Performance of piezoelectric energy harvesters at various angles

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ABSTRACT

Piezoelectric materials are capable of generating electricity in response to mechanical strain, making them suitable for energy harvesting applications. Piezoelectric energy harvesters (PEHs) are promising alternatives for renewable energy generation, particularly because mechanical strain can be induced in various ways, including utilizing wind flows. This study investigates the performance of a PEH integrated with a laboratory-scale wind-driven micro-windmill. The experiment is carried out by rotating blades of the windmill intermittently; thus, it contacts the PEH, inducing oscillatory motion and generating strain, which finally produces electricity. The configuration angle is varied with 30°, 45°, and 60° to produce variation of power output analyzed in this study. The results demonstrate that a lower configuration angle, specifically 30°, produces the highest voltage near 1.4 V. This is due to the alignment of the applied force with the natural bending direction of the cantilever, resulting in greater induced strain and increased voltage output. Conversely, increasing the configuration angle reduces the effectiveness of force induced to PEH, diminishing strain induction and electrical generation, which only about 1.2 V. The finding of this study can potentially contribute to advance the design and optimization of PEHs for renewable energy applications, particularly in powering microelectronic devices.

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1. INTRODUCTION

The rapid development of microelectronics technology has contributed to the arrival of several low-power electronic devices, including wireless network nodes. These devices often rely on portable and long-lasting power sources to function effectively in diverse environments. Nevertheless, most electronic devices rely on chemical batteries, which significantly increase maintenance costs [1]. Therefore, finding a sustainable energy alternative to replace batteries with electronic devices is a promising approach.

The potential solution that offers sustainability is harvesting energy from the surrounding environment. Based on output energy, energy harvesting is divided into two powers, namely high power and low power. High-power energy harvesting includes methods such as solar and wind energy conversion [2]. Low-power energy harvesting includes methods such as mechanical vibration and acoustic energy conversion using piezoelectric technology [3], [4]. Sensors are the implementations of energy harvesting in recent years that have a low-power energy output. Nowadays, more experiments use piezoelectric due to their small size, simple handling, and good energy density [5]–[8]. A common device for generating mechanical energy into electrical power is a simple linear cantilever beam with a piezoelectric patch. The cantilever construction is the most popular method in piezoelectric energy harvesting applications due to its simplicity.

A cantilever system for a piezoelectric energy harvester (PEH) consists of a flexible beam fixed at one end and free at the other, often integrated with a piezoelectric material. When subjected to external vibrations or mechanical forces, the cantilever bends, generating strain in the piezoelectric layer. An electric charge is generated from this strain, enables mechanical energy to get transformed into electrical energy. The capabilities of energy conversion, high sensitivity in low-frequency vibration, and simple set up are considered the cantilever systems are widely used in energy harvesters. Research on PEH with cantilever system has developed well from year to year. Three ratios (1:1; 1:2; 1:3) between micro-windmill and substrate has been studied [9]. Results show that the highest voltage is 12.67 volts for the 1:1 ratio and wind speed 8 m/s. Liu *et al.* [10] study the effect of stiffness, thickness and substrate material in piezoelectric with macro fiber composite (MFC) material. The aluminium substrate was attached to MFC-2807 with wind speed of 7.5 m/s and generate maximum peak-to-peak open-circuit voltage of 82 V. According to the results and discussion, substrate, stiffness, and thickness are crucial for energy harvesting efficiency. When researchers made modifications to the cantilever, the electromechanical coupling coefficient increased six-time with the resulting power up three-time compared to conventional designs [11]. Izadgoshasb *et al.* [12] observed energy harvesting in human motion where the addition of piezoelectric patches placed at the ends of cantilever beams. Results show that PEH produces maximum power output when the human foot is oriented at a 70° angle relative to PEH system. PEH with tensile mode cantilever consist of two segment cantilever beam that connect with polyvinylidene fluoride (PVDF) film is proposed [13]. The design demonstrates that voltage output will increase when the length of the elastic beam is added. Additionally, voltage output can increase with the addition of mass to the cantilever tip. Miyajima and Yamada [14], suggest a way to develop PEH with enhancing their manufacturing feasibility. A topological approach is developed and generates solutions that meet the requirement for low output voltage, substrate, and the cross-sectional shape. Besides that, integration beams with piezoelectric patches are practical and effective convenient method for energy harvesting [15], [16].

Although PEH has been widely studied by many researchers due to their excellent advantages, the role of slope positioning in its performance under impact/collision conditions has not been examined. The main point to study slope positioning is understanding in energy transfer and performance of PEH. The energy transfer is visible in capturing collision image and related with generating output voltage. The slope location also presents stress distribution and deformation that leads to better output voltage. Investigating slope location could lead to a novel design approach for multi-directional energy harvesting using PEH.

2. METHOD

PEH in this study consist of substrate and PVDF as piezoelectric material. Several crystal forms become constituents in PVDF such as δ, α, β, γ, and ε, where the β phase structure providing the strongest piezoelectric response [17]. Physically, PVDF is both flexible and lightweight, exhibit significant deformation and enabling for a range of vibration frequencies [18]. The flexibility of PVDF film led to resist extensive mechanical motion without sustaining microstructural destruction [19]. As against rigid and brittle piezoelectric ceramics, which are inappropriate for flexible electronic applications and difficult to manufacture, PVDF are highly valued in research due to their flexibility and simple fabrication processes [20]. Additionally, PVDF stands out for its high dielectric constant, excellent strength, and resistance to thermal, chemical, nuclear, and ultraviolet (UV)-induced degradation [21]. PVDF is capable of generate output voltage in natural phenomenon like raindrop and wind [22]. The PVDF used in this experiment measures 100 mm in length, 50 mm in width, and 110 µm in thickness. The rectangular substrate is made of polypropylene, with dimensions of 115 mm in length, 60 mm in width, and 1 mm in thickness. Detailed specifications are presented in Table 1 and illustrated in Figure 1. Two PVDFs, each wrapped in substrate, are arranged side by side at various angles namely 30°, 45°, and 60°. Two PEHs are placed near a 3-blades windmill with an impact area of 5 mm between blade and PEH. The objective is to expose the deflection that can generate voltage because of the collision between them. Figure 2 depicts detailed illustration of the blade and PEH-1 and PEH-2 configurations with different settings of Figures 2(a) 30°, (b) 45°, and (c) 60°.

Table 1. Specification of PVDF material

No.	Properties	Values
1	Length	100 mm
2	Width	50 mm
3	Thickness	110 μm
4	Piezoelectric strain coefficient (d31)	>28 pC/N
5	Piezoelectric stress coefficient (d33)	~30 pC/N
6	Dielectric constant	~12.5
7	Modulus	>2000 MPa

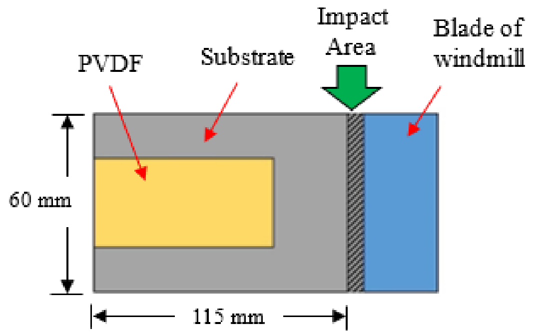


Figure 1. Illustration of PEH with PVDF and substrate

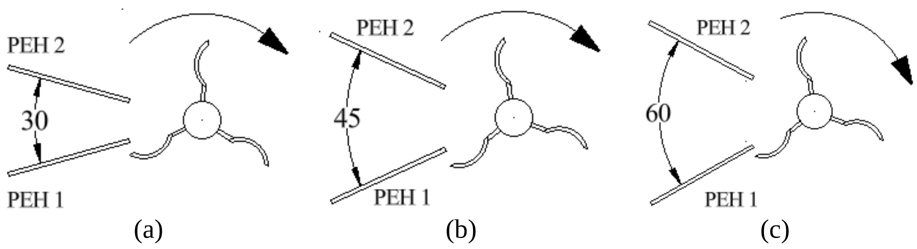


Figure 2. Various angles between PEH 1 and PEH 2: (a) 30°, (b) 45°, and (c) 60°

Based on the previous studies by Gamayel *et al*. [23] the experimental setup shown in Figure 3 was designed to include flow rectifiers, micro windmills, and a PEH within a wind tunnel of 250×250 mm cross-section. Airflow was generated by a 12-inch blower operating at 350 Pa static pressure and 550 Watts of power, maintaining a wind speed of 6 m/s. Mini tube pipes stabilized the airflow, and a flow rectifier ensured precise wind direction onto the micro windmill blades. The spinning blades struck the PEH, generating voltage, while a video camera captured these interactions until the PEH deflected. The recorded footage was converted into JPEG images for curvature analysis using "Free Video to JPG Converter." Voltage measurement using a DATAQ DI-245 data acquisition system, with 25 data points recorded per second over a 60-second period. The combination of airflow stabilization and mechanical interaction is carried out in experimental installations as a manifestation of effectively real-world energy harvesting. To indicate the energy transfer consistently in PEH, micro-windmill and flow rectifier use in this installation. Furthermore, the behavior of PEH during deflection was captured in video analysis, enable to correlate between mechanical deformation and electrical output. Systematic data acquisition allows precise assessment of the voltage output and its variability under several operational conditions, ensuring the system is stable for testing piezoelectric energy harvesting in dynamic conditions.

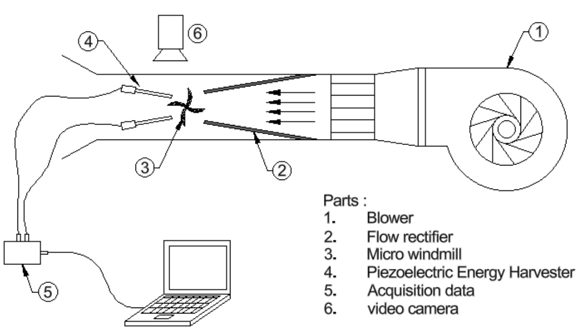
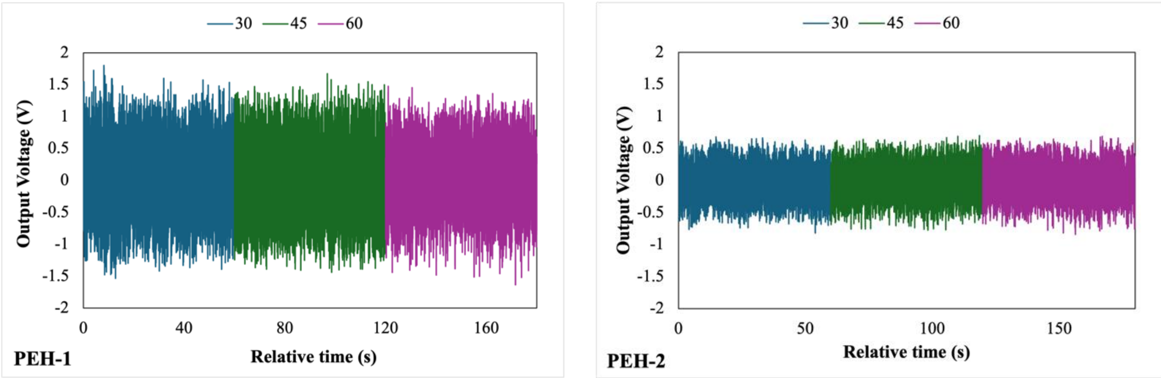


Figure 3. Experimental set-up

3. RESULTS AND DISCUSSION

Figure 4 shows correlation between the output voltage (V) with relative time (s) for Figure 4(a) PEH1 and Figure 4(b) PEH2 at three different angles namely 30°, 45°, and 60°. For both PEH, the output voltage oscillates toward zero periodically, reflecting the alternative current (AC) attributes of the voltage. Based on voltage amplitude in PEH1, it decreases as the angle increases, wherein the angle of 30° the amplitude is highest and the lowest at 60°. In contrast, PEH2 exhibits almost a similar voltage amplitude at three various angles, with only slight variation. This indicates that angle adjustment has a greater impact on PEH1's performance, while PEH2 generates a more reliable output despite the angle variation. The damping characteristics and resonance frequency are the important factors that affect performance of PEH1 and PEH2. PEH1 is more efficient at converting mechanical energy to electrical energy by resonating better at smaller angles, while PEH2 may have a broader frequency response, allowing more stable output voltage. Several factors can influence the behavior of PEH in response to angular variations i.e., their design, material properties, and mechanical configuration [24], [25]. If PEH1 and PEH2 have similar material, then the determining factor is design and mechanical configuration. In this scenario, the applied force becomes a critical factor, along with other considerations. The strain on piezoelectric materials can vary depending on how the harvesters are mounted and whether the force is applied as a concentrated load or distributed evenly. PEH1 may be more susceptible to stress variations caused by angular changes, while PEH2 could maintain steady performance through optimized mounting.



(a) (b)

Figure 4. The output voltage in various angles: 30°, 45°, and 60° for (a) PEH-1 and (b) PEH-2

The cantilever system is designed to convert mechanical motion or vibrations into electrical energy via strain induced in the piezoelectric material. The cantilever beam can provide greater stress and strain with less ambient vibrational force since it has a lower resonance frequency than other configurations. The angle of the system determines effectively the applied force, or vibration generates bending or flexural strain. At smaller angles (e.g., 30°), the force may be aligned more favorably with the cantilever's natural bending direction, leading to higher strain and, consequently, higher voltage output for PEH1. As the angle increases, the force becomes less effective in inducing strain, reducing the output voltage. The cantilever system of PEH1 appears to be optimized for a specific range of angles (likely smaller ones), where the mechanical energy transfer is most efficient. The strain generated in the piezoelectric material decreases significantly as the angle increases, reducing the voltage amplitude. This indicates that the cantilever system in PEH1 has a high sensitivity to angular changes, where its mechanical response will decrease rapidly when the angle is outside of its optimal range. The cantilever system in PEH2 exhibits relatively consistent performance at various angles, indicating that the design is angle independent. This can be due to a uniform force distribution mechanism that ensures strain generation remains relatively unaffected by angular changes. It can also imply that the cantilever system in PEH2 is designed to adapt to a wider range of angles and accommodate variations in applied forces. The potential to utilize a wider range of angles offers benefits for various applications of PEH, including integration with wind turbines that share a similar design to our experimental setup. However, the relatively low power output limits its feasibility for industrial-scale applications.

V_{rms} or roots mean square voltage is the effective output voltage generated by a PEH when converting mechanical vibrations into electrical current. V_{rms} is crucial for evaluate the PEH's output voltage due to the information of energy that can harvest and used in powering electronic device [26]. PEH may achieve improved effectiveness and reliability by focusing on increasing V_{rms} through mechanical, material, and circuit improvements. Figure 5 exhibits the V_{rms} output of PEH1 and PEH2 at three different angles (30°, 45°, and 60°). PEH1 generates V_{rms} with higher values than PEH2 at all angles, but the values tend to decrease as the angles increase. Based on this, PEH1 has better performance in output voltage when operating at small angles due to good force distribution in the cantilever structure. However, PEH1's performance is more sensitive to angular changes. Overall, PEH2 is less efficient and has no effect on angle variation. The greatest possibility is that the impact of the windmill in the cantilever position results in a centralized stress distribution.

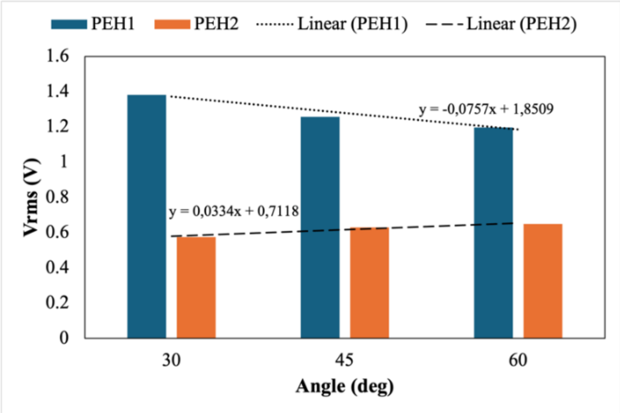
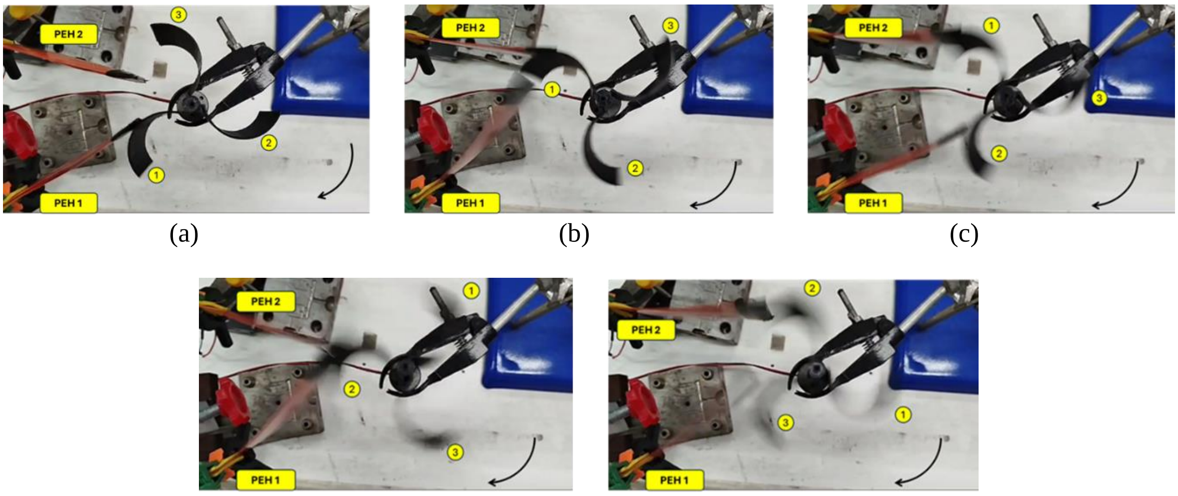


Figure 5. The effective voltage (V_{rms}) at various angle with its linear regression estimation

According to Figure 5, The linear equations describe how the V_{rms} (output voltage) changes with respect to the angle for PEH1 and PEH2. Each equation provides insight into the relationship between the angle (x) and the voltage (y). PEH1 has slope negative (-0.0757), indicate that the voltage output decreases as the angle increases. Specifically, for every 1° increase in angle, the V_{rms} decrease by approximately 0.0757 V. This shows that PEH1's performance is highly sensitive to angular changes. PEH1 would produce 1.8509 V at zero angles, assuming the linear relationship holds. The declining trend in PEH1 suggests that its structural design or the way force is applied becomes less effective at larger angles, reducing its ability to generate voltage. In linier equation of PEH2, the positive slope indicates that the voltage output slightly increases as the angle increases. There is a 0.0334 V rise in the V_{rms} for every 1° angle increase. According to this, PEH2 performs slightly better at bigger angles, despite an overall slower rate of growth than PEH1's performs. The upward trend in PEH2 shows that the mechanism transfer of impact force works well along with the increase in angle.

The behavior differences between PEH1 and PEH2 as shown in Figure 5 demonstrate the importance of angular optimization and system design in energy harvester. PEH1 optimizes operate at smaller angles because impact energy is more effectively generated in cantilever systems. In contrast, a slight positive trend observed on PEH2 implies that it is suitable for working over a larger angular input range. The results exhibit the importance to angle adjustment in a multi-element system to balance the performance of each component on the energy harvester, ensure operate efficiently, and maintain reliability in overall system.

Figure 6 illustrates a system with two PEH in angle of 30°. Figure 6(a) depicts the initial stage, where the first blade impacts PEH1, pushing it toward the PEH2 region. Figures 6(b) and (c) show the first blade releasing its thrust on PEH1 while beginning to push PEH2 to achieve maximum deflection. In Figure 6(c), PEH 1 starts returning to its initial position, where it will be impacted by the second blade. Figure 6(d) demonstrates the second blade driving PEH1 to its maximum deflection while preparing to impact PEH2. At this sequence, the position of PEH1 and PEH2 are very close, with PEH1 in maximum deflection and PEH2 return to its initial position. As seen in Figure 6(e), completing collision between the second blade and PEH2, with PEH1 returning to its initial position and ready collision to the third blade. The continuous rotational motion in micro windmill leads the collision with the PEH elements in cantilever system. Each blade generates a periodic force, which cause the PEH1 and PEH2 not to deflect simultaneously and the energy transferred consistently between blade and PEH in dynamic behavior. This mechanism is designed to optimize the energy utilization of the impact event between the blade and the PEH.



(a) (b) (c)

(d) (e)

Figure 6. The PEH collision step with 30° angle configuration: (a) the first blade strikes PEH1 and pushes it toward PEH2, (b) the blade releases thrust on PEH1, (c) the blade pushes PEH2 with maximum deflection, (d) the second blade pushes PEH1 as it approaches PEH2, and (e) the second blade impacts PEH2 as PEH1 returns to its initial position

The positions of PEH1 and PEH2 are important to the energy harvester system's operation. All the components operate in a synchronous system, with one PEH in maximum deflection condition while the other resets to its initial position. The rotational motion in blade causes transferred energy efficiently through the operation system. Angular spacing and collision time of the blades are attributed to the deflection that relates with performance of PEH1 and PEH2. Aligning the blades and PEH positions in this way reduces energy loss and ensures a smooth and stable operational rhythm.

Different transduction mechanisms suit different mechanical spectra [27], since different transduction mechanism have different impact into the piezoelectric, subsequently its mechanical spectra with which finally have different characteristics in generating power. Piezoelectric devices excel in compact form factors and moderate frequencies with high voltage/impedance this setting is dependent to the type of the piezoelectric where natural frequency play crucial factor; electromagnetic (EM) devices favor very low frequencies and larger strokes; triboelectric (TENG) devices provide ultra-high voltage but require careful surface management [28]. Hybrid PEH–EM designs can widen bandwidth and raise power under high- or low-frequency inputs which potentially produce higher power in average. Recent reviews and case studies corroborate these trends, and recent rotational EM work shows that when substantial rotation is available, EM can out-power piezo/TENG for the same volume [29]. However, because the optimal blade–PEH angle and inter-impact interval depend on characteristics of impact and its generated frequency, damping factor, and load matching, tuning the PEH is challenging and remains an open area of research.

Figure 7 exhibits the collision of two PEH in angle of 45^{o} with blade. In Figure 7(a), PEH1 is initially contact with the second blade at the base, while PEH2 is in contact with the first blade at the end. It states that angle 45^{o} is suitable for each blade to interact with PEH at the same time where the sequence of deflection and recovery position take place together. In Figure 7(b), the first blade initiates to separate from PEH2, which in this condition starts to deflection in maximum position. At the same time, the second blade presses on PEH1 in the direction of maximum deflection. This simultaneous action establishes the energy transfer takes place without interruption, keeping the rhythm of operational system. In Figure 7(c), the first blade is totally free and separate from PEH2, which returns to initial position and has reached maximum deflection. Meanwhile, PEH1 continues to be pushed by the second blade, nearing its maximum deflection. At this stage, PEH1 and PEH2 are positioned close together, indicating a moment of overlap in their deflection cycles. This overlap helps maintain continuity in the system's dynamics. In Figure 7(d), the second blade releases PEH1, which is now at its maximum deflection and oscillating, while it begins to push PEH2 towards its maximum deflection. This phase demonstrates the sequential handoff of energy transfer between the blades and PEH elements, ensuring that each component alternates between deflection and resetting. Finally, in Figure 7(e), the positions of PEH1 and PEH2 return to their initial states, as depicted in Figure 7(a). This reset ensures that the system can repeat the process, maintaining its cyclical behavior for sustained operation.

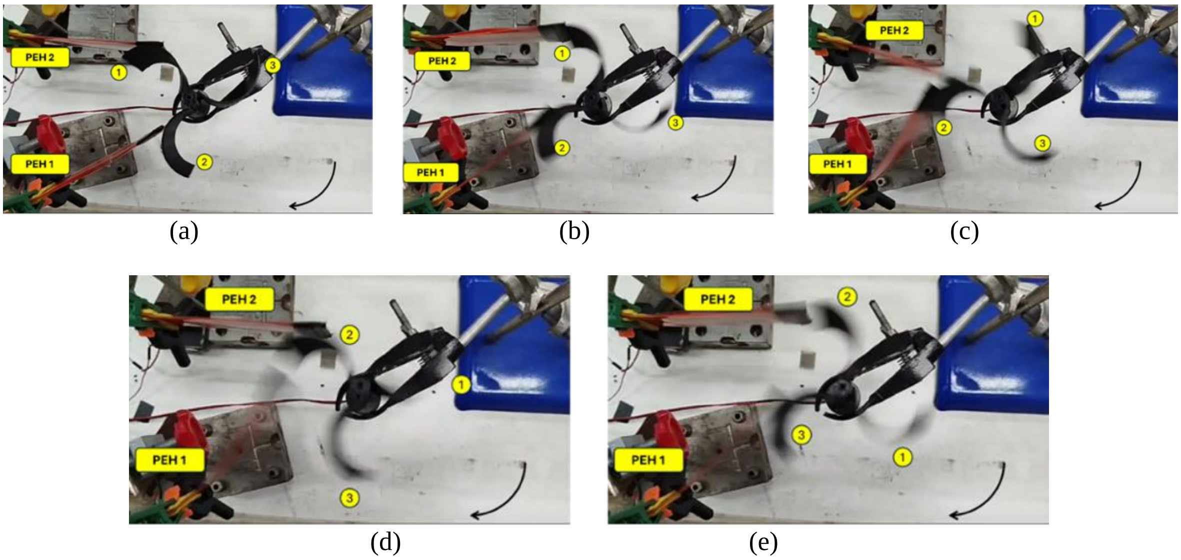


Figure 7. The PEH collision step with a 45° angle configuration: (a) PEH1 contacts the second blade while PEH2 contacts the first blade tip, (b) the first blade begins to detach as PEH2 reaches maximum deflection, (c) the first blade fully releases, (d) the second blade pushes PEH1, and (e) the second blade then pushes PEH2 as both return to their initial positions

Figure 8 illustrates the sequence impact blade to PEH where the angle between PEHs is 60°. Figure 8(a) shows that the blade sticks and starts pushing PEH1 and PEH2. Figures 8(b) and (c) show that the thrust of the first blade has caused a vibration in PEH2 so that there is a resonance while waiting for the impact of the second blade. At this moment it also happens that PEH1 still gets a boost from the 2nd blade to produce maximum deflection. In Figure 8(d) the second blade has left PEH1 and is preparing to punch PEH2. In this condition, PEH2 is vibrating and moving towards the second blade. In Figure 8(e) the second blade preparing to hit PEH2, then PEH1 experiences high vibrations because of the maximum deflection condition after detaching from the second blade and preparing to hit the third blade.

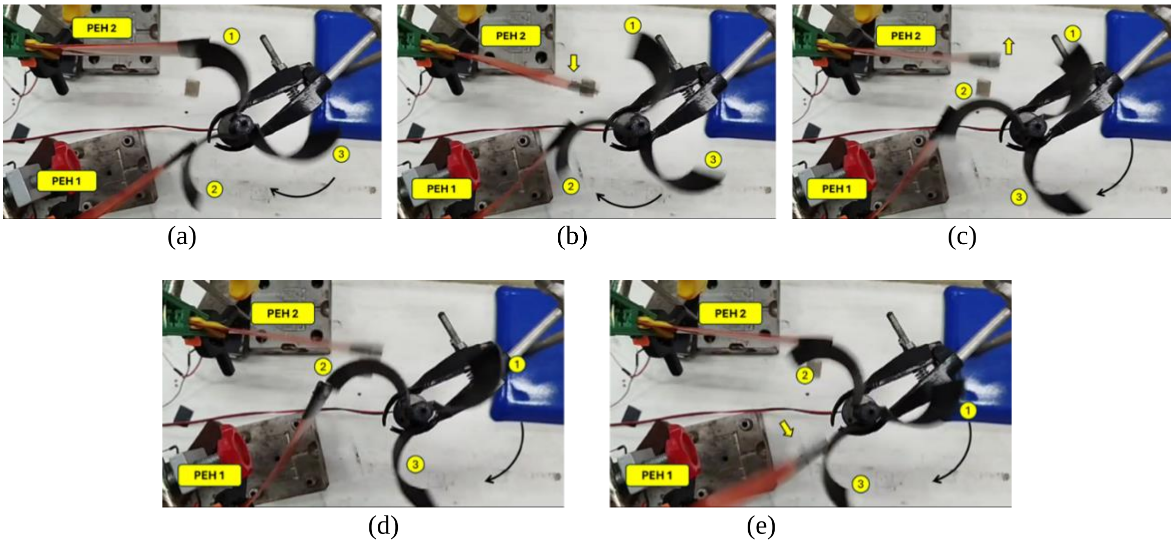


Figure 8. The PEH collision step with 60° angle configuration: (a) the blade contacts and pushes PEH1 and PEH2, (b) thrust from the first blade excites vibrations in PEH2, (c) thrust from the first blade continues as PEH2 vibrates, (d) the second blade detaches from PEH1 and approaches PEH2, and (e) the second blade impacts PEH2 as PEH1 exhibits increased vibration amplitude

The difference between the 30°, 45°, and 60° angles lies in the movement of PEH2 immediately after the impact. At 30° and 45°, PEH2 returns to its starting position after the impact, where it is ready for the next blade to make contact. This behavior indicates a tightly synchronized system, where the deflection caused by the blade's impact is quickly neutralized, preparing PEH2 for the next cycle. This direct return suggests that the energy imparted to PEH2 is quickly dissipated, likely due to system damping or design constraints that prioritize stability and readiness for subsequent interactions. Conversely, at a 60° angle, PEH2 has time to experience self-oscillation, without collision with the blades (as shown in Figures 8(b) and (c). The cantilever system in PEH requires an initial disturbance, such as a force or moment from collision with blade, to initiate oscillations. Once the disturbance is released, the PEH2 can oscillate independently around the equilibrium position. In this moment, PEH2 retain and release energy over a longer duration until a new collision with blade to bring it back in initial position.

PEH behavior at angles of 30° and 45° tends to be better for systems that require controlled and precise energy transfer, because energy generation takes place quickly so that synchronization appears well. Conversely, the behavior allows additional utilization of energy from the oscillatory motion of PEH2 at an angle of 60°, as a result potentially increasing the energy output of the system. The angle variations focus on the influence of angular configuration on the moment of blade interactions with PEH and the mechanical resonance of the system. The collision of the blade and PEH at an angle of 60° creates independent oscillations, resulting in well-controlled vibrations.

Our single-pair blade–PEH results can generally be developed into a ring array of PEHs that can be distributed azimuthally. If coupling among beams is small, array power scales approximately as:

$$P_{array} \approx N\eta_{pm} \cdot P_{device}.$$

where N is the number of cantilevers and $N\eta_{pm}$ the power-management efficiency (rectification, storage), and P_{device} is the power generated per device. In rotational settings, mechanical plucking/impact is a well-established strategy to excite beams near their natural frequency and then let them freely oscillate, boosting energi per-impact, precisely the mechanism we observe at 60° (free oscillation between blade strikes). Recent rotational harvesters use magnetic or mechanical plucks for this reason and report higher output at low rotational speeds, though it depends on the type of the PEH being utilized. These trends support scaling our 60° mode into multi-PEH rings on shafts, ventilation ducts, or low-speed wind auxiliaries intended to power embedded sensors and low-power radios, i.e., micro-nano electro-mechanical device [30], [31].

4. CONCLUSION

Based on the findings of this investigation, the performance of PEHs is influenced by angle position between PEH1 and PEH2. PEH1 is more efficient at converting mechanical energy to electrical energy by resonating better at smaller angles. PEH2 is less efficient and has no effect on angle variation, thus this configuration is not considered as good enough. The angle variations focus on the influence of angular configuration on the moment of blade interactions with PEH and the mechanical resonance of the system, which then influence the deflection of the PEH that generates electricity. The angle of the system determines effectively the applied force, or vibration generates bending or flexural strain. At smaller angles (i.e. 30°), the force may be aligned more favorably with the cantilever's natural bending direction, leading to higher strain and, consequently, higher voltage output for PEH1. As the angle increases, the force becomes less effective in inducing strain, reducing the output voltage. These findings contribute to the development of PEH as renewable energy alternative, especially for micro-electromechanical machines (MEMS) that uses small amount of power, but critical for application such as sensors and transducers.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest that could potentially influence the research.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, AG.

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