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Wind tunnel and initial field tests of a micro generator powered by fluid-induced flutter

Vu Dinh Quy *, Nguyen Van Sy, Dinh Tan Hung, Vu Quoc Huy

Department of Aeronautical and Space Engineering, Hanoi University of Science and Technology, No. 1, Dai Co Viet Road, Hai Ba Trung Dist., Hanoi, Vietnam

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ABSTRACT

Aeroelastic flutter is a self-oscillating phenomenon resulting from interaction between a structure and the surrounding flow. This is well-known as a destructive phenomenon. However, it can also be used as a powerful mechanism to harvest wind energy at the scales and costs beyond the reach of turbines. Windbelt is a micro generator exploiting wind energy with small size and capacity, which was invented and developed a few years ago (Humdinger wind energy LLC, 2007) basing on aeroelastic flutter. The aim of this paper is to investigate the influences of the design parameters on the performance of a windbelt with the goal of maximizing its output power. An experimental apparatus is developed to study the effects of parameters such as wind speed, position and size of the magnets, pre-applied tension of the membrane, angle of attack of the membrane, and the direction of the generator on the output power and frequency of the windbelt. The experimental tests are carried out in a subsonic wind tunnel. After that, we deduce optimal parameters from experimental results to maximize the output power. Two micro generators are then fabricated and tested in both wind tunnel and real condition. The results show that a single micro generator (windbelt) can generate a power of from 3 to 5 mW and a windpanel of 5 single windbelts (larger ones) can generate a power of from 30 to 100 mW at the wind speed of less than 8 m/s. This output is sufficient to power many micro devices such as wireless sensors, electronic chips, LEDs, and cell phone chargers. Therefore, this micro wind energy generator may be widely used in practice.

Introduction

Wind energy is the kinetic energy of the air moving in the Earth's atmosphere (Hughes, 2012) and man has taken advantage of this kind of energy for thousands of years (Kalmikov and Dykes, 2010). After the oil crisis in the '70s, the study of energy production from alternative sources of energy has been enhanced around the world (Japan Center for Economic Research (JCER), 2012). These sources include but not are limited to wind energy, which has been considered as a clean and inexhaustible source. After the invention of electricity and electric generator, the idea of using wind energy to generate electricity soon came into being.

The most common way to harvest wind energy is rotating a turbine generator. However, wind turbines or windmills only work well for large-scale applications. Micro wind turbine, which is the smallest-sized wind turbine in the market, has a rotor diameter of from 0.5 to 1.25 m (Gipe, 2009) and the power of from 20 to 100 kW. They are still quite large for some applications such as charging battery and powering sensors. Also, wind turbine is very expensive and costly to manufacture, maintain, and repair. It also needs a very large space for installation. In addition, wind turbine may cause noise pollution, problems with television reception, or interference to radar installations (Pedersena and Waye, 2004). In fact, in the market, there still exist demands for a milliwatt-sized wind generator which is small, simple, and cheap.

Recently, some micro wind energy harvesting devices have been developed. Allen and Smits (2001) investigated the feasibility of placing a piezoelectric membrane in the wake of a bluff body and using the induced Von Karman vortices formed behind the bluff body to induce the oscillations of the membrane which generate an output power. Bryant and Garcia (2011) investigated a novel piezoelectric energy-harvesting device driven by aeroelastic flutter vibrations of a simple pin-connected flap and beam. A maximum power output of 2.2 mW at the flow velocity of about 8 m/s was reported. Sirohi and Mahadik (2009) tested a device that uses a galloping D-shaped beam exciting a PZT piezoelectric beam. It is reported that a maximum power output of 1.14 mW was achieved. Li et al. (2011) proposed and investigated a bio-inspired piezo-leaf architecture which converts wind energy into electrical energy by wind-induced fluttering motion. A series of experiments demonstrated a peak output power of approximately 0.6 mW and maximum power density of approximately 2 mW/cm^3 from a single leaf. Other works on micro wind energy harvester can be found in Tang et al. (2009), Erturk et al. (2010), and Bibo et al. (2011).

In 2007, S. Frayne developed a non-turbine or non-rotary wind energy harvesting device called windbelt, known as an aeroelastic instability

* Corresponding author.
E-mail address: quy.vudinh@hust.edu.vn (V. Dinh Quy).

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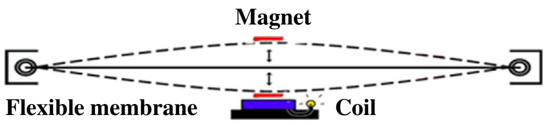

Fig. 1. Principle of operation of windbelt.

energy harvester (AIEH) (Humdinger wind energy LLC, 2007). A windbelt often has three components (Fig. 1): flexible membrane fixed at two ends subject to elastic oscillation, a magnet, and a coil. As the air flows through the membrane at sufficiently high speed, the flutter phenomena happens (Lombard, 1939) and the membrane oscillates. If the magnet is attached to the membrane, it oscillates accordingly. When the coil is put near the magnet, variable magnetic flux will appear through the coil to generate induction electricity in accordance with electromagnetic induction law of Faraday. This device has a typical cut in wind speed of around 2.7 m/s and a peak power output of ~5 mW (Humdinger wind energy LLC, 2007).

Among micro wind energy harvester cited above, windbelt expressed several advantages such as small size, inexpensive, no requirement of high manufacture technology or special materials, easy to repair and maintain, and generating higher output power. However, it is a new development and still has many areas which can be improved upon. There is also a need to make the process of manufacturing more standardized.

The aims of this paper are

- firstly, to investigate experimentally the effects of some parameters such as wind speed, position and size of the magnets, pre-applied tension and angle of attack of the membrane and the direction of the generator on
  + oscillating frequency of the membrane,
  + operational ability of the windbelt;
- secondly, to design and fabricate a windbelt model using optimal parameters deduced from experimental results; and
- finally, to test the fabricated windbelt in both wind tunnel and real wind condition and estimate its output power in order to draw out its potential applications.

Experiment

Test model

The operation of the windbelt is mainly subjected to the oscillation of the flexible membrane. However, the oscillation is affected by a lot of factors which are hardly pre-measured theoretically. Therefore, in order to characterize the performance of the windbelt, we used an experimental method. The main factors which can affect the operational ability of the windbelt are

- pre-applied tension of the membrane,
- angle of attack of the membrane,
- direction of the windbelt,
- position of the magnet, and
- size of the magnet.

In order to investigate the influences of all above factors on the operational ability of the generator, a test model was designed and fabricated as demonstrated in Fig. 2. The main characteristics of the test model are presented in Table 1.

The test model consists of four main components, including

(1) coil: a coil of 2500 rounds of 0.12 mm diameter copper;
(2) magnet: circular-shaped permanent magnet with 10 mm of diameter and 1.5 mm of thickness;
(3) flexible membrane: ripstop nylon fabric (one type of kite fabric) with 10 mm of width and 350 mm of length; and
(4) support: made of 3 mm plywood.

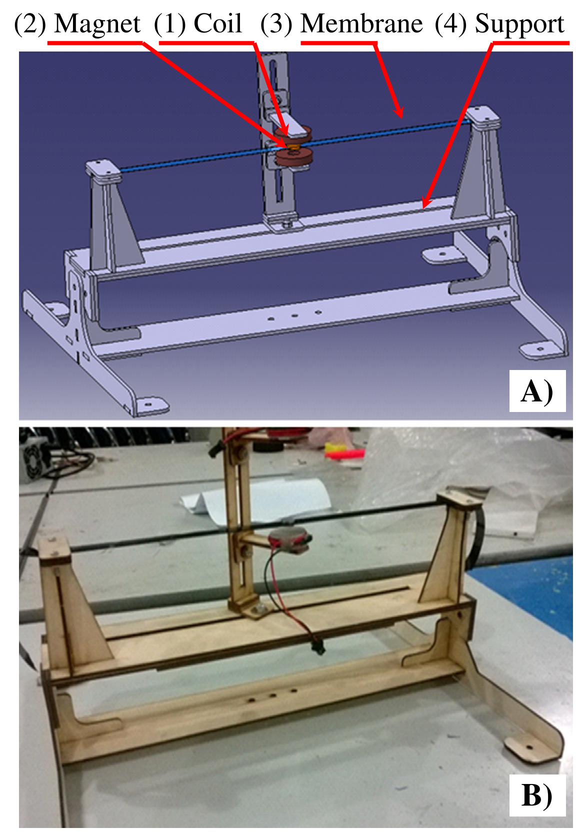

Fig. 2. (A) 3D design. (B) Fabricated test model.

To study effects of different parameters, the test model must satisfy the following requirements:

- operating well in the wind tunnel (Table 2);
- pre-applied tension force, direction, magnet position, membrane's angle of attack can be easily modified.

Experiment setup to study the effects of design parameters on operational characteristics of the windbelt

Fig. 3 shows the experiment setup and also experiment procedure.

The test model is put in the wind tunnel where the air flow velocity (wind speed) can be changed precisely from 0 m/s to about 30 m/s. Air flows through the tunnel as it operates to generate induction power. The output signals (voltage and current) then go through an analog/digital converter which is connected to a computer. Thus, the output voltage and current data will be directly registered, stored, and processed.

Table 1
Characteristics of the test model.

Parameters	Value	Unit
Pre-applied tension	0–50	N
Angle of attack	$0 - \pm\frac{\pi}{3}$	rad
Dimension	$0.35 \times 0.2 \times 0.2$	m
Dimension of membrane	0.01×0.35	m

Table 2
Characteristics of the wind tunnel.

Parameters	Value	Unit
Test section dimensions	1.0 × 0.4 × 0.5	m
Wind speed range	0–30	m/s
Turbulence level	≤0.2	%
Length	7.11	m
Width	1.6	m
Height	2.25	m
Power (*electric motor*)	8.0	kW
Honeycomb flow straightener: expanded aluminum, 0.1 m deep hexagonal cells		

Experiment setup to study the effects of design parameters on the oscillating frequency of the membrane

In this series of experiments, the test model is slightly different from the one used above.

There is a thin and weightless reflective tape fixed on the membrane by a very small carbon fiber rod. This tape is placed parallel to the wind direction. We assume that its presence does not affect the vibration of the membrane. A tachometer measures the rotation speed by sending a laser beam and receiving the reflected signal. In the configuration presented in Figs. 4 and 5, the laser is only reflected when the membrane is at its equilibrium position. Thus, by using the tachometer, we can measure the vibration frequency of the membrane.

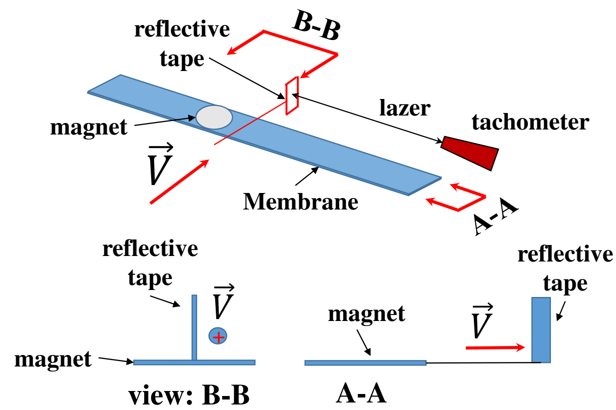

Fig. 4. Measurement of the oscillating frequency of the membrane using a tachometer (1).

Results and discussions

Effects on the oscillating frequency of the membrane

A series of tests were carried out in the subsonic wind tunnel using the experiment setup presented in the section "Experiment setup to study the effects of design parameters on the oscillating frequency of the membrane" to investigate:

- Effects of the pre-applied tension of the membrane on the oscillating frequency.
- Effects of the angle of attack of the membrane on the oscillating frequency.
- Effects of the position of the magnet on the oscillating frequency.
- Effects of the direction of the generator on the oscillating frequency.

Each test was repeated three times to ensure the reliability of the experiment data.

Effects of the pre-applied tension of the membrane on the oscillating frequency

Fig. 6 shows the evolution of the oscillating frequency with respect to the pre-applied tension of the membrane at different wind speed of 2, 4, 6, and 8 m/s. The curves show that the frequency increases strongly with the increase of the pre-applied tension.

Alternatively, by analyzing the videos recorded during the experiments for each pre-applied tension, we observed that, unlike frequency, the oscillating amplitude decreases with the increase of the pre-applied tension.

Fig. 7 shows the evolution of the oscillating frequency with respect to the wind speed at different pre-applied tensions of 5 N, 10 N, 15 N, and 20 N. The results show that the oscillating frequency does not depend on the wind speed. For each value of the pre-applied tension, the membrane vibrates at almost the same frequency while increasing the wind speed from 2 to 12 m/s. With a small pre-applied tension (5 N in our case), the oscillation becomes unstable when the wind speed is too high (above 8 m/s) and we cannot measure the oscillating frequency.

Effects of the angle of attack of the membrane on the oscillating frequency

Fig. 8 shows the evolution of the frequency with respect to the wind speed while the angle of attack of the membrane (Fig. 7) varies from 0° to 20°.

The frequency does not depend on the wind speed as shown in the section "Effects of the pre-applied tension of the membrane on the oscillating frequency." In Fig. 8, we can see that the curves of different angles of attack almost correlate with each other; it shows that the angle of attack of the membrane (or windbelt) does not affect the oscillating frequency. However, by analyzing the videos recorded during the experiments, we observed that the oscillating amplitude increases by increasing the angle of attack.

Effects of the position of the magnet on the oscillating frequency

The relative position of the magnet is defined in Fig. 9. In this series of tests, we placed the magnet at 25%; 35% and 50% of the membrane length, respectively.

Once again, we can see in the Fig. 10 that the oscillating frequency is not affected by the wind speed. For all positions of the magnet, the

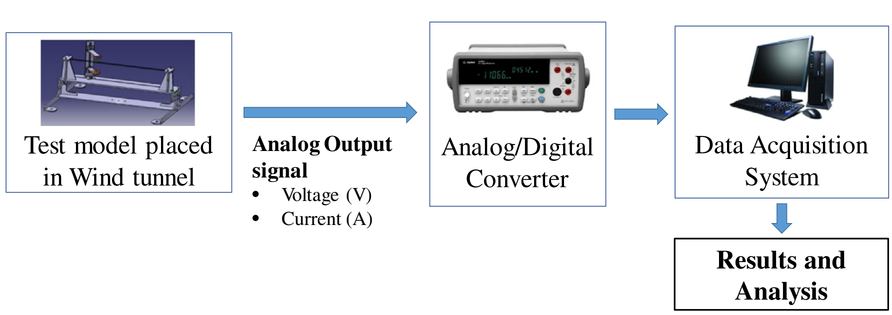

Fig. 3. Experiment procedure.

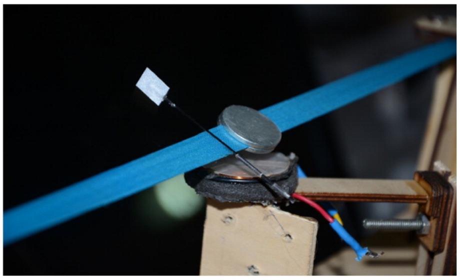

Fig. 5. Measurement of the oscillating frequency of the membrane using a tachometer (2): actual setup.

membrane vibrates with almost the same frequency while increasing the wind speed from 2 to 12 m/s.

At the same wind speed, we can observe that the oscillating frequency decreases strongly when moving the magnet to the center of the membrane (from 25% to 50%).

General conclusions of the effects on oscillating frequency

From the experimental results, we draw out some general conclusions as follows:

- The oscillating frequency increases strongly by increasing the pre-applied tension.
- The oscillating frequency decreases strongly by moving the magnet toward the center of the membrane.
- The oscillating frequency does not depend on the angle of attack of the membrane.
- Most importantly, the oscillating frequency does not depend on the wind speed. This is not how we thought before carrying out these experiments.

The oscillating frequency mostly depends on the position of the magnet and the pre-applied tension of the membrane. However, during the operation, those parameters are fixed. This causes the oscillating frequency of the membrane unchanged. Therefore, the frequency of the output current can be considered constant.

Effects of design parameters on the operational ability of the windbelt

A series of tests were carried out in the wind tunnel using the experiment setup presented in the section "Experiment setup to study the effects of design parameters on operational characteristics of the windbelt" to investigate

- effects of the pre-applied tension of the membrane on the critical and maintaining wind speed;
- effects of the angle of attack of the membrane on the critical, maintaining wind speed and the generated power;
- effects of the position of the magnet on the output voltage and current;
- effects of size of the magnet on the output voltage and current; and
- effects of the direction of the device on the output voltage and current.

Each test was repeated three times to ensure the reliability of the experiment data.

Effects of the pre-applied tension of the membrane on the critical and maintaining wind speed

The generator does not operate at any wind speed. When the wind speed is sufficiently high, the membrane and the magnet start vibrating. In this study, we consider two values of the wind speed, which are

- critical wind speed: the wind speed at which the magnet reaches its stable oscillation;
- maintaining wind speed: the minimum speed at which the magnet's oscillation remains stable.

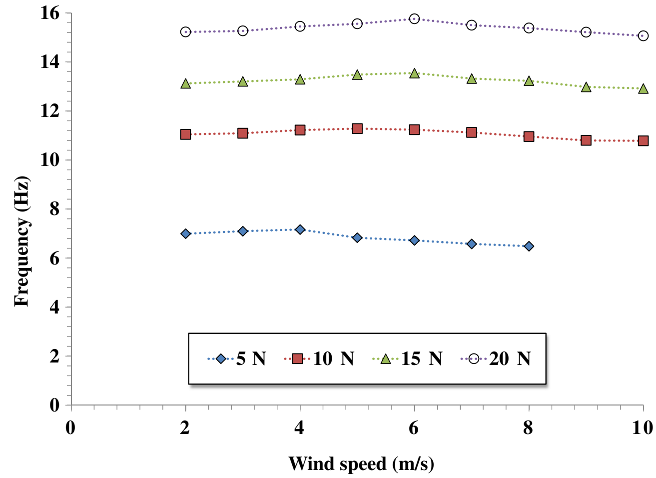

Fig. 7. Evolution of the oscillating frequency with respect to the wind speed at different pre-applied tensions: 5 N; 10 N; 15 N; 20 N.

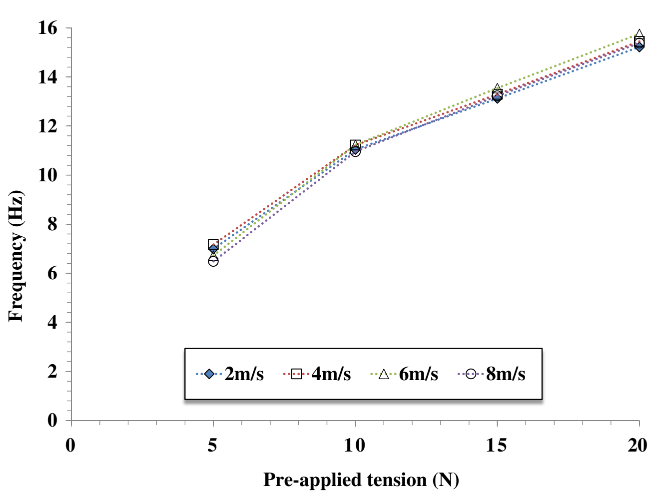

Fig. 6. Evolution of the oscillating frequency with respect to the pre-applied tension.

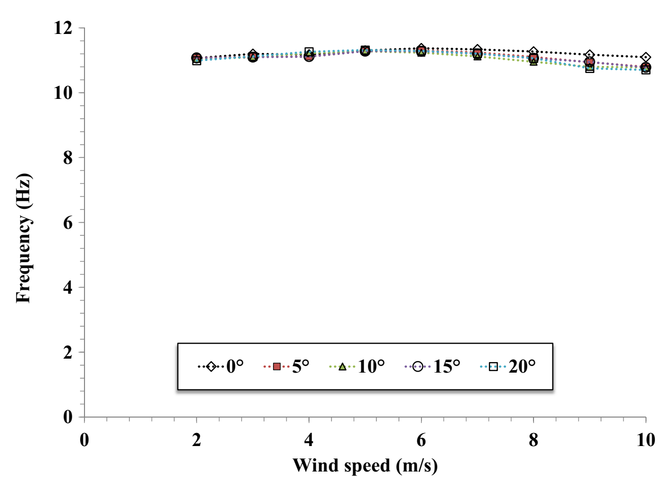

Fig. 8. Effects of the angle of attack of the membrane on the oscillating frequency.

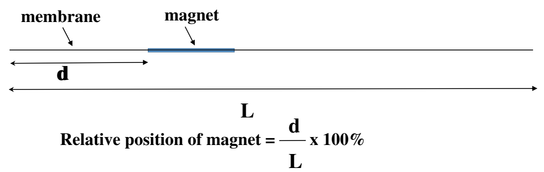

Fig. 9. Definition of the relative position of the magnet on the membrane.

At each pre-applied tension, we vary the wind speed from 0 m/s at the interval of 0.5 m/s and observe the oscillation of the membrane and the magnet. Fig. 11 shows the evolution of the critical and maintaining wind speed in function of the pre-applied tension of the membrane.

It can be seen that critical wind speed for the membrane to oscillate depends on the pre-applied tension. The tauter the membrane is pre-applied, the higher wind speed is required for the membrane to oscillate. In addition, the maintaining wind speed is always lower than the critical wind speed.

Therefore, it is required to choose the appropriate pre-applied tension of the membrane in regarding on the wind speed. The generator will be unable to operate in normal condition if the membrane is too taut.

Effects of the angle of attack of the membrane on the critical and maintaining wind speed

These tests study the effects of the angle of attack on the critical wind speed and maintaining wind speed of the generator. The variation of the angle of attack to a value other than zero shall be considered in order to initiate the oscillation of the membrane. In this series of tests, the membrane was pre-applied with the tension of 10 N. At each angle of attack, we vary the wind speed from 0 m/s at the interval of 0.5 m/s until reaching the critical wind speed.

The evolution of the critical and maintaining wind speed is presented in Fig. 12. We can observe that when the value of the angle of attack is other than zero, the critical wind speed for the generator to operate is reduced slightly. Particularly, the higher the angle of attack is, the lower the critical wind speed is; this is to say, the higher the advantage is. However, the experimental test demonstrated that too high value of the angle of attack will lead to an unstable oscillation of the magnet.

*Notes: In the experiments presented the section "Effects of the pre-applied tension of the membrane on the critical and maintaining wind speed," the coil is placed as close to the magnets as possible in order to obtain the maximum power, but in the experiments in the section "Effects of the angle of attack of the membrane on the critical and maintaining wind speed" the coil must be placed far enough to the magnets to avoid the collision when the membrane is not very taut. Therefore, the effects of the air flows through the coil (aerodynamics forces) on the oscillation of the magnet are different in these two cases. This leads to the fact that the critical and maintaining wind speed in those sections (at the angle of attack of 0^0 and at the pre-applied tension of 10 N) are significantly different.

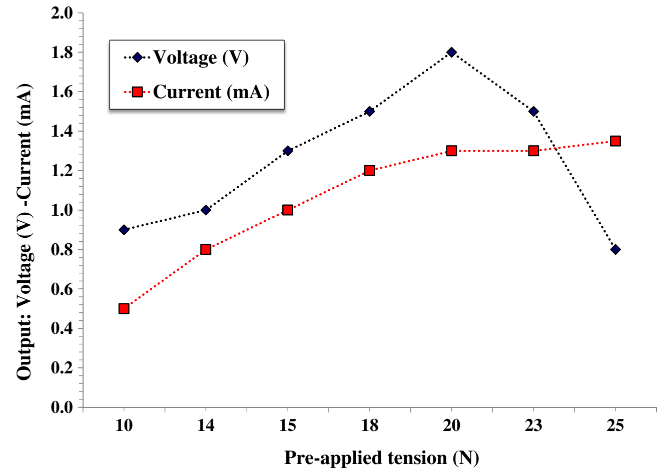

Fig. 11. Effects of the pre-applied tension of the membrane on the critical and maintaining wind speed.

Effects of the angle of attack on the generated power

In the above experiment, we have concluded that the angle of attack other than zero is more advantageous with respect to the minimum wind speed. However, we also need to consider the effects of the angle of attack on the output current before drawing final conclusions on the advantages of the angle of attack's values other than zero. This series of tests were carried out at the wind speed of 7 m/s, the membrane is pre-applied with the tension of 10 N.

Fig. 13 shows the evolution of the output voltage with respect to the angle of attack. It can be seen that the higher the angle of attack is, the higher the output voltage is generated; this is to say, the generator operates more effectively.

When manufacturing the generator for practical operation, if the wind direction is stable, we can initially set the angle of attack at a high value for a higher efficiency of the generator. In case the wind direction is unstable, we can install the generator in a fixed direction

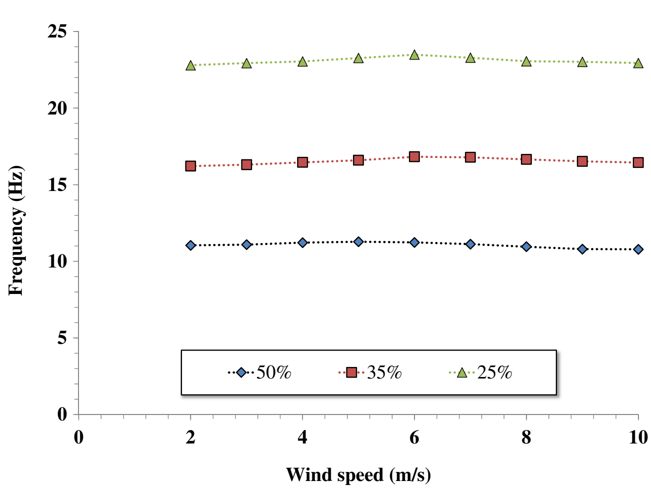

Fig. 10. Effects of the position of the magnet on the oscillating frequency.

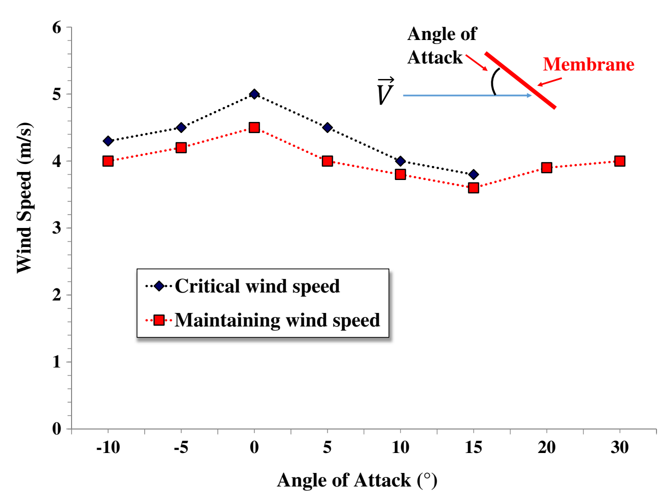

Fig. 12. Effects of the angle of attack of the membrane on the critical and maintaining wind speed.

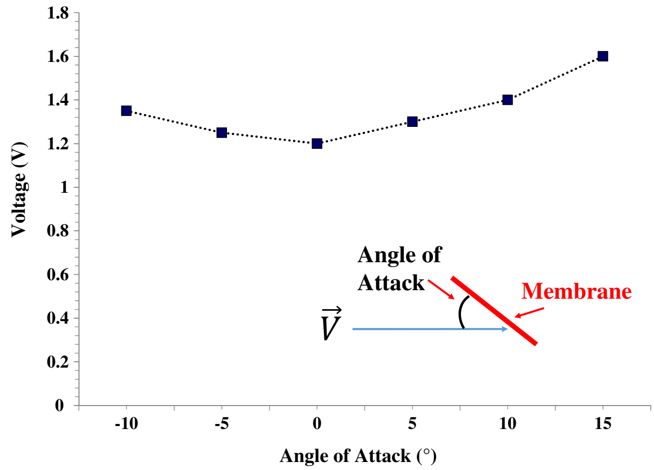

Fig. 13. Effects of the angle of attack on the output voltage.

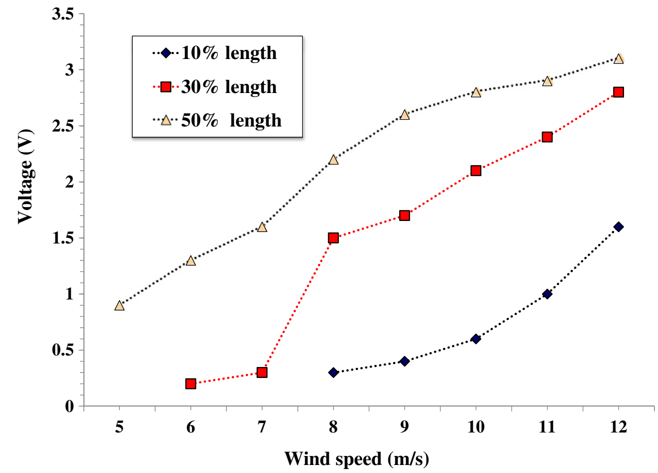

Fig. 15. Effects of the magnet position on the output voltage.

and still ensure that its capacity will be reduced insignificantly in constantly changeable wind direction.

Effects of the direction of the generator (horizontal or vertical)

As we already know, when the generator is placed horizontally, the weight of the magnet will be perpendicular to the membrane. However, in case it is placed vertically, the weight will be axial to the membrane. In this test, we consider the effects of the generator direction on its performance.

Fig. 14 shows the comparison of the evolutions of the output voltage with respect to the wind speed when the generator is placed horizontally and vertically. We can see that two curves are nearly coincident, the difference of voltage is insignificant. Therefore, the operating direction of the generator does not have significant effects on the generator performance. We can choose the appropriate placing direction in regarding to the installation and using conditions.

Effects of the position of the magnet

In the above tests, we always put the magnet in the middle of the membrane. However, in this experiment, we consider how the magnet position affects the performance of the generator.

Fig. 15 presents the output voltage with respect to the wind speed when the magnet is located at 10%, 30%, and 50% length of the membrane. The results show that the closer to two ends of the membrane the magnet is, the higher the critical wind speed is. In addition, it can be seen that the closer to the center of the membrane the magnet is, the higher the output voltage is generated. Therefore, setting the magnet at the center of the membrane will bring about the best performance. However, in specific cases, we can put the magnet at small deviation to the center but not too close to the two ends of the membrane.

Effects of the size of the magnet

The flutter aeroelastic phenomenon occurs in the combination of aerodynamic force, elastic force, and inertial force. The variation of the size of the magnet leads to the change of the inertial force which affects the self-oscillation of the magnet. This experiment will consider the effects of the magnet size on the output voltage of the windbelt.

Fig. 16 presents the evolution of the output voltage of the windbelt with respect to the wind speed when using three different magnet sizes: small (diameter of 7 mm, thickness of 1.5 mm), medium (diameter of 10 mm, thickness of 1.5 mm), and big (diameter of 20 mm, thickness of 1.5 mm). We can observe that the bigger the size of the magnet is, the lower the critical wind speed is. The output voltage of the generator with the big magnet is also much higher than that with the small magnet. However, at a high wind speed, the generators using small and medium magnets may also generate increased voltage but the generator with the big magnet soon reaches a wind speed at which the generated voltage increases slightly as the wind speed increases.

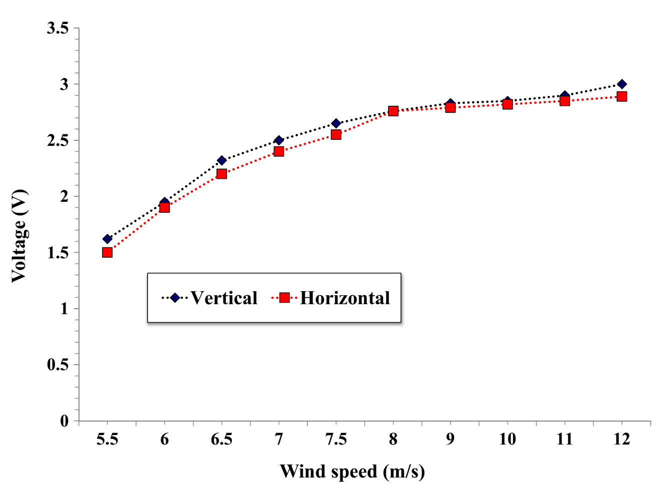

Fig. 14. Effects of the generator direction on the output voltage.

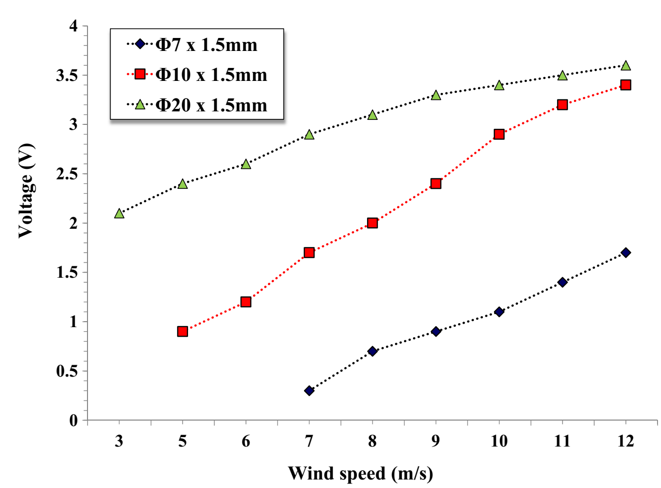

Fig. 16. Effects of the size of the magnet on the output voltage of the windbelt.

Table 3
Parameters of the single membrane generator.

Parameters	Value	Unit
Pre-applied tension	20	N
Angle of attack	0	rad
Magnet size (*Φ × thickness*)	Φ0.02 × 0.0015	m
Dimension (*L × H × W*)	0.35 × 0.2 × 0.2	m
Membrane (*L × W*)	0.35 × 0.01	m
Coil (*Φ 0.12 mm copper*)	2500	round

General conclusions

From the experimental results, we can give some general conclusions as follows:

- Effects of the pre-applied tension of the membrane:
  - o The higher the tension force is, the higher possibility of the magnet operating towards angular oscillation is.
  - o The tauter the membrane is, the higher the minimum wind speed required for the generator operation is.

- Effects of the angle of attack of the membrane:
  - o The higher the angle of attack is, the lower the wind speed required for operation is.
  - o Angle of attack values other than zero provide a better performance. A great angle of attack leads to an inefficient operation of the generator.

- Effects of the direction of the generator (vertical or horizontal): the direction of the generator has the insignificant effects on its performance.
- Effects of the magnet position: the closer to the center the magnet is, the higher the critical speed and the performance of generator are.
- Effects of the size of the magnet: The big magnets provide significantly better performance than the small ones.

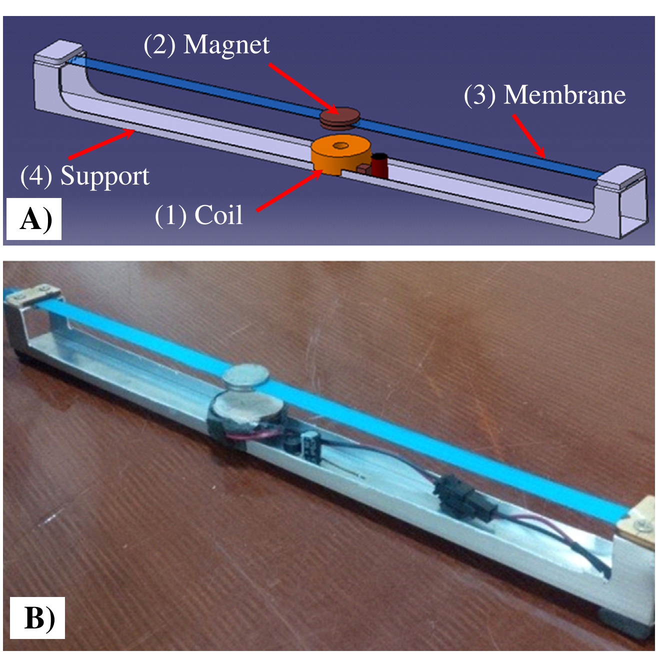

Fig. 17. Single membrane generators: (A) 3D design. (B) Fabricated model.

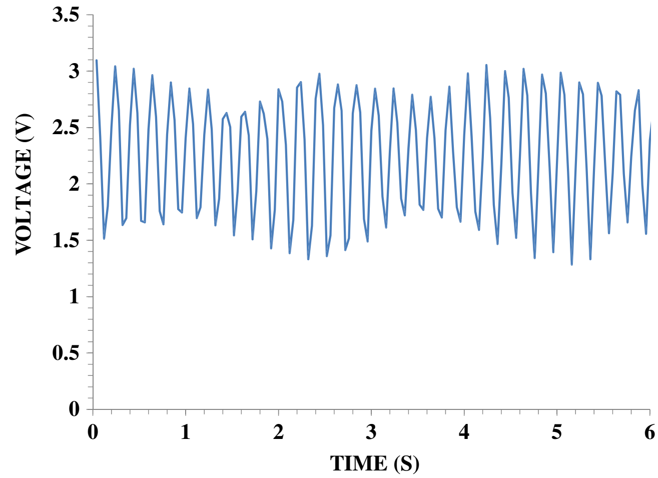

Fig. 18. The output voltage of the single membrane generator at the wind speed of 3 m/s.

Design, fabrication, and testing of the micro wind generators

From the general conclusions of the effects of some main factors on the operation performance of the generator, we design, fabricate, and test two generator models using optimal parameters:

- Model 1: single membrane generator, windbelt.
- Model 2: multi-membrane generator, windpanel, by combining multi single membrane generators.

Single membrane generator: Windbelt

The main parameters of the single membrane generator are presented in Table 3.

Fig. 17 presents the 3D design and fabricated single membrane generator using the parameters in Table 3.

The single membrane generator is tested in the wind tunnel at different wind speeds to evaluate its performance including voltage, ampere, and power.

The output voltage of the single membrane generator by time at the wind speed of 3 m/s is presented in Fig. 18. It can be seen that the value of the voltage is varied in sine-wave form corresponding to the rotary oscillation of the magnets. In addition, the voltage amplitude also varies

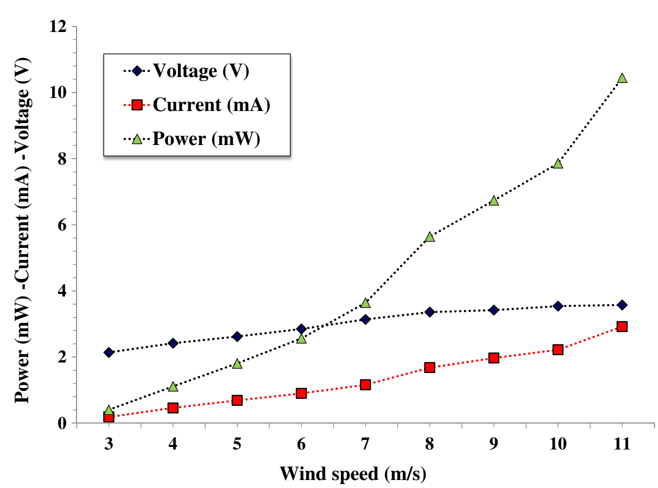

Fig. 19. The output voltage, current, and power of the single membrane generator with respect to the wind speed.

Fig. 20. Testing the single membrane generators in outdoor condition.

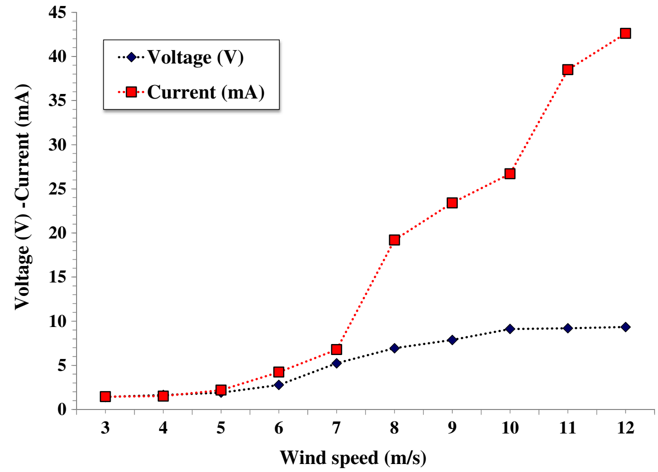

Fig. 22. The output voltage and current of the windpanel with respect to the wind speed.

in sine-wave form, which is due to the up and down movement of the magnets.

Fig. 19 presents the output voltage, current, and power of the single membrane generator with respect to the wind speed. We can observe that, at low wind speed (3–6 m/s), the output current is about 0.2–0.5 mA, the voltage is about 2–2.5 V, the frequency is approximately 5 Hz, and the generated power is about 2–3 mW.

The generator was also tested in outdoor wind conditions to power a LED light (Fig. 20). The voltage and current measured are approximately 2.5 V and 2 mW, respectively.

The authors observe that the generator worked well in normal wind condition; its output capacity may be used to power some small electronic devices such as led light, sensor, chip.

Multi-membrane generator: Windpanel

After the successful design, fabrication, and testing of the single membrane generator, we combined several single membrane generators to form a windpanel in order to increase the output performance. We can combine the windbelts in series or in parallel to generate expected voltage and current. The design of the windbelt is improved to be easily combined as well as separated. In this windbelt, we use 2 coils of 4000 rounds placed symmetrically through the magnets and in parallel with each other.

Fig. 21 demonstrates a windpanel combining five windbelts. The generator is put horizontally.

When combining windbelts to form a windpanel, it should pay attention to the avoidance of the mutual effects among the magnets. In fact, when the magnets are put closely to each other, in addition to aerodynamic force, inertial force, and elastic force, the affecting forces will include attractive force of the magnets. Accordingly, the flutter phenomenon would not be as expected.

Firstly, the windpanel model was put into the wind tunnel to measure the output current, voltage, and power at various wind speeds. Figs. 22 and 23 present the output voltage, current, and power of the windpanel measured in wind tunnel at different wind speeds. We can observe that the windpanel generates the power of about 50 mW at the wind speed of 7 m/s and the output power increases sharply as the wind speed increases.

In outdoor wind conditions at the wind speed of about 8 m/s, the windpanel operates stably and generates the power of about 100 mW which is sufficient to power a small LED light (Fig. 24). The authors observed that the generator operated well in normal wind condition; its output capacity is high enough to power some electric and electronic devices.

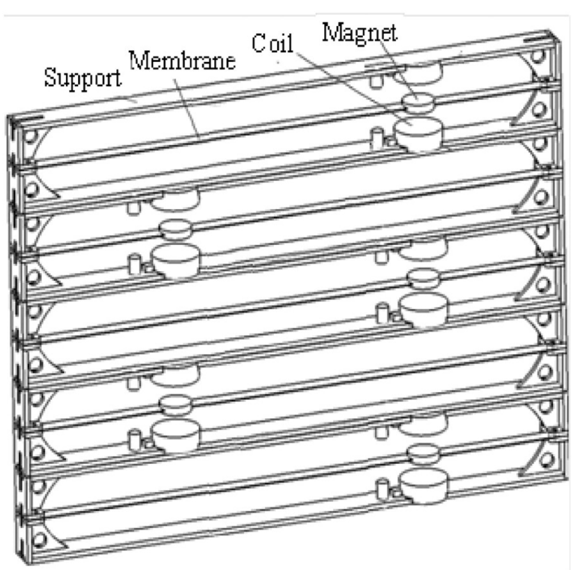

Fig. 21. The 3D design of the windpanel combining 5 windbelts.

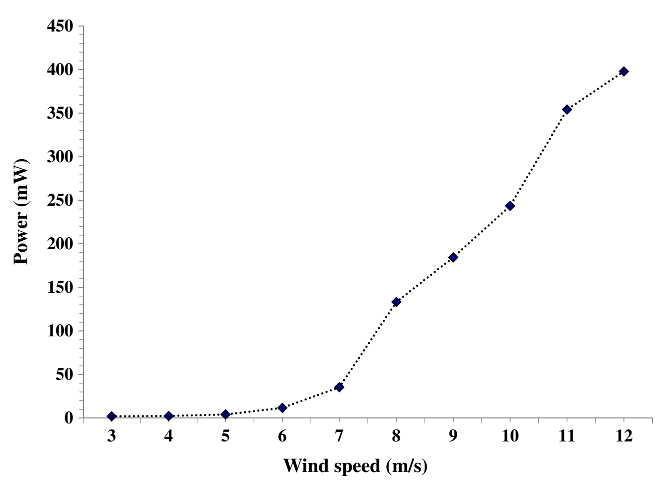

Fig. 23. The output power of the windpanel with respect to the wind speed.

Fig. 24. Testing of the windpanel powering a LED light in real wind condition.

Conclusions

In this paper, the influences of design parameters such as wind speed, position and size of the cap magnets, pre-applied tension and angle of attack of the flexible membrane and direction of the generator on the output power, and frequency of a micro generator powered by fluid-induced flutter (called windbelt) were investigated. The results show that the oscillating frequency strongly depends on the position of the magnet and the pre-applied tension of the membrane. It can be explained by the fact that they are intrinsic parameters of the system. However, during the operation of the windbelt, those parameters are fixed. Therefore, the frequency of the output current can be considered constant.

From experimental results, we can give some conclusions about the effects of design parameters on operational capability of the windbelt as follows:

- Effects of the pre-applied tension of the membrane:
  - o The higher the tension force is, the higher possibility of the magnet oscillating towards angular mode is.
  - o The tauter the membrane is, the higher the minimum wind speed required for generator operation is.

- Effects of the angle of attack of the membrane:
  - o The higher the angle of attack is, the lower the wind speed required for operation is.
  - o Angle of attack values other than zero provide a better performance. A great angle of attack leads to an inefficient operation of the generator.

- Effects of the direction of the windbelt (vertical or horizontal): Direction of the generator has insignificant effects on its performance.
- Effects of the position of the magnet: the closer to the center the magnet is, the higher the critical wind speed and the performance are.
- Effects of the size of the magnet: Big magnets provide significantly a better performance than small ones.
- Two micro generators were fabricated with the optimal parameters deduced from the experimental results and tested in both wind tunnel and real condition. It was shown that the single micro generator (windbelt) can generate the power of from 3 to 5 mW and the windpanel combining five single windbelts (larger ones) can generate the power of from 30 to 100 mW at the wind speed of less than 8 m/s.

In this paper, the size of the testing model was limited by the size of the testing section of the wind tunnel. However, it is interesting to employ a larger wind tunnel in order to investigate the effects of the length of the flexible membrane on the performance of the windbelt.

Also, it was shown that the effects of the angle of attack of the membrane on the critical wind speed and the output voltage of the windbelt are not negligible. Thus, it is interesting to design an inlet to guide the airflow toward the membrane with an appropriate angle of attack without regarding on the wind direction.

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