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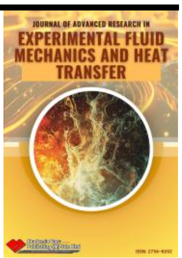

# Optimizing Wind Power Efficiency with Integrating Vortex-Induced Vibration and Piezoelectric Energy Harvesting

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**ABSTRACT**

This article delves into the optimization of energy harvesting through the utilization of piezoelectric technology, with a specific focus on wind-induced vibration as a primary energy source. Emphasizing their potential application in powering microelectromechanical systems while mitigating the environmental impact associated with traditional batteries. In the first section the research covers review on various aspects, including the selection of piezoelectric materials, considerations of bluff body shape, optimal wind speed ranges and optimal resistance parameters. The second section of the study delves into piezoelectric energy harvesting from wind-induced vibrations on various bluff bodies. The research aims to comprehensively analyse the vibration response of a splitter plate, configured as a simple cantilever beam, when exposed to wind-induced vibrations on these bluff bodies. It investigates the effectiveness of utilizing PZT-5A as a piezoelectric actuator attached to the splitter plate to convert these vibrations into electrical energy. The experiment employs a vibrometer laser to capture vibration responses, while Oscilloscope data stream monitors the energy conversion of piezoelectric materials. By comparing three different bluff designs, the study highlights the significant impact of geometric shape on bluff body vibration characteristics. It demonstrates that rectangular bluff bodies are most efficient at converting vibrations to electricity at certain frequencies.

***Keywords:***
Energy harvesting; piezoelectric; wind-induced vibration; bluff body aerodynamics

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## 1. Introduction

Small-scale energy harvesting techniques hold significant promise for providing a reliable and continuous energy source to power wireless sensors and low-power portable electronic devices. These applications span a wide range of fields, including wireless communication sensors, portable electronic gadgets and structural health monitoring [1-5], implantable medical electronics, engine

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vibration [6], pavement power generator [7,8] military [9], and electronic devices for the Internet of Things [10-12].

In the midst of advancements in energy harvesting technology, the sustainability and feasibility of enhancing power supply to small grids have become critical topics of discussion within academic discourse. Among these challenges, a key focal point is the extension of the lifespan of energy storage systems, particularly batteries, while also managing maintenance and replacement costs to ensure economic viability. In addition to this, there is a growing demand for energy storage systems to exhibit minimal self-discharge characteristics and undergo a conscientious evaluation regarding their environmental impact during disposal. Furthermore, the restricted operational longevity of these systems presents a formidable obstacle to ensuring the enduring and self-sufficient operation of associated devices [13-15].

Renewable energy harvesting technology has emerged as a prominent solution for mitigating energy shortages [16,17]. Among the spectrum of renewable energy sources, wind-induced vibration (WIV) has garnered considerable recognition due to its rapid proliferation and minimal environmental impact. Within the realm of wind energy harnessing techniques, piezoelectric harvesters have gained notable prominence due to their straightforward design, effective mechanical-electrical transduction mechanisms, and high-power density characteristics. These devices typically comprise flexible structural components, often in the form of beams [18] or plates, incorporating integrated or bonded piezoelectric materials. When subjected to wind flow-induced motion, these systems undergo periodic bending of the piezoelectric material, thus facilitating energy conversion [19-22].

Extensive research has been dedicated to in-depth investigations of wind energy conversion efficiency in piezoelectric energy harvesters. Numerous methods have been explored to enhance the power generation capacity of wind energy harvesters. This review focuses primarily on conventional energy harvesting methods that do not involve magnetic coupling or other external influences. The primary factors affecting the enhancement of power generation, including the type of piezoelectric material, optimal wind velocity and bluff shape and condition. These elements play a substantial role in influencing the amount of power generated by the harvester.

## 2. Major Influence of Piezoelectric Energy Harvesting

This extensive review delves into providing a comprehensive and in-depth discussion of the critical factors that shape the landscape of piezoelectric energy harvesting. By thoroughly investigating these factors, this review aims to shed light on the intricate orchestration of influences that ultimately determine the transformative potential of piezoelectric energy harvesting technologies. This thorough analysis contributes significantly to a better understanding of energy harvesting through piezoelectric technology.

### *2.1 Piezoelectric Materials*

Piezoelectric energy harvesting offers a convenient means of harnessing ambient mechanical energy and transforming it into electrical power [23]. This is facilitated by the piezoelectric effect, which relies solely on the intrinsic polarization of the material, eliminating the need for an external voltage source, magnetic field, or contact with another material, as required by electrostatic, electromagnetic, and triboelectric energy harvesting mechanisms, respectively [24]. Piezoelectric generators are known for their durability, reliability, heightened sensitivity to minor strains, and the ability to produce power output with approximately three to five times greater density and higher voltage output [25-29]. Piezoelectric materials can manifest in various forms, encompassing high-output single crystals exemplified by piezoceramics such as lead zirconate titanate (PZT) [30], microscale fiber composites (MFC) [31], film-based polyvinylidene fluoride (PVDF) [32], and lead magnesium niobate-lead zirconate titanate (PMN-PZT) [33]. Piezoelectric materials typically exhibit anisotropic characteristics; thus, the properties of the material differ depending on the direction of forces and the orientation of polarization and electrodes. This section delves into an in-depth comparison of these four major piezoelectric materials with others used in prior research, examining their respective capabilities and applications in the field.

PZT, initially identified at the Tokyo Institute of Technology, boasts superior piezoelectric properties compared to PVDF, making it the preferred material for this research. Among various PZT types, PZT-5A and PZT-5H stand out as widely utilized engineering piezoelectric ceramics [34]. Li and Pooi [35] investigated the integration of PZT and PVDF polymers, with the goal of harnessing the strength of both materials. Although PZT materials are susceptible to depolarization and fracture under significant strain, PVDF polymers possess a higher tensile strain threshold but lack the essential thermal characteristics required for automotive tire applications. While comparing PVDF and macro-fiber composite (MFC) counterparts, it became evident that the composite, despite having lower material properties leading to reduced charge output, showcased a significant advantage in terms of stability. In contrast to the PVDF and MFC samples that experienced irreversible degradation when subjected to elevated temperatures, the composite's performance decline was primarily associated with the glass transition of the PU phase, which could subsequently be restored.

Piezoelectric material possesses a unique set of advantages and disadvantages, and these intrinsic characteristics are instrumental in determining their suitability for specific applications. Sodano *et al.,* [36] examined the influence of materials called PZT and MFC to make devices that can generate electricity for charging batteries. The former produced more electrical current than the latter. In energy harvesting applications, PZT and MFC are often used as energy harvesters [32]. Wang *et al.,* [33] explored the potential of PZN-PT and PMN-PT materials in the context of energy harvesting and compared them with the PZT material. Their comparative investigation unveiled that single crystal materials like PZN-PT and PMN-PT exhibited notably higher piezoelectric coefficient and voltage constant values, implying superior energy harvesting capabilities. Based on the findings of the experiments involving cantilever samples subjected to both off-resonance and on-resonance conditions, it was demonstrated that single crystal samples outperformed PZT materials in terms of power generation and efficiency [37,38].

Satyanarayana *et al.,* [19] investigated the effectiveness of piezoelectric energy harvesting using bimorph cantilevers made from different materials (PZT-5A, PZT-8, and cadmium sulfide) and featuring various proof mass patterns. PZT-5A demonstrated exceptional efficiency, achieving rates of 98.79% for frequency response and 98.87% for load response. The research highlights the significant potential of piezoelectric energy harvesting, with PZT-5A standing out as the most promising material among those studied. Kanno [39] conducted an experiment with attached PZT and Lead-Free (K,Na)NbO_3 KNN films onto a stainless-steel cantilever. A comparative analysis of their output power revealed that the KNN films exhibited a lower output power due to their substantial dielectric loss, whereas the PZT film, characterized by low dielectric loss, demonstrated higher output power. Sezer and Muammer [15] proposed a lead-free non-toxic (Na, K) Nb-based lead-free piezoceramics NKN as an alternative material of PZT, which possessed a favorable piezoelectric coefficient and electromechanical coupling constant. However, it is important to note that the piezoelectric coefficient and electromechanical coupling of NKN remain considerably lower than those of PZT-based materials.

PZT stands out as a superior material choice in various aspects. It offers ease of manufacturability, allowing for the fabrication of bulk, film, or composite forms with different dimensions and shapes at reasonable costs. PZT exhibits a wide bandwidth and high natural frequency, making it suitable for both off- and on-resonance applications. This versatile material encompasses ceramics, polymers, single crystals, composites, nanomaterials, and lead-free alternatives, making it a benchmark for piezoelectric energy harvesters. Its notable features include a high piezoelectric coefficient and a high mechanical coercive field, making it promising for high-voltage applications. The characteristics of PZT, such as its Curie temperature, dielectric constant, and low tangent loss, make it an ideal choice for energy harvesting, particularly from human vibration. PZT material is versatile and suits different levels of power generators [40-42].

### *2.2 Bluff Shape*

In the realm of piezoelectric energy harvesting, the manipulation of bluff body shape and the design of bluff with different conditions are obstructions to airflow, and this method presents a promising avenue to amplify energy production driven solely by air motion. This strategy entails an examination of how incoming airflow interacts with these obstructions. The unique geometry of the bluff body induces accelerated airflow along its flanks, leading to the generation of swirling air patterns known as vortices, a consequence of cross-sectional alterations [43]. Introducing an obstruction upstream generates alternating vortex patterns, prompting periodic shifts in air pressure and consequently augmenting the fluctuating lift force, driving the bluff body's vertical movement. Several studies have explored the impact of diverse bluff body shapes and system parameters on energy harvesting [13].

Poudel *et al.,* [20] designed a harvester with curve-shaped attachments on the bluff body, comparing it with circular, triangular, square, and Y-shaped variants. Song *et al.,* [44] revealed that the amplitude ratio of the fin shape attachment (FSA) cylinder exhibited a distinctive pattern, initially increasing and then decreasing with FSA height, peaking at 2.3 times the cylinder diameter (2.3D) when the FSA height was 0.33 times the cylinder diameter (0.33D) at a wind speed of 6.8 m/s. Liu *et al.,* [45] introduced a passively adaptive piezoelectric wind energy harvester featuring a double airfoil bluff body (DABB) to optimize energy harvesting under varying wind speeds. The DABB's attack angle significantly influenced its performance, leading to three distinct working modes: VIV, galloping, and vibration suppression. Kan *et al.,* [46] explored a novel approach to wind energy harvesting using a downwind-vibrating piezoelectric energy harvester with a downstream baffle.

Ding *et al.,* [47] introduced a novel approach to piezoelectric wind energy harvesting using a double-bluff body exciter with a downwind structure, aimed at addressing the reliability, environmental adaptability, and operating bandwidth limitations of existing wind energy harvesters. Wang *et al.,* [48] employed the "concave H" model as a case study to investigate the effects of load resistance and electromechanical coupling strength on energy harvesting performance. Wang *et al.,* [49] presented the development of a novel piezoelectric energy harvester, known as VIVPEH-S, which aims to improve energy harvesting efficiency by converting vibration modes from VIV to galloping.

Le Scornec *et al.,* [50] introduced an ultra-flexible piezoelectric airflow energy harvester designed to power a wireless sensor. They proposed an adaptable aero-electric generator method for harnessing wind energy efficiently, focusing on low wind speeds at 2-12 m/s. Mehdipour *et al.,* [51] explored the potential of harnessing energy from low-speed wind (2-12 m/s) through VIV using flexible piezoelectric flags PVDF as transducers. The research aims to optimize the combination of different bluff body shapes and flag configurations to enhance energy harvesting efficiency. Kim *et al.,* [52] presented a novel piezoelectric energy harvester (i.e., a piezoelectric energy harvester based on coupled transverse and interference galloping effect) designed to significantly improve electrical energy harvesting compared to conventional systems. Lei *et al.,* [53] identified the optimal configuration with a 1.0 MΩ load resistance, a 40 mm diameter bluff body, and a spacing ratio of 3.0 for efficient vortex shedding energy harvesting. A subsequent analysis revealed that the harvester achieved maximum power. Wang *et al.,* [54] aimed to improve wind energy harvesting by manipulating the inclination angle of a circular cylinder to enhance the effective wind speed bandwidth of a piezoelectric energy harvester based on VIVPEH.

Shi *et al.,* [55] compared wind energy harvesters with square and arc-plate-shaped bluff bodies. The results showed that the harvesters with arc-plate-shaped bluff bodies outperformed those with square bluff bodies. Li *et al.,* [56] focused on the symmetrical aerofoils of vortex-induced flutter composite nonlinear piezoelectric energy harvester (VFPEH) on both sides of a cylindrical bluff body, enabling coupling between VIV and flutter, resulting in energy harvesting in two degrees of freedom motion direction. Kouritem *et al.,* [42] explored a novel energy harvester employing the automatic resonance tuning (ART) technique to enhance energy harvesting. It consists of a cantilever beam and a sliding mass with varying positions to automatically adjust the harvester's natural frequency in response to ambient vibration frequencies. Finite element method simulations were validated with the experimental and analytical results, and the outcome demonstrated that the ART harvester significantly broadened its natural frequency bandwidth by 1,130% compared to traditional resonance harvesters.

Lim *et al.,* [38] studied the performance of different bluff body shapes attached to a rotating bluff body for piezoelectric wind energy harvesting under natural wind conditions. The equilateral triangle, square, and D-shaped bluff bodies were tested, and their frequency cut-in speeds and voltage production were analyzed. Wang [57] introduced a hybrid piezoelectric wind energy scavenger featuring various cross-sectioned bluff bodies to enhance energy scavenging performance by harnessing both VIV and galloping. The study combined theoretical analysis, experimental validation, and computational fluid dynamics simulations to investigate the scavenger's performance with different bluff body designs and attack angles. Zhao *et al.,* [58] introduced a novel galloping piezoelectric energy harvester with a funnel-shaped bluff body with square and triangular shapes, which were designed to enhance energy harvesting efficiency and decrease the onset wind speed. Ding *et al.,* [59] established that optimal angles ranging from 30° to 60° substantially expanded the synchronization region of the vibrating cylinder. This expansion allowed the harvester to efficiently capture wind energy even at low speeds, as slow as 1.0 m/s, and continued to operate beyond critical wind speeds. Wang *et al.,* [60] introduced a high-performance piezoelectric wind energy harvester, GPEH-Y, featuring Y-shaped attachments. These attachments modify the harvester's aerodynamics. Sun *et al.,* [61] investigated this phenomenon both theoretically and experimentally, focusing on two commonly used cross-sectional shapes (circular and square cylinders). A novel bulb-shaped cross-sectional cylinder (15 × 10 bulb cylinder) was proposed as an optimized bluff body, capitalizing on the synergistic effects of VIV and galloping.

In the pursuit of optimizing wind energy conversion using piezoelectric materials, researchers have undertaken a comprehensive exploration of diverse bluff body shapes and conditions. The weight, diameter, and length of the bluff are significant to energy harvesting, where numerous researchers have proposed specific diameters, lengths, and weights of bluffs. The common size (diameter × length) of the bluff is 32 mm × 168 mm (5.73 g) [62] and 50 mm × 160 mm [58]. The bluff body weighed from 3.45 g to 26 g, as proposed by previous researchers [63-66]. The selection of an appropriate bluff body shape emerges as a critical factor in fine-tuning the energy harvesting process.

### *2.3 Wind Velocity*

In the context of piezoelectric energy harvesting systems, wind velocity stands out as a pivotal factor influencing their performance. Among various configurations, the elastic setup proves to be remarkably efficient over a wide spectrum of wind speeds. A noteworthy insight gleaned from the analysis pertains to the intricate relationship between wind velocity and the energy derived from WIV. Rather than adhering to a linear relationship, this connection demonstrates a compelling characteristic wherein the harvested power experiences a disproportionate amplification as the wind speed escalates. This phenomenon takes on a captivating mathematical form, in which the harvested power exhibits a cubic relationship with wind speed, emphasizing the non-linear nature of this crucial aspect in energy harvesting research.

Numerous studies have consistently revealed that the power output of energy harvesters exhibits an upward trajectory in response to both increases in wind velocity and cylinder diameter. Under low-speed wind conditions, the most effective configuration entails a thinner and longer flag that is fully covered by a piezoelectric layer. In such conditions, the optimal combination involves a bluff body characterized by the highest drag coefficient paired with a flag configuration featuring extended active and total lengths [51,67,68]. However, it is noteworthy that in higher-speed wind environments, this same combination, albeit with a shorter flag, demonstrates superior performance. Lei *et al.,* [53] investigated the energy conversion efficiency of a designed piezoelectric wind energy harvester (PWEH) as the wind speed varies. It was revealed that efficiency initially increased with increasing wind speed, reaching a maximum value of 11% at a wind speed of 8.5 m/s, and then decreased. This research provides insights into the efficiency characteristics of airflow energy harvesting and highlights that the designed PWEH outperforms other reported harvesters in the literature under high wind speed conditions, with significantly enhanced efficiencies between 7.5 and 10.0 m/s.

From the data there is a trend where wind speeds below the 10 m/s threshold are associated with notably higher energy output levels. This finding underscores the pivotal role of lower wind speeds in influencing energy production and highlights the potential benefits of optimizing energy harvesting systems for such conditions. A thorough examination of the mechanisms and technologies that facilitate effective energy capture at sub-10 m/s wind speeds may contribute significantly to the advancement of wind energy solutions. This research underscores the importance of tailoring energy harvesting strategies to specific wind speed ranges to enhance overall efficiency and output in wind energy applications, particularly for low wind speed conditions.

### *2.4 Resistance*

The role of resistance in piezoelectric energy harvesting is twofold. Firstly, higher resistance values in the circuit result in increased power dissipation, leading to the loss of harvested energy as heat and reduced overall efficiency. Secondly, resistance affects the power output by influencing the impedance matching between the piezoelectric material and the load. Striking the right balance in resistance is critical to maximize energy harvesting efficiency. Too low resistance can lead to power losses due to impedance mismatch, while overly high resistance can cause excessive power dissipation. Careful selection of resistance, considering the specific piezoelectric material and circuit characteristics, is essential. Moreover, resistance also influences damping, which can affect vibration amplitudes and generate voltage. According to Abdelkefi *et al.,* [63], resistance is a key factor in energy harvesting circuits, significantly influencing efficiency, power output, and overall system performance. It affects the flow of current generated by piezoelectric materials and interacts with the circuit's electrical properties, affecting the conversion of mechanical vibrations into electrical energy. Load resistance also plays a role in determining system stability and harvested power levels.

Du *et al.,* [69] asserted that load resistance is a critical factor impacting the power generation capability of piezoelectric energy harvesting systems. To achieve maximum output power, it is essential for the capacitive reactance of the piezoelectric element to match the load resistance. This match depends largely on the excitation frequency, meaning that the optimal resistance value for the piezoelectric energy harvesting system is contingent on the excitation frequency for achieving the highest power output. Liu *et al.,* [45] explored the influence of external load resistance on the output performance of an energy harvester and observed that as load resistance increased, the output voltage exhibited a gradual rise. However, the output power reached a consistent maximum point, representing the theoretical optimal load resistance, which was approximately 500 kΩ for different attack angles. This study underscores the significance of load resistance in optimizing the output performance of energy harvesters, particularly in the context of wind energy conversion.

## 3. Methodology

### *3.1 Experimental Setup*

The experimental trials for the study were conducted in the Aerodynamics Laboratory at the University Tun Hussein Onn Malaysia (UTHM) using an open-loop speed wind tunnel. The wind tunnel had dimensions of 6.1 meters in length and 2.1 meters in height. The test section was 40cm wide and 40cm high, with a length of 125cm. This setup primarily relied on the wind tunnel for testing the bluff body, as depicted in Figure 1. The bluff body was secured in the test section using a rod with screws, and the laser of the vibrometer was directed towards the splitter plate to measure the vibration of the bluff body design during the test. The measurement of electrical power involves the utilization of a multi meter.

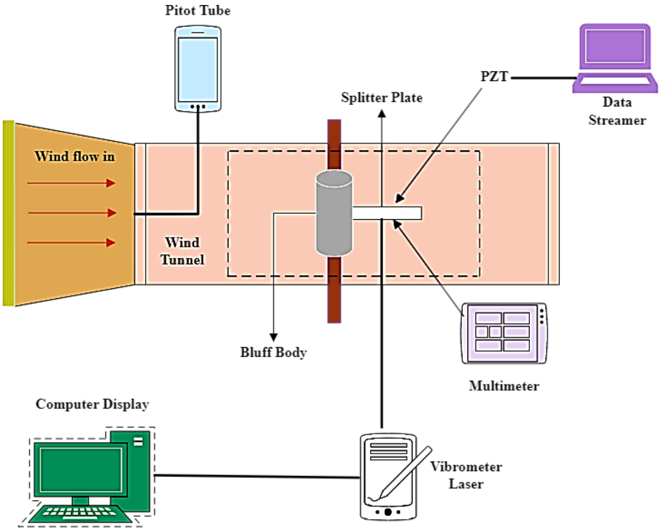

**Fig. 1**. Experimental setup

### *3.2 Experimental Procedure*

To accomplish the objectives of this study, an experimental approach was undertaken to obtain test results. In this experiment, three distinct bluff body shapes were tested to determine which elicits the most significant vibration response on a splitter plate. Once the bluff body generating the highest vibration response was identified, the experiment proceeded to examine the effectiveness of attaching piezoelectric technology to the splitter plate in converting flow-induced vibrations on bluff bodies into electrical energy. Figure 2 illustrates the complete experimental setup in the aerodynamic laboratory.

i. A circular bluff body with an attached splitter plate was prepared and installed in the test section of the wind tunnel.
ii. The bluff body was secured in the test section using a rod inserted through the centre of the bluff body and attached to a screw.
iii. After setting up the bluff body in the test section, a vibrometer laser was directed at the end of the splitter plate with reflective tape.
iv. The fan speed was set to 10 m/s, measured by a pitot tube, and the wind tunnel was activated.
v. Vibration response data was collected using Vibsoft software, linked with the vibrometer laser, and recorded on the splitter plate.
vi. Steps 1 through 5 were repeated with the ellipse and rectangular bluff bodies.
vii. Data for all bluff bodies were recorded and analysed to determine which one produced the highest vibration response in terms of acceleration.
viii. The experiment proceeded by attaching piezoelectric material to the splitter plate to convert mechanical vibration into electrical energy for all bluff bodies.
ix. Data was recorded using Data Streamer in Excel, and a oscilloscope Tektronix TDS2024C was connected to the piezoelectric material to measure voltage output for all bluff bodies.

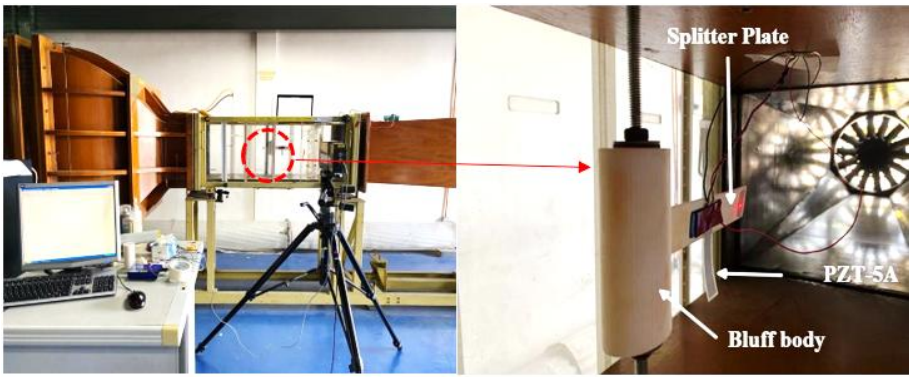

**Fig. 2.** Experimental setup

## 4. Results and Discussion

### *4.1 Vibration Response*

In this study, experiments were conducted to explore the vibration responses of various bluff body designs, encompassing cylindrical, rectangular, and elliptical shapes. The experimental setup entailed measuring vibration amplitudes using a vibrometer, coupled with Vibsoft software for data acquisition. The key findings from this experiment were summarized in Figure 3, revealing significant differences in amplitude responses among the various bluff body designs. Additionally, the relationship between amplitude (m/s²) and frequency (Hz) was plotted using OriginPro software. The data collected in the graph illustrates the vibration response of three different bluff body shapes which are cylindrical, rectangular, and elliptical – captured by the vibrometer laser in the wind tunnel. Amplitude in this experiment was measured in terms of acceleration (m/s²), and the data for all bluff bodies were presented by plotting amplitude against frequency.

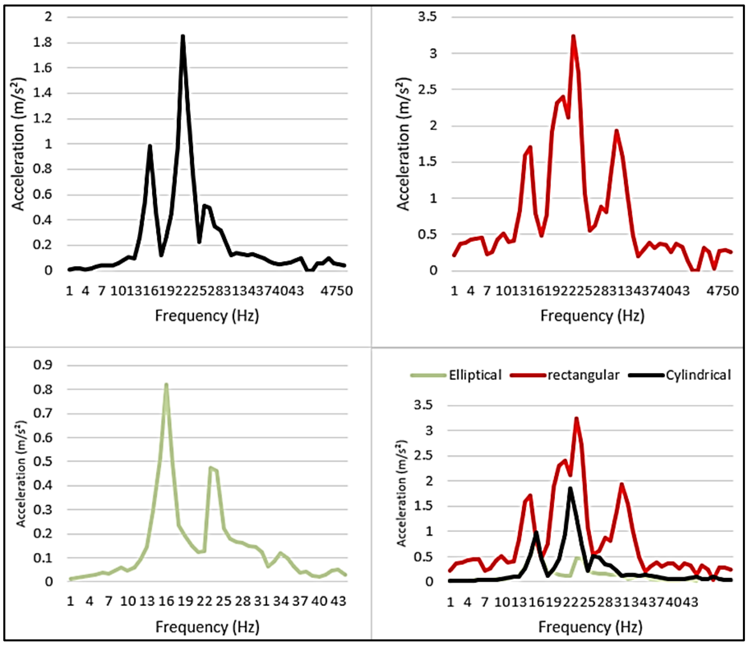

**Fig. 3.** Amplitude versus frequency

The experimental data obtained from the study offers valuable insights into the vibration responses of cylindrical, rectangular, and elliptical bluff bodies across a range of frequencies (1 Hz to 50 Hz). A notable observation is the unique behavior exhibited by each bluff body design in response to the applied frequencies. For the cylindrical bluff body, there is a discernible pattern of gradual acceleration increase with frequency, culminating in a prominent peak at 16 Hz (0.9786 m/s²). This peak indicates resonance, where vibrations intensify as the applied frequency aligns with the body's natural frequency. Subsequently, the acceleration values display decreasing trends, indicative of the structure exiting the resonance zone, followed by a period of stabilization. In contrast, the rectangular bluff body shows more erratic responses to changing frequencies. Acceleration exhibits significant spikes at 14 Hz (1.5908 m/s²) and 20 Hz (2.3082 m/s²). These abrupt increases may stem from the distinctive aerodynamic effects of the rectangular body's flat surfaces and sharp edges, potentially enhancing turbulent flow and vortex shedding, thereby increasing vibration response.

Subsequently, the elliptical bluff body presents a different pattern, with a relatively constant acceleration increase leading to a peak at 16 Hz (0.8209 m/s²) and a secondary peak at 23 Hz (0.4733 m/s²). From the result obtain the frequency of vibrations, on the other hand, denotes the rate at which the piezoelectric structure oscillates or vibrates. This frequency is determined by various factors, including the natural frequency of the structure and the frequency of the external mechanical excitation. The results obtained from the piezoelectric energy harvesting system reveal a significant correlation between frequency and amplitude, which greatly influences the efficiency of energy conversion. Typically, higher vibration frequencies result in greater oscillation amplitudes within the piezoelectric material, leading to enhanced electrical output. Nonetheless, there exists an optimal frequency range wherein the piezoelectric structure demonstrates its maximum responsiveness and, consequently, achieves the highest efficiency in converting mechanical vibrations into electrical energy [42].

### *4.2 Voltage Output*

In this study, the experiment was conducted as to understand the conversion of the vibration energy into electrical energy by piezoelectric material attached to a splitter plate of various bluff body designs, including cylindrical, rectangular, and elliptical shapes. The experimental setup involved measuring the voltage output generated using an Excel file named Data Streamer that links with the Oscilloscope for data acquisition. The obtained results indicate a linear relationship between velocity and voltage, as demonstrated by the Figure 4. Specifically, the rectangular bluff shape exhibited a notably higher voltage of 7.3 V, whereas the ellipse shape showed a comparatively lower voltage of 3.99 V. This disparity suggests that the geometric configuration of the bluff body has a significant influence on the voltage output generated by the piezoelectric material attached to the splitter plate. The higher voltage recorded for the rectangular bluff shape implies a greater conversion efficiency of mechanical vibration into electrical energy compared to the cylinder and ellipse shape.

Further analysis and experimentation may elucidate the underlying factors contributing to this discrepancy and provide insights for optimizing energy harvesting from wind-induced vibrations. The relationship between wind speed and voltage for piezoelectric energy harvesting can be complex and multifaceted, influenced by various factors such as the design of the bluff body, the characteristics of the piezoelectric material, and the environmental conditions. From the finding wind speed affects the amplitude and frequency of vibrations experienced by the bluff body, which, in turn, impacts the voltage generated by the attached piezoelectric material. Higher wind speeds typically result in increased airflow velocity around the bluff body, leading to higher-frequency vibrations and greater vibration amplitudes. As a result, the voltage output from the piezoelectric material may increase proportionally with wind speed [53].

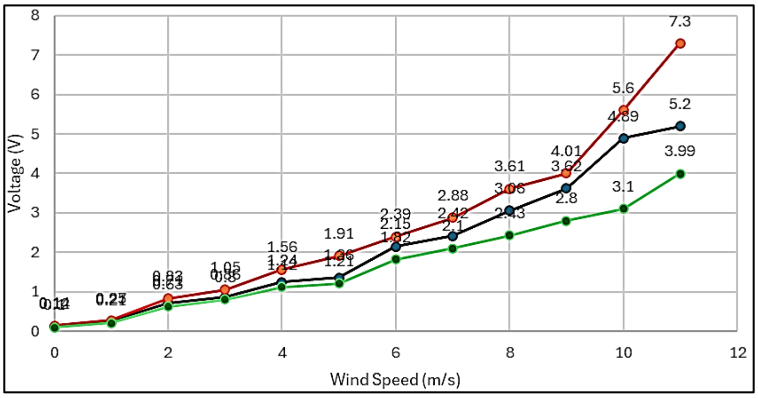

**Fig. 4.** Voltage output against frequency

## 5. Conclusions

In summary, our experiments successfully investigated the vibration response and voltage output of piezoelectric materials across various bluff body shapes, including cylindrical, rectangular, and elliptical forms. These bodies were tested alongside a splitter plate in a wind tunnel, with Oscilloscope facilitating data collection and analysis. Our findings highlight the rectangular bluff body's superior efficiency in converting vibrational energy into electrical energy, particularly at specific frequencies. This underscores the importance of aligning wind-induced vibrations with the system's natural frequencies for optimal energy harvesting. Moreover, the voltage output's variability across the frequency spectrum underscores the frequency dependency of energy harvesting. Distinct bluff body shapes interact uniquely with airflow, leading to variations in vibration frequency and amplitude. Rectangular shapes, for instance, may experience heightened turbulence-induced vibrations at certain frequencies, while streamlined shapes like elliptical ones exhibit more consistent vibrations across a wider frequency range due to reduced aerodynamic drag.

The interplay between bluff shape, frequency, amplitude, and voltage in piezoelectric energy harvesting systems is intricate and interconnected. Bluff shape influences airflow response, impacting vibration frequency and magnitude. Typically, higher frequency and larger amplitude vibrations result in increased voltage generation due to the piezoelectric material's enhanced mechanical-to-electrical energy conversion efficiency under such conditions. However, this relationship is complex and can vary based on system design and operational factors. To optimize energy conversion efficiency, a thorough understanding of this relationship through experimental testing and analysis is crucial. Such efforts are essential for improving energy harvesting system designs and performance under diverse operational conditions.

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