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Performance of piezoelectric energy harvester with various ratio substrate and micro windmill

Adhes Gamayel, Ade Sunardi
Department of Mechanical Engineering, Jakarta Global University, Depok, Indonesia

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ABSTRACT

One of the mechanical energy harvesters, piezoelectric energy harvesters (PEHs), produces electricity in response to an external load, which leads to stress and strain in the cantilever beam. The study focused on performance PEH due to collisions between micro windmill blades and PEH substrate. The substrate has dimensions of 10 cm × 6 cm × 1 mm in length, width, and thickness, respectively. Experimental setup was in wind tunnel with a cross-section of 250 mm × 250 mm and blower to generated wind flow inside the tunnel. The wind speeds were set up at 6, 7, and 8 m/s, and then three ratios, namely 1:1, 1:2, and 1:3, were analyzed in output voltage and the deflection. The performance of energy harvesting in a ratio of 1:1 and wind speed of 8 m/s produces a deflection of 2.05 cm, the highest voltage of 12.67 volts, and an effective voltage of 5.62 volts. It was found that ratio 1:1 has a greater mass weight and cross-section than others, leading to more curvature in the PEH beam when the collision occurs. Besides that, the high speed of the micro windmill rotation causes collisions between the blades and PEH to become more frequent.

Corresponding Author:

Adhes Gamayel
Department of Mechanical Engineering, Jakarta Global University
Depok, Indonesia
Email: adhes@jgu.ac.id

1. INTRODUCTION

The demand for renewable energy is critical for achieving future energy requirements [1]. Mechanical energy harvesting has increased interest due to the availability of energy resources. Energy harvesting is a potential method that can provide clean and renewable energy. The phrase “energy harvesting” was frequently used by researchers to find the literature [2]. An energy harvester is a device that can transform energy from temperature, thermal radiation, light, kinetic energy, the sun, and vibration into an electrical energy system. Numerous studies have been conducted on the vibration energy harvester, which is classified into four methods: electromagnetic, electrostatic, triboelectric, and piezoelectric [3], [4]. In contrast to all of the three methods, The structure of the piezoelectric energy harvester (PEH) is simple, and it has a high energy density. [5]–[8]. PEH is a very easiest process for preserving natural mechanical energy and transforming it into electric power due to the piezoelectric effect is purely based on the inherent polarization of the stuff [9], [10]. Piezoelectric materials are typically attached to flexible beams that can deform due to mechanical vibration and generate strain in piezoelectric material to induce the piezoelectric effect [11].

The linear piezoelectric cantilever is a typical PEH with a simple structure and energy recovery that effectively harvests vibration energy in one direction [12]. Due to the power generated in milliwatts or microwatts, it is categorized as micro-level energy harvesting [13]. In the past few years, many studies have been conducted on piezoelectric cantilever-generated voltage utilizing vortex-induced vibration (VIV). One experiment reported that piezoelectric generated a maximum electrical power of 8.97 μW at a wind speed of 19 m/s through a cylindrical bluff body [14]. By another study, a wind speed of 3 m/s passing through a triangular bluff body generates an output voltage of 0.01 to 0.02 volts [15]. The voltage generated increases as more fluid flow thrusts into the piezoelectric, causing the plate to sink and vibrate. The bluff body of D-type can generate voltage of up to 4.5 volts at wind speeds of 9 m/s [16]. When the wind speed is higher, the vibration's amplitude rises; when the wind speed is lower than 2 m/s, the amplitude remains consistent [6], [17]. Airflow causes the pressure to fluctuate until it reaches the PEH, which causes it to vibrate and generate the voltage [18].

The galloping piezoelectric energy harvester (GPEH), which stands for galloping-based piezoelectric energy harvester, can continuously produce significant amplitude voltage when the wind speed exceeds a requirement value, might be characterized as a motion generated aeroelastic energy harvester [6]. The GPEH with a Y-shape is stuck on the bluff body fixed with a cantilever beam. It was discovered that the rise in wind speed was accompanied by an increase in the GPEH-Y's output voltage. The GPEH-Y had recently arrived in the region of galloping when the wind was at a low speed. In another experiment, the GPEH with a V-shape in 45° is the greatest in generated voltage due to the appropriate sharp angle, creating the fluid vortex falling off and producing varying pressure [17]. The other study of the bluff body's shape reported that reverse trapezoidal and square cylinders perform better as energy harvesting devices than triangular and trapezoidal cylinders [19]. The highest voltage and power generated for backward trapezoidal and square cylinders are 1.806 V and 16.30 μW, respectively. The study stated that galloping is characterized by low-frequency vibration and large amplitude. The impact of the upstream and downstream plate placements on the energy harvesting system's output performance was studied [20]. The upstream and downstream plates can provide high-pressure and low-pressure effects, which the multi-interference structure can combine. A bluff body's large amplitude galloping vibration can be generated through this method at a low wind speed.

In theory, the flutter phenomenon of flutter-based energy harvesters is caused by the convergence of the two modal resonance frequencies of torsion and bending modes [6]. Flutter is a phenomenon of aeroelastic instability that affects both bend and twist motion. The vibration system continuously absorbs fluidic energy, increasing the vibrations' amplitude. The divergences result show when the mechanical damping is larger than the aerodynamic damping. A phenomenon that is both self-excited and self-sustaining and also has a significant dependence on the structure's length and stiffness [21]. Researchers investigated the effects of various wind speeds and installation positions on the device's performance. The outcome provides information about the feasibility of incorporating the harvester into an advanced infrastructure or structure. The peak-to-peak voltage from the flutter energy harvester was 8.72 V. When the electrical system is subjected to airflow with an inlet speed of 2.3 m/s, a short-circuit current of 1 mA could potentially reach [22]. Another researcher created a flutter energy harvesting system with a flexible piezoelectric membrane placed in what is known as the "inverted-flag-like" position [23]. Under a wind speed of 9 m/s, a peak electrical power of 5.0 mW/cm^3 may be generated. When the wind speed was low (approximately 3.5 m/s), the devices could generate roughly 0.4 mW/cm^3 of power. The PEH is appropriate for environments with more ambient wind. An innovative PEH system is offered applying the piezoelectric with macro fiber composites (MFC) based on flutter mode [24]. It is shown the PEH-MFC system effectively absorbs the power of wind energy and displays outstanding features like flexibility on large deformation and consistency in energy harvesters. The results of the study demonstrate that the PEH substrate's stiffness and thickness have an important effect on the efficiency of energy harvesting. The results of the research show that the suggested MFC-based flutter energy harvesting system can provide 9.18 mW/cm^3 of power, which is sufficient to match the requirements of conventional self-sustained integrated microelectromechanical systems (MEMS).

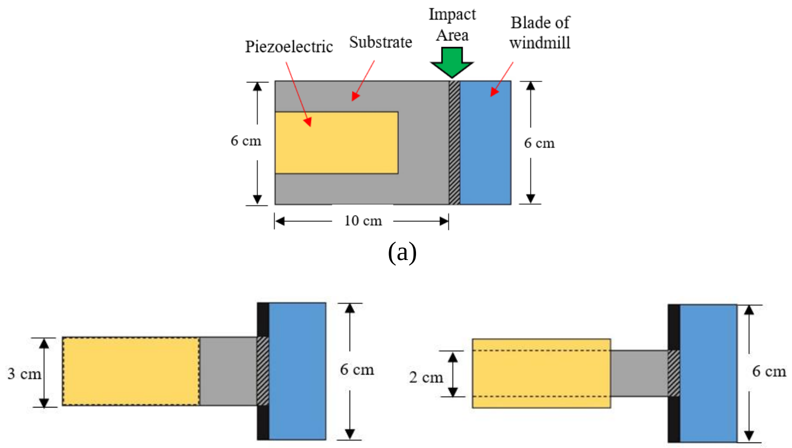
The introduction discusses some of the present or recently proposed energy capture concepts and devices, as well as the most widely used flow-induced vibrations energy harvesting systems, including numerical and experimental studies. Piezoelectric energy harvesters must align their natural frequency to the vibration source and adopt an appropriate harvester geometry to effectively generate power [25]. However, the study of PEH, which focuses on deflection that generates the voltage, is rare. The study focused on the magnitude of deflection due to collisions between micro windmill blades and PEH Substrate. At the same time, the micro windmill blades' rotation is influenced by wind speed variations. The main objective is to study the effect of the width area ratio between the PEH substrate and blade of the micro windmill to generate voltage. Three various ratios, namely 1:1, 1:2, and 1:3, were analyzed in output voltage and the correlation with deflection.

2. METHOD

PEH, in this study, consists of piezoelectric bimorph and rectangular substrate. Bimorph harvesters are more common since they offer an additional piezoelectric layer without introducing any design constraints [26]. The material of piezoelectric bimorph in this study used lead zirconate titanate (PZT) with the specification in Table 1. PZT was effectively synthesized using rather advanced production processes, with good piezoelectric coefficients [27]. PZT is the most widely utilized piezoelectric material because of the stresses and strain greater than other piezoelectric materials. More strain in the PZT means more power is generated in PEH [28]. PZT is a polycrystalline ferroelectric material with the highest electromechanical coupling coefficients and dielectric constants. The dimensions of PZT used in this experiment are a length of 8 cm, a width of 3 cm, and a thickness of 0.6 mm. The material of the rectangular substrate is polypropylene, which includes flexible polymers with excellent anti-fatigue performance. The substrate has dimensions of 10 cm × 6 cm × 1 mm in length, width, and thickness, respectively. The piezoelectric bimorph was placed on top of the substrate, and the impact area between PEH and the blade was set at 5 mm. The objective is to expose the deflection that can generate voltage because of the collision between them. Various ratios between rectangular substrate and blade, namely 1:1, 1:2, and 1:3, were set up in this study. The detail of different ratios is described in Figure 1. In Figure 1(a) the substrate has a length of 10 cm and a width of 6 cm. The width of the substrate is greater than the width of the piezoelectric, but equal to the width of the blade micro windmill. Figure 1(b) shows that the width of the substrate is equal to the width of piezoelectric, which is 3 cm. Figure 1(c) illustrates that the substrate has a width smaller than the width of piezoelectric, which is 2 cm in size.

Table 1. Specification of PZT material

No.	Properties	Values
1	Density (103 kg/m^3)	7500
2	Young modulus (Gpa)	56
3	Poisson's ratio	0.36
4	Piezoelectric strain coefficient (d31) C/N	-186×10^{-12}
5	Permittivity at constant stress $(\varepsilon_{11}/\varepsilon_0)$	3130
6	Permittivity at constant strain $(\varepsilon_{33}/\varepsilon_0)$	3400



(a)

(b) (c)

Figure 1. Ratio width substrate of PEH and blade of micro windmill: (a) 1:1, (b) 1:2, and (c) 1:3

The experimental setup is described in Figure 2. Equipment such as flow rectifiers, micro windmills, and PEH was in wind tunnels with a cross-section of 250×250 mm. A 12-inch blower with a static pressure of 350 Pa and power of 550 watts produced wind flow inside the tunnel. The anemometer measures the wind speeds set up at 6, 7, and 8 m/s. To stabilize the wind flow, the wind tunnel was fitted with mini tube pipes. A flow rectifier was installed before the micro windmill to precisely direct wind flow and pound the blade. The wind flow caused the micro windmill to rotate, and then the blade collisions with PEH to generate a voltage. The video camera recorded the collision when the blades hit PEH until PEH deflected. The result of the video recording is to be converted to an image in JPEG format using "Free Video to JPG Converter" to know the details of the curvature PEH. The conversion method is similar to some other experiments with different subjects [29], [30]. Voltage measurement was recorded using an acquisition data system (DATAQ DI-245), with the measurement duration set up in 60 seconds with a record of 25 data per second.

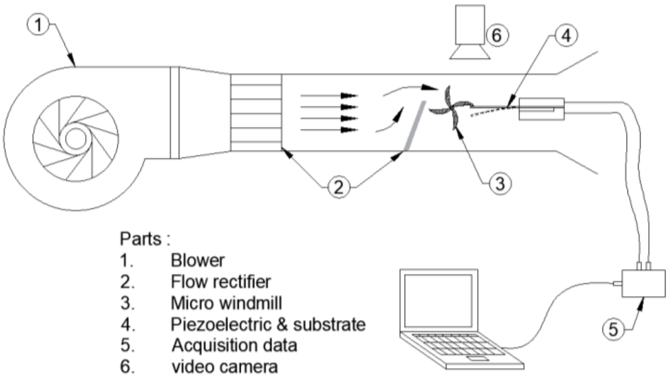
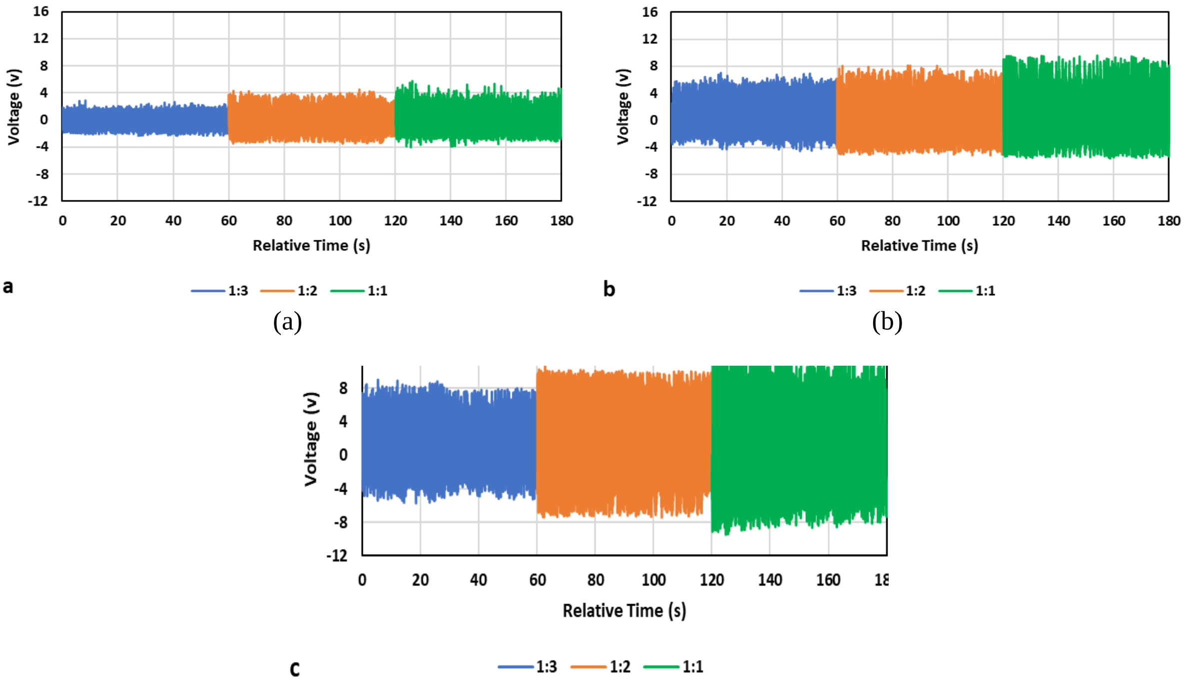


Figure 2. Experimental setup

3. RESULTS AND DISCUSSION

The output voltage in various wind speeds is described in Figure 3. The ratio 1:3 has minimum voltage, and ratio 1:1 has maximum voltage at various wind speeds. Figure 3(a) states the maximum output voltage in wind speed 6 m/s with a ratio of 1:1 is 5.77 volt, a ratio of 1:2 is 4.49 volt, and a ratio of 1:3 is 2.92-volt. Figure 3(b) for wind speed 7 m/s, the maximum voltage in each ratio 1:1, 1:2, 1:3 namely 6.84 volt, 8.14 volt, 9.59 volt. Figure 3(c) describes that greater voltage was generated in ratio 1:1 with 12.67 volt, ratio 1:2 generated voltage in 10.51 volt, and ratio 1:3 generated voltage in 8.87 volt. The ratio between the rectangular substrate and blade correlates with an oscillation of the PEH beam. The differences between the three ratios are about the different dimensions of the rectangular substrate that sticks in piezoelectric bimorph. It means having different total mass weights and cross-sections in the PEH beam. Centre gravity of the attached mass is the device's important characteristic that affects its dynamic response [31]. Ratio 1:1 has a greater mass weight and cross-section than others, leading to more curvature in the PEH beam when the collision occurs. The surface area between the PEH beam and blade for the ratio 1:1 is bigger than the other, giving more impact for the PEH beam to deflect and generate the voltage.



(a) (b)

(c)

Figure 3. The output voltage in various wind speeds: (a) 6 m/s, (b) 7 m/s, and (c) 8 m/s

When the wind speed increases, the rotational speed of the micro windmill increases, which later causes a collision blade with PEH to create more oscillation. The higher output voltage was generated due to the increasing change amplitude in PEH [32]. However, high wind speed leads to inefficiency due to the PEH beam not recovering to its initial shape before the subsequent impact occurred [33]. Besides that, due to excessive vibration amplitude at high wind speeds, PEH beams might suffer damage [34]. The impact resulting from the collision blade with PEH is an external load that transfers electrons, inside PZT, from one electrode to the other. In lack of a short circuit, the material generates electricity through producing pressure leading to an increase in voltage [35]. Continuous rotational micro windmill movement can impact PEH repeatedly, which generates a constant AC voltage.

Figure 4 shows the effective voltage (Vrms) at various wind speeds; when the wind speed increases, the effective voltage at each ratio will also increase. In general, the ratio of 1:1 has the highest value at speeds of 7 m/s and 8 m/s, namely 4.43 volts and 5.62 volts. The Vrms value at a 1:1 ratio is slightly lower at 6 m/s at 2.03 volts, compared to 2.14 volts at a ratio 1:2. The high speed of the micro windmill rotation leads collisions between the blades and PEH to become more frequent. It also leads the frequency resonance of the PEH beam 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 [36]. However, the frequency will decrease as the length of the substrate increases. As the width of the substrate increases, the frequency of collision increases [37]. It is the reason why the ratio of 1:1 to have better Vrms at each speed due to the width of substrate PEH at a ratio of 1:1 is higher than the ratio of 1:2 and the ratio of 1:3.

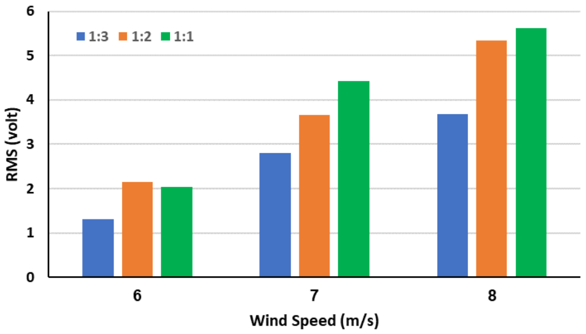
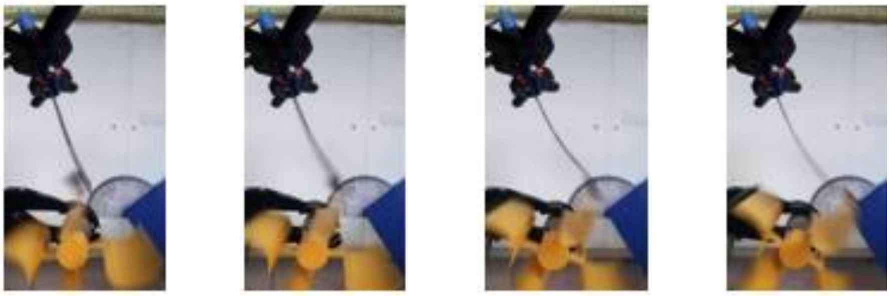


Figure 4. The effective voltage (Vrms) at various wind speeds

According to Figure 5, there is a sequence of events in the collision between the blade and PEH, where Figure 5(a) the beginning will be collision, Figure 5(b) collision, Figure 5(c) maximum deflection, and Figure 5(d) the blade is detached from PEH. Each ratio tested has a moment of occurrence, according to Figure 5. Different results appear in the deflection distance that occurs in PEH due to collisions from windmill blades. In Figure 5(b), when the blade hits PEH, there is absorption of kinetic energy by PEH in the cantilever system until maximum deflection occurs in Figure 5(c) and then detached, causing repeated oscillation movements. When energy is harvested, some of the available power is used for electrical damping (power extraction) and some for mechanical damping (mechanical losses) [38]. The surface condition, shape, and thickness of the cantilever will affect the vibration pattern and mechanical damping in the PEH system.

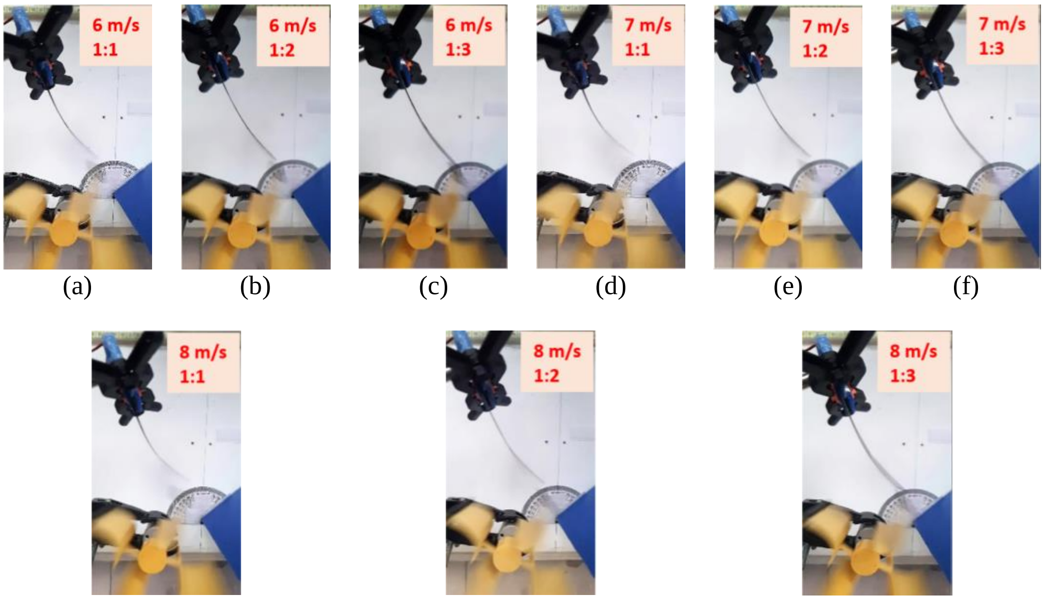


(a) (b) (c) (d)

Figure 5. A sequence of events in the collision between the blade and substrate of PEH: (a) the beginning will be collision, (b) collision, (c) maximum deflection, and (d) the blade is detached from PEH

Figure 6 shows deflection events that occur at various ratios and wind speeds. Deflection in each Figures 6(a) to 6(i) are 1.79 mm, 1.68 mm, 1.46 mm, 1.84 mm, 1.73 mm, 1.67 mm, 1.85 mm, and 1.68 mm, respectively. The largest deflection of 2.05 cm occurred in Figure 6(g) with a ratio of 1:1 and wind speed of 8 m/s. It is in line with the performance of energy harvesting, which in these conditions produces the highest voltage of 12.67 volts with an effective voltage of 5.62 volts. The greater the deflection that occurs in PEH, the greater the electric voltage generated. However, more excellent resistance leads to greater damping and less strain in the PZT leads to low voltage [39]. The deflection that occurs in the PZT material in the PEH installation results in the conversion of kinetic energy into electrical energy.

Ratio 1:1 has higher deflection in each wind speed than ratio 1:2 and 1:3. At wind speeds 6 m/s, 7 m/s and 8 m/s, ratio 1:1 has deflection in 1.79 cm, 1.84 cm, and 2.05 cm, respectively. External load, total weight mass, and cross-section influence the deflection. Based on Figure 7, deflection slightly increases when the wind speed increases and leads the resonance frequency to increase slightly. The resonance frequency decreases with the increase of the length of the substrate. In another way, the folded beam can reduce the device's resonance frequencies without increasing the harvester's overall length [40]. With an increase in cantilever beam width, the piezoelectric cantilever beam's resonance frequency rises. The dimensional change (such as length, width, and thickness) of the piezoelectric plate and substrate alters the system's resonance frequency and gets the best energy harvesting performance.



(a) (b) (c) (d) (e) (f)

(g) (h) (i)

Figure 6. Deflection in various wind speed and ratio: (a) 6 m/s, 1:1, (b) 6 m/s, 1:2, (c) 6 m/s, 1:3, (d) 7 m/s, 1:1, (e) 7 m/s, 1:2, (f) 7 m/s, 1:3, (g) 8 m/s, 1:1, (h) 8 m/s, 1:2, and (i) 8 m/s, 1:3

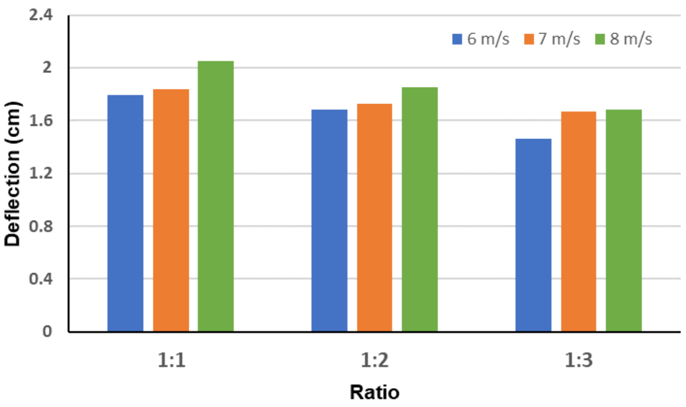


Figure 7. The distance of deflection in various ratio and wind speed

4. CONCLUSION

Various ratios between micro windmill blade and substrate PEH have been tested in the wind tunnel with a cross-section of 250 mm × 250 mm. The most significant deflection of 2.05 cm occurred in a ratio of 1:1 and wind speed of 8 m/s. The performance of energy harvesting, which in those conditions produces the highest voltage of 12.67 volts and an effective voltage of 5.62 volts. It was found that ratio 1:1 has a greater mass weight and cross-section than others, leading to more curvature in the PEH beam when the collision occurs. This condition reaches the more significant deflection in PEH, creating a greater electric voltage generated. Besides that, the high speed of the windmill rotation causes collisions between the blades and PEH to become more frequent. Various ratios between substrate PEH and blade micro windmill can alter resonance frequency, which creates deflection and affects the voltage generated.

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BIOGRAPHIES OF AUTHORS

Adhes Gamayel received the B.Eng. degree and the master's degree in Mechanical Engineering from the University of Brawijaya, Malang, Indonesia, in 2000 and 2007, respectively. The Ph.D. degree in Mechanical Engineering from the Management and Science University, Shah Alam, Malaysia, in 2021. He is currently a senior lecturer in Jakarta Global University. He has published 3 (three) books where two are tutorial in finite element method. He also has two intellectual properties right in industrial design. His current research interests in renewable energy, biofuel, mechanical design, and analytical in finite element method. He can be contacted at email: adhes@jgu.ac.id.

Ade Sunardi currently working as lecturer at Jakarta Global University, Depok. His research interest is in the field of energy conversion. He has published several research papers in various journals ranging from international conferences to international journal indexed on Scopus and ISI. Further information can be contacted at ade@jgu.ac.id.