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Effect of windmill blade variations on the performance of piezoelectric energy harvesters: Enhancing vibration stability and power generation

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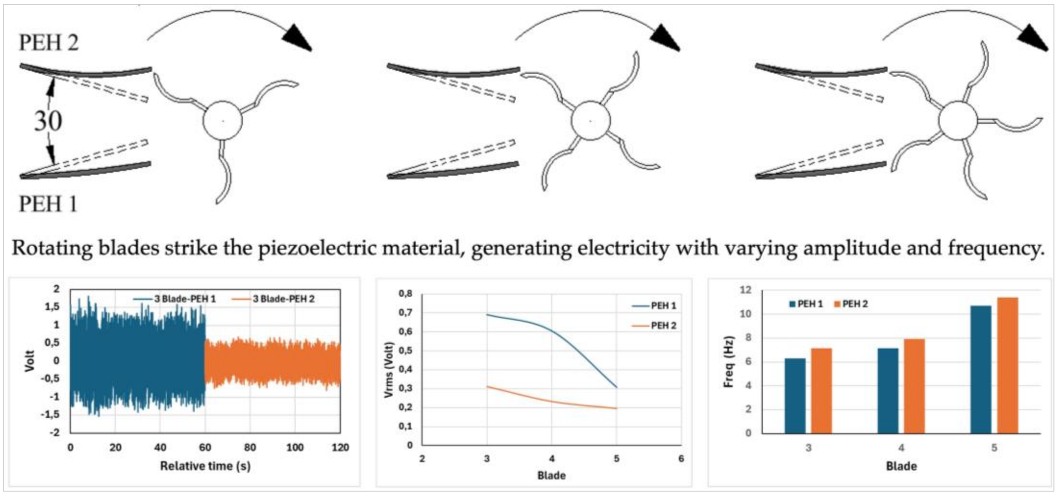

Highlights:

- The number of windmill blades directly affects the performance of piezoelectric energy harvesters (PEHs), with a 3-blade configuration yielding the highest voltage and deflection.
- Increasing the number of blades results in higher frequencies but smaller deflections, which leads to a decrease in voltage generation.
- Maximum energy output is achieved with large deflections and minimal vibrations, highlighting the importance of balancing blade count and deflection.

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Abstract

Piezoelectric energy harvesters (PEHs) are gaining attention for their ability to generate electrical energy from environmental vibrations, with applications in various industries. This study focuses on optimizing the performance of a PEH using a cantilever system driven by wind energy through the impact of windmill blades. The objective is to evaluate how the number of windmill blades affects the PEH's voltage output and vibration stability. Experiments were conducted in a wind tunnel with a 250 mm × 250 mm cross-section equipped with a 12-inch blower to generate airflow. Three windmill configurations—3 blades, 4 blades, and 5 blades—were analyzed for output voltage and deflection of two PVDF-based PEHs placed at a 30° angle. Results indicate that the 3-blade configuration produced the highest voltage (1.79V), 4% and 43% higher than the 4-blade (1.71V) and 5-blade (1.01V) configurations, respectively. This configuration also exhibited maximum deflection and lower frequency vibrations. Increasing blade count led to higher frequency vibrations but reduced deflection and voltage output. The study highlights that fewer blades result in greater deflection and better energy harvesting performance. These findings contribute to ongoing research in PEH systems, offering insights into optimizing energy harvesting from fluctuating wind conditions by balancing deflection amplitude and vibration frequency.

Keywords: Piezoelectric Energy Harvester; PVDF-based energy harvesters; Vibration stability analysis; Renewable energy systems; Energy conversion efficiency

1. Introduction

Energy is essential in technological progress in all fields, namely the manufacturing industry, national defense, medical care, aerospace, agriculture, and many more. Therefore, it is important to provide stable energy to support the sustainability of industries by generating greener electricity. Until now, many studies related to micro-energy conversion have been reported, whose output is an energy harvester. Several studies have been conducted, such as energy harvester rotation systems [1], [2], vibration [3], [4], ocean waves [5], [6], human movement [7], [8] and wind [9], [10]. Wind energy causes vibrations, so it can be harnessed to harvest energy by triboelectric [11], [12], electrostatic [13], [14], electromagnetic [1], [15], and piezoelectric methods [16], [17]. Among the four methods, the piezoelectric energy harvester (PEH) stands out as it can generate compact electrical energy for electronic devices due to its high energy density and can be easily integrated in various system [18].

The piezoelectric energy harvester (PEH) with a cantilever design efficiently converts vibrations in a single direction into electrical energy. Currently, research on cantilever-based piezoelectric energy harvesters primarily focused on device design, development, and performance testing. Kan *et al*. [19] developed a cantilever-based piezoelectric energy harvester featuring a cylindrical end and an integrated piezoelectric element within the pendulum. The results indicated that the length of the elastic pendulum beam, mass, and wind speed significantly influenced the electrical output. Lim *et al.* [20] developed a galloping-based cantilever PEH incorporating a bluff body to amplify aerodynamic oscillations. Their system achieved an output voltage range of 5–12 V under consistent wind speeds of 6 m/s, demonstrating the relationship between airflow intensity and electrical generation in galloping-induced vibration systems. In the study of Sun *et al*. [21], the D-type bluff body can produce an electrical voltage of up to 4.5 Volts at a wind speed of 9 m/s. Gamayel & Sunardi [17] study the effect of variational area of impact of the PEH substrate so that it obtained a maximum output voltage of 12 Volts at a wind speed of 8 m/s. The results of the above study have contributed to the development of cantilever-based PEH, but wind sources with fluctuating speeds cause vibrations to become unstable. As a result, PEH's performance has not been maximized because it captures unstable vibrations during operation.

Recent advancements in materials science, mechanical design, and wind energy conversion technologies offer promising avenues for addressing the challenges of unstable vibrations in PEH systems. By optimizing key parameters such as windmill blade geometry, rotation speed, and collision dynamics, it may be possible to achieve more consistent and reliable energy generation. Although in some cases, study may be conducted with model such as computer simulation—which alloy various structure, geometry, and condition—the experimental investigation still needs to be addressed to improve our understanding in different aspects of PEH, thus allows us to improve the performance of PEH, especially in generating a stable electricity by stabilizing the vibration generated from the system. Despite notable advancements in the design and performance of cantilever PEHs, a critical gap persists in the comprehensive understanding of how unstable vibrations—driven by fluctuating wind speeds—detrimentally impact energy harvesting efficiency. Prior research has largely focused on achieving high output voltages under relatively stable conditions, often neglecting the analysis of deflection patterns that serve as indicators of vibrational stability. This study aims to bridge this gap by systematically investigating the effects of various windmill blade configurations on both the electrical voltage and deflection responses of PEH systems.

Based on the above background, it is essential to carry out primary research on PEH installations to achieve relatively stable vibrations, thereby maximizing the performance of the PEH. The stability of these vibrations can be examined through the analysis of the resulting deflection patterns, which serve as indicators of consistent energy generation and system reliability. In this study, wind causes the windmill to spin, which then leads to contact between the blades and a device called a piezoelectric energy harvester (PEH). This contact creates vibrations in the PEH. The number of blades on the windmill affects how steady these vibrations are. The main goal of this research is to measure the electrical energy produced and the movement caused by different types of windmill blades when they collide with the PEH.

2. Method

This study follows a systematic process that begins with reviewing current research to identify gaps in piezoelectric energy harvesting. Next, specialized equipment and sensors are developed and calibrated for accurate measurement. Custom windmill blades and cantilever structures are then fabricated using 3D printing to create realistic test conditions. Controlled experiments expose these devices to wind, generating vibrations that is impacting the piezoelectric and corresponding electrical outputs that are recorded and carefully checked for accuracy. Finally, the validated data is analyzed to understand the relationship between mechanical deflections and electrical performance, and the findings are reported in detail. The detailed research flowchart is depicted in **Figure 1**.

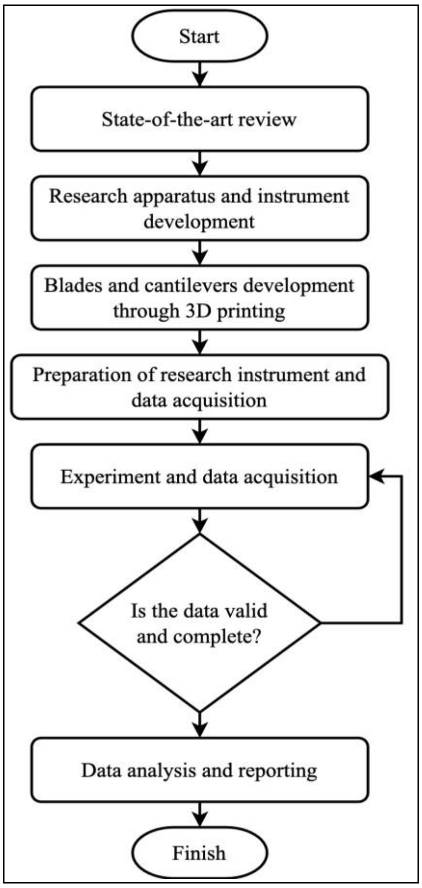

Figure 1. Lithium-ion battery data extraction results testing

The component of PEH consists of Piezoelectric polymer (PVDF-Polyvinylidene Fluoride) material and substrate. PVDF is a semi-crystalline polymer made up of various crystal forms (δ, α, β, γ, and ε), with the β phase crystal structure demonstrating the most effective piezoelectric response [22]. PVDF is a lightweight and flexible Piezoelectric material which shows a large deformation response and a wide range of vibration frequencies [23]. The flexibility of PVDF film can resist micro structural damage after a long-time exposure to mechanical motion [24]. In contrast to rigid and brittle piezoelectric ceramics, which are unsuitable for processing and flexible electronics, PVDF and its copolymers have gained significant attention in research due to their exceptional flexibility and ease of fabrication [25]. PVDF possesses numerous remarkable properties, such as a high dielectric constant, exceptional strength, superior thermal and chemical stability, and resistance to nuclear radiation and UV exposure [26]. The dimensions of PVDF used in this experiment are a length of 100 mm, a width of 50 mm, and a thickness of 110 µm. Detailed technical specifications are shown in **Table 1**. The material of the rectangular substrate is polypropylene, which includes flexible polymers with excellent anti-fatigue performance [17]. The substrate has dimensions of 115 mm x 60 mm x 1 mm in length, width, and thickness, respectively.

Table 1. Crystallinity of CMC film

No	Properties	Values
1	Length	100 mm
2	Width	50 mm
3	Thickness	100 µm
4	Piezoelectric Strain Coefficient (d_{31})	> 28 pC/N
5	Piezoelectric Stress Coefficient (d_{33})	~30 pC/N
6	Dielectric Constant	~12.5
7	Modulus	> 2000 MPa

Two PVDFs, each wrapped in substrate, are arranged side by side at an angle of 30°. Two PEHs are placed near a windmill with an impact area of 5 mm between the blade and PEH. The objective is to subject the deflection that can generate voltage because of the collision between them. Various amount of blade namely 3 blades, 4 blades, and 5 blades, were set up in front of two PEH with an angle of 30°. The details are depicted in **Figure 2**. This configuration allows us to identify the optimal number of blades for maximizing voltage amplitude and improving frequency stability. The configuration also considers the speed of rotation of the blades, where the frequency generated from the PEH will be approximately $F = RPM \times n_{blades}$, where F is the frequency in Hz, RPM is the rotational speed in rotation per minute, and n_{blades} is the number of blades.

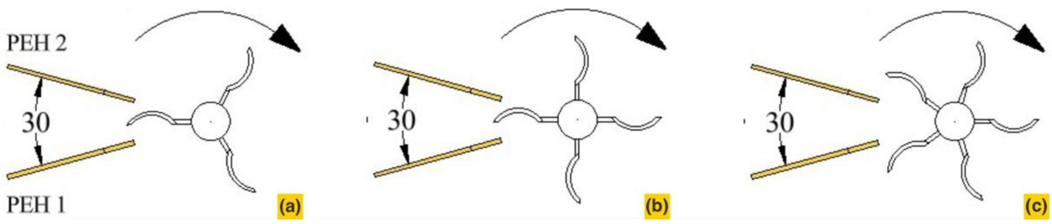

Figure 2. Configuration of blades in micro windmill with different number of: (a) 3 blades; (b) 4 blades; (c) 5 blades

The experimental setup developed from previous studies [16], [17], are described in **Figure 3**. The equipment, including flow rectifiers, micro windmills, and PEH, is placed in wind tunnels with a 250 mm × 250 mm cross-section. A 12-inch blower, delivering a static pressure of 350 Pa and 550 watts of power, generated airflow inside the tunnel. The wind speed was set to 6 m/s. Mini tube pipes were installed in the wind tunnel to stabilize the airflow. A flow rectifier was positioned in front of the micro windmill to direct the wind precisely onto the blades. As the wind caused the micro windmill to spin, the blades struck the PEH, producing a voltage. A video camera captured the blade-PEH collisions until the PEH bent. The video footage was converted into images in JPEG format using "Free Video to JPG Converter" to analyze the PEH's curvature, following a similar approach used in other experiments [27], [28]. Voltage measurements were taken using a data acquisition system (DATAQ DI-245), with a recording duration of 60 seconds at a rate of 25 data points per second.

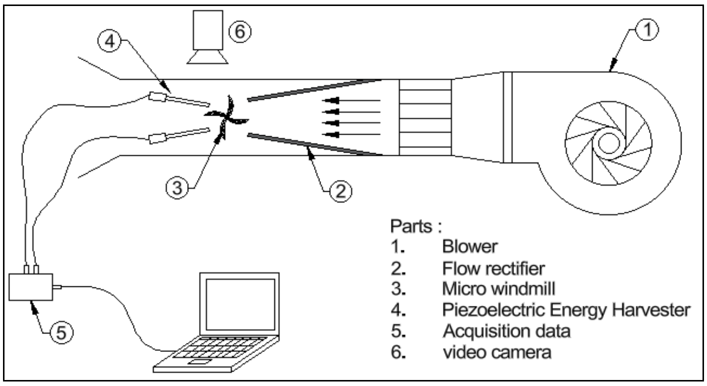

Figure 3. Experimental set-up

3. Result and Discussion

3.1. Experimental Results

The voltage magnitude in PEH 1 and PEH 2 on windmills with varying numbers of blades is depicted in **Figure 4**. A windmill with 3-blades can generate a maximum voltage of 1.79 Volts. The value of 1.71 Volts represents the best voltage a windmill with 4-blades can produce. The 5-blade windmill can generate up to 1.01 Volts at maximum voltage. Based on the number of blades, more blades used to pound the PEH generate a smaller voltage, but higher frequency. This is possible because many blades produce rapid collisions and vibrations, so the deflection is slight. If we look more specifically, the position of PEH (which we call PEH 1 and PEH 2) in the face of windmill collisions affects the voltage produced. Based on **Figure 5**, the ratio of the maximum voltage values of PEH 1 to PEH 2 is 0.54%, 0.38%, and 0.16% respectively. It indicates that PEH 1 has a large deflection when a windmill pounds it first. In contrast to PEH 2, where the deflection that occurs is not large, collisions often occur. The windmill hitting PEH 1 causes deflection until a repetitive deflection is called oscillation. Oscillation has an amplitude value where the more significant the amplitude that occurs, the greater the voltage value produced [29] PEH 2 experiences rapid oscillations with a small amplitude so that the vibrations produced are high. PEH 2 has a position opposite to the direction of rotation of the windmill, so it tends to move back to the starting position with high vibration. This vibration causes a brief deflection, which prevents the PEH position from returning to its original shape in time to avoid a collision between the PEH and the windmill blade [23]. Elevated vibrations have the potential to induce disruptive oscillations, which could lead to initial damage to PEH 2 [9]. Because polypropylene sheets have anti-fatigue properties, PEH is coated with them to prevent damage during oscillation [30].

The effective voltage (V_{rms}) at each number of blades is displayed in **Figure 5a**. The effective voltage at each PEH drops as the number of blades increases. In general, a 3-blade windmill has the highest effective voltage value of 0.69 Volts for PEH 1 and 0.312 Volts for PEH 2. The smallest V_{rms} values occurred in windmills with 5-blade, namely 0.307 Volts for PEH 1 and 0.197 Volts for PEH 2. The number of blades affects the PEH impact pattern and frequency. Collisions are more probable to occur when there are more blades. It elevates the frequency and generates strong vibrations in small deflections. Meanwhile, in **Figure 5b**, the higher the frequency generated, the more blades there are. The relationship between the number of blades and the voltage is the opposite of the relationship between the number of blades and the frequency generated. It is logical and follows the PEH concept, where PEH performance improves if it can experience deflection with a large amplitude so that a high voltage is produced. The value of V_{rms} and frequency indicates the quality and stability of the voltage generated from the piezoelectric, where in this study higher Vrms often means higher power and lower frequency indicate more stable behavior.

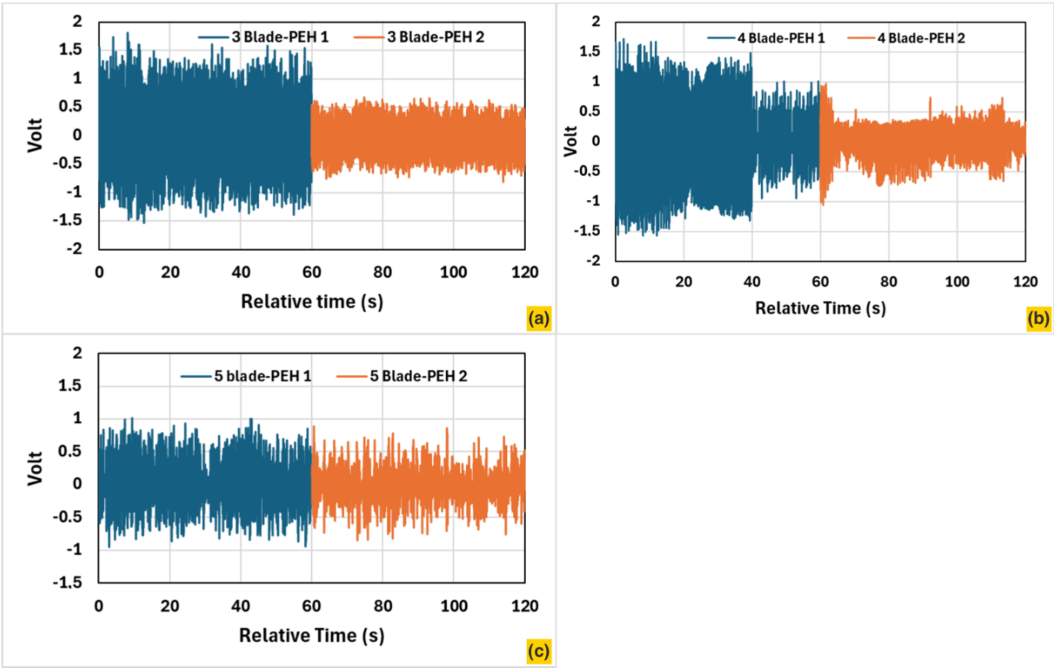

Figure 4. Voltage generated from the experiment with different number of blades: (a) 3 blades; (b) 4 blades; (c) 5 blades. Different number of blades affect the level of average voltage generated from PEH, where less fan produces a more stable and higher voltage

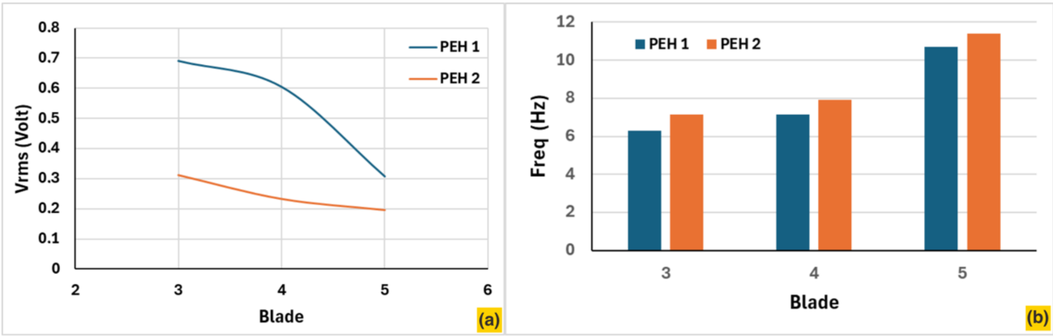

Figure 5. Experimental results of (a) V_{rms}; (b) Frequency of PEH

The collision and vibration mechanisms that PEH 1 and PEH 2 cause are described in **Figure 6**. The first windmill blade in **Figure 6a** is positioned to contact PEH 2 after releasing the vibrating PEH 1, whereas the second blade will strike PEH 1. In **Figure 6b**, PEH 1 is still curved—not entirely straight—and getting ready to take impact from a second blade. Moreover, PEH 2 oscillates downward after the windmill's first blade departs. Due to the windmill's determination, PEH 2's oscillation slows down in **Figure 6c** and moves upward with PEH 1. Due to their close proximity, the second blade punched PEH 1 and PEH 2 virtually simultaneously in this session. This sequence explains why the vibration frequency generated by PEH 2 is greater than that of PEH 1. There is a more significant deflection in PEH 1 compared to PEH 2 because the windmill collision process takes longer there. PEH 2, with a shorter impact time, experiences more vibrations than PEH 1. In addition, the range of PEH 1 deflection can be maximized, while the deflection in PEH 2 is limited due to the meeting with PEH 1 in **Figure 6c**. Because of the significant deflection and minimal vibration, PEH 1 produces a comparatively higher voltage than PEH 2.

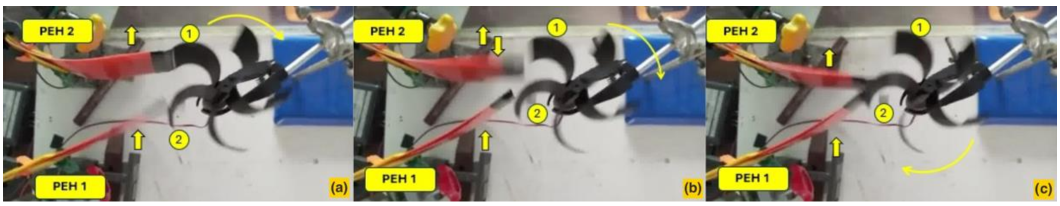

Figure 6. Sequence of impact with different of blade and PEH: (a) 2 blades and two PEHs; (b) vibration in PEH 2; (c) 1 blade and two PEHs

According to **Figure 7**, the sequence of collision events has five frames, and each frame has an event length of 0.03 seconds. Consequently, it takes 0.15 seconds to complete one collision cycle. In **Figure 7a**, the first blade approaches PEH 2 and punches PEH 1 at the maximum deflection position. Meanwhile, in **Figure 7b**, the first blade smashes PEH 2 while PEH 1 is still collapsing and returning to its initial position. The point in **Figure 7c** where PEH 2 deflects the most is where the first blade starts to leave it, and the second blade gets ready to pound PEH 1. The second blade in **Figure 7d** begins contacting PEH 1, which has returned to its initial straight position. In line with **Figure 7a**, **Figure 7e** depicts the situation where the second blade pounds PEH 1 at its maximum idle position. Based on the cycle in **Figure 7**, PEH 1 experiences maximum deflection because the impact process occurs when PEH 1 is in the starting perpendicular position. It explains that with a 3-blade, the deflection process can reach its maximum and produce a higher voltage than a 4-blade and a 5-blade.

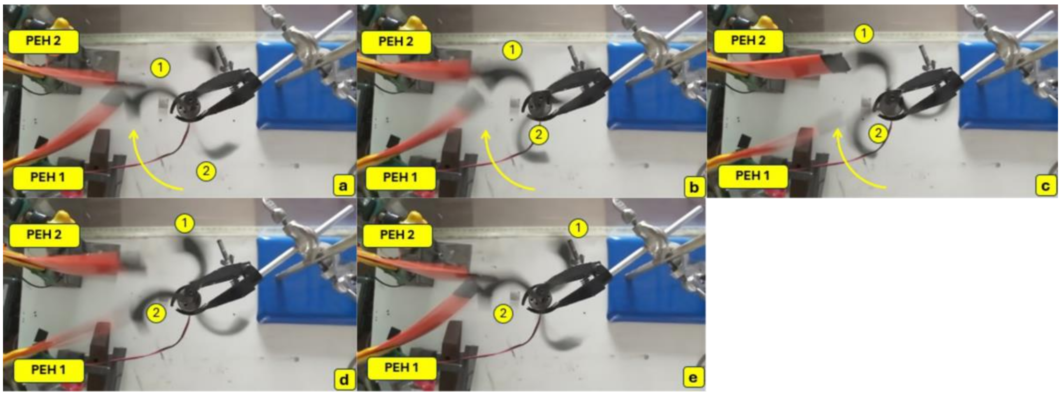

Figure 7. Sequence of collision of 3 blades

Based on **Figure 8**, the duration for one deflection cycle for a 4-blade occurs in 5 frames, i.e., 0.15 seconds; this duration is the same as that for a 3-blade. Looking closer reveals that the second blade of this 4-blade does not crush PEH 1. The second blade observed passing PEH 1 and prepared to pound PEH 2. In **Figure 8d**, the third blade prepares to pound PEH 1, and the second blade prepares to pound PEH2. Based on this event, it was answered that a 4-blade has a higher voltage value than a 5-blade and lower than a 3 blade.

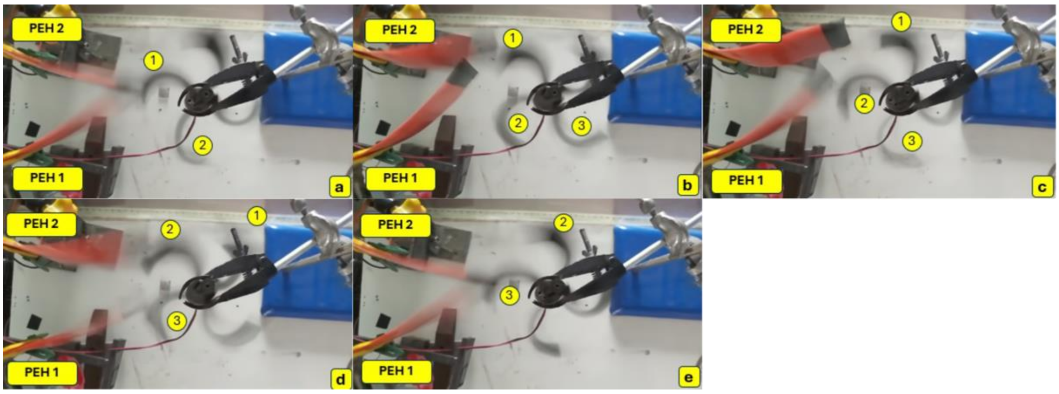

Figure 8. Sequence of collision of 4 blades

3.2. Discussions

The cantilever beam structure consists of a thin piezoelectric layer (or two layers) and a non-piezoelectric layer (usually a conductive metallic layer) fixed at one end to achieve a structure operating in its flexural mode and is the most widely used due to its simple geometry and generation of the maximum amount of stress-strain. **Figure 9** theoretically illustrates the cantilever concept in a wind turbine's power extraction system (PEH), initiated by the impulsive force exerted by the turbine blade. The cantilever system is fixed at one end, allowing the free end to undergo vertical oscillations upon impact. This oscillatory motion, when graphically represented, forms a transverse sinusoidal wave with distinct crests and troughs [31]. According to the equation $y(x,t) = A \sin a$, and upon differentiation, we obtain the equation:

$$Y(x,t) = A \sin\left(2\pi f t + \frac{2\pi x}{\lambda}\right) \tag{1}$$

The formula thus can be used in terms of voltage by the equation:

$$V(t) = V_{max}\ sin\left(2\pi f t + \frac{2\pi x}{\lambda}\right) \tag{2}$$

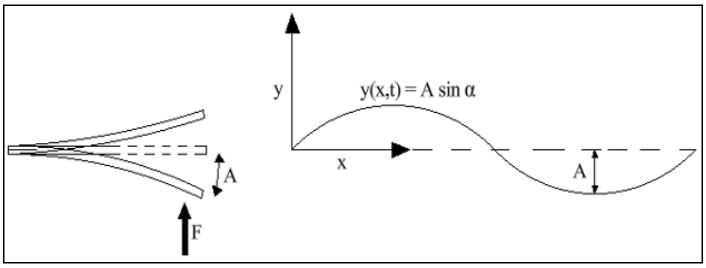

Figure 9. Oscillation of piezoelectric and its relationship to the voltage generated

Using this equation, V_{max} represents the amplitude (≠), meaning that in order to achieve the highest (maximum) voltage, the amplitude must be large, or in other words, the deflection must be significant.

In general, piezoelectric transducers consist of multiple layers of piezoelectric, elastic, conducting, or insulating materials. When an electric potential is applied between the conducting layers, an actuation force is generated in the piezoelectric layers, and the direction of the stress-strain components and the electric field determines the modes of operation (transverse or longitudinal). When modeling a piezoelectric energy harvester, one of the key characteristics that must be represented is the working mode. There are three piezoelectric working modes: Transverse mode (d_{33} mode); Longitudinal mode (d_{31} mode); and Piezotronics mode. In this study, since the motion is oscillatory, the predominant working mode is the transverse mode, where the piezoelectric stress coefficient (d_{33}) plays a significant role. The illustration of the piezoelectric working mode is depicted in **Figure 10**.

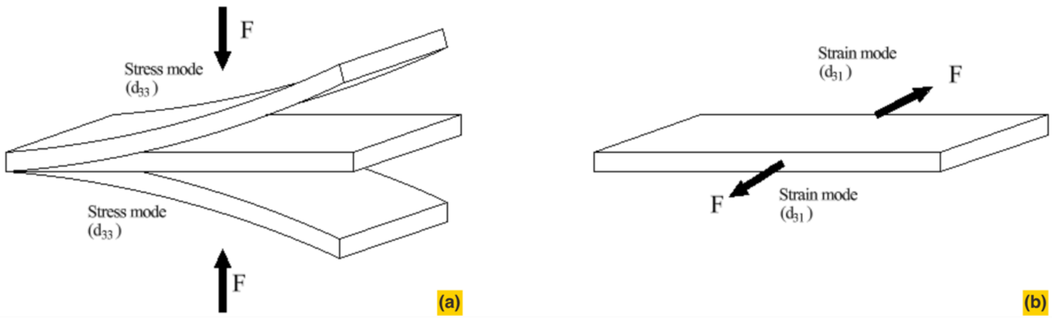

Figure 10. Working mode of piezoelectric

In this study, the experiment is conducted in a limited environment, thus it is not quite right to conclude the reported performances as presented in the Results section into a sole conclusion. In a broader environment, where the wind blows from various directions, it is still necessary to see the effect of even blades in a windmill. An even number of blades in a windmill may possess a symmetry and vibration issue, that is when two blades are positioned directly opposite to each other, leading to alternating lift forces. This event may be excluded in the experiment, since the experiment conducted in this study assumes that the wind blows from a sole source to only one side of the blades, thus reducing—if not entirely passed—the effect of symmetry and vibrational issue due to blades positioned directly opposite to each other. It is worth mentioning that, although the reducing performance due to the symmetry and vibration issue may occur, it is essential to emphasize that, in this study, both frequency and amplitude of voltage are dependent to the number of blades. Both frequency and amplitude have different behavior, where increasing the number of blades will increase the frequency but decrease the amplitude of voltage generated. Similar behavior has been reported in [23].

Furthermore, the relationship between the number of blades and the voltage and frequency generated from the PEHs is simply due to the deflection as a result from the impact between the blades and the piezoelectric. Therefore, if the number of blades increases, the impact speed of blades and piezoelectric also increases. The increased number of impacts per second, and thus higher frequency, limits the piezoelectric material's ability to reach maximum deflection, reducing the generated voltage—that is the voltage amplitude. Therefore, to optimize power generation from the PEH, both voltage and frequency must be balanced. The frequency should not be so high that it restricts full deflection, nor too low, as frequent deflections are needed to produce higher power. However, this scheme only would take effect in the case where a voltage rectifier is connected to the PEH. If there is no voltage rectifier, a smaller frequency is preferred, as it promotes higher voltage amplitude for which it may be more useful in broader application instead of lower voltage.

4. Conclusion

Based on the findings of this study, the performance of piezoelectric energy harvesters (PEHs) is influenced by the number of blades in the windmill and the resulting impact on deflection and vibration. A 3-blade windmill produced the highest voltage and deflection, while increasing the number of blades led to higher frequencies but smaller deflections, which reduced the generated voltage. The study confirmed that maximum energy harvesting occurs with large deflections and minimal vibrations. The PEH 1 exhibited higher deflection and voltage compared to the PEH 2, due to the collision and oscillation sequence. Therefore, the choice of windmill blade configuration significantly affects the efficiency of the PEH system. Future designs should focus on optimizing the number of blades to balance deflection and vibration, thereby maximizing energy output. The insights from this study can be used to optimize the use of piezoelectric energy harvesters (PEH) as an alternative energy harvesting technology across various applications.

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Authors' Declaration

Authors' contributions and responsibilities - Conceived and designed the experiments (A.G, M.Z); Performed the experiments (A.G); Analyzed and interpreted the data (A.G, M.Z); Wrote the original paper (A.G, D.S.W, M.Z); Wrote the revised manuscript (M.Z).

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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