Airflow energy harvesting with high wind velocities for industrial applications

Z J Chew, S B Tuddenham and M Zhu
College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, EX4 4QF, UK

E-mail: m.zhu@exeter.ac.uk

Abstract. An airflow energy harvester capable of harvesting energy from vortices at high speed is presented in this paper. The airflow energy harvester is implemented using a modified helical Savonius turbine and an electromagnetic generator. A power management module with maximum power point finding capability is used to manage the harvested energy and convert the low voltage magnitude from the generator to a usable level for wireless sensors. The airflow energy harvester is characterized using vortex generated by air hitting a plate in a wind tunnel. By using an aircraft environment with wind speed of 17 m/s as case study, the output power of the airflow energy harvester is measured to be 126 mW. The overall efficiency of the power management module is 45.76 to 61.2 %, with maximum power point tracking efficiency of 94.21 to 99.72 % for wind speed of 10 to 18 m/s, and has a quiescent current of 790 nA for the maximum power point tracking circuit.

1. Introduction

Airflow is one of the most promising sources to be harvested in industrial environments since the velocity of air in ventilation systems or induced by fast moving objects is quite high, which can be more than 10 m/s [1]. So far, miniaturized wind turbines [2, 3] or flapping airflow generators [4, 5] are often used to harvest energy from airflow. Wind turbine generators generally consist of vaned wheels to convert direct airflow into electrical energy via electromagnetic transducers. On the contrary, flapping airflow generators are usually composed of elastic cantilevers which require vortexes to oscillate the cantilevers. Oscillating motion of the cantilever can be converted into electrical energy via piezoelectric or electromagnetic transductions. These airflow energy harvesters are capable of producing high output power of around 10 mW at air speed of around 10 m/s [2, 5]. The harvested power can be used to power wireless sensors to monitor physical quantities or environment phenomena, which is important in many industries [6-10] so that appropriate measures can be taken for the safety and well-being of the lives in the environment that is being monitored. However, these airflow energy harvesters are mainly designed to operate under airflow coming at a certain angle and/or direction, which greatly constrained their applications because airflow can come in any direction in the real-world. Also, obstructions and cavities present in the real-world environment prevent airflow from smoothly passing through, creating micro-climates of swirling air vortexes. Although flapping airflow generators can capture vortexes for energy harvesting, the operation of flapping airflow generators is limited to a certain airflow speed. The flapping airflow generator will stall and therefore could not generate any power if the air speed is too high and also be in a risk of
breaking due to excessive stress sustained by the cantilever which is bended to one side [5]. This paper herein presents an airflow energy harvesting system that can harvest swirling airflow at high speed.

2. System descriptions
The implemented system consists of a modified helical Savonius to capture the swirling airflow, a DC motor as the electromagnetic generator and a power management module for the power conditioning. The DC motor used is a brushed motor with dimensions of \( \text{Ø}7 \times 16\text{mm} \) (Hubsan, Shenzen, China).

2.1. Modified helical Savonius turbine
A Savonius turbine which is a drag-type device is capable of harvesting both the direct and swirling airflows. However, standard Savonius turbine is a vertical-axis wind turbine which captures airflow in the direction normal to the rotating shaft [11]. Therefore, based on a standard Savonius turbine, a modified helical Savonius turbine with horizontal axis is implemented as shown in figure 1. The prototyped modified helical Savonius turbine has a diameter of 15 mm and length of 20 mm, which is small so that it can fit into small gaps or spaces. The modified helical Savonius turbine is connected to the shaft of an electromagnetic generator to convert the captured airflow in the form of rotational kinetic energy into electrical energy as the shaft is rotated by the turbine due to the airflow.

![Figure 1. The designed turbine.](image1)

2.2. Power management module
The power management module consists of a maximum power point tracking (MPPT) circuit and a commercially available boost converter (bq25504, Dallas, USA). A boost converter is used because the output voltage from the electromagnetic generator is typically lower than 1 V, which is insufficient to power up a wireless sensor node. The maximum power point finding is based on maximum power transfer that occurs at half of the open-circuit voltage of the electromagnetic generator [12]. Therefore, the circuit is implemented using low power analog components without the need of a power hungry microcontroller as shown in figure 2 since the operation is simple. The circuit momentarily disables the boost converter. The boost converter appears as open-circuited when disabled so that open-circuit voltage of the generator can be obtained and sampled using a sampling capacitor \( C_{\text{REF1}} \). The sampling capacitor is then disconnected from the generator output and connected in parallel with another capacitor \( C_{\text{REF2}} \) of similar value. Voltage across the capacitors becomes half due to charge sharing between the capacitors. The half-open-circuit voltage is used as the reference voltage to harvest energy from the generator and is sampled every second to obtain a new reference voltage as the air speed in actual environment is dynamic, causing voltage from the electromagnetic generator to change.

3. Experiment
The airflow energy harvester was positioned behind a vortex inducing plate in a wind tunnel as shown in figure 3. Vortex is produced when the air stream hits the plate as shown in figure 4. By using the aircraft environment as a case study, the wind tunnel was set to produce an air speed of 17 m/s. This air speed was obtained based on the boundary layer airflow at a distance of 20 mm from the wing surface at the trailing edge, where the wing has a chord length of 13 m and when the aircraft is
travelling at the take-off free stream air speed of 77 m/s. The generator output was connected to a variable resistor to determine its power generation capability by manually tuning the resistor.

To determine the maximum power point finding capability of the power management module, tests for the output power of the generator when connected with a variable resistor were carried out at different air speeds of 10 to 18 m/s. Then, the tests were repeated with the electromagnetic generator connected to the power management module. Output power from both tests were compared to obtain the maximum power point tracking efficiency of the implemented circuit based on an open-circuit voltage method. Overall system efficiency of the power management module and the current consumption of the MPPT circuit were also measured using Keithley 2612B.

4. Results

Figure 5 shows the power, voltage and current generated by the airflow energy harvester using different resistance load at air speed of 17 m/s. Results indicate that maximum power of 126 mW can be achieved with optimal load resistance of 3.1 Ω. Figure 6 shows the power generated by the airflow energy harvester when connected to its optimal load resistance at different air speed from 10 to 18 m/s. The power generated is 25.5 mW to 140 mW in the range of tested airspeed where the power generated at 10 m/s is double of previously reported airflow energy harvester [2, 4].

Overall system efficiency is 45.76 to 61.2 %, which is mainly dictated by the efficiency of the boost converter which has to boost voltages below 0.7 V to 3.1 V. The maximum power point finding efficiency using the MPPT circuit is 94.21 to 99.72 % as shown in figure 7 while consuming 790 nA.
of quiescent current consumption with short peaks of no more than 4 μA as shown in figure 8. This indicates the effectiveness of the implemented circuit in harvesting energy close to maximum power point of the airflow energy harvester without the need of power hungry components, which is essential in energy harvesting applications so that most of the harvested energy can be delivered to the wireless sensors to perform the intended tasks instead of consumed by the power management module and minimizes the energy loss to prevent further decrease in the system efficiency.

![Figure 7](image1.png)  
*Figure 7.* MPPT of the power management module at different wind speeds.

![Figure 8](image2.png)  
*Figure 8.* Current consumption of the maximum power point finding circuit.

5. Conclusion
An airflow energy harvester which is able to operate under swirling air at high speed and its associated power management module are presented and demonstrated. The airflow energy harvester produces up to 126 mW of power under vortex induced by airflow of 17 m/s. Overall system efficiency is 45.76 to 61.2 %. The maximum power point finding based on open-circuit voltage has high efficiencies between 94.21 and 99.72 % and the MPPT circuit has a low quiescent current of 790 nA. The capability of the implemented airflow energy harvester to run by vortex at high speed and generated high power of several hundreds milliwatts makes it suitable for industrial applications.

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