Energy Harvesting Piezoelectric Wind Speed Sensor

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Abstract. In this paper, we demonstrate a miniature wind speed sensor consisting of a triangle-shaped bluff body and a cantilever incorporating a commercial PVDF piezoelectric film. In the wind, the bluff body causes regular vibration of the cantilever based on galloping, and the piezoelectric film converts the vibration energy into electrical energy. The vibration frequency of this device has an approximately linear dependence on wind speed, and so can be used to detect wind speed directly with high accuracy. In wind tunnel tests, a wind speed sensor based on this principle could detect the wind speed from 4.45 to 10 m/s, and measured speed was typically within 2\% of the value obtained using a Pitot tube.

1. Introduction

Zero-power sensors based on micro energy harvesters have attracted much attention because they effectively decrease the power consumption of sensing systems, even making them self-powered \cite{1,2}. Miniature piezoelectric energy harvesters based on flow-induced vibration \cite{3} could form the basis of zero-power wind speed sensors. Previous research has demonstrated both flap-shaped \cite{4} and T-shaped \cite{5} energy harvesters, piezoelectric cantilevers with cylindrical extensions \cite{6} and energy harvester arrays \cite{4}. The influence of wind speed on the output of these wind energy harvesters has been reported. However, the output voltage of such devices is generally unsteady which limits their use as a direct sensor of wind speed.

Here, we demonstrate a miniature wind speed sensor consisting of a triangle-shaped bluff body and a cantilever incorporating a commercial polyvinylidene fluoride (PVDF) film (Figure 1). For our device, the bluff body causes regular vibration of the cantilever based on galloping, which is a kind of flow-induced vibration. The PVDF piezoelectric film on the cantilever then converts vibration energy into electrical energy. The vibration frequency varies linearly with the wind speed to a good approximation, so this frequency, rather than the unsteady output voltage, is used to detect the speed.

2. Structural design

In our device, the bluff body is prismatic with a triangular cross-section and is mounted with one of its rectangular faces pointing into the wind (Figure 1a). The length of the bluff body is 3 cm. The multi-layer piezoelectric film contains a PVDF layer sandwiched between two silver ink layers acting as electrodes, with a PET layer on the top to move the position of the mechanical neutral layer outside of the PVDF. This multi-layer piezoelectric film is 1.5 cm × 1 cm in area. A prototype of this sensor is shown in Figure 1c. The bluff body is mounted on the tip of the piezoelectric film.

When there is wind toward this sensor, galloping happens because of the interaction between the bluff body and the wind flow. The bluff body has a variable attack angle to the cross-flow, which may
induce negative dynamic damping under certain flow conditions. This negative dynamic damping leads to the periodic vibration of the bluff body and piezoelectric film. The periodic deformation and polarization of the piezoelectric film generates alternating current (AC) through the silver ink electrodes and the external circuit. Based on the mechanical principles of galloping, the frequency of vibration is expected to remain near the natural frequency of the cantilever. However, we have found that there is an easily measurable and approximately linear variation of vibration frequency with wind speed which is used to develop a wind sensor here.

Figure 1. Miniature piezoelectric energy harvester based on flow-induced vibration. (a) Schematic of device. (b) Cross-section of cantilever showing 4-layer structure with PVDF film. (c) Photograph of prototype.

3. Test environment
In our experiments, the piezoelectric wind sensor was fixed in the test section of a computer controlled low-speed wind tunnel (FLOTEK 1440) as shown in Figure 2. The wind speed could be varied continuously from 0 to 12 m/s with a controller. The cross-section of the test section is 12"×12". During the experiments, a Pitot tube was always placed in the test section parallel with our piezoelectric wind sensor to calibrate the wind speed in the tunnel.

Figure 2. Photo of wind tunnel, type FLOTEK 1440, with 12"×12" test section, 36" in length.

4. Results

4.1. Influence of wind speed on voltage and power
We first tested the device to understand the influence of wind speed on the output voltage and power when it was operating as an energy harvester. Figure 3 shows the variations of peak-peak voltage and average power with wind speed for different load resistances. Both increased rapidly at low wind speeds, while at higher wind speeds, in the range 8 to 10 m/s, the output still increased but more slowly and less steadily. For this wind speed sensor, the cut-in speed was 4.45 m/s. When the wind speed exceeded 10 m/s, the vibration became unsteady, and the bluff body tended to be bent to one side. Once this had happened, the bluff body could not return to its rest position because of the force of the wind.
4.2. Influence of wind speed on frequency

As our goal was to implement a frequency-based sensor, we investigated the effect of wind speed on the frequency of flow-induced vibrations. First, we measured the natural frequency by observing free vibration of the device (Figure 4). The natural frequency is of importance for galloping because the vibration frequency of the bluff body in the wind is around the natural frequency. In this experiment, the bluff body was displaced by 3 mm and released, and the displacement at a point on the cantilever (tip of the piezoelectric film) was monitored during ring-down using a laser displacement sensor. The natural frequency was found to be 10 Hz.

We then measured the vibration frequency at different wind speeds in the range 5 to 10 m/s. Figure 5 shows the output voltages in both time and frequency domains at two different wind speeds. The experiments revealed a variation of vibration frequency with wind speed. For example, in Figure 5b, the frequency spectra show that with a wind speed of 9 m/s the frequency is 9.16 Hz, while the frequency shifted to 9.94 Hz at a wind speed of 6 m/s.

4.3. Sensing tests
In our study, the vibration frequency of the sensor was found to decrease monotonically with increasing wind speed (from 5 m/s to 10 m/s) as shown in Figure 6a. A linear best fit to the data with a 10 MΩ load is shown in Figure 6b. This fitted relationship was used to try and estimate wind speed from the frequency of the output voltage. Figures 6c and 6d show two experiments testing the accuracy of our wind speed sensor. A Pitot tube was used as a standard reference. The voltage waveforms, shown in Figure 6c, had estimated frequencies 9.71 Hz and 9.43 Hz. Using the fitted linear relationship, we estimated the wind speeds to be 6.82 m/s and 7.68 m/s, respectively. The wind speeds were also measured with the Pitot tube which recorded values of 6.69 m/s and 7.77 m/s. Our sensor was typically in agreement with the Pitot tube to within 2% at both measurement points.

Figure 6. Variations of frequency with wind speed and tests as a wind speed sensor.
(a) Vibration frequency versus wind speed.
(b) Linear fitting of result with 10 MΩ load resistance.
(c), (d) Two tests of our device with different wind speeds.

5. Introduction
We have demonstrated an energy harvesting piezoelectric wind speed sensor that can work without any power supply and detect the wind speed with a relatively high accuracy. With a proper power management module, it could form a zero-powered sensing system. Such a system could be used in many fields, such as local wind speed detection, large-scale environment monitoring, and other applications related to the IoT.

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Acknowledgments
The authors would like to acknowledge assistance from Dr Nigel MacCarthy and Mr Ian James with the aerodynamic test facilities.