoelectric cantilever arrays in parallel configuration [55]

The paper presents a comprehensive study on the design, fabrication, and characterization of a MEMS piezoelectric cantilever array using AlN thin films with a single Si proof mass for vibration energy harvesting. The prototype consists of five AlN cantilevers that were fabricated using standard MEMS processes. The researchers connected the five piezoelectric elements in both series and parallel configurations and compared the results. The findings showed that using five parallel piezoelectric cantilevers produced a higher power output of 3.249 µW through 70 kΩ, while the power consumption in the rectifier for the parallel case was larger than that for the series case. For array harvesters, connecting the cantilevers in series can effectively increase the output voltage and decrease the power loss in the rectifier. These results provide valuable insights for the design of piezoelectric cantilever arrays for vibration energy harvesting applications [56].

The paper presents valuable insights into the design of piezoelectric cantilever beam arrays for low-frequency vibration energy harvesting. The authors provide practical guidelines for achieving optimum design, and suggest a simple power-transfer circuit that allows for extraction of electrical power close to theoretical maximum, while minimizing diode losses. The experimental results indicate that connecting three parallel cantilevers with full wave bridge rectifier results in a power output of 1.5 mW at 41.5 Hz. Fig. 19 show two piezoelectric cantilevers (denoted as PZ1, PZ2) with the individual full wave bridge rectifiers connected parallel to the resistance RL.

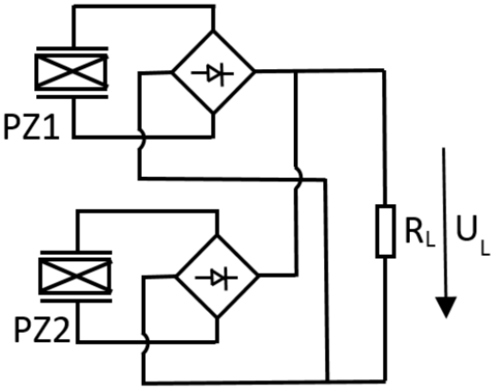


Fig. 19. Two piezoelectric cantilevers (denoted as PZ1, PZ2) with the individual full wave bridge rectifiers connected parallel to the resistance RL [57]

The characteristics of energy harvesting of a piezoelectric circular diaphragm array in series and parallel connection have been investigated. a prestress of 0.8 n at 150 Hz was applied to an array consisting of four 40-mm-diameter, 0.4-mm-thick piezoelectric plates in series connection, resulting in an electrical power generation of 28 mW through a 160-kΩ resistor, whereas a maximal output power of 27 mW can be obtained from the array in parallel connection through four separate rectifier circuits and across a resistive load of 11 kΩ under the same frequency, prestress, and acceleration conditions. The experimental results show that the array in series and parallel connection can achieve remarkably cumulative energy compared with the use of a single plate. Fig. 20 show parallel connection through four separate rectifier circuits.

A piezoelectric generator fabricated by multiple piezoelectric circular diaphragm oscillators array has been studied for broadband energy harvesting in this paper. Four circular diaphragm piezoelectric harvesters with four different tip masses show in Fig. 21 are integrated for array. The maximum output power is 10mW using three piezoelectric at 197 Hz when switch 2 on under a resistive load 33.3 kΩ.

The characteristics of energy storage in a piezo- electric circular diaphragm array have been investigated. A pre-stress of 0.8N at 150 Hz applied on the array consisted of three piezoelectric plates in parallel connection with a dimension of diameter 40mm×0.4mm resulted in an electrical power generation of 21mW through an resistor RL = 11 kΩ [60].

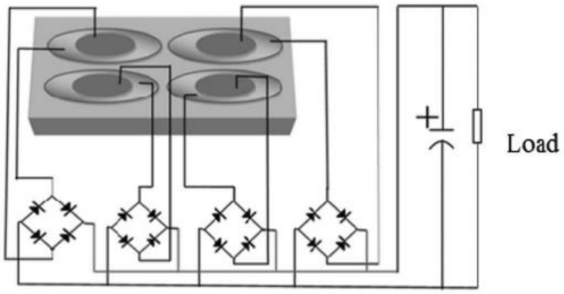


Fig. 20. Parallel connection through four separate rectifier circuits [58].

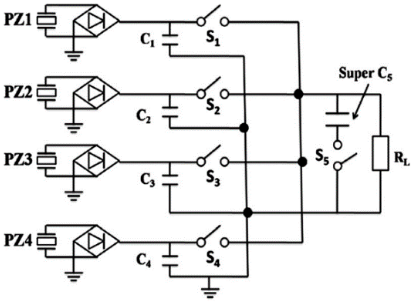


Fig. 21. Schematic diagram of the electrical circuit used in the generator [59].

This paper investigates the performance of the power converter for PREH system. A series of experiments was performed by comparing different piezoelectric con- figuration, different types of the diode and different values of the capacitor filter. The result found that the double layer PVDF piezoelectric generated the highest voltage 19.66 V and current 42 μA respectively. Fig. 22 show PVDF piezoelectric configuration single, X-Shaped and double layer.

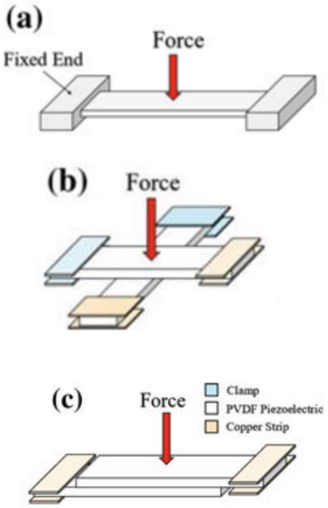


Fig. 22. PVDF piezoelectric configuration a() single, (b) X-Shaped, (c) double layer [61].

TABLE II: SUMMARY OF PREVIOUS STUDIES ON TYPES OF SHAPE PIEZOELECTRIC CANTILEVER

Authors (Year)	Input energy	Shaped Piezoelectric Cantilever	Load	Output
Khaled Mohamed (2020) [41]	none	T-shape	316.3 Ω	28 mW
Md. Naim Uddin (2016) [42]	Ambient low vibration energy	T-shape	none	0.28 mJ
Seyedfakhreddin Nabavi (2018) [43]	Ambient low vibration energy	T-shape	none	5V
Seyedfakhreddin Nabavi (2019) [44]	Ambient low vibration energy	T-shape	none	2.33V
Salem Saadon (2014) [45]	Ambient low vibration energy	Rectangular Trapezoidal T-shape	none	1.9μW 2.3μW 2.4μW
Samah Ben Ayed (2013) [46]	none	Quadratic shape	13 kΩ	0.009 Ws^4/m^2
Yingwei Tian (2018) [47]	none	Rectangular hole	60 kΩ	216.66 μW
Nan Chen (2018) [7]	none	Trapezoidal	none	2.3 – 2.5 mW/cm3
Ashutosh Anand (2019) [48]	none	Spiral structure	none	5.3 mW
K.F. Wang (2019) [49]	none	exponential shape	10 MΩ	0.14 W

TABLE III: SUMMARY OF PREVIOUS STUDIES ON TYPES OF ARRAY CONNECTION

Authors (Year)	Types of piezoelectric	Input energy (Hz)	Types of array connection	Load (kΩ)	Output
Chin-Hoong Teoh (2019) [51]	strip piezoelectric	none	3S-2P	none	255.2mV
Eduard Dechant (2017) [33]	strip piezoelectric	41.5	3 Parallel	275	121mW
Se Yeong Jeong (2016) [52]	strip piezoelectric	none	2 Parallel	250	4 mW
Chaohui Wang (2018) [53]	Pavement piezoelectric	15	4 Parallel 4 series	20	51.2 mW 0.46 mW

Bong Yu Jing (2017) [54]	strip piezoelectric	275	4 series	10	3.2 V
Chung Wei Chee (2017) [55]	strip piezoelectric	none	2P-3S	none	1.25 V
Bong Yu Jing (2017) [56]	strip piezoelectric	300	2 Parallel	6.5	521 μW
Wei Wang (2011) [57]	circular piezoelectric	150	4 Parallel	11	27 mW
Zhao Xiao (2014) [58]	circular piezoelectric	225	4 Parallel	15	10 mW
Wei Wang (2014) [59]	circular piezoelectric	150	4 Parallel	11	21 mW
Xingqiang Zhao (2015) [60]	strip piezoelectric	230.4	5 Parallel	70	3.249 μW
M. Izrin (2019) [61]	strip piezoelectric	none	2 series	none	19.66 V

V. CONCLUSION

This paper has done a comprehensive review on the shape of piezoelectric transducers and compares the performance of an array of piezoelectric transducers with and without an AC-DC converter. The performance of the harvesters in terms of their conversion efficiency, power output and power density were also discussed.

Improving upon the existing works, the power output of piezoelectric harvesters has been extensively researched and analyzed. The current range of power output for these harvesters falls within the micro-watt to milliwatt range, limiting their suitability to specific low-power applications. However, significant advancements have been made, and the T-shape piezoelectric energy harvester has demonstrated the highest power output among the various designs studied.

To further enhance the performance of piezoelectric energy harvesters, the development of array configurations is crucial. By employing an array setup, the harvested energy can be significantly increased. However, due to the small electrical energy obtained from vibrations, it is necessary to find the optimal combination of array piezoelectric configuration and rectification techniques.

Previous research has shown that a parallel array configuration combined with an efficient rectifier yields the highest power output compared to other combinations. This configuration allows for effective harvesting of energy from multiple piezoelectric elements simultaneously. Additionally, the rectifier plays a crucial role in converting the AC voltage generated by the piezoelectric elements into a usable DC voltage, maximizing the energy.

ACKNOWLEDGMENT

This research was not funded by any grant.

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