A miniature airflow energy harvester from piezoelectric materials

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Abstract. This paper describes design, simulation, fabrication, and testing of a miniature wind energy harvester based on a flapping cantilevered piezoelectric beam. The wind generator is based on oscillations of a cantilever that faces the direction of the airflow. The oscillation is amplified by interactions between an aerofoil attached on the cantilever and a bluff body placed in front of the aerofoil. A piezoelectric transducer with screen printed PZT materials is used to extract electrical energy. To achieve the optimum design of the harvester, both computational simulations and experiments have been carried out to investigate the structure. A prototype of the wind harvester, with the volume of 37.5 cm^3 in total, was fabricated by thick-film screen printing technique. Wind tunnel test results are presented to determine the optimum structure and to characterize the performance of the harvester. The optimized device finally achieved a working wind speed range from 1.5 m/s to 8 m/s. The power output was ranging from 0.1 to 0.86 μW and the open-circuit output voltage was from 0.5 V to 1.32 V.

1. Introduction

Energy harvesting, also known as energy scavenging, describes the process of capturing the ambient energy and then converting it into electrical energy. Large scale energy harvesting has been applied for centuries in the form of windmills, watermills and passive solar power systems etc. With the advance of microelectronic technology such as wireless sensors, micro-energy harvesting attracts more attention [1].

For airflow energy harvesting, the most common and widely used devices are wind turbines. Although most wind turbine generators are used in large-scale applications, some researchers have designed wind turbines in smaller scales. Holmes *et al* [2] from Imperial College have reported some micro wind turbines with electromagnetic generators, of which the rotor area was down to approximately 1.5 cm^2. An output power of 4.3 mW at average flow speed of 10 m/s was achieved. Priya *et al* [3] have combined small windmills with piezoelectric material for energy harvesting and managed to achieve a 5 mW continuous power at flow speed of 4.5 m/s. For wind turbine generators, due to the increased friction losses of the bearings and the reduced surface area of the blades, the efficiency of conventional turbines reduces with size.

This concern is addressed in many novel approaches for wind energy harvesting based on vortex induced vibration, aeroelastic flutter, wake galloping and other aero-elastic instability phenomena. The windbelt which utilizes aeroelastic flutter phenomenon showed power outputs in milliwatt range, but suffered from a threshold wind speed of 3 m/s [4]. Li *et al* [5] suggested a flapping piezo-leaf-based wind generator using PVDF material, which produced an output power of 1.8 μW at a flow speed of

3.5 m/s due to the low piezoelectric strain coefficient of flexible materials. A device by Bryant and Garcia [6] used a cantilevered piezoelectric bender based on aeroelastic flutter vibrations which showed a minimum threshold wind speed lower than 2 m/s. However the bender was over 25 cm long which was too large for microelectronic systems and the efficiency at small scale was unclear. Zhu *et al* [7] proposed a promising flow-induced energy harvester using oscillatory cantilevered wing that can operate at wind speeds as low as 2.5 m /s with a corresponding electrical output power of 470 μW. When the wind speed was 5 m/s, the output power was 1.6 mW.

Most researchers reviewed above have investigated airflow induced energy harvesters with electromagnetic transducer or piezoelectric transducer made from flexible materials such as PVDF. This paper report an oscillating airflow generator utilizing screen printed PZT materials. The strategy in this work lies in building the harvester with an optimum structure for a wider air speed range for operation. To do this, both computational simulations and experiments are carried out. Final the test results of the prototype are presented and discussed.

2. Theory

The wind generator presented here is based on oscillations of a cantilever that faces the direction of the airflow. An aerofoil is attached to the free end of the cantilever spring while the other end is clamped as shown in figure 1. If there is no wind, the aerofoil will slightly bend downward due to gravity. When air is flowing towards the aerofoil, it will bend upward and the degree of bending is related to the spring constant, mass and the lift/drag force form the aerofoil caused by the flow. In this condition, however, the cantilever will remain still with a static deflection without oscillation. In order to oscillate the cantilever, a bluff body is required to be placed in front of the cantilever which reduces the flow of air behind the bluff body and thus the lift force, causing the cantilever to operate primarily under inertial effects and spring back. However when the cantilever is springing back to the original position where the aerofoil can be fully exposed to the airflow again, energy can be extracted from the wind and the cycle is repeated. Such a configuration can self-start and sustain the necessary oscillations under uniform and steady flow conditions. In addition, this device can potentially operate at a lower flow speed. By attaching the aerofoil to the free end, the deflection of the beam can be larger and its performance can be better tuned for various flows. The position of the bluff body, both its distance to the cantilever and its height affect the oscillations of the cantilever.

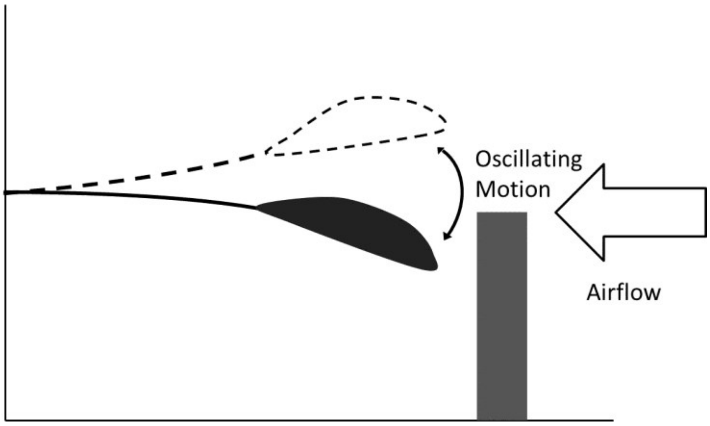

Figure 1. Operation principle of the flapping generator.

3. Design and Fabrication

3.1. Simulation Model

To assess the effect of the bluff body and the attack angle of the aerofoil, series of finite element simulations were conducted using ANSYS CFX. For simplification, a static analysis model was set up to estimate the lift force applied on the wing, which was used as a guide to determine the threshold wind speed of the device. Since the consequence that a large lift force acting on aerofoil will provide a relatively low threshold wind speed, configurations generating larger lift force should correspond with those having lower threshold wind speed. The simulation parameters to be studied included the distance from the cantilever, the height of the bluff body, and the attack angle of the aerofoil. Results from different configuration arrangements were compared and plotted using ANSYS commercial package for Design Optimization. Figure 2 and 3 show how the lift force changes with the position of the bluff body and the attacking angle respectively. As seen in these figures, the maximum values of the lifting force, which indicate lower threshold wind speed, occur at distances from 3 mm to 10 mm and heights from 18mm to 21mm, and attack angle from 5°-8°. These results will be compared with the experimental results in the later section. It should be noted that simulation in this section was purely on mechanical structure and the transducer was not taken into account.

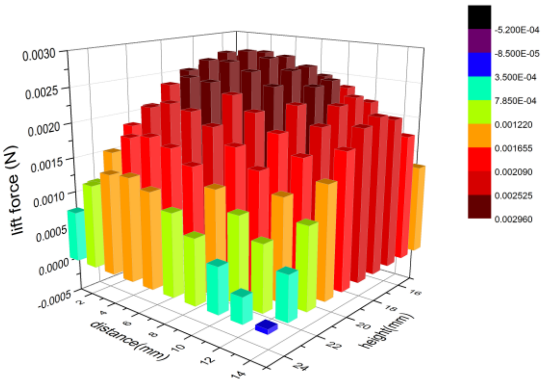

Figure 2. 3D bar chart of the lift force with different heights and distances from bluff body. (Attack angle of 5° is taken as an example.)

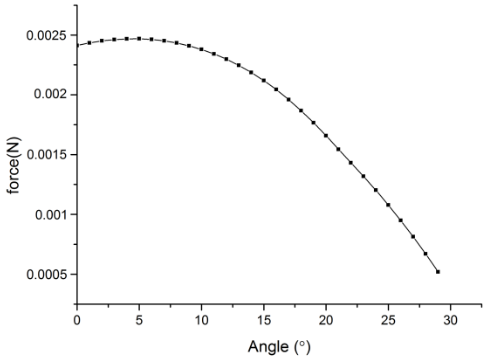

Figure 3. Lift force at different attack angles with the same height and distance. (Distance of 28 mm and height of 15 mm is taken as an example.)

3.2. Fabrication Process

A prototype of the wind harvester, with the volume of 37.5 cm^3 in total is shown in figure 4. Both the base of the generator and the bluff body were made of acrylic. The cantilever was made of type 304 stainless steel and had dimensions of 30 mm × 5 mm × 0.08 mm. The wing, made of balsa wood, was an aerofoil with shape of profile NACA 4424 whose dimensions were 30 mm × 11 mm × 5 mm. The overall mass of the wing was 0.25 grams. The piezoelectric transducer was fabricated by normal thick-film screen printing steps including paste preparation, screen-printing deposition, drying, firing and poling process [8]. After printing, samples were poled using a hot plate at 225 °C and an applied electric field of 3.5 MV/m. Finally, 6 samples that achieved maximum piezoelectric property d_{33} of 130 pC/N approximately were selected for testing.

3.3. Experimental Work

Tests were carried out in the centre of a wind tunnel, where the air flow generated by a centrifugal fan was conducted by a steel air duct of approximately 2 m in length. Another transparent dust was connected to the steel duct so that oscillation of the harvester can be observed during the test. The cross section of the opening window was 20 cm×35 cm. Some small holes in the ducting allowed for an anemometer probe to be inserted measuring the flow speed. The anemometer has a 2% precision error. Airspeed can be adjusted by the fan using a controller, which allows tests from 0 to 8 m/s. Since the speed level of air turbulence changes slightly at different position in the wind tunnel, the harvester was placed near to the end of the steel duct where the air flow is most steady. During the tests, the voltage across a load resistance was measured with an oscilloscope in order to determine the power generated by the wind energy harvester, meanwhile the operation wind speeds of the harvester were measured by the anemometer.

4. Results

The objective of the experimental analysis was to explore the influence of the bluff body and attacking angle on the power output and threshold wind speed. In this work, the threshold wind speed is defined as the airflow speed at which a peak-to-peak displacement of the wing is over 1 cm. After testing and comparison, the experimental results showed relatively good correlation with the simulation in ANSYS (shown in table 1). Both results verify that to achieve the lowest threshold wind speed, optimum positions of the bluff body are approximately between 3 mm to 10 mm in horizontal distance and 18 mm to 20 mm in vertical distance with attack angle around 6°- 8°, which validates the simulation model used in this study. For further investigation of the performance, four configurations were designed using results above. As seen in figure 5, the power outputs with various bluff body positions were tested. The maximum output power occurred in 7m/s wind speed from a configuration with distance of 11 mm and height of 16 mm, which was chosen for final tests. It can also be observed that at distance smaller than 5 mm, performance at high wind speed was not stable, thus resulting in even lower power output. After testing, the optimized device achieved a working wind speed range from 1.5 m/s to 8 m/s. The power output with optimal load (800 kΩ) was ranging from to 0.1 μW to 0.86 μW and the open-circuit output voltage was from 0.5 V to 1.32 V (shown in figure 6 and figure 7 respectively). Results verified the harvester can effectively convert wind energy into large amplitude mechanical vibration without strict frequency matching constraints. However, the power generated is not as large as expected due to the added stiffness of the beam from the presence of the printed piezoelectric layers and this will be improved in the future by increasing the length of the piezoelectric part of the beam.

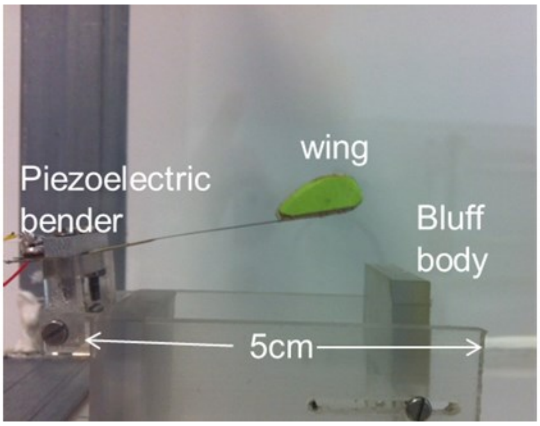

Figure 4. Prototype of the energy harvester oriented for airflow from right to left.

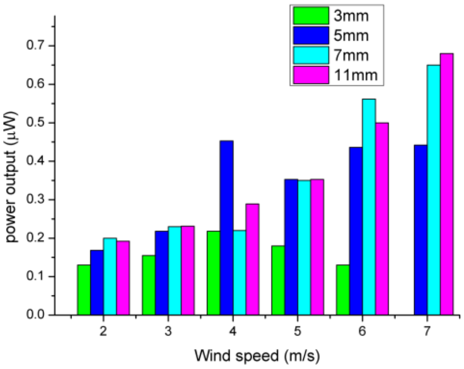

Figure 5. RMS power outputs in varying flow speed conditions of four configurations (Attack angle is 7°, distances are 3mm, 5mm, 7mm and 11mm and heights are 19 mm, 18 mm, 17 mm and 16 mm respectively)

Table 1. Comparison of optimal configurations of the harvester in simulation and test results.

	Simulation Analysis	**Wind Tunnel Tests**
Attack angle of aerofoil	5°-8°	6°-10°
Height of the bluff body	18 mm-21mm	17 mm-20 mm
Distance between bluff body and aerofoil	3 mm-10 mm	3 mm-11mm

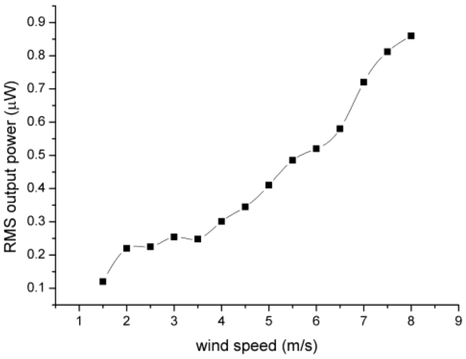

Figure 6. RMS Output power in varying flow speed conditions with optimal configuration and load (plotted line was used to indicate the trend)

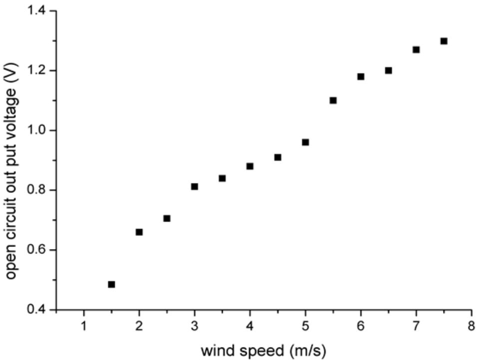

Figure 7. Open circuit output voltages in varying flow speed conditions with optimal configuration and load

5. Conclusion

In this report, a miniature, scalable piezoelectric wind generator was proposed and investigated theoretically, numerically and experimentally. The volume of the device was 37.5 cm^3 in total. The significance of this work lied in building the harvester with an optimum structure for wider wind speed range for operation. Final device achieved a working wind speed range from 1.5m/s to 8m/s with optimum structures and a maximum power output of 0.86 μW. The open-circuit output voltage was from 0.5 V to 1.32 V.

References

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