A Miniature Radial-Flow Wind Turbine Using Piezoelectric Transducers and Magnetic Excitation

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Abstract. This paper presents a miniature radial-flow piezoelectric wind turbine for harvesting airflow energy. The turbine’s transduction is achieved by magnetic “plucking” of a piezoelectric beam by the passing rotor. The magnetic coupling is formed by two magnets on the beam’s free end and on the rotor plate. Frequency up-conversion is realized by the magnetic excitation, allowing the rotor to rotate at any low frequency while the beam can vibrate at its resonant frequency after each plucking. The operating range of the device is, therefore, expanded by this mechanism. Two arrangements of magnetic orientation have been investigated, showing that the repulsive arrangement has higher output power. The influence of the vertical gap between magnets was also examined, providing guidance for the final design. A prototype was built and tested in a wind tunnel. A peak power output of 159 \( \mu \text{W} \) was obtained with a 270 k\( \Omega \) load at 2.7 m/s airflow speed. The device started working at 3.5 m/s and kept operating when the airflow speed fell to 1.84 m/s.

1. Introduction
Airflow energy is a ubiquitous energy source in many situations, including ventilation systems, mining tunnels and moving vehicles, where wireless sensor nodes are often installed [1–3]. Hence, airflow energy harvesting is a potential solution to autonomously power these nodes, instead of using conventional batteries which have a limited lifetime [4].

Miniaturization of wind turbines is one research direction in airflow energy harvesting [5, 6]. Howey et al. demonstrated a centimeter-scale electromagnetic wind turbine with a high energy density [7]. However, numerous components were required in this device, which undermined its further miniaturization potential and increased the fabrication complexity. Priya et al. developed a piezoelectric windmill with a simpler structure [8], but the mechanical excitation might damage the brittle piezoelectric materials and the size of the device was undesirable for wireless sensing applications. Contactless excitation methods have been used in other areas. Pillatsch et al. employed magnetic coupling in a non-harmonic motion energy harvester, in which the piezoelectric beam can be actuated without physical contacts [9]. By taking advantage of this feature, in this paper, a miniaturized wind turbine with piezoelectric transducers and a contactless plucking mechanism has been designed with high reliability and simplicity.

2. Design and Operating Principle
The schematic of the harvester is presented in Figure 1 and Figure 2. The turbine rotor is supported by a rolling bearing mounted on a shaft that is fixed on the rear casing. The rear
casing is stationary with the front casing enclosing the turbine rotor. There is a slot, which is designed to hold the piezoelectric beam using a screw, on the rear casing. Two magnets, which form the magnetic coupling, are installed in the harvester: one on the piezoelectric beam’s free end (tip magnet in Figure 1) and the other on the rotor plate (primary magnet in Figure 1).

Figure 1. Front and back view of the piezoelectric airflow energy harvester.

Airflow, which enters the turbine radially and exits axially, activates the turbine rotor. The rotor plucks the piezoelectric beam once per rotation cycle by magnetic coupling, providing non-contact excitation. Frequency up-conversion is also implemented by the magnetic excitation, allowing the rotor to rotate at low frequencies while the beam can keep operating at its resonant frequency, enabling the device to have a wide working range. In addition, the non-contact excitation method avoids the mechanical impact on the piezoelectric beam, which enhances the reliability of the device.

3. Optimization of Magnetic Coupling

The magnetic coupling is a critical design factor, as the power output of the beam and the start-up airflow speed of the harvester are directly determined by the magnetic coupling force between the magnets. In order to understand the influence of magnetic coupling on the performance of the piezoelectric beam, an equivalent experimental set-up was built as shown in Figure 3.

Figure 3. Experimental set-up to optimize the magnetic coupling.

The piezoelectric beam is installed on an adjustable platform so that the gaps between the two magnets in 3 dimensions can be tuned accurately by the micrometers on the platform. A DC motor is used as an analogy to the rotating turbine. A plate with the same diameter as the turbine rotor is mounted on the motor’s rotor with a magnet fixed on it. The magnetisation
direction is in the vertical direction as shown in Figure 4. The sizes of these components are listed in Table 1.

| Item            | Dimension          |
|-----------------|--------------------|
| Rotor Magnet    | $5 \text{ mm} \times 4 \text{ mm} \times 1 \text{ mm}$ |
| Beam Magnet     | $1 \text{ mm} \times 1 \text{ mm} \times 1 \text{ mm}$ |
| Piezoelectric Beam | $26.5 \text{ mm} \times 1.5 \text{ mm} \times 0.3 \text{ mm}$ |

Two arrangements of the magnetic orientation were investigated against rotational frequency of the primary magnet. The repulsive arrangement has better performance at high frequencies with larger energy output (Figure 5). The influence of the vertical gap between the magnets is also illustrated in Figure 6, which shows the variation of output voltage against the vertical gap. A 2 mm gap was chosen for the final design as a compromise between the start-up airflow speed and the output power.

![Figure 5. RMS output voltage for attractive and repulsive arrangements of magnets versus rotational speed.](image1)

![Figure 6. Influence of the vertical gap between magnets on output voltage of the beam.](image2)

### 4. Prototype and Experimental Set-Up

Rapid prototyping was used to fabricate the turbine rotor and casing. Other components were purchased as off-the-shelf products, including cuboidal magnets, piezoelectric beams and rolling bearings. A prototype was assembled as shown in Figure 7(a). The overall size of the device is $47 \text{ mm} \times 42 \text{ mm} \times 25 \text{ mm}$.

![Figure 7. Prototype (a) and experimental set-up (b).](image3)
The harvester was tested in the wind tunnel shown in Figure 7(b). This wind tunnel is an open loop wind tunnel with continuously variable airspeed control. It is comprised of four major components: contraction, test section, diffuser and fan. Airflow enters the tunnel from the contraction section and exits from the diffuser. The performance of the harvester was measured in the test section, whose dimension is 100 mm × 85 mm × 85 mm. A pitot tube used to measure the airflow speed was installed in parallel with the harvester in the test section, and the reading of airflow speed was received from a micro manometer.

5. Results

Figure 8 shows the successful implementation of the concept of frequency up-conversion by this device. The turbine rotor rotates at 11 Hz which can be derived from the excitation frequency of the beam. The beam operates in a free-damped-vibration form at its resonant frequency, i.e. 133 Hz after each plucking. The vibration frequency is unaffected by the excitation frequency due to the plucking behaviour.

![Figure 8. Output voltage with a 1.8 MΩ load at 2.7 m/s, showing the implementation of frequency up-conversion.](image)

![Figure 9. Output power against load resistance at airflow speed 2.74 m/s.](image)

The device has also been tested with different loads and airflow speeds. Figure 9 illustrates the peak and average output power against differing load resistances at 2.7 m/s. A peak power output of 159 µW was obtained with a 270 kΩ load. The fluctuation of output power is caused by the instability of the shaft and the variation of airflow speed. Figure 10 depicts the rotational frequency of the turbine rotor and the output peak power against airflow speed. The device started working at 3.5 m/s and kept operating when the airflow speed fell to 1.84 m/s. The start-up airflow speed is quite high compared to the operating range of the harvester. A self-regulating concept [10] will be implemented in future work to decrease the start-up airflow speed.

In addition, the output power at high airflow speeds decreases sharply due to the high plucking frequency which makes the output of the piezoelectric beam between two excitation cycles overlap with each other, as illustrated in Figure 11. The output voltage is undermined due to the cancelling effect of the overlapping. In order to maintain the output power at high airflow speeds, the rotational speed of the rotor should be controlled without rising with the increase of the airflow rate. Hence, more energy should be consumed from the turbine rotor in other ways. Solutions to expand the operating range will be investigated in future work.

6. Conclusions and Future Work

This paper presents a miniaturized piezoelectric wind turbine for airflow energy harvesting. Magnetic excitation is employed to pluck the beam without any physical contact, enhancing the
reliability of the device. Frequency up-conversion is implemented using the magnetic plucking method, which allows the beam to operate irrespective of the rotational frequency of the turbine rotor.

Two magnet arrangements were investigated, showing that the repulsive arrangement had a better performance at high airflow speeds. The influence of the vertical gap between magnets was also examined. The peak voltage output had a sharp drop with the increase of the vertical gap, which means the torque needed for start-up is decreased as well.

A prototype was fabricated and tested in a wind tunnel. A output power of 159 \( \mu \text{W} \) was obtained with a 270 k\( \Omega \) load at 2.7 m/s. The device started working at 3.5 m/s and kept operating when the airflow speed fell to 1.84 m/s. Future work will be focused on decreasing the start-up airflow speed and improving the power output at high airflow speeds.

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