Experimental investigation on voltage performance of piezoelectric energy harvester with various slopes of flow rectifier

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Abstract
In this study, we investigated the PEH performance in a wind tunnel experiment with a 250 mm × 250 mm cross-section. The PEH comprised a piezoelectric bimorph and a rectangular substrate. Wind flow induced by a blower within the tunnel achieves 6, 7, and 8 m/s speeds. A rectifier directed the flow toward the windmill blade for optimal energy generation. Three variation slopes of the flow rectifier were analyzed in terms of output voltage and deflection. The results show that the PEH performance improves as wind speed and the slope angle increase. At an angle of 40° and a speed of 6 m/s, PEH generates a voltage of 5.77 V and increases by 1.2 times at a windspeed of 8 m/s and an angle of 60° (12.67 V). Similar conditions occur in effective voltage (V_{rms}), where the value increases 1.6 times from 2.02 V to 5.33 V. Likewise, the deflection of the PEH increased by 37% from 1.49 cm to 2.05 cm. An Angle of 60° has a shorter narrowed area, thus changing the velocity vector to become faster. Wind speed increases encourage the windmill to rotate faster, which leads to the deflection of PEH and, therefore, generates higher electricity.
Keywords: piezoelectric, energy harvester, rectifier flow, Root Mean Square Voltage

1. Introduction

The demand for alternative clean and renewable energy has increased in various sectors [1]. From domestic use to industrial activity, alternative clean and renewable energy has been encouraged to meet the sustainable development goals [2] since it will result in many benefits in terms of economic advantages to the depreciation of various sources of pollution found in fossil-based energy sources. The lack of utilization of renewable energy, where, in some cases, the use of fossil-based energy for domestic use is dominant, has been posing severe socioeconomic and health concerns. Renewable energy refers to sources derived from natural sources and constantly replenished at a higher rate than consumed, such as sunlight and wind. In 2016, renewable energy accounted for 17.5% of global energy consumption [2,3]. Integrating renewable energy into mainstream energy systems is critical for achieving a more sustainable and resilient energy landscape, contributing to a healthier environment and long-term socioeconomic well-being [4–6]. Therefore, the effort to widen the use of renewable and clean energy must be continued in various sources and technologies.

Furthermore, there are different needs for renewable energy sources on multiple occasions. For instance, in terms of micro- to nano-sized equipment, an independent source of energy harvester can be used, such as solar cells, wind turbines, and piezoelectric. Although the micro- and nano-sized equipment only needs a small amount of energy, its application is still sometimes complicated, and the mentioned alternative energy source is an excellent alternative [7–9].

Energy harvesting can yield both ecological advantages and novel technological prospects. It engenders the creation of environmentally sustainable devices, concurrently diminishing operational expenses and facilitating user-friendly applications. The extraction of energy from the ambient surroundings serves as a viable means to power electronic devices, supplanting conventional battery reliance for future applications.

Noteworthy sources for energy scavenging encompass solar, wind, and vibration energy harvesting. In vibration energy harvesting, three distinct mechanisms, piezoelectric, electrostatic, and electromagnetic, are employed to generate electrical power [10–12]. A piezoelectric energy harvester (PEH) incorporating a piezoelectric actuator to induce a modifiable axial force, facilitating a self-tuning process, has been developed [13]. The envisaged design showcases a simply supported piezoelectric main beam featuring an elongated beam affixed to its roller end and a tip mass to attenuate the resonant frequency [14]. A theoretical framework for optimizing the potential well has been established to enhance the electric energy harvesting efficiency of the bistable piezoelectric energy harvester device [15]. An innovative approach to augment energy harvesting has been proposed, involving water flow-induced vibrations. It is achieved through a tandem arrangement of two piezoelectric energy harvesters (PEHs) aligned with the flowing water's direction, substantiated by simulation modelling and experimental validation [16].

The ongoing research in the field focuses on vibration energy harvesting, specifically exploring advancements in materials and structural design. Utilizing mechanical structural design within the framework of the existing material emerges as a critical research area, aiming to extend the energy harvesting frequency and enhance efficiency, particularly in scenarios involving low-frequency vibrations. Higher energy harvesting is pursued by refining structural parameters or broadening the frequency band using optimization methods [17,18]. Researchers and institutions commonly design energy harvesters with bistable and multistable states to optimize performance. Multistable energy harvesters featuring multiple potential wells prove advantageous when ambient vibrations are sufficient to drive the oscillator beyond the potential barrier, resulting in inter-trap motion between potential wells and, consequently, enhanced energy generation [19–22]. This detailed exploration underscores the multifaceted strategies employed in advancing the understanding and application of vibration energy harvesting.

Given that external excitation often falls short of overcoming the potential barrier and is typically characterized by random patterns in natural environments, recent years have witnessed notable advancements in improving the structural aspects of energy harvesters to enhance their performance—a study in refs. [23,24] demonstrated substantial enhancements by introducing a rotating joint mechanism to replace part of the edge in a cantilevered piezoelectric energy harvester. This modification effectively reduced the stiffness and damping coefficient, resulting in a remarkable 670% increase in the output power compared to a piezoelectric energy harvester lacking the embedded rotating mechanism, as validated through experimental verification. Shi *et al.* in 2021 [25] achieved significant gains by adjusting the length of the piezoelectric spring in a designed vibration energy harvester, securing a maximum output power of 5.68 mW. Consequently, the strategic improvement of mechanical structures is a promising avenue for optimizing energy harvesting efficiency. The conversion of low-frequency vibrations into high-speed rotational motion through structural design has gained favour among researchers. Researchers have innovatively employed a rope-spun rotor structure to efficiently harvest random low-frequency vibrations, achieving a notable breakthrough in converting ultra-low-frequency vibrations into high-speed rotational motion [26,27]. Other researchers have also explored altering mechanical structures to enhance energy harvesting efficiency. In a review by Siddique *et al.* [28], the significant improvement of the piezoelectric transducer mechanism has been highlighted, showing potential applications for various applications, such as microelectromechanical systems. These diverse approaches underline the significance of innovative mechanical design in unlocking greater efficiency in energy harvesting systems, including piezoelectric.

In this study, the piezoelectric energy harvester is utilized to generate low-power electricity in a scheme where a piezoelectric is attached to the mini windmill blades, and a wind flow is generated with various speeds through a tunnel which rotates the windmill blades. This rotating movement generates vibration of distinct characteristics. Subsequently, a slop rectifier with multiple angles is placed in such a way to create different vibration characteristics. This setup allows us to study the difference in vibrational traits that impact the piezoelectric, thus generating various voltage and electric currents and finally affecting power generation. Several slope rectifiers with multiple degrees of slope are experimentally investigated, and the results are presented and discussed in detail.

2. Method

In this study, PEH is composed of piezoelectric bimorph and rectangular substrate. A piezoelectric bimorph is used with the following dimensions: 8 cm in length, 3 cm in width, and 3 mm in thickness. Lead zirconate titanate (PZT) material is used in piezoelectric bimorph with specifications in Table 1. Using relatively advanced methods of manufacture, PZT was successfully synthesized with excellent piezoelectric coefficients [29]. PZT is the most widely used piezoelectric material because it has a more considerable stress constant and piezoelectric strain than other materials. PZT is a polycrystalline ferroelectric material with maximum dielectric and electromechanical coupling coefficient values. A rectangular substrate's length, width, and thickness are 10 cm × 6 cm × 1 mm, respectively and is attached to the piezoelectric. The material of the rectangular substrate is polypropylene, which includes flexible polymers with excellent anti-fatigue performance. The impact area between the rectangular substrate and the blade was 5 mm. The details of PEH are described in Fig. 1(a) and Fig. 1(b) illustrate the rotational motion of micro windmill.

Devices, including flow rectifier, micro windmills, and PEH, were situated in wind tunnels measuring 250 mm × 250 mm cross-section as depicted in Figure 2. Wind flow was generated inside the tunnel using a 12-inch blower with a power of 550 W and static pressure of 350 Pa. Mini tube pipes were installed in the wind tunnel to stabilize the wind flow. Before the micro windmill, a flow rectifier was added to accurately concentrate wind flow and strike the blade of the micro windmill. In this study, a flow rectifier was set to slope variations at an angle of 40°, 50°, and 60° and speed variations, including 6 m/s, 7 m/s, and 8 m/s. The micro windmill rotated due to the wind flow, and a voltage was generated while the blades of the micro windmill contacted PEH. Video camera recording starts from the beginning of the collision until the deflection of PEH. Video files are converted into JPG files to see the sequence of collision events between the blade and PEH. The conversion mechanism exhibits similarities with previous studies performed with different objects [30]. An acquisition data system, DATAQ DI-245, captures the voltage measurement, recording 25 data points per second for a measurement duration of 60 seconds.

3. Result and Discussion

Figure 3 describes the generated voltage under various wind speeds and the slope of the flow rectifier. Figure 3a explains that the maximum voltage generated at a speed of 6 m/s at an angle of 40° is 5.77 V, at an angle of 50° is 5.39 V, and at an angle of 60° is 6.84 V. Figure 3b illustrates that at a speed of 7 m/s, an angle of 40° generates a maximum voltage of 5.34 V, an angle of 50° generates 5.56 V, and an angle of 60° generates 0.59 V . Various generated voltages with a speed of 7 m/s are described in Figure 3c with an angle of 40°, 50°, and 60°, which are 7.25 V, 9.92 V, and 12.67 V, respectively. Based on Figure 3, an angle of 60° is the best slope of the flow rectifier that generates voltage in maximum value. The slope of the flow rectifier influences the voltage generated by PEH. A high slope will increase voltages because airflow speed increases when out of the flow rectifier. The airflow will encourage the windmill to rotate, and the blade will collide with the PEH substrate until it deflects. The continuous deflection of PEH generates the voltage in a stable way, where the peak voltage is similar. The frequency during the test varied from about 1 Hz to 4 Hz, where the average frequency was about 1.2 Hz. From the calculation, the value of the natural frequency of PZT piezoelectric with the size of 8 cm × 3 cm with a thickness of 3 mm is around 1.4 Hz.

This means that the power generated from PEH is already near the optimum value but can still be improved significantly by adjusting the frequency response during electricity generation from vibrational movement. Furthermore, a high slope velocity of airflow is increased in the flow direction due to the smaller downstream area [31], allowing the wind flow to be focused on the micro windmill. This principal design is similar to previous studies where the fluid flow causes the rotation of the turbines, which generates electrical power from the piezoelectric nanogenerator (PENG) components [32].

All various slopes of the flow rectifier have similar downstream areas but have different narrowed areas in the wind tunnel. An angle of 40° has longer narrowed areas than 50° and 60°. With a longer narrowed area, the velocity vector changes slowly following the tunnel. Another case is if the airflow is in a short-narrowed area, where the velocity vector changes drastically, so the airflow through the downstream area becomes faster. The entire inlet section's length impacts the rise of wind velocity to the downstream area. Another study [33] states that the wind speed at the throat region can increase if the stream is continuously narrowing and expanding.

Measuring the effective voltage (RMS voltage) as a function of wind speed contributed to evaluating PEH's energy harvesting capabilities. The RMS voltage in various slopes of the rectifier is described in Figure 4. An angle of 60° is the angle that generates the highest RMS at different wind speeds. At wind speed 6 m/s, RMS voltage at an angle of 60° is slightly higher than at the angles of 50° and 40°. A significant difference occurs at a speed of 7 m/s where an angle of 60° has an RMS Voltage of 4.43 V, greater than 30% RMS voltage of 50° (3.06 V), and more significant 50% than an RMS voltage of 40° (2.21 V). In general, all various slopes of the rectifier have an RMS that increases as the wind speed increases.

High wind speed will drive the windmill to rotate quickly. The rotational speed of the windmill will result in a collision between the blade and PEH. The collision leads the PEH beam's frequency resonance to increase. The device's resonance will result in higher deformation and displacement when the external excitation frequency is near the device's inherent frequency [34]. The more frequent collisions occur, the more voltage is generated. Therefore, it causes an angle of 60°, with a higher RMS voltage than 40° and 50°. Nevertheless, The PEH beam has a slight vibration amplitude and cannot efficiently harvest energy at high wind speed when collision frequency reaches a threshold value. It happens when the PEH beam cannot recover its initial shape before the subsequent collision occurs [35].

Deflection occurrences at various slopes of the rectifier and wind speeds are depicted in Figure 5. The most significant deflection appears in Figure 5(i) with the slope of the rectifier at an angle of 60° and wind speed of 8 m/s. Figure 5(i) is related to Figure 3(c), where it is stated that an angle of 60° generates the highest voltage in this experiment. Based on these two Figures, the greater the deflection that occurs, the higher the voltage generated. The deflection behaviour in PEH is subjected to harmonic base excitation [36]. Kinetic energy is converted to electrical energy in the PEH installation due to the deflection of the PZT material. Kinetic energy repeatedly arises due to the rotational motion of the windmill, which causes a collision between the windmill's blade and the PEH substrate. Meanwhile, the air flowing through the flow rectifier can generate the rotational motion of the windmill.

Based on Figure 6, wind speed and the rectifier's slope correlate with the displacement magnitude. At each wind speed tested, displacement increases with the slope of the rectifier increasing. The most significant displacement occurs at the largest slope of the rectifier at an angle of 60° and the largest wind speed of 8 m/s. The significant deflection problem of a cantilever beam subjected to different forces has been used as the fundamental model for many structural designs, such as soft, smart material-based, compliant mechanisms and cable-driven flexible structures [37]. The difference in force in the cantilever beam is caused by the difference in wind speed that flows through the rectifier to hit the windmill's blade and then create rotational motion for the windmill. Therefore, wind speed and the rectifier's slope influence deflection and displacement, which have implications for generating voltage in electrical energy.

4. Conclusion

This investigation has effectively formulated a straightforward experimental protocol for examining the performance of a piezoelectric energy harvester by utilizing wind flow and a slope rectifier. The vibrational motion of the piezoelectric material produces an alternating current with distinctive characteristics depending on the wind speed and the slope rectifier's degree of inclination. A noteworthy observation is the direct correlation between the angle degree of the slope and the Root Mean Square (RMS) Voltage generated by the piezoelectric energy harvester. This phenomenon is attributed to the variances in vibrational characteristics induced by the wind flow rate and the alterations in its direction, influenced by the placement of the slope rectifier preceding the windmill blades attached to the piezoelectric material. This correlation aligns with the amplitude of displacement exhibited by the piezoelectric material across varying wind speeds and degrees of slope rectification. The proposed alternative approach to electricity generation utilizing piezoelectric materials has been thoroughly investigated, contributing to the enrichment of the role of piezoelectric as an energy harvester.

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Conflict of Interest

The authors declare no conflict of interest.

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List of Captions

Figure 1. (a) Dimension of PEH and Micro Windmill, (b) Illustration rotational motion of micro windmill.

Figure 2. Experimental setup.

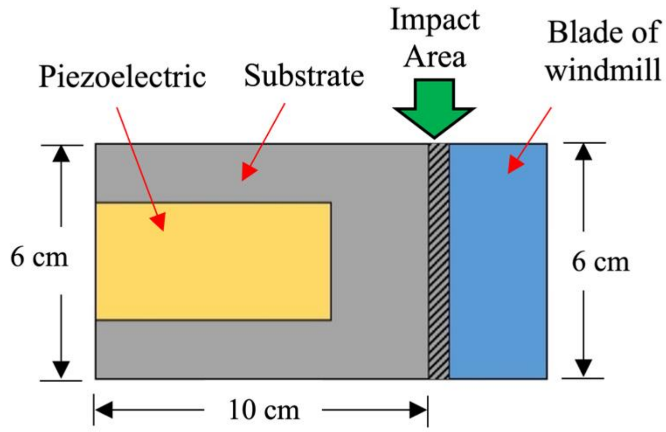
Figure 3. Voltage in various degrees with the wind speed (a) 6 m/s, (b) 7 m/s, (c) 8 m/s.

Figure 4. RMS Voltage in various degrees.

Figure 5. Deflection in various wind speed and slope of the rectifier, (a) 6 m/s, 40°; (b) 6 m/s, 50°; (c) 6 m/s, 60°; (d) 7 m/s, 40°; (e) 7 m/s, 50°; (f) 7 m/s, 60°; (g) 8 m/s, 40°; (h) 8 m/s, 50°; (i) 8 m/s, 60°.

Figure 6. Displacement in various wind speed and slope of rectifier.

Table 1. Specification of PZT material.



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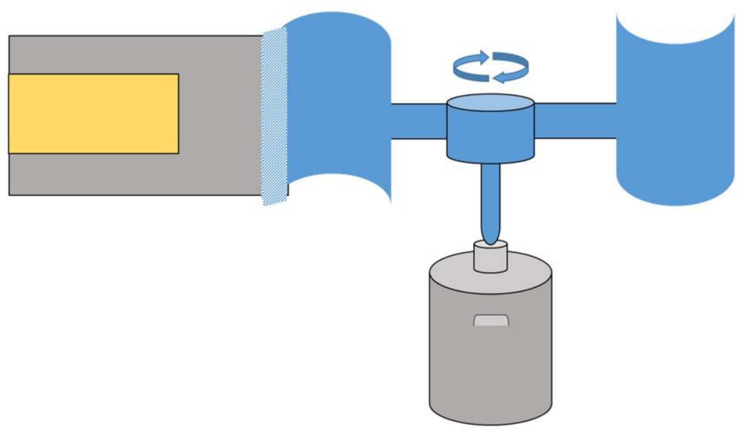

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Figure 1. (a) Dimension of PEH and micro windmill, (b) illustration rotational motion of micro windmill.

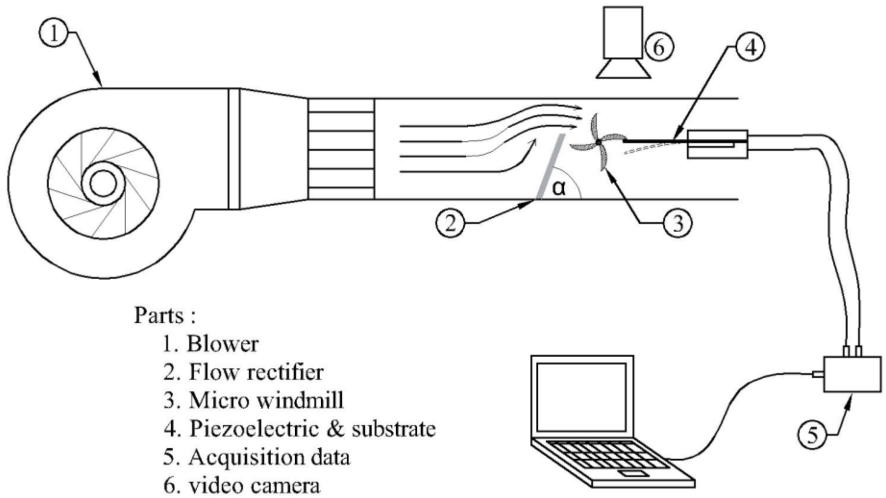
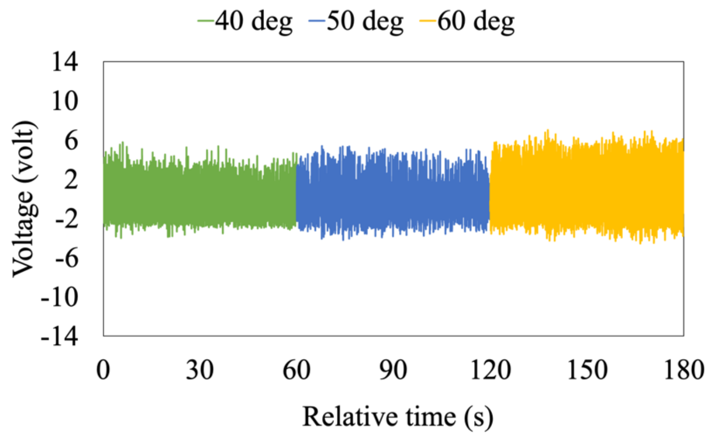


Figure 2. Experimental setup.



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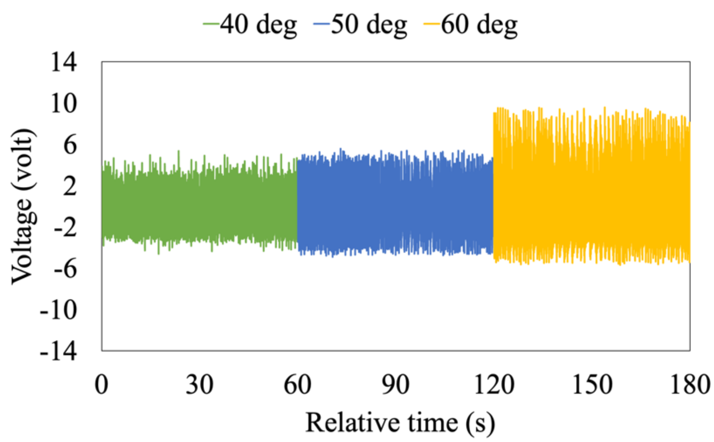

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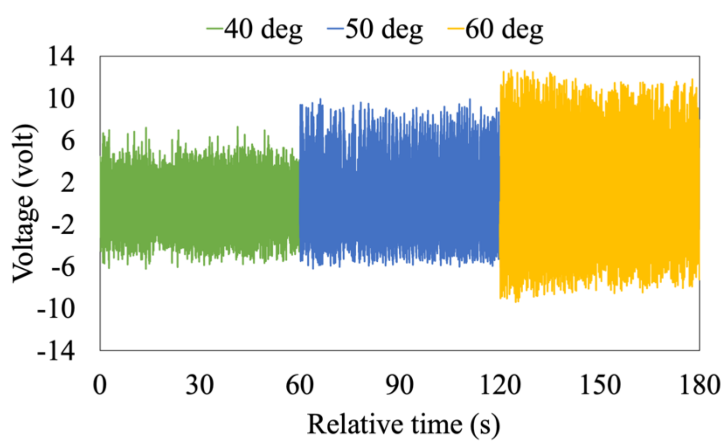

(c)

Figure 3. Voltage in various degrees with the wind speed (a) 6 m/s, (b) 7 m/s, (c) 8 m/s.

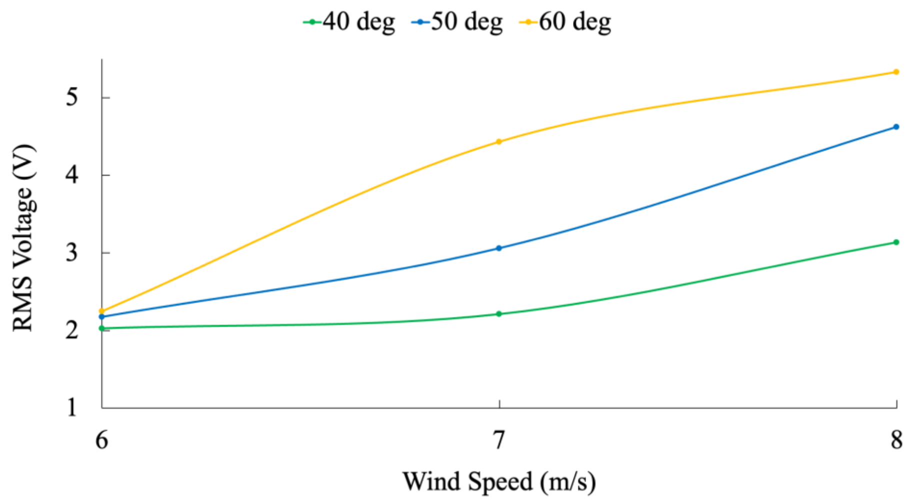

Figure 4. RMS Voltage in various degrees.

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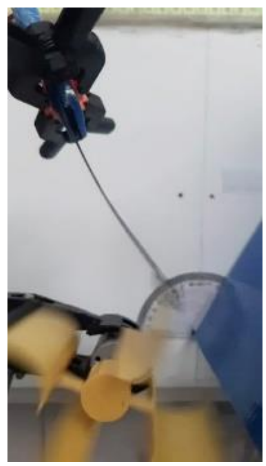

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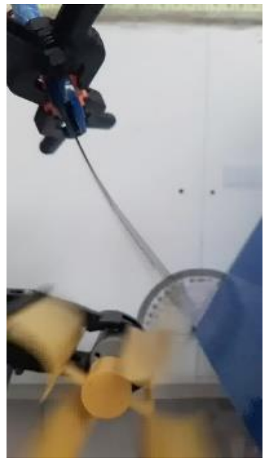
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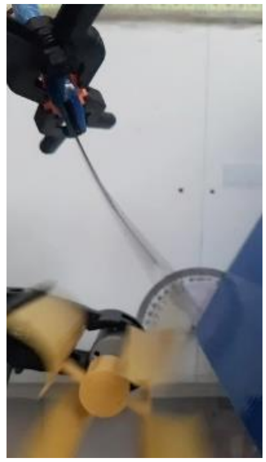

(g)

(h)

(i)

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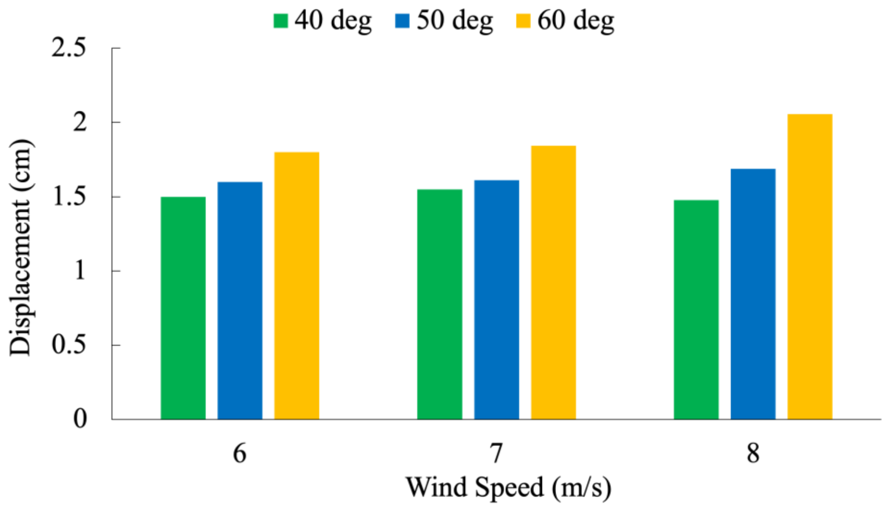

Figure 6. Displacement in various wind speed and slope of rectifier.

Table 1. Specification of PZT material.

No.	Properties	Values
1	Density (kg/m^3)	7500
2	Young modulus (GPa)	56
3	Poisson's Ratio	0.36
4	Piezoelectric Strain Coefficient ($d31$) (C/N)	$-186\ x\ 10^{-12}$
5	Permittivity at constant stress ($\varepsilon_{11}/\varepsilon_0$)	3130
6	Permittivity at constant strain ($\varepsilon_{11}/\varepsilon_0$)	3400

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