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# The Potential of Flutter-Based Windbelt for Energy Generation in Low-Wind-Speed Regions: A Case Study in Malaysia

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**ABSTRACT**

The need to reduce carbon emissions from conventional electricity generation has led to research into alternative renewable energy solutions, including wind energy. However, conventional wind turbines are not practical in Malaysia due to their size, cost and low wind speeds. Therefore, recent research has focused on the development of small wind energy generation systems, such as wind-induced vibratory devices, for small-scale power generation. This study aims to enhance the design parameters of a flutter-based windbelt with an electromagnetic conversion mechanism specifically tailored to optimise the use of low wind speeds in Malaysia. Various factors such as wind speed, wind direction, magnet position, magnet size and device length were studied to understand their influence on energy generation. The study conducted experiments in controlled and uncontrolled environments, with the latter chosen in a location known for its high wind potential. Five experiments were conducted and measurements were taken three times to ensure accuracy of the data. The results showed that wind speed and magnet size were positively correlated with voltage generation, while wind direction and magnet coil position had more complex relationships. These results contribute to a better understanding of windbelt performance and identify opportunities to optimise windbelt design and placement. Future research could further investigate factors such as turbulence and find ways to integrate the wind belt into more significant devices.

## 1. Introduction

The effects of global warming are becoming increasingly apparent as carbon dioxide levels in the atmosphere continue to rise. One of the main contributors to excessive carbon dioxide emissions is conventional power generation, which relies on coal to facilitate fuel burning of the fuel. According to the United States Energy Information Administration, 31,780.36 million tonnes of carbon dioxide was emitted in 2010 alone, and this figure has only increased over time. Despite growing concerns regarding climate change, coal remains the world's most important source of energy. Therefore,

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more solutions are being sought, particularly in renewable energy generation, to reduce carbon emissions from electricity generation [1]. There are many renewable energy resources, including solar, wind, thermal, mechanical vibration, and human activity. Wind energy is a viable option that can be harnessed indoors through heating, ventilation, and air conditioning systems and outdoors through natural wind [2].

Wind energy is typically generated using large turbines or windmills, which can be expensive to manufacture, maintain, and repair. In addition, these turbines require considerable space and are usually located far from residential areas to avoid noise pollution and interference with radar and television reception. Another important consideration is the availability of a wind source with a sufficient cut-in speed [3,4]. Malaysia is in equatorial wind doldrums with the average wind speed less than 4.1 m/s during more than 90% of the total wind hours [5]. As a result, harvesting wind energy with conventional wind turbines is impractical in Malaysia since they are not ideal for low wind speeds. This resulted in additional research and development in the field of low-speed wind energy harvesting systems in Malaysia such as windbelt [6]. Windbelt is a wind-induced vibration energy harvesting devices, consisting of flexible ribbon that vibrates as the wind blows across it. Then, it converts the mechanical vibration into electricity. This small-scale energy harvesting system can power a variety of microdevices, such as wireless sensors, electronic chips, LEDs, and mobile phone chargers. Despite their limited application in small devices, they are a great alternative to depleted batteries [2].

Wind energy harvesting consists of two major steps, capturing energy from the environment or called energy coupling mechanism, and electromechanical conversion. Energy coupling mechanism includes vortex-induced vibration (VIV), aero-elastic flutter, galloping and wake galloping which able to capture the wind energy and vibrates resulting from the interaction of the structure and wind flows. The captured energy is then converted from mechanical to electrical energy by electromechanical conversion mechanism such as piezoelectric, electromagnetic, or electrostatic devices [7]. The electromechanical conversion technique employed by piezoelectric devices involves applying pressure on piezoelectric material. Although capable of producing more power than electromagnetic and electrostatic devices, the device is expensive, suffers from fatigue and decrease of performance over time, and may result in significant leakage voltages [8,9]. In electromagnetic conversion devices, the voltage is induced when the coil travels through a varying amount of magnetic flux, according to Faraday's Law of Induction and Lenz Law. According to previous study Torres and Rincón-Mora [8], the voltage produced is low and unstable. However, the performance can be improved by establishing the optimum design of the structure parameters. Electrostatic devices, on the other hand, employ a variable capacitor structure to create charges from the relative motion of two plates and a capacitor. It offers a similar power density to a typical generator-transformer-rectifier combination and is easier to integrate into a microsystem, but the manufacturing process is challenging and expensive [7,10].

## 2. Related Study

Wind-induced vibrations, including VIV, flutter, galloping and wake galloping are promising method for harnessing wind energy utilizing the instability of the structures to generate electrical energy. Among these, flutter-induced vibrations have the advantage of causing significant structural deformations and can be generated at low wind speeds, making them useful for the construction of energy generation systems. For instance, Arroyo *et al.,* [12] have developed an omnidirectional flutter band energy harvester with an electromagnetic generator, with the aim of increasing the power output by increasing the input vibration acceleration, minimising the structural size for maximum power density, and lowering the critical wind speed for triggering ribbon flutter. The simulation and experimental results show that reducing the ribbon dimensions increases the critical speed, which must be compensated for to achieve low wind speed performance [12].

Lu *et al.,* [13] investigated a flutter-based electromagnetic wind energy harvester in a small tunnel. They proposed an analytical model for windbelt harvesters, which was consistent with previous empirical equations and experimental data. The results showed that positioning the magnet closer to the centre of the membrane increased the performance of the harvester. By optimising the design parameters, the harvester was able to produce a maximum average power of 705 µW at a wind speed of 10m/s. In another study, Aquino *et al.,* [14] used computational fluid dynamics (CFD) simulations to investigate the effects of external conditions on the performance of an aeroelastic belt for powering small-scale building devices. Owing to the high wind speed, the aeroelastic belt generated the highest power of up to 62.4 mW at the peak of the building roof.

Fernandez *et al.,* [15] investigated the design optimisation of a low power wind energy harvester using a piezoelectric transducer. They investigated the influence of frame length, belt length, belt material, and transducer exposure length on the performance of the harvester. The best frame and belt lengths were found to be 0.86 m and 0.75 m respectively, with latex rubber as the best belt material. The optimal exposure length of the piezoelectric transducer was 75%. Vinayan *et al.,* [5], on the other hand, investigated the quantification of an aeroelastic windbelt using an electromagnetic array and found that taffeta silk outperformed all other materials. The optimal length and width of the belt were 1 m and 12 mm, respectively, and the best position for the magnet was 20 cm from the edges of the main frame. Pimentel *et al.,* [16] developed a wind collection system based on aeroelastic flutter and connected it to an electromagnetic transducer to investigate the effects of the wind speed, belt tension, angle of attack, and load on the performance of the device. They discovered that increasing the ribbon tension produced more power, but at lower wind speeds, the ribbon did not flutter when high tension was applied to the ribbon. Furthermore, the output power gradually decreases as the angle of attack increases, but power generation is still possible if the angle of attack is smaller than the minimum angle of attack.

According to the above related studies, energy can be generated using flutter-based windbelt because it can cause significant structural deformation and can be generated at low wind speeds. To improve the performance of flutter-based windbelt, few studies have been conducted to optimise the design parameters, materials, and exposure length windbelt. The performance of the windbelt is strongly influenced by the position of the magnet, reduced size and tension of the ribbon, and angle of attack. Overall, the studies show that flutter-based windbelt is very promising for generating energy with low power consumption; however, further studies are needed to increase its effectiveness and performance. Therefore, the main objective of this study is to improve the design parameters of an aeroelastic flutter windbelt with an electromagnetic conversion mechanism. This particular device has shown great development potential and cost effectiveness in terms of manufacturing and maintenance [3,11]. This study fills a research gap by analysing the specifics of low-wind regions and proposing an innovative method to increase wind energy efficiency. In this way, we can minimise our dependence on traditional energy producing technologies.

The study analyses the effects of various factors such as wind speed, wind direction, position of the magnet coil, magnet size and device length on the performance of the flutter-based windbelt for energy generation at low wind speeds. The windbelt proved to be efficient at a wind speed of about 2.7 m/s and generated a peak power of about 5 mW [3]. The development of these micro wind energy systems represents a promising solution for small-scale energy generation and could be a viable alternative to conventional battery-powered microdevices.

## 3. Study Area

The tropical climate of Malaysia ensures high temperatures and humidity throughout the year. However, the country faces the major challenge of low wind speed, which makes conventional wind turbines unsuitable for electricity generation. Over 90% of total wind hours in Malaysia have an average wind speed of less than 4.1 m/s, which is insufficient for electricity generation [17]. The mountainous terrain and hills in Malaysia also contribute to low wind speeds, thereby reducing the potential for wind energy. To address this challenge, this study investigates the performance of a flutter-based windbelt for power generation at low wind speeds in both controlled and uncontrolled environments. The controlled environment used an enclosed space and an electric hair dryer as the wind source, while the uncontrolled environment was located at Bukit Ko'bah Lay-by on PLUS Highway in Kedah at kilometre 65.0, a site known for its high wind potential. This study investigated the effects of various factors such as wind speed, wind direction, magnet-coil position, magnet size, and device length on the performance of the windbelt.

## 4. Research Method

### *4.1 Research Workflow*

The research was conducted in accordance with the workflow shown in Figure 1. The primary impetus for this research was the global goal of reducing carbon emissions and combating global warming by maximising renewable energy sources, particularly wind energy. In order to gain a comprehensive understanding of how the wind belt works and to identify gaps in previous research, a thorough literature review was conducted. The aim of this research was to find out how the design features of the windbelt can be modified to increase its performance. Based on the results of the literature review, specific design parameters were selected for testing and analysis in this study. A test model and the necessary equipment were constructed and developed to facilitate the experiments. Data from all experiments conducted in the study were collected, processed and described in detail in this publication. The goal was to gain useful insights into the performance of the wind belt and how it can be further improved.

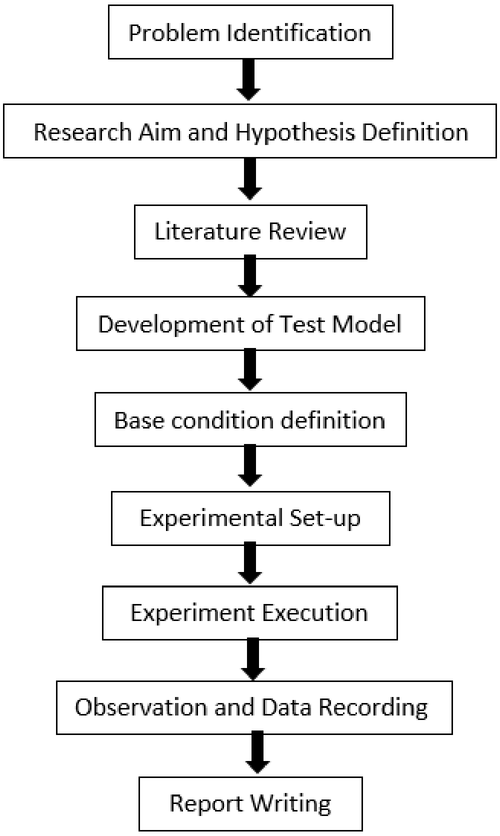


**Fig. 1.** Research workflow

### *4.2 Material and Equipment Used*

The energy coupling mechanism of the experiment used a flutter mechanism in conjunction with an electromagnetic system for electromechanical conversion. The experiment consisted of several main components such as a ribbon, magnet, copper coil, and body structure. A windbelt is a membrane that is made to vibrate by the external force of the wind. This leads to fluttering, an aeroelastic instability phenomenon that involves bending and twisting. The material used for the ribbon is significantly affected by this property. Therefore, ripstop nylon was selected because of its light weight, strength, and durability. The ripstop nylon had a length and width of 170 mm and 20 mm, respectively, a thickness of 0.51 mm and a density of 0.222479 kg/m$^3$.

A disc-shaped permanent magnet was used for the experiment, and NdFeB magnets of grade N52 were selected for their excellent magnetic properties. Three different magnet dimensions were tested:20 mm × 5 mm, 15 mm × 5 mm, and 10 mm × 5 mm. A copper coil shown in Figure 2 was used to generate current by cutting the magnetic flux. The SWG25 grade was chosen because it has low resistance per meter of wire and good formability for winding. The copper coil has a diameter of 0.1 mm and 2500 turns.

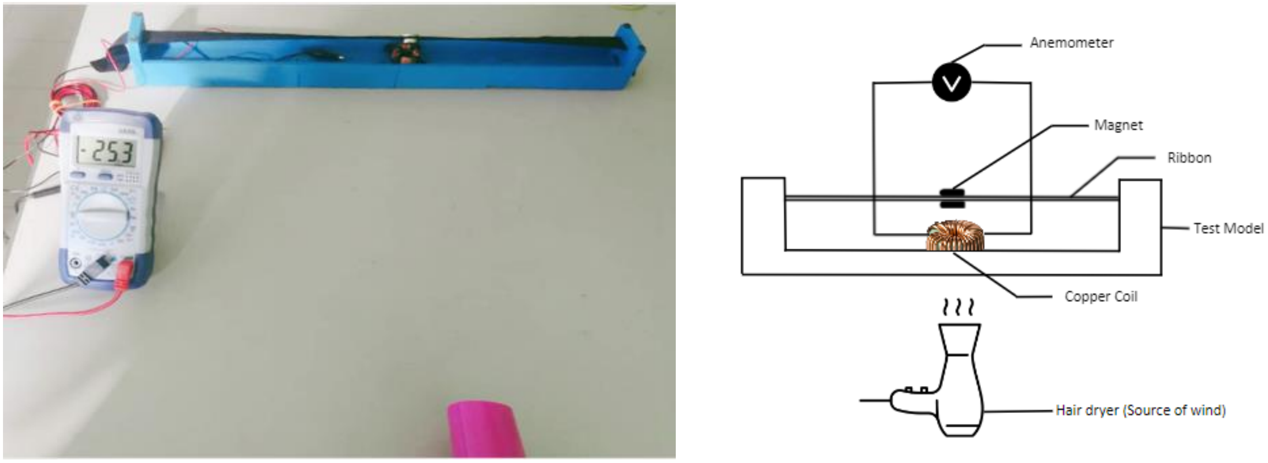
The body structure of the windbelt was made using a 3D printer, and polylactic acid (PLA) was used as the filament material. PLA was selected because it is biodegradable and offers a high-quality surface. The structure was designed based on the model proposed by Lu *et al.,* [13]. To observe the effect of the length of the body structure on the output power generated, models with three lengths, 150 mm, 300 mm, and 500 mm, were printed as shown in Figure 3. The end of the ribbon was bolted to the body structure, and magnets were attached to the top and bottom of the ribbon. A copper coil was attached to the bottom of the body structure and connected to the wire and a multi-meter to measure the generated voltage. The test model was placed at the same level and 1 m from the wind source. The space used was spacious and had a few obstacles to avoid turbulence.

**Fig. 2.** Copper coil

**Fig. 3.** 3D printed test model

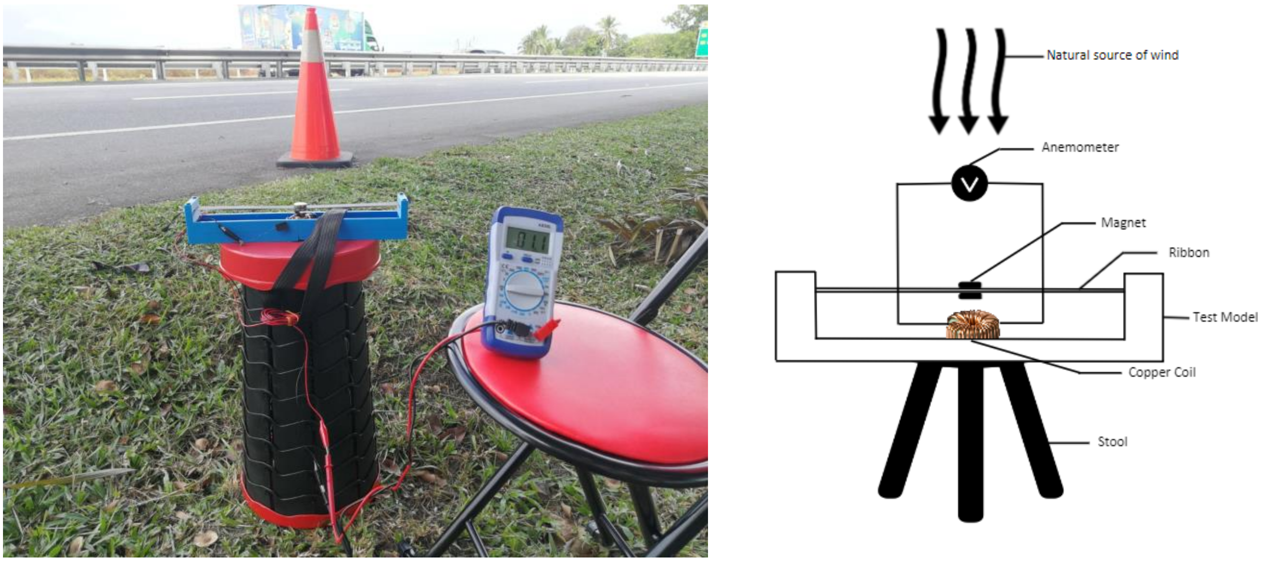
### *4.3 Experiment Set-up*

A series of five experiments was conducted to determine the best settings for the test model and its environment. Each experiment focused on one variable simultaneously while maintaining the basic conditions of the other variables. A multi-meter connected to the circuit was used to measure the voltage produced by the test model under each test condition to assess its performance. Figure 4 shows the experimental set up for the experiments conducted under controlled environments, that is, in a closed room with an electric hair dryer as the wind source. All the variables are tested under the controlled environments. In contrast, for uncontrolled environment, due to erratic and variable wind speeds and directions, just the size and position of the magnet and the length of the test model are tested. As shown in Figure 5, this experiment was conducted at kilometre 65.0 on the PLUS Highway in Kedah. Table 1 presents the basic conditions of the test model. All measurements were taken three times to ensure the accuracy of data collection. The obtained data will then be appropriately analysed.



(a) (b)

**Fig. 4.** Experiment set-up for controlled environment (a) Real experiment set-up (b) Sketch of experimental set up (consists of anemometer, magnet, ribbon, test model, copper coil and hair dryer)



(a) (b)

**Fig. 5.** Experiment set-up for Uncontrolled Environment (a) Real experiment set-up (b) Sketch of experimental set up (consists of anemometer, magnet, ribbon, test model, copper coil and stool)

**Table 1**
The basic conditions of the test model

| Variables | Value |
|---|---|
| Wind Speed | 4.3 m/s |
| Wind Direction | 90° to The Test Model |
| Size of Magnet | 10mm x 5mm |
| Magnet-coil position | 150mm from side |
| Length of the Test Model | 300mm |

## 5. Results and Discussion

The performance of the flutter-based windbelt can be assessed by measuring the voltage of the power generated by the windbelt. A multi-meter circuit is connected to the copper coil for measurement.

### *5.1 The Effects of Wind Speed on Windbelt Performance*

In this study, the effect of the wind speed on the performance of a windbelt in a controlled environment was investigated by testing two different speeds. As shown in Table 2, the results indicated that a wind speed of 7.7 m/s produced a higher voltage (45.2 mV). These results support the argument that a higher wind speed can improve the performance of the windbelt (see Figure 6). This result is consistent with previous research showing that higher wind speeds result in more aggressive flutter of the ribbon, which in turn results in more cutting of magnetic flux [2,3]. The practical implications of this finding include the potential to improve power generation in small wind energy systems, especially in urban areas where wind turbines are not feasible. This study highlighted the importance of conducting experiments in controlled environments to isolate the effects of certain variables. Future research could investigate other factors that affect the windbelt performance.

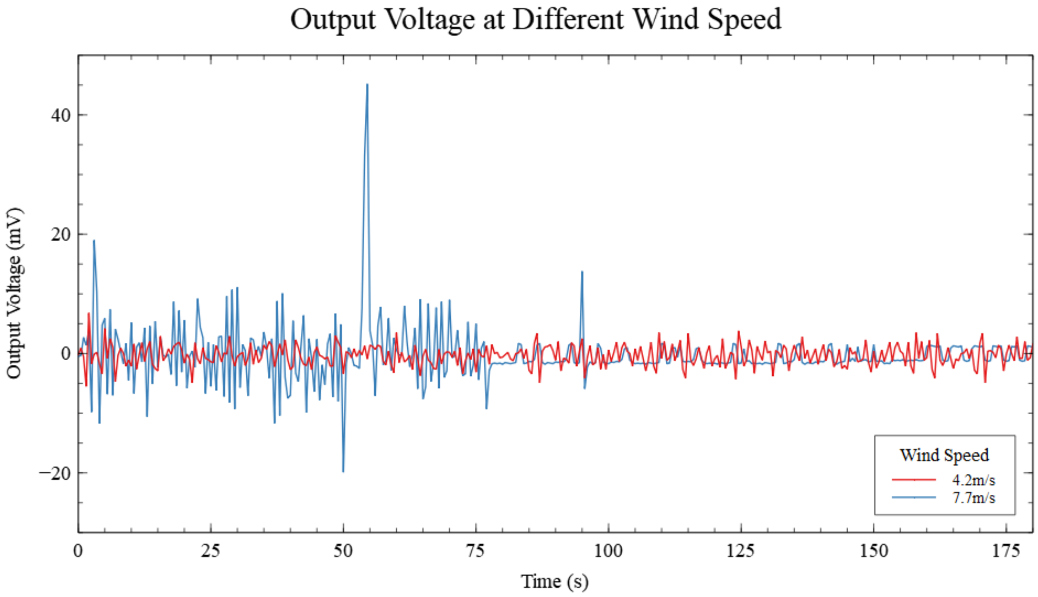


**Fig. 6.** The diagram of the output voltage as a function of time during the wind speed test in a controlled environment

**Table 2**
Maximum output voltage recorded for different wind speed

| Wind Speed (m/s) | Max Output Voltage (mV) |
|---|---|
| 4.2 | 7.4 |
| 7.7 | 45.2 |

### *5.2 The Effects of Wind Direction on Windbelt Performance*

In this study also, the influence of wind direction on the performance of a windbelt was investigated by testing three different angles of attack: 30°, 60°, and 90° (see Figure 7). The results revealed that wind direction significantly affected the voltage generated by the windbelt. In particular, the highest voltage (7.4 mV) was observed at an angle of attack of 90°, compared to the other two angles (see Table 3). This is because the wind at a 90° angle of attack can force the ribbon perpendicular to its surface, maximise wind energy, and generate more electricity. However, the voltage decreased over time, suggesting that other factors, such as wind speed, turbulence, and the angle of the ribbon itself, may also influence its performance. These results are important for optimising wind power generation using windbelt. Future research can focus on optimising the design and placement of windbelt for optimal power generation by studying the effects of wind direction on the windbelt performance.

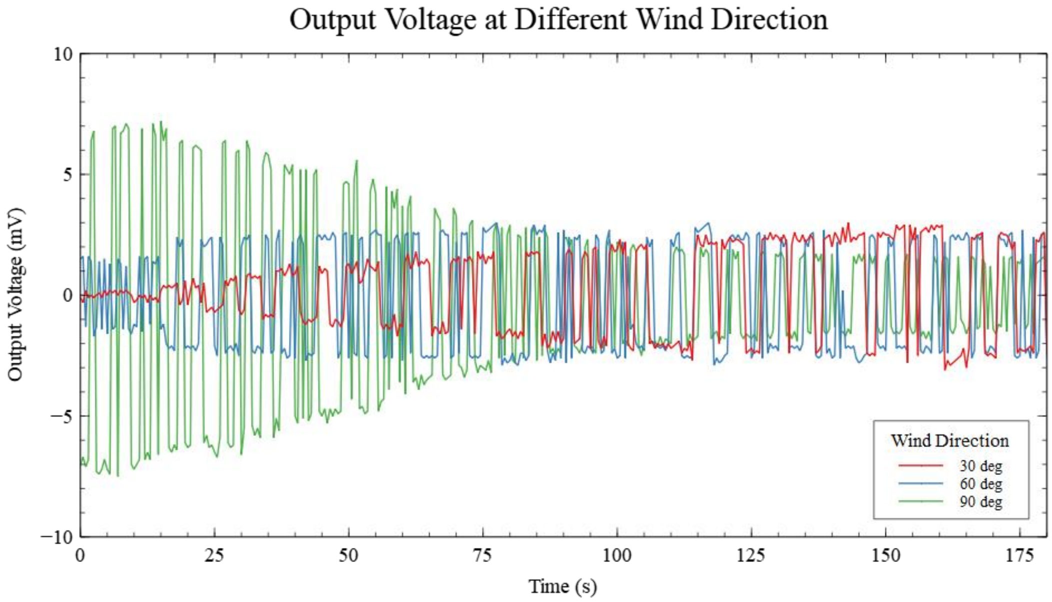


**Fig. 7.** The diagram of the output voltage versus time during the wind direction test in a controlled environment

**Table 3**
Maximum output voltage recorded for different wind direction

| Wind Direction (°) | Max Output Voltage (mV) |
|---|---|
| 30° | 2.8 |
| 60° | 2.9 |
| 90° | 7.4 |

### *5.3 The Effects of The Magnet-Coil Position on Windbelt Performance*

The position of the magnet in relation to the coil can affect the voltage generated by the windbelt. An experiment was conducted to investigate the effects of the magnet-coil position on the performance of the wind band using three different positions: 10%, 30%, and 50% from the end of the test model. The experiment was conducted in both controlled and uncontrolled environments. In the controlled environment (Figure 8), the position of the magnet coil at 50% of the test model yielded the highest voltage, followed by 30% and 10%, with the highest voltage value of 7.4 mV (see Table 4). This is because the centre of the ribbon has the highest amplitude of movement compared to the sides, resulting in more frequent intersections of the magnetic flux and higher voltage generation. This result is consistent with those of the previous studies by Quy *et al.,* [3], Lu *et al.,* [13] and Vinayan *et al.,* [17].

In an uncontrolled environment shown in Figure 9, the wind speed was measured during the experiment to ensure the validity of the results. The wind speed was unpredictable, particularly at the 10% magnet-coil position, where it fluctuated between 0.5 and 3 m/s. However, at the 30% and 50% positions, the wind speed improved and ranged between 3.8 m/s and 4.2 m/s. Despite the fluctuating wind speed, the magnet-coil of 50% reached the highest voltage with a peak of 19.1 mV, followed by 30% with a peak of 7.1 mV and 10% with a peak of 3.5 mV (see Figure 10 and Table 5). The results show that the wind speed can affect the performance of the windbelt, but the optimum position of the magnet-coil remains the same for both environments, regardless of the wind speed. These results are significant because they provide insight into the best position for magnet-coil in windbelt power generation and highlight the importance of wind speed on windbelt performance.

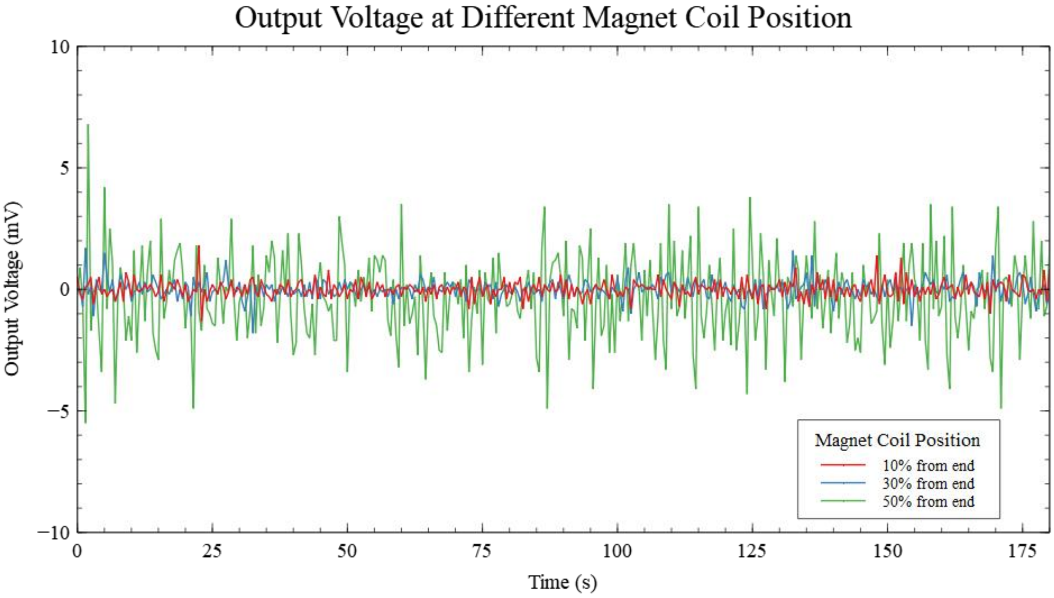


**Fig. 8.** The diagram of the output voltage in relation to time during the test of the magnet-coil position in a controlled environment

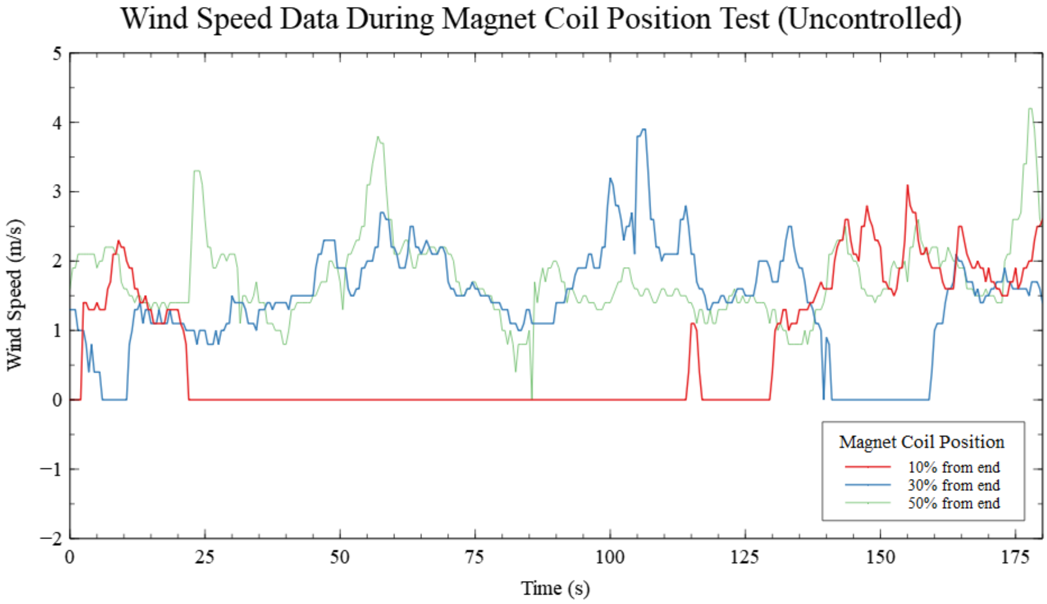


**Fig. 9.** The graph of wind speed as a function of time during the test of the magnet-coil position in an uncontrolled environment

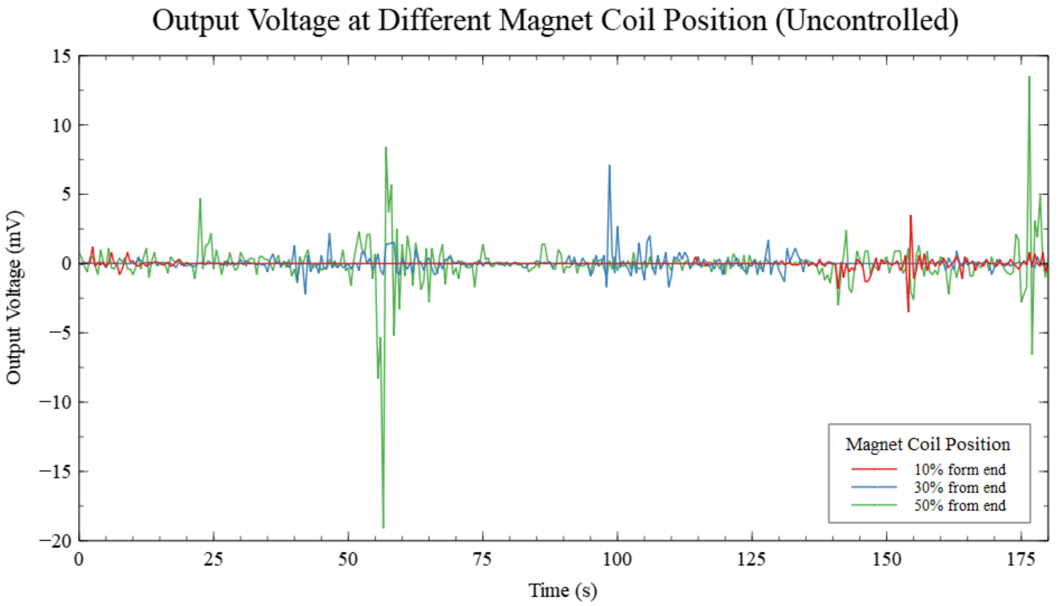


**Fig. 10.** The diagram of the output voltage in relation to time during the test of the magnet-coil position in an uncontrolled environment

**Table 4**
Maximum output voltage recorded for different magnet coil position in controlled environment

| Magnet-coil Position (%) | Max Output Voltage (mV) |
|---|---|
| 10 | 1.8 |
| 30 | 1.9 |
| 50 | 7.4 |

**Table 5**
Maximum output voltage recorded for different magnet coil position for uncontrolled environment

| Magnet-coil Position (%) | Max Output Voltage (mV) |
|---|---|
| 10 | 3.5 |
| 30 | 7.1 |
| 50 | 19.1 |

### *5.4 The Effects of The Magnet Size on Windbelt Performance*

In this study, the influence of magnet size on the performance of a wind band was investigated in a controlled environment (see Figure 11). Three magnet sizes were tested:20 × 5 mm, 15 × 5 mm, and 10 × 5 mm. The results showed that, as the magnet size increased, the range of voltage generated also increased. The largest magnet size, 20 mm × 5 mm, produced the widest voltage range and achieved a maximum voltage measurement of 12.2mV (see Table 6). This is because a larger magnet can produce a stronger magnetic field, resulting in a greater electromagnetic force and current generation. This result is consistent with previous research [10].

However, wind speed measurements have yielded contradictory results for the uncontrolled environment. As shown in Figure 12, the variation in wind speed was greatest during the test with the 10 mm × 5 mm magnet, reaching a maximum of 4.6 m/s. The maximum speed during the 15 × 5 mm test was 4.2 m/s, while the maximum velocity during the 20 × 5 mm test was 3.9 m/s. Furthermore, as illustrated in Figure 13, the voltage generated by the 15 mm × 5 mm magnet was the highest at 19.1 mV (see Table 7), followed by the 20 mm × 5 mm magnet, and then the 10 mm × 5 mm magnet. This could be due to the fact that the wind speed was stronger during the 15 mm x 5 mm magnet test, resulting in a higher voltage.

These results suggest that the size of the magnet has a significant impact on the performance of the windbelt, with a larger magnet producing more energy. However, the optimal magnet size can vary depending on the wind speed conditions. Indeed, previous studies have also investigated the influence of magnet size on wind turbine performance, with similar results [10].

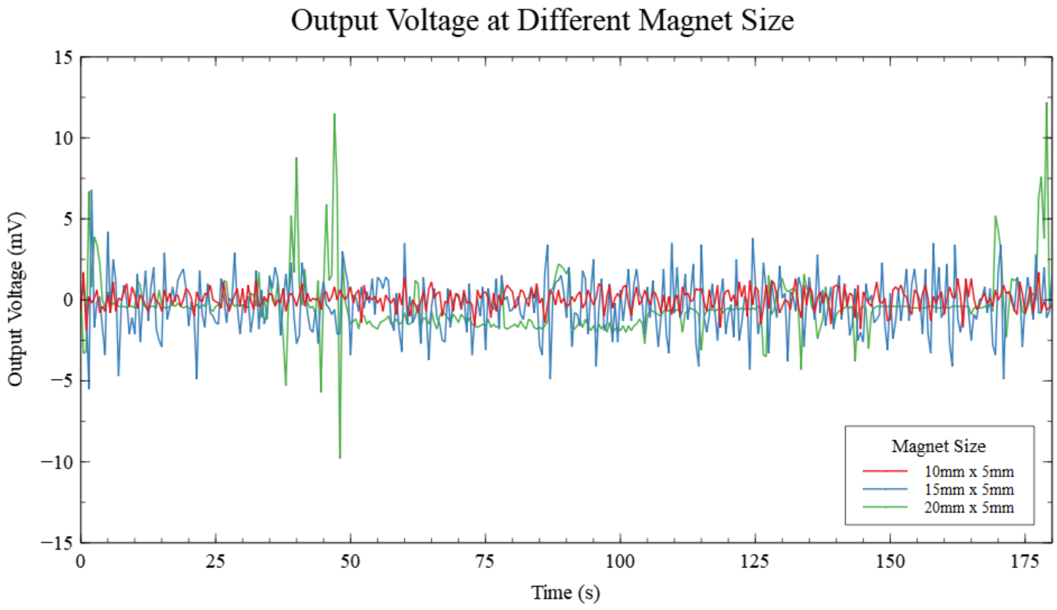


**Fig. 11.** The diagram of the output voltage in relation to time during the magnet size test in a controlled environment

**Table 6**
Maximum output voltage recorded for different magnet size for controlled environment

| Size of Magnet | Voltage generated (mV) |
|---|---|
| 10mm x 5mm | 1.9 |
| 15mm x 5mm | 7.4 |
| 20mm x 5mm | 12.2 |

**Table 7**
Maximum output voltage recorded for different magnet size for uncontrolled environment

| Size of Magnet | Voltage generated (mV) |
|---|---|
| 10mm x 5mm | 1.2 |
| 15mm x 5mm | 19.1 |
| 20mm x 5mm | 9.8 |

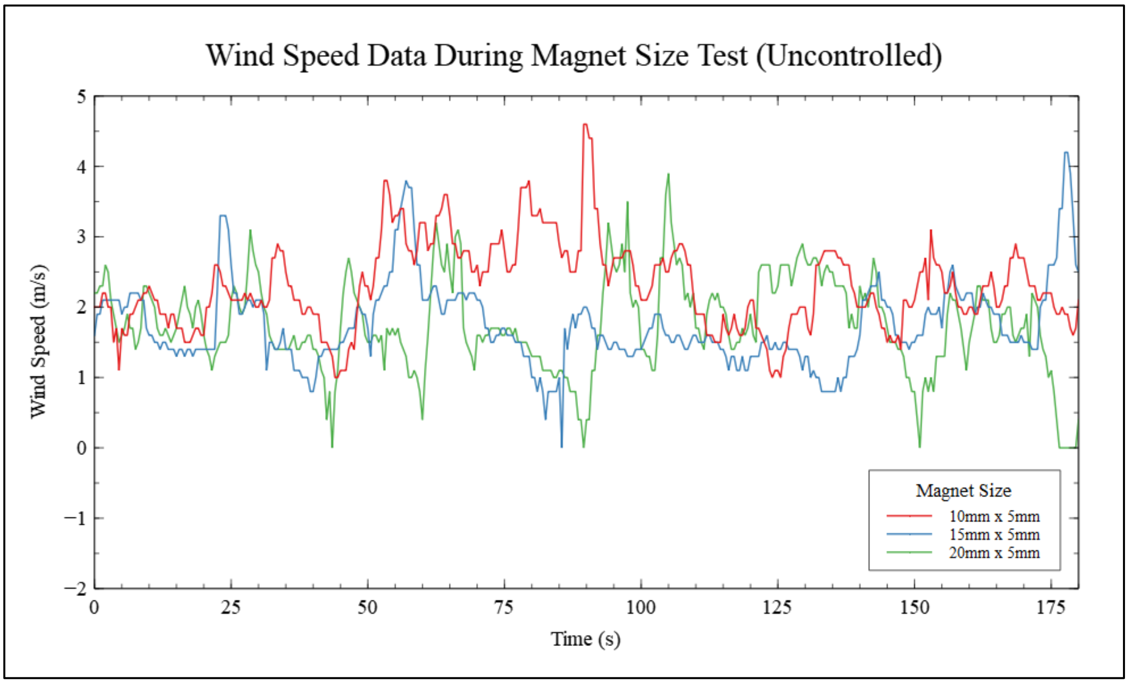


**Fig. 12.** The diagram of wind speed versus time during the magnet size test in an uncontrolled environment

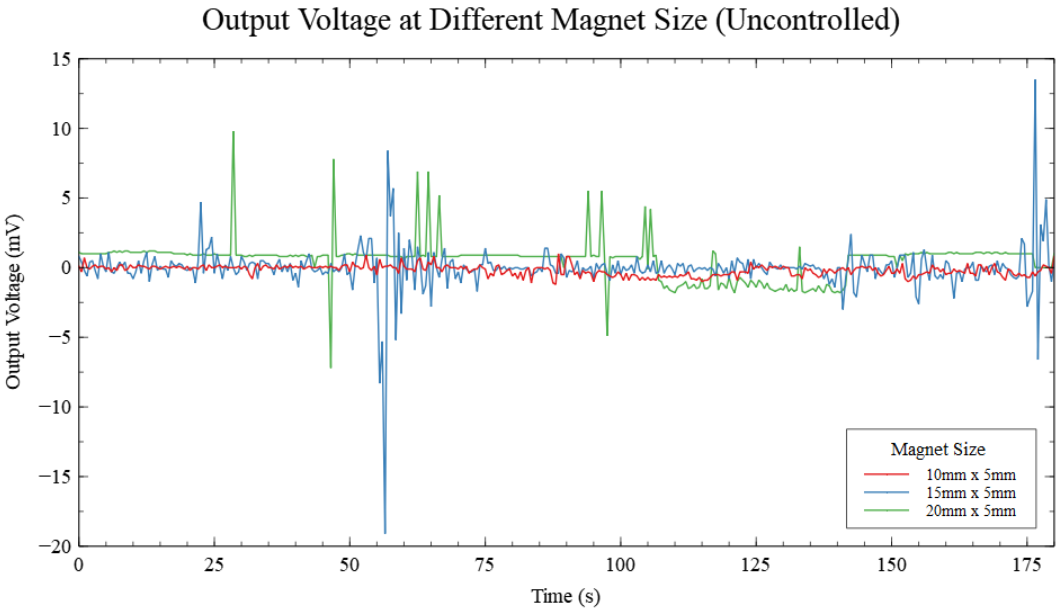


**Fig. 13.** The diagram of the output voltage in relation to time during the magnet size test in an uncontrolled environment

### *5.5 The Effects of Length of The Test Model on Windbelt Performance*

As shown in Figure 14, this study investigated the effects of different test model lengths on the performance of windbelt. The experiment included three test models with lengths of 150, 300, and 500 mm. The results showed that the longest test model, 500 mm, produced the highest output voltage of 31.4 mV (see Table 8), which was three times that of the shorter test models. This result can be attributed to the influence of the test model length on the fluttering motion of the belt, which induces a magnetic flux. Faraday's law of electromagnetic induction explains this relationship, according to which the voltage generated in a conductor is proportional to the rate of change in the magnetic field through the conductor. The study also found that test model with longer strips generate electricity more efficiently, a principle that also applies to other wind harvesters such as conventional wind turbines. The results of the uncontrolled environment (see Figure 15) showed that during the 300-mm test, the wind speed is at the highest. However, the highest voltage was obtained with the 500-mm test model, while the maximum voltage of 19.1 mV (see Table 9) was obtained with the 300-mm test model (see Figure 16). This result is consistent with that of the controlled experiment, which showed that longer test model energy harvesters performed better. The results indicate that the length of the test model is a crucial factor in the performance of the windbelt and that longer belts are more efficient in generating electricity.

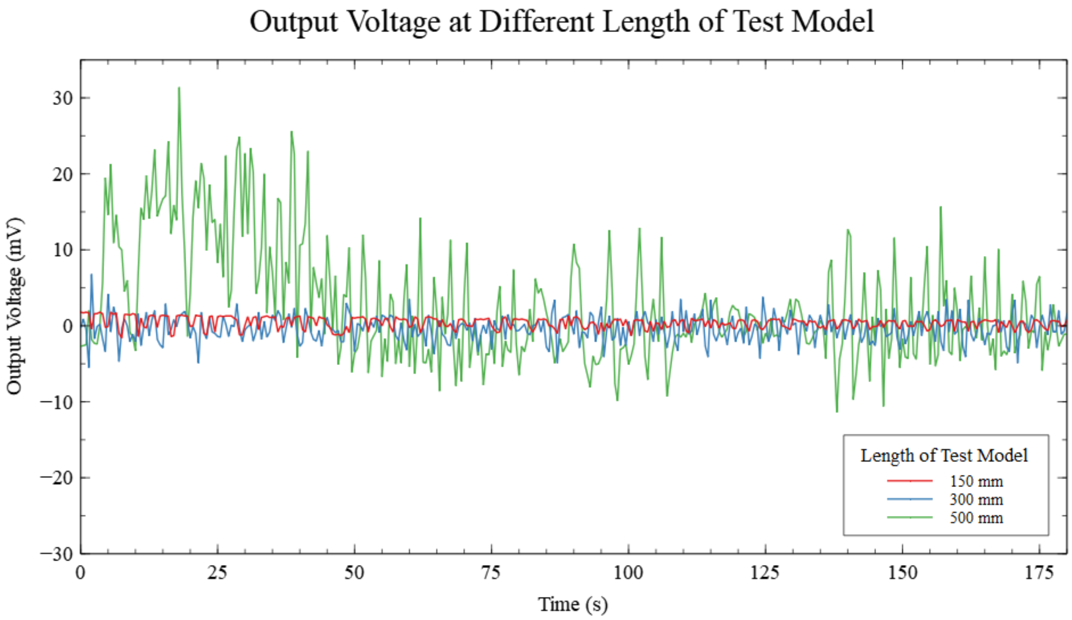


**Fig. 14.** The diagram of the output voltage as a function of time during the length of the test model in a controlled environment

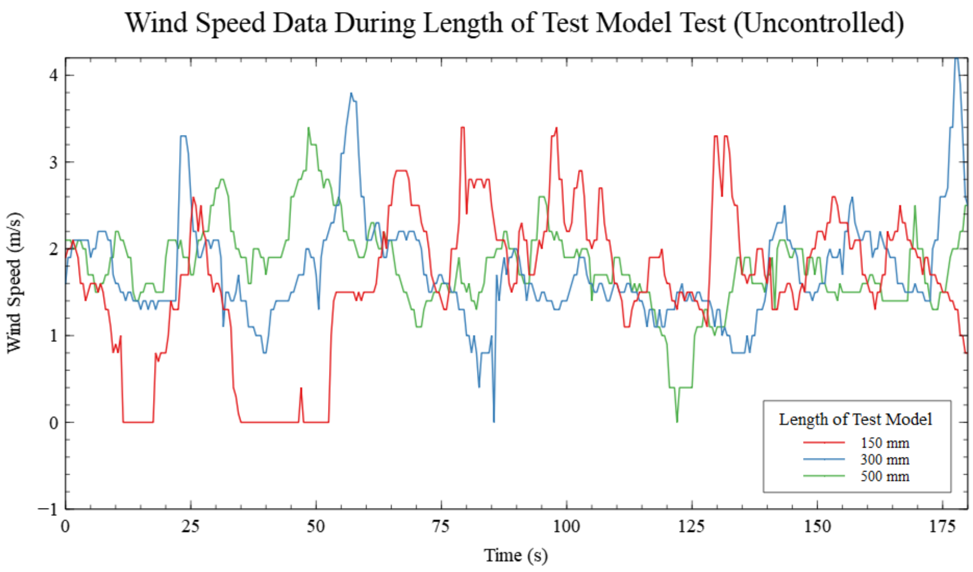


**Fig. 15.** The graph of wind speed as a function of time during the duration of the test model in an uncontrolled environment

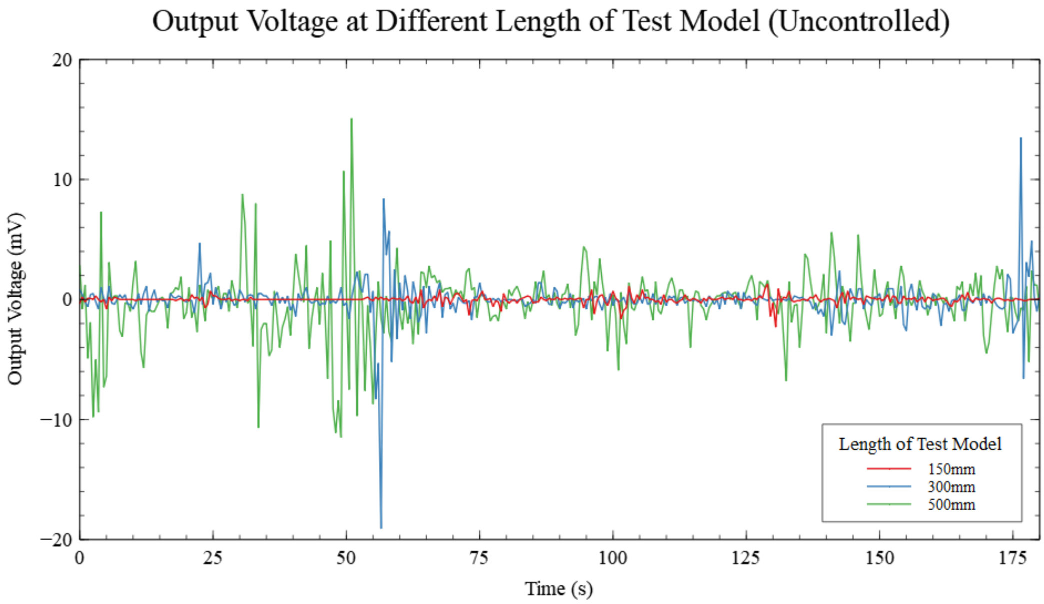


**Fig. 16.** The diagram of the output voltage in relation to time during the duration of the model test in an uncontrolled environment

**Table 8**
Maximum output voltage recorded for different length of test model for controlled environment

| Length of Test Model | Voltage generated (mV) |
|---|---|
| 150mm | 1.8 |
| 300mm | 7.4 |
| 500mm | 31.4 |

**Table 9**
Maximum output voltage recorded for different length of test model for uncontrolled environment

| Length of Test Model | Voltage generated (mV) |
|---|---|
| 150mm | 2.3 |
| 300mm | 19.1 |
| 500mm | 15.1 |

## 6. Conclusions

In summary, the five sub-themes identified in the Results and Discussion section examine the elements that affect wind turbine performance in relation to energy generation. The effects of wind speed, wind direction, magnet-coil position, and magnet size on the voltage generated by windbelt have been studied. As the data show, all of the above characteristics have a significant impact on the voltage generated by wind turbine. Wind speed, magnet size and test model length were found to have a positive correlation with voltage generation, whereas wind direction and magnet-coil position had more complex correlations. Important conclusions we can draw from this are

1. Wind speed had a significant influence on the performance of the windbelt because the generated voltage showed a positive correlation with wind speed.
2. With regard to the wind direction, it was found that the perpendicular orientation of the windbelt to the wind source resulted in higher electricity generation.
3. The positioning of the magnet-coil also played a crucial role in the performance of the windbelt, with central positioning yielding the maximum voltage owing to its greater amplitude.
4. The size of the magnet has been found to be a significant factor in wind turbine performance, with larger magnets resulting in higher voltage generation.
5. It has been observed that the length of the test model has a positive effect on the performance, with longer belts producing higher voltages.

Studies have also shown the importance of conducting experiments in controlled environments to isolate the effects of certain variables and optimise the use of wind bands in different applications. These findings have important practical implications for optimising wind power generation using windbelt. Windbelt are a low-cost and lightweight alternative to conventional turbines, making them particularly attractive for small wind energy systems in urban areas where wind turbines are not feasible. The results of these studies provide valuable insights into the factors that influence windbelt performance and identify opportunities to optimise windbelt design and placement. Future research could investigate other factors that affect windbelt performance, such as turbulence, and explore ways to integrate windbelt into more significant devices. Overall, the studies presented here contribute to our understanding of the windbelt technology and its potential role in renewable energy generation.

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