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# Piezoelectric Clamped Beam Energy Harvester Using Vibration Caused by Centrifugal Force at High Wind Speeds

DOI 10.1515/ehs-2016-0023

**Abstract:** In this study, a piezoelectric wind energy harvester was vibrated that aims to convert high-speed wind energy into electrical energy using vibrations caused by centrifugal force. Vibrations induced by centrifugal force enabled effective distortion of the piezoelectric clamped beam and thus produced electric charge through the piezoelectric effect. A clamped beam was used rather than a conventional thin cantilever to harvest the wind energy in the proposed harvester. The centrifugal force was introduced by a pair of rotating eccentric turbines that are installed on two ball bearings on both sides of the piezoelectric unimorph. Benefiting from the rotating eccentric masses of these turbines, the harvester is capable of capturing wind energy in high speed wind environments. A prototype was set up to examine the effects of the wind speed and the structural parameters on the electrical output of the harvester. It is found that the harvester worked efficiently with wind applied from the axial directions in a 20–55 m/s speed range and produced a maximum open-circuit voltage of 47.2 V. When connected to an external load of 50 kΩ, the harvester showed a peak output power of 3.69 mW at a wind speed of 55 m/s.

**Keywords:** energy harvesting, high wind speed, eccentric turbines, vibration, piezoelectric

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## 1 Introduction

In modern society, the exploration of new energy sources that provide renewable, sustainable, and environmentally friendly energy has become a serious challenge (Priya 2007). With the ongoing developments in wireless technology and microelectromechanical systems (MEMS), great progress has been made in the development of miniaturized, low power consumption electronics for applications in aerospace, construction, transportation, medicine and other fields (Truitt and Nima Mahmoodi 2013; Tsai, Wang, and Su 2014; Collins 2006). The use of piezoelectric materials to harvest ambient energy sources has also been investigated for sources including wind energy, thermal energy and even light energy (Holdren 2007; Cook-Chennault et al. 2008; Bose and Valan Arasu, 2016; Chen et al. 2015). Many studies have demonstrated that the energy from air flow is a greater potential power source than most of the available ambient energy sources (He and Gao 2013; Erturk, Hoffmann, and Inman 2009; Beeby, Tudor, and White 2006). These investigations have also explored mechanisms to convert mechanical vibration energy into electrical energy using piezoelectric materials. The energy density of piezoelectric materials is higher than that of electrostatic and electromagnetic materials (Khameneifar, Moallem, and Arzanpour 2010; Daniels, Zhu, and Tiwari 2013). Over the last decade, numerous energy harvesters that use piezoelectric materials to capture wind flow energy have been successfully designed and assembled. Myers et al. investigated a wind energy harvester using a small-scale windmill that was tested at average wind speed of 4 m/s and provided 5 mW output power (2007). Zhao et al. designed an arc-shaped elastic beam, rather than the conventional thin cantilever beam, to extract wind energy, and their harvester showed a peak output power of 1.73 mW at 17 m/s (2015). Zakaria et al. discussed the complex relationship between aerodynamic loading and its effects on static deflection and amplitudes (2015). Li et al. designed an ambient wind energy harvester using cross-flow fluttering, and prototypes were produced using flexible piezoelectric materials (2011). Li et al. designed a resonant frequency excitation device using a beam clamped at both ends to capture its highest displacement vibration energy (2011). These studies show that electrical energy can be generated from vibration, bending and impact. However, only high-strength structures can work at high wind speeds. The bending of flexible materials requires low strength in both the material and the structure. High impact strengths and the uncontrolled nature of the impacts mean that impact modes are not suitable for energy harvesting at high wind speeds. Therefore both of these modes are unsuitable for working at high wind speeds. A vibration-type mode with high strength and high stability is capable of working and generating electrical power at high wind speeds. These properties can be used on flying objects to determine their running parameters or in high altitude locations such as mountain tops to power wireless sensor nodes. However, existing piezoelectric energy harvesters are designed for wind speeds below 20 m/s. The aim of this study is thus to design, assemble and test a new piezoelectric clamped beam that uses the vibration induced by centrifugal force to capture wind energy for use in high wind speed situations.

In this study, a new piezoelectric wind energy harvester structure was designed. In addition to the use of piezoelectric-induced vibration to harvest dynamic wind energy and convert it into electrical energy, the device reported in this work has other advantages. (1) At high wind speeds, beam vibration is obtained from the centrifugal force induced by rotating eccentric turbines. This is based on a previously solved problem so the excitation frequency is not unstable. (2) Based on the magnitude of the energy flow in the surrounding environment and the required output power, the device can be designed and optimized using different numbers of piezoelectric ceramics to adjust the output power effectively. (3) Because of the asymmetric structure of the turbine, the device can effectively adapt to the natural environmental disturbances in the wind flow direction.

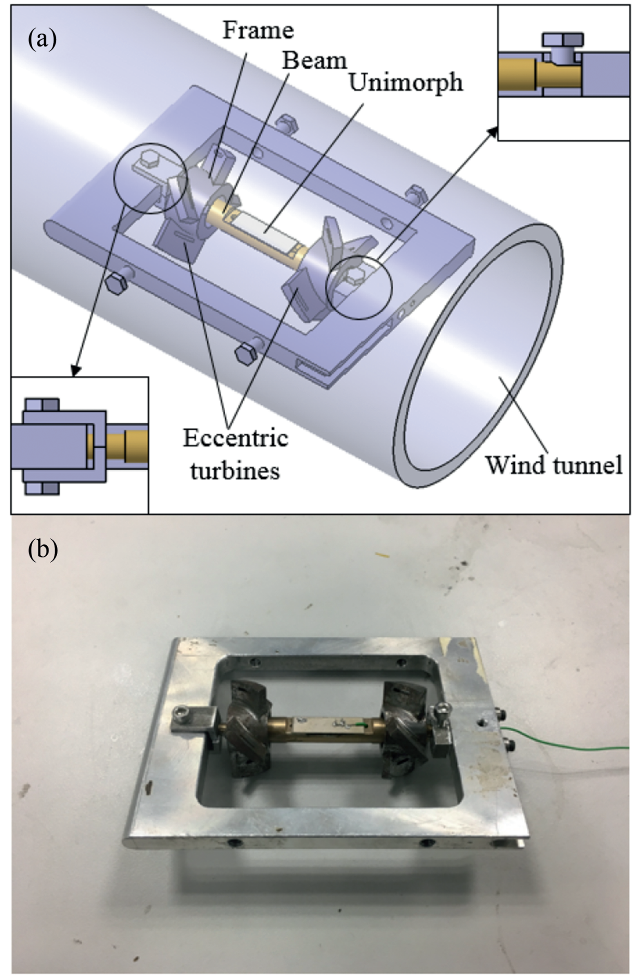


**Figure 1:** (a) Schematic (b) prototype of proposed energy harvester.

## 2 Structure Design

In this study, a device has been designed to convert wind energy into electrical energy using piezoelectric transducer which vibrates at the centrifugal force induced by a pair of eccentric turbines. When wind flows through the harvester, the clamped beam is forced to deform. The distorted piezoelectric ceramics will produce electric charge because of the piezoelectric effect. Figure 1 shows the design of the device. The clamped-clamped beam was fabricated from a stepped copper cylinder and fixed with fasteners through bolts (M3) at both ends. To stick the piezoelectric unimorph (PZT-5H), two surfaces have been cut to flat in the middle of the cylinder. As beam excitation sources, a pair of eccentric turbines was installed on the two sides of the beam through the bearing. The assembled device was fixed to an aluminum frame. The whole harvester was mounted at a wind tunnel through bolts (M4). Wind in the tunnel was generated using an air compressor.

Steel was used as the material of the eccentric turbine. Figure 2 shows the different locations of the holes that cause the center of mass offset and illustrates the principle of how the device works. When high speed wind contacts the turbines, they will rotate at high speeds. Therefore, Figure 2(a) can be simplified to the situation of Figure 2(b), where the rotation of the

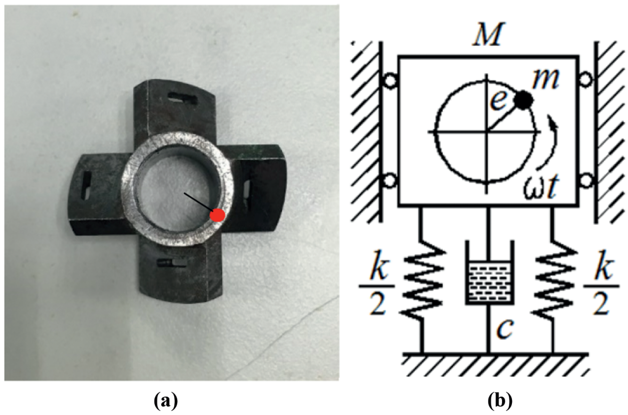


**Figure 2:** (a) Different holes on turbine fan (b) Centrifugal force acting on Y direction.

eccentric mass generates centrifugal force, and thus causes the beam and unimorph to deform. The device outputs electricity via the piezoelectric effect. The eccentric turbines rotate easily for any wind direction and can produce high-frequency excitation under high wind speeds, which produces the highest output amplitude. A prototype was fabricated using the geometrical properties listed in Table 1.

**Table 1:** Geometrical properties of proposed device.

| Description | Value |
|---|---|
| Beam length | 38 mm |
| Groove length | 26 mm |
| Intermediate structure diameter | 8 mm |
| Distance between two surfaces | 4 mm |
| Turbine blade height | 8.5 mm |
| Turbine blade thickness | 3 mm |
| Turbine thickness | 12 mm |
| The angle between the turbine blade and the axis | 45° |
| Turbine outer diameter | 20 mm |
| Piezoelectric ceramic length | 21 mm |
| Piezoelectric ceramic width | 5 mm |
| Piezoelectric ceramic thickness | 0.4 mm |

In this study, eccentric turbine as the beam excitation source, is the core of the device energy conversion mechanism. Because of the turbines with eccentric mass, it will produce the obvious centrifugal force when turbines were rotating under high speed airflow. The centrifugal force is regarded as the exciting force and can be forced beam vibration. The externally excited of the beam can be simplified to the following equation

$$F = me\omega^2 sin(\omega t + \varphi) \quad [1]$$

$$\omega = 2\pi f \quad [2]$$

where $m$ is the eccentric mass, $e$ is the eccentricity, $\omega$ is the the angular velocity of the turbine and $f$ is the rotational frequency. After calculation and measurement, $m$ is 0.14 kg and $e$ is 7.07 mm. The turbine parameters of rotational and centrifugal force with wind speed were measured and calculated (Table 2).

**Table 2:** Parameters of turbines.

| Wind speed (m/s) | 15 | 25 | 35 | 45 | 55 |
|---|---|---|---|---|---|
| Rotational frequency (Hz) | 190 | 247 | 354 | 520 | 600 |
| Centrifugal force (N) | 0.92 | 1.55 | 3.18 | 6.86 | 9.14 |

From Table 2, we can find that the rotational frequency increased with the wind speed and reached 600 Hz at wind speed of 55 m/s. through calculation, the max centrifugal force reached 9.14N. In this experiment, the piezoelectric ceramic was d31 mode, so we can only consider the vibration at vertical direction of the beam. And the frequency for vibrations of the beam in the vertical direction is equal to the rotational frequency of the turbine.

The experimental set up is shown in detail in Figure 3. Wind is generated in a wind tunnel. The wind speed was measured using an oscilloscope. The voltage was monitored via an HP 54601A digital four-channel oscilloscope with an HP 10071A probe. The individual transducer was connected using a full-wave bridge containing four diodes (1N4148), as shown in Figure 3. After rectification, the voltage was obtained across the 33 μF capacitor.

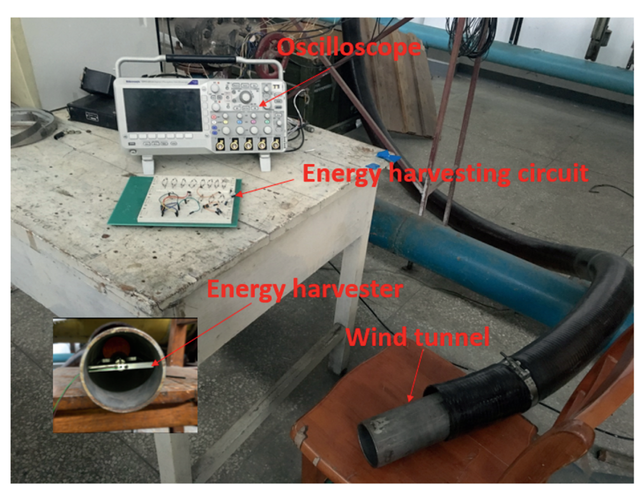


**Figure 3:** Photograph of experimental setup.

## 3 Results and Discussion

When wind flows in a wind tunnel, it produces a buzzing sound, and this sound or noise could also be an energy source. To discuss the capabilities of piezoelectric energy, we should first research the effects of this noise energy. As the Figure 4 shows, none of the turbines were installed in the device. The DC power initially ramped up and then declined with increasing load. The maximum DC power of 0.043 mW was found for a load of approximately 180 kΩ. The vibration did not change at the different wind speeds from 20 m/s to 55 m/s.

Figure 5 shows the relationship between the maximum output voltage of the device and measured for several different wind speeds. The output voltage increased with increasing wind speed. The maximum voltage reached 47.2 V at 55 m/s. We tried to make the device work at higher wind speeds, but it could not work continuously and the device would be damaged at higher speeds. To prevent destruction of the energy harvester, the maximum wind speed was limited to 55 m/s during the experiments.

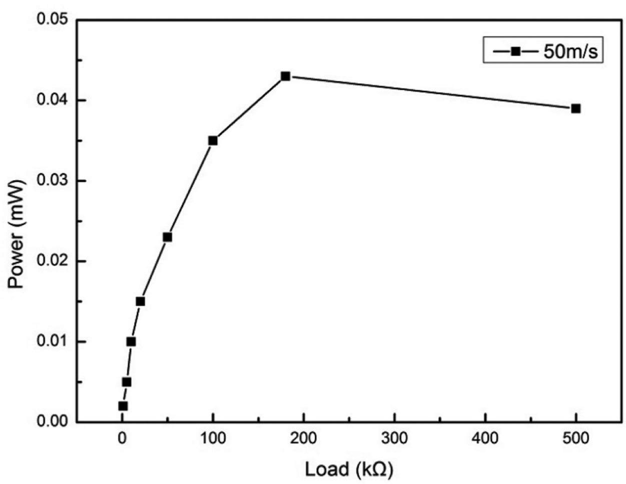


**Figure 4:** DC power-load relationship under influence of noise.

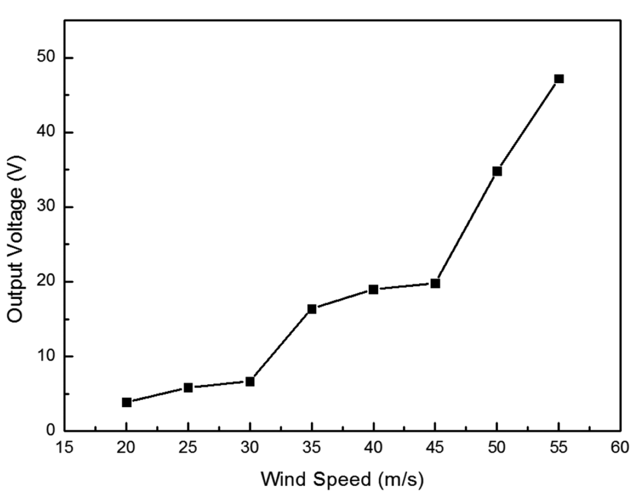


**Figure 5:** Maximum voltage for various wind speeds.

Most electronic devices are driven by DC power. DC-like output voltages are useful for charging batteries or powering low-power electronics. While we measured the peak-to-peak (P-P) voltage across the piezoelectric unimorph, we also recorded the DC output voltage across the load applied. Figure 6 shows that the output voltage measured across load applied became constant at different wind speeds. When a capacitor was used in the circuit, the output voltage decreased.

Figure 7 (a) shows the relationship between the DC power and the different loads at several wind speeds. The DC power increased as the wind speed increased, regardless of the load value. We also found that the DC power values for the different loads were very close at speeds up to 40 m/s; subsequently, the values began to separate into two parts. The matching load was found experimentally to be 50 kΩ. As the plots of Figure 6(b) showed, the DC power density shows a trend of decrease after first increase. The density decreases sharply with the load in excess of about 180 kΩ at 50 m/s and 55 m/s. The maximum energy density was 104.55 μW/cm$^3$ at a wind speed of 55 m/s across a 50 kΩ.

The AC output voltage generated by the prototype was applied to an electrolytic capacitor (where $C = 33\,\mu F$) across full wave bridges. When the capacitance value stopped increasing because of the internal dielectric loss of the capacitor, the DC voltage was recorded. The electrical energy, $E$, can be calculated using

$$E = \frac{1}{2} C V_{DC}^2 \qquad [3]$$

Figure 8 shows the relationship between energy and load for various measured wind speeds. The energy increased with the increased in the load and wind speed. It can be found that there is a node (180 kΩ) in every line. The slope before the node is higher than after the node. Although the energy increasing is followed by the load adding under the same wind speed, the tendency of the climbing is dropping that trend to flat. The maximum energy was 13.3 mJ for a 1 MΩ resistor.

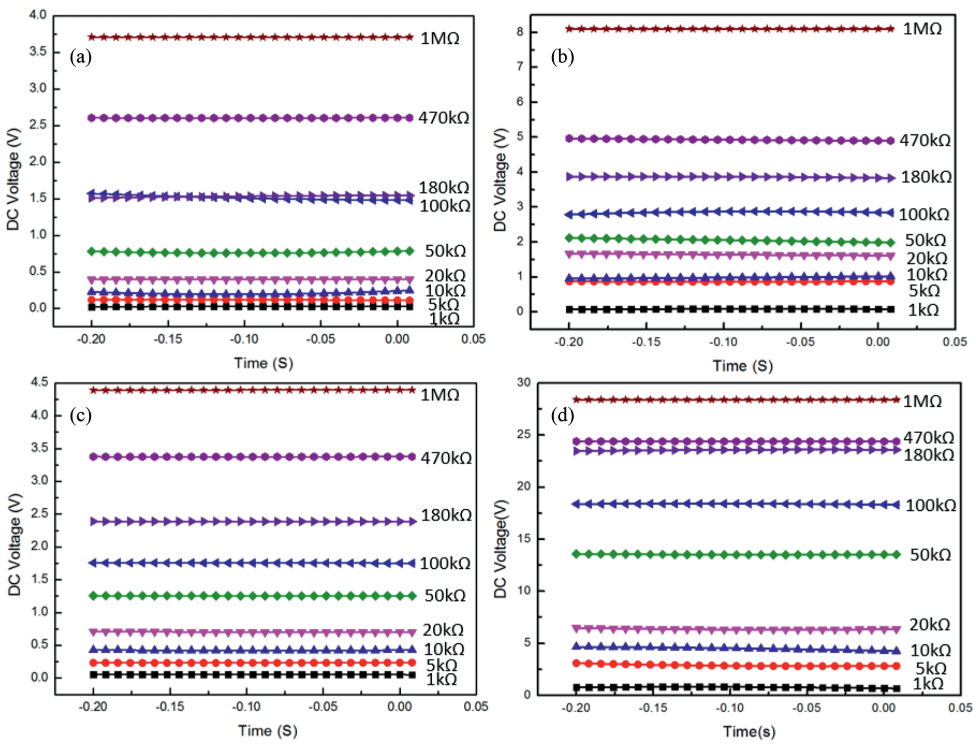


**Figure 6:** DC-like voltage produced for different loads using a 33 μF capacitance at a wind speed of (a) 20 m/s, (b) 30 m/s, (c) 40 m/s, (d) 55 m/s.

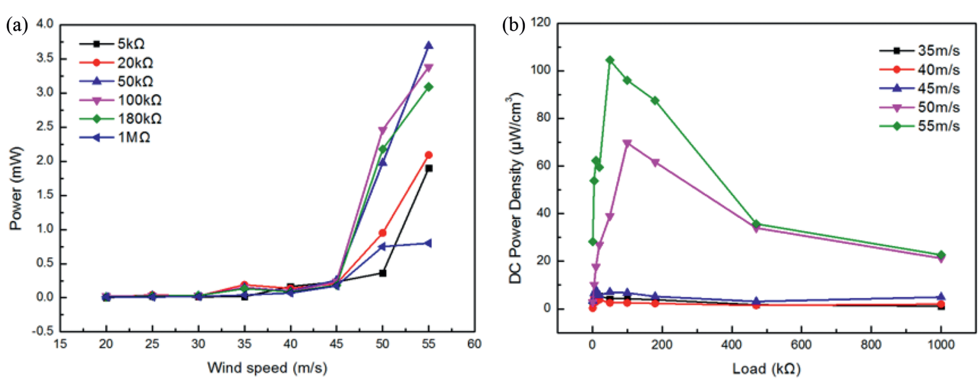


**Figure 7:** (a) DC power variation as function of resistive load for various wind speeds. (b) Density of the DC power generated with different loads and wind speeds.

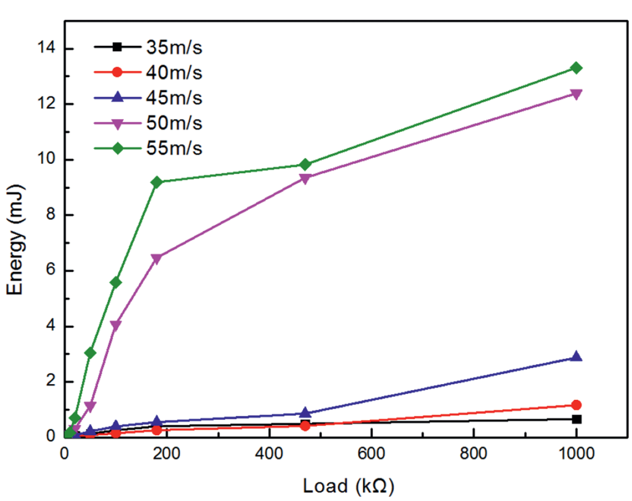


**Figure 8:** Energy connecting to 33 μF capacitance generated under different load and wind speed conditions.

## 4 Conclusion

In this work, a clamped piezoelectric beam that uses vibrations induced by centrifugal force has successfully converted wind energy into electrical energy, and provides a stable and efficient energy source because the required turbine can rotate smoothly and steadily at high wind speeds. Simultaneously, vibrations were induced by the centrifugal force during high speed rotation. The piezoelectric unimorph was forced to distort at higher wind speed, which then produces higher output voltage amplitudes and output power. The device works successfully using a clamped beam, which prevents beam damage at high wind speeds. At a wind speed of 50 m/s when the load resistance is 50 kΩ, the DC output power after the full-wave bridge circuit was 3.69 mW. The power density was

104.55 mW/cm (Tsai, Wang, and Su 2014). The optimized energy obtained is 13.3 mJ with the 1 MΩ load and the 33 μF capacitance. The generated electricity can be stored in a supercapacitor and can be used to power light-emitting diodes (LEDs) and small electronic devices.

**Funding:** This paper was supported by the Natural Science Foundation of China (grant nos. 51177072 and 91023020), the National Key Project for Basic Research of China (2012CB619406), the Jiangsu Provincial University Scientific Research Achievement Transformation Promotion Project (no. JH10-7), and the 111 project (no. B12020).

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