Airflow energy harvesting for high speed vehicles

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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 18 m/s as case study, the output power of the airflow energy harvester is measured to be 140 mW. The maximum power point finding circuit operates based on open-circuit voltage of the airflow energy harvester. It is implemented using low power analogue circuit with a quiescent current of 790 nA. The maximum power point finding efficiency is 94.21 to 99.72 % for wind speed between 10 to 18 m/s.

1. Introduction

Airflow is one of the most promising sources to be harvested in high speed vehicles since the velocity of air induced by fast moving vehicles 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 is a conventional brushed motor with dimension of Ø7 × 16mm.

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.

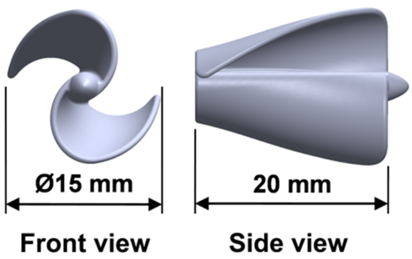

Figure 1. The modified helical Savonius turbine**.**

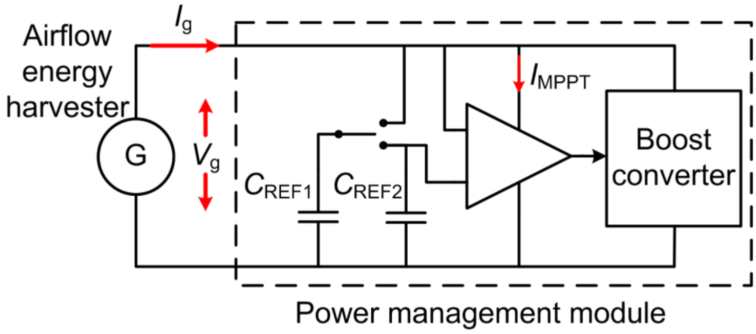

Figure 2. Schematic of the power management module.

2.2. *Power Management Module*

The power management module consists of a maximum power point tracking (MPPT) circuit and a boost converter. The 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_{REF1}. The sampling capacitor is then disconnected from the generator output and connected in parallel with another capacitor C_{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. The maximum power point finding process occurs every one second.

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 can be seen 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 speed over an aircraft wing at the trailing edge at a distance of 20 mm from the wing surface, where the wing has a chord length of 13 metres 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. The current consumption of the maximum power point finding circuit was also measured using Keithley 2612B sourcemeter for all the tests.

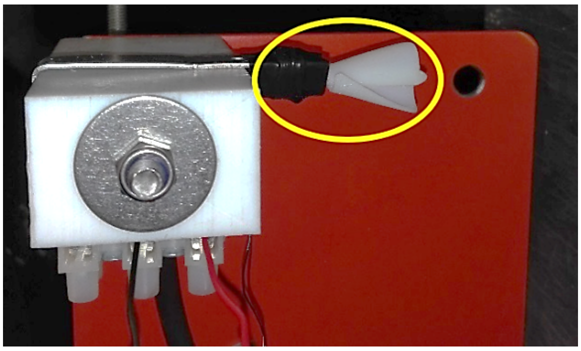

Figure 3. Prototyped airflow energy harvester behind a vortex inducing plate as indicated by the yellow line.

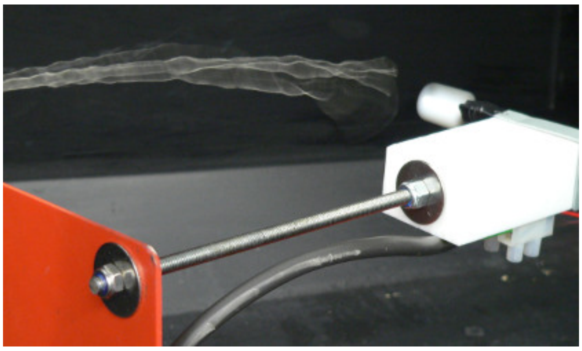

Figure 4. Airflow energy harvester rotating within single vortex shed from plate where the vortex is indicated by string tell-tail.

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].

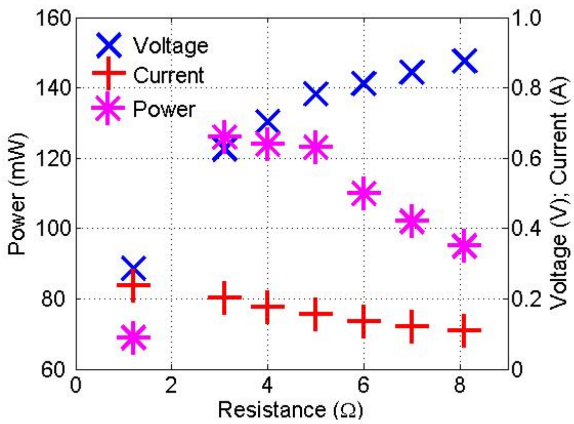

Figure 5. Power, voltage, and current generated by the vortex shedding energy harvester with different resistive load at air speed of 17 m/s.

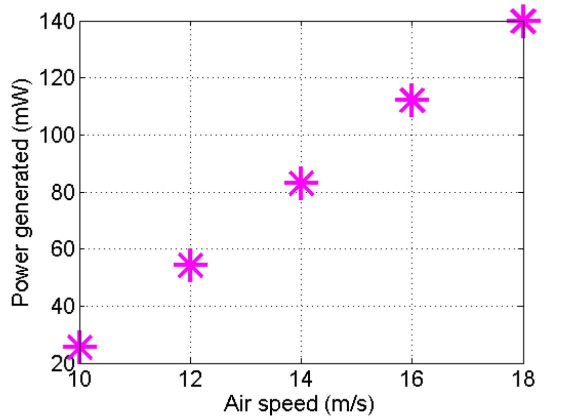

Figure 6. Power generated by the airflow energy harvester subjected vortexes induced by airflow with speed of 10 to 18 m/s.

The maximum power point finding efficiency using the implemented circuit is 94.21 to 99.72 % as shown in figure 7 while consuming just 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.

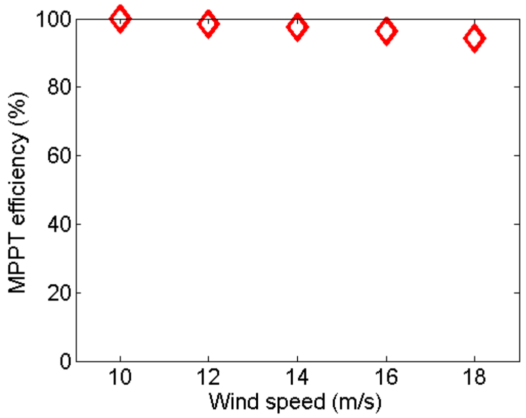

Figure 7. MPPT of the power management module at different wind speeds.

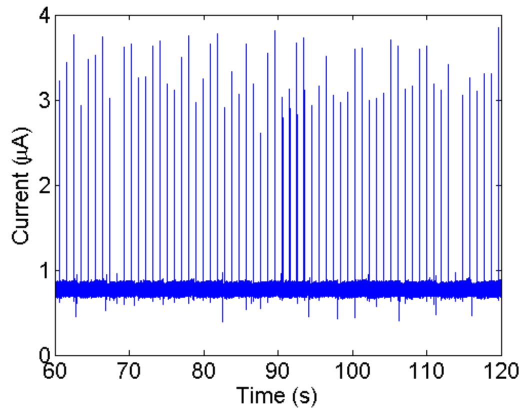

Figure 8. Current consumption of the maximum power point finding circuit.

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 140 mW of power under vortex induced by airflow of 18 m/s. The maximum power point finding based on open-circuit voltage has high efficiencies between 94.21 and 99.72 % and the implemented circuit has a 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.

Acknowledgments
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References

[1] Fei F, Zhou S, Mai J and Li W 2014 *Energies* **7** 2985-3003
[2] Holmes A S, Howey D A, Bansal A and Yates D C 2010 *Proc. PowerMEMS* 115-8
[3] Brunelli D 2016 *Sensors* **16** 327 (19 pp)
[4] Erturk A, Vieira W G R, De Marqui C and Inman D J 2010 *Appl. Phys. Lett.* **96** 184103 (3 pp)
[5] Zhu D, Beeby S P, Tudor M J, White N M and Harris N R 2013 *IEEE Sensors J.* **13** 691-700
[6] Jurik A D and Weaver A C 2009 *IEEE Softw.* **26** 71-3
[7] Morais R, Matos S G, Fernandes M A, Valente A L G, Soares S F S P, Ferreira P J S G and Reis M J C S 2008 *Comput. Electron. Agr.* **64** 120-32
[8] Kafi M A, Challal Y, Djenouri D, Doudou M, Bouabdallah A and Badache N 2013 *Procedia Comput. Sci.* **19** 617-26
[9] Gilbert J M and Balouchi F 2008 *Int. J. Autom. Comput.* **5** 334-47
[10] Chew Z J, Ruan T and Zhu M to be published *Procedia Eng.*
[11] Mahmoud N H, El-Haroun A A, Wahba E and Nasef M H 2012 *Alexandria Eng. J.* **51** 19-25
[12] Tan Y K and Panda S K 2011 *IEEE Trans. Power Electron.* **26** 38-50