

Recent Developments of Piezoelectric Energy Harvester for Scavenging Vibration Energy

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ABSTRACT

The increasing reliance on non-renewable energy sources has led to severe environmental challenges, including pollution and a global energy crisis. These pressing issues have motivated researchers to develop and explore alternative energy harvesting systems capable of capturing ambient energy from the surrounding environment. One promising solution is the use of piezoelectric energy harvesters (PEHs), which generate electrical energy in response to mechanical pressure or vibrations. These devices typically incorporate piezoelectric materials mounted on mechanical structures, such as cantilever beams or flexible plates, which deform under external excitations. This deformation produces strain within the material, inducing the piezoelectric effect and resulting in electricity generation. This paper reviews and compares five of our previous studies focusing on different mechanical excitation mechanisms for enhancing the performance of piezoelectric energy harvesters. Specifically, we investigate and analyse three methods: direct collision, vortex-induced vibration (VIV), and rotational-based collision. Each method involves distinct excitation elements and physical interactions, such as varying mass weights, gravitational force, fluid-induced vortices, deflection of cantilevers, momentum transfer, and impulse forces. By evaluating the influence of these excitation characteristics on the resulting voltage outputs, we identify the key parameters that contribute to efficient energy harvesting. The findings highlight the importance of the interaction between mechanical components and the piezoelectric materials. This work provides valuable insights for the development of next-generation self-powered systems and low-power electronics that rely on sustainable and renewable energy sources from ambient mechanical vibrations.

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1. INTRODUCTION

Energy is a crucial driver of technological advancement across various sectors, including manufacturing, defense, healthcare, aerospace, and agriculture. To ensure the long-term sustainability of these industries, a stable and reliable energy supply is essential. One promising approach is to harness ambient energy from the surrounding environment. Numerous studies have explored micro-scale energy conversion systems, commonly referred to as energy harvesters. These systems have been developed to capture energy from diverse sources such as rotational motion [1], [2], mechanical vibrations [3], [4], ocean waves [5], [6], human body movements [7], [8], and wind [9], [10]. Wind energy is especially effective at generating vibrations, which can be converted into electrical energy through various harvesting techniques such as triboelectric [11], [12], electrostatic [13], [14], electromagnetic [1], [15], and piezoelectric [16], [17] methods. Among the available methods, piezoelectric energy harvesters (PEHs) are particularly advantageous because of their high energy density, small size, and ease of integration with electronic systems [18].

Piezoelectric energy harvesters (PEHs) are a kind of energy harvester that generates electricity due to pressure or vibration. Piezoelectric materials are typically attached to mechanical structures (such as flexible beams) that can undergo mechanical vibration-induced deformation and lead to strain in the piezoelectric material to enable the piezoelectric effect. Even though PEH depends on the intrinsic polarization of the material, it is a very useful method for absorbing mechanical energy from the environment and converting it into electrical power. Compared with other energy harvesting methods, PEH shows three to five times higher voltage output and density generation. They are also more reliable, and sensitive to even the smallest strains. Furthermore, PEH are easily integrated into microelectromechanical systems and able to develop in smaller sizes. Moreover, they are not dependent by external influence like humidity. Consequently, PEH is the most promising ambient energy harvesting technology, which has found use in various industries and fields of application.

In recent years, there have been some excellent review papers published on various issues relating to piezoelectric energy harvesting, including materials [19], [20], [21], device architectures [22], circuit designs [23], energy sources [24], [25], [26], applications [27] and performance optimization [28]. Even though some literature studies emphasize some of the characteristics mentioned earlier of piezoelectric energy harvesting, none of the recent reviews compile the PEH development research journey of a single research team based on the scavenging method in vibration energy. The objective of this review paper is to provide information related to the progress of research conducted by the author over a five-year duration. In this paper, we review, compare, and analyze our previous studies on vibration energy harvesting. Firstly, detail methods such as direct collision, flow induced vibration, and rotational based collision are discussed. Then, the performance of PEH in every method is displayed and discussed. The paper highlights the strengths and limitations of each energy harvesting approach, providing insights into the effectiveness of various excitation mechanisms.

2. METHOD

This study employs a comparative review method by analyzing five previous experimental studies conducted by the authors related to piezoelectric-based vibration energy harvesting. Each study utilized different configurations of piezoelectric materials, mounting mechanisms, and excitation sources such as mechanical collisions, spring-mass systems, and wind-induced vibrations. A detailed comparison of these experimental setups is provided in Table 1. The performance of each setup was evaluated based on the resulting output and root mean square (RMS) of voltage. By examining and comparing the experimental data from these studies, the aim is to identify the most effective configuration and operational conditions for optimizing the performance of piezoelectric energy harvesters. The insights gained from this analysis are expected to support future development of self-powered systems, including the integration of piezoelectric energy harvesters into low-power applications such as autonomous street lighting in urban or remote environments.

Table 1. Comparative Summary of Previous PEH Experimental Studies

No	Study Reference	Piezoelectric Type	Dimension	Setup Description	Mechanism
1	Sunardi & Gamayel, 2019 [29]	Piezoelectric ceramic plate	120 mm × 50 mm × 0.5 mm	Rubber ball collisions with piezoelectric material	Direct impact; influenced by gravity, momentum
2	Gamayel et al., 2019 [30]	Piezoelectric ceramic plate	120 mm × 50 mm × 0.5 mm	Spring-mass energy harvester	Sinusoidal output based on resonance frequency
3	Gamayel, Dionova, et al., 2023 [31]	Piezoelectric coin	Ø 35 mm	Spring-mass energy harvester	Sinusoidal output
4	Gamayel, Zaenudin, et al., 2023 [16]	Piezoelectric element plate	80 mm × 30 mm × 0.6 mm	Micro windmill as piezoelectric collider	Wind-induced deflection
5	Gamayel & Sunardi, 2024 [17]	Piezoelectric element plate	80 mm × 30 mm × 0.6 mm	Micro windmill as piezoelectric collider	Wind-induced deflection

In the five previous experimental studies analysed in this research, lead zirconate titanate (PZT) was used as the primary material for the piezoelectric ceramics. The specifications of the PZT material are provided in Table 2. This material was selected due to its reliable performance and effective synthesis through advanced fabrication processes, which yield favourable piezoelectric coefficients [32]. PZT is widely recognized as the most used piezoelectric material, primarily because of its excellent stress and strain tolerance in comparison to other piezoelectric materials. The power output in piezoelectric energy harvesters (PEH) is closely linked to the amount of strain applied to the PZT material [33]. As a polycrystalline ferroelectric compound, PZT also exhibits some of the highest dielectric constants and electromechanical coupling coefficients available, making it highly suitable for energy harvesting applications.

Table 2. Specification of PZT

No.	Properties	Values
1	Density (10^3 kg/m^3)	7500
2	Young modulus (Gpa)	56
3	Poisson's Ratio	0.36
4	Piezoelectric Strain Coefficient (d31) C/N	-186×10^{-12}
5	Permittivity at constant stress (ϵ_{11}/ϵ_0)	3130
6	Permittivity at constant strain (ϵ_{33}/ϵ_0)	3400

In the first study [29], output voltage was generated from direct collisions between rubber balls and piezoelectric material. In this event, mechanical energy is affected by altitude, gravity, momentum, and restitution coefficient. The second [30] and third [31] study used a spring-mass energy harvester model which the sinusoidal equation is simply written $V(t) = V_{max} \sin(\omega_n t)$, where V represent the output voltage, ω_n is the natural frequency obtained from the equation $(\omega_n) = \sqrt{k/m}$, and it is influenced by the spring constant (k) and mass (m). Based on the equation, the maximum output voltage can be generated at high kinetic energy, low resonance frequency and low damping energy level. The fourth [16] and fifth [17] studies used micro windmills as piezoelectric colliders, resulting in deflection that leads to output voltage generation. The data acquisition system is used for output voltage data collection, with the ability to record data every 0.04 seconds. The data displayed by DATAQ is then converted into Excel format to create sinusoidal graphs. These graphs exhibit both negative and positive values, indicating that the voltage represents an alternating electric current.

3. RESULTS AND DISCUSSION

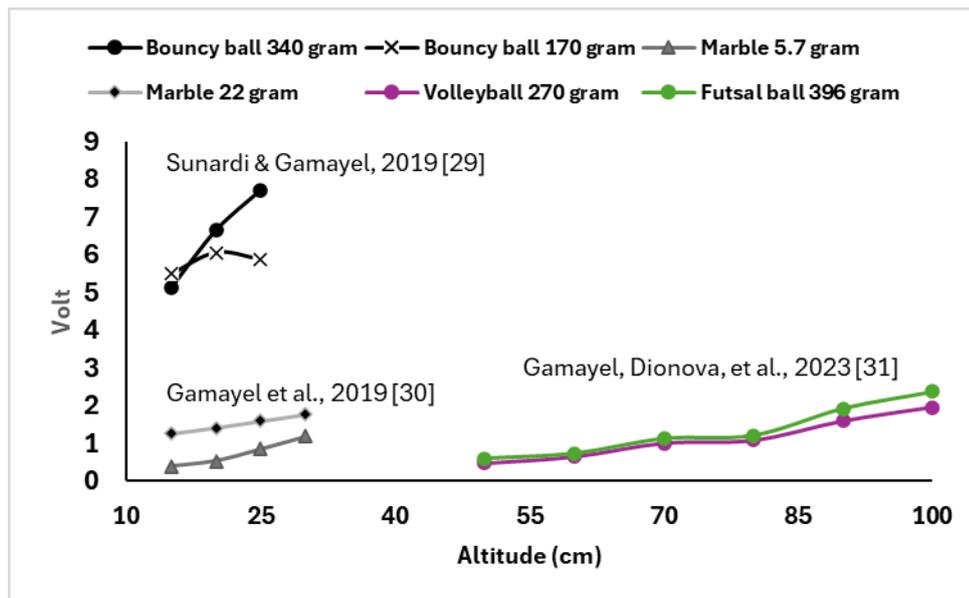


Figure 1. comparison of five study in scavenging vibration energy harvester using piezoelectric

Figure 1 depicts a grouping of research results where the scavenging vibration energy method employs direct collision with a ball against a piezoelectric material. According to Figure 1, research outcomes using a bouncy ball yield the highest results compared to marbles and sports balls. The impact momentum between the bouncy ball is greater than that of the marble and the sports ball, resulting in the highest deflection and substantial electric voltage generation. There is a correlation between the concepts of momentum and conservation of energy in the study of bouncy balls and marbles. This is due to the bouncy ball's greater mass weight compared to the marble, resulting in a higher momentum for the bouncy ball. In this study, it is evident that the mass weight significantly impacts the electric voltage produced. Contrasting results were observed in scavenging studies using trampolines. Although sports balls have greater mass weight than bouncy balls, the energy generation yields a smaller voltage, like that produced by marbles. The type of piezoelectric and the collision-prevention shield are responsible for this occurrence. The type is piezoelectric coin with a total of 16 parallel coin-shape affixed to sponge sheet as a shield with a thickness of 5 mm and width area $30 \times 30 \text{ cm}^2$. When sport balls collide with the mattress, the sponge sheet effectively absorbs the impact, then piezoelectric

vibrates in minimum oscillation to generate a small voltage. Comparing the outcomes, it becomes evident that mass weight and altitude play a positive role in electricity generation, aligning with the principles of conservation of energy. However, the shield, which is the sponge sheet, makes it more difficult to generate voltage efficiently. Further investigation is necessary to determine a sort of shield that can protect the piezoelectric material without reducing the efficiency of energy conversion.

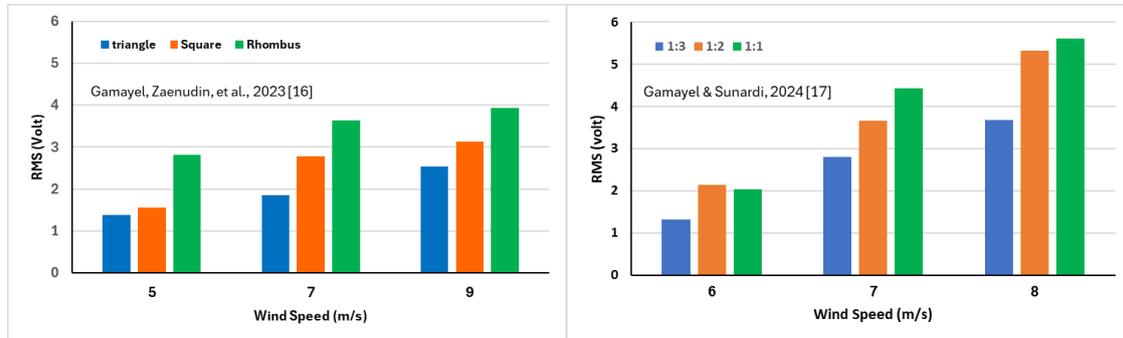


Figure 2. Root Mean Square of Voltage

The 2023 investigation [16] focuses on the concept of vortex-induced vibration (VIV) with the various wind speeds. The presence of a bluff body is one of the factors triggering this vortex phenomenon beside the wind speed. Moreover, this vortex serves as a collision mechanism in the piezoelectric energy harvester, which is affixed to a cantilever system. In contrast, the 2024 study [17] explores the concept of rotational based collision where the direct collisions between mini windmills and piezoelectric materials due to wind speed the rotation of windmill takes place when the wind strikes the windmill blades. Subsequently, the blade strikes the piezoelectric energy harvester (PEH), which is attached to the cantilever system, lead to oscillation. Comparing the root mean square (RMS) graphs from both studies reveal that windmill-based approaches yield higher RMS values than those based on the VIV concept. In the VIV concept, wind with compressible flow properties and relatively small mass effectively pounds the piezoelectric harvester (PEH), leading to the minimum output voltage. However, the scenario changes when the wind directly impacts the windmill, causing it to rotate at a specific speed. When the windmill rotates faster, the blades pound the PEH more forcefully, leading to greater deflection in the cantilever system. Consequently, higher deflection corresponds to increased output voltage.

These observations underscore the complexity and interdependence of factors involved in optimizing piezoelectric energy harvesting. While current configurations have shown promising results, particularly with direct impact and rotational systems, there remains significant potential for refinement. Future work should focus on material innovation, system miniaturization, and adaptive shielding mechanisms that protect without compromising efficiency. Moreover, integrating computational modelling and real-time monitoring could lead to smarter energy-harvesting systems tailored for specific environments. This evolving field holds promise not only for sustainable micro-energy solutions but also for advancing the design of autonomous low-power devices in various engineering applications.

4. CONCLUSION

Studies on scavenging vibration energy using piezoelectric energy harvesters (PEHs) have been conducted over the past five years. Methods such as direct collision, vortex induced vibration, and rotational based collision are used to generate voltage. Based on the results, direct collisions yield higher voltage when the mass weight and altitude are increased. In the VIV concept, wind with compressible flow properties and relatively small mass effectively impacts the piezoelectric harvester (PEH), resulting in modest voltage generation. The rotational-based collision concept is a modification that utilizes wind energy to rotate the windmill and create collisions with the PEH. These collisions result in significant deflection of the PEH, leading to substantial voltage generation. These findings emphasize the need for continued exploration of material properties, structural configurations, and energy transfer mechanisms to optimize piezoelectric energy harvesting systems for various applications.

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