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A cm-scale, low wind velocity and 250°C-compliant airflow-driven harvester for aeronautic applications

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Abstract. This paper reports the design, fabrication, and testing of a centimeter-scale ($\text{Ø}_{\text{rotor}}=35\text{mm}$), 250°C-compliant microturbine for aeronautic applications. Dedicated to low-speed air flows (≈ 3 m/s and down to 2 m/s), this device is the first flow-driven harvester withstanding such high temperatures and high vibration levels (10^7 cycles at 20G). Furthermore, the proposed harvester exhibits the highest output power per unit cross sectional area compared to prior art in the cm-scale and low velocity ranges.

1. Introduction

Among small-scale ambient energy sources (light, thermal gradients, vibrations, strains and shocks), airflow energy harvesting has revealed a great innovation potential and particularly at small-scale. Particularly in environments where light or thermal powers are insufficient, this source of power can be relevant to supply Wireless Sensors Nodes (WSN). Moreover, airflow energy harvesting can be a reliable source of power as it mainly depends on the fluid velocity amplitude contrary to vibration harvesters which are also frequency-dependents. Even if airflow energy harvesters exploiting aeroelastic flutter phenomena [1] can be an alternative to lift-based rotors, horizontal axis propellers show better aerodynamic efficiencies (C_p above a few percent) and very low cut-in speeds (v_{start} below a few m/s). Furthermore, the classical electromagnetic conversion has been chosen here for its interesting power density above a few cubic centimeters. In recent years, many works have been proposed on the miniaturization of classical wind turbines, from 2cm to 6cm rotor diameters [2–4] but most of them show poor performances at low-speed air flows and/or exhibit large cross-sectional areas. Our work aims to compete with previous electromagnetic-based microturbines whose cross-sectional areas are below 30cm^2 ($\text{Ø}<6\text{cm}$) while addressing harsh operational environments.

Our harvester has been designed to supply a wireless sensor system interfacing with aeronautic-grade pressure/strain transducers [5]. Thus, in order to withstand severe aeronautic environment constraints such as high temperature values and vibrations amplitudes, particular materials and specific design rules have been used. Design, fabrication, performances measurements and ageing tests of the device are summarized in the following sections.

2. Design and fabrication

Our prototype (figure 1) is a horizontal axis wind turbine coupled to a coreless permanent magnet generator which converts mechanical rotations into electricity. Indeed, coreless alternators are particularly suitable when targeting low cut-in speeds as they do not suffer from cogging torque.

The device is composed of several mechanical parts screwed and/or glued together as depicted in figure 1 and figure 2. The coreless alternator (figure 2.a) includes a machined shaft (Aluminum), a 250°C tolerant copper wire wrapped around two casings slotted together and a drilled cylindrical magnet with radial orientation glued to the shaft. The magnet is made of SmCo (Curie temperature: 800°C). Two micro ceramics bearings allow the magnet and the shaft to rotate inside the alternator's casings. A 35mm diameter three-blade propeller (figure 2.b) is screwed to the shaft and converts the kinetic power of the air into rotation. A carter, made of two parts screwed together (figure 2.c) embeds the alternator and protects the propeller from unexpected shocks which may occur during the installation. The propeller, the alternator's casing and the carter have been machined in a high-performance polyimide-based plastic (Vespel®) withstanding a maximum continuous operating temperature of 260°C. A picture of the final assembled prototype is given in figure 2.d.

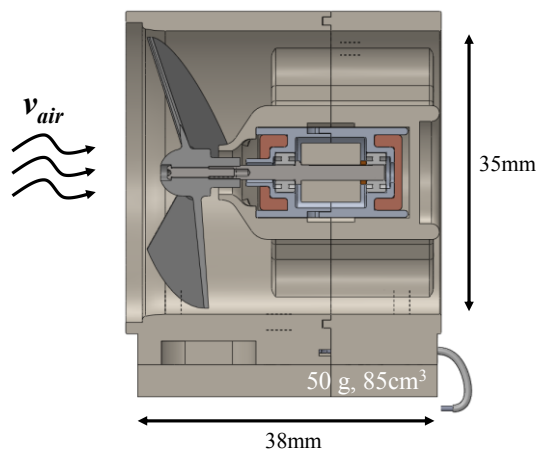


Figure 1. Cross-sectional view of the proposed harvester and its overall dimensions

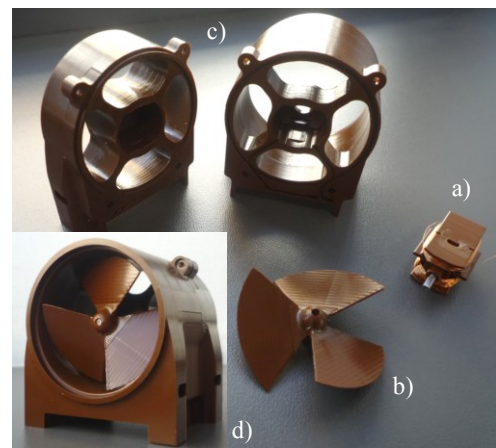


Figure 2. a) to c) main parts of an unassembled harvester and d) photograph of the final harvester

The propeller has been optimized thanks to an empirical study performed on several propeller designs and based on the Schmitz's theory. Various pitch angles, chord lengths and blade profiles have been tested. This empirical study, which cannot be covered in this paper, led us to choose a flat, 700 μ m (tip) to 1mm (noze) thick, 3-blade propeller and whose projected area is around 70% of the entire flow section. Each blade keeps a constant pitch angle of 25° and its chord varies linearly with the radius. This design was found to be the best compromise between performance (high power, low cut-in speed), mechanical robustness and ease of manufacturing (machining). It is worth mentioning that the carter surrounding the propeller has a significant impact on the propeller performances, more than the propeller design itself.

Thanks to finite element simulations, the Von Mises stress of all parts (propeller alone and assembled device) at 20G have been kept below 20MPa for all their resonant frequencies in the x, y and z directions. Furthermore, several design iterations led us to thicken the arms' casing and their fillets and to increase the number of arms (from 3 to 4) to reject the resonant frequencies as much as possible above the [0-2kHz] band at 250°C. These choices slightly disadvantage the device performances but they allow its operation in harsh aeronautic environment.

3. Power performances and ageing tests in temperature

In a dedicated low speed wind tunnel, 50 resistive loads [5 Ω to 10 M Ω] were successively connected to the generator at constant wind velocity. The RMS output voltages were measured to compute the AC

electrical power (V_{rms}^2/R_{load}). The rotation frequency of the harvester is also measured. It enables to plot the output power vs the Tip Speed Ratio (TSR), shown in figure 4. The TSR corresponds to the ratio between the tangential speed of the blade tip and the actual speed of the wind. Four harvesters have been assembled and characterized at room temperature in a wind tunnel at various wind velocities (2 to 4 m/s) and up to 10 m/s. Their performances in the low speed range are plotted in figure 5. The harvester has a cut-in speed of 2.5m/s and outputs 350 μ W @ 2 m/s and up to 4.5mW @ 4 m/s at maximum power points (figure 4 and 5).

After fabrication, accelerated ageing tests in the x, y and z directions have been carried out in a vibration chamber (figure 3) during 10^7 cycles at 20G / 250°C on each resonant frequencies in the [0-2kHz] band. Ageing tests at 180°C (200 hours) and 250°C (4 hours) have been performed with an air-jet actuating the propeller inside the climatic chamber, showing a permanent power decrease of about 8% at 180°C and 34% at 250°C and validating its good operation in harsh environments.

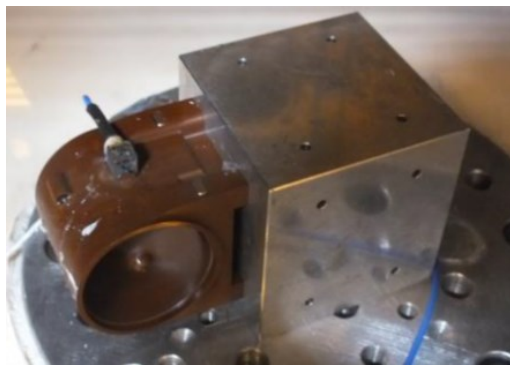


Figure 3. Photograph of the harvester under tests in the vibration chamber (x direction)

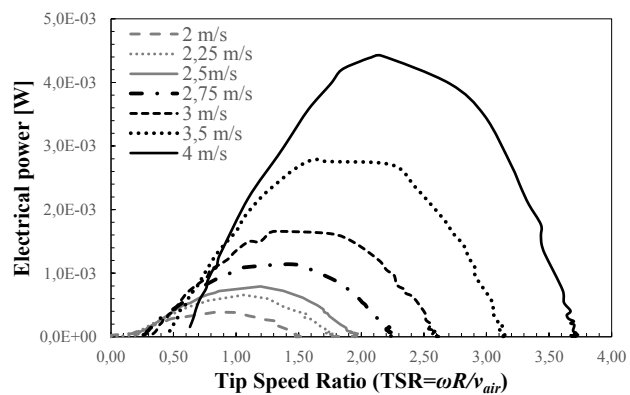


Figure 4. Electrical power as a function of the Tip Speed Ratio (Harvester n° 1) for various air speeds at room temperature

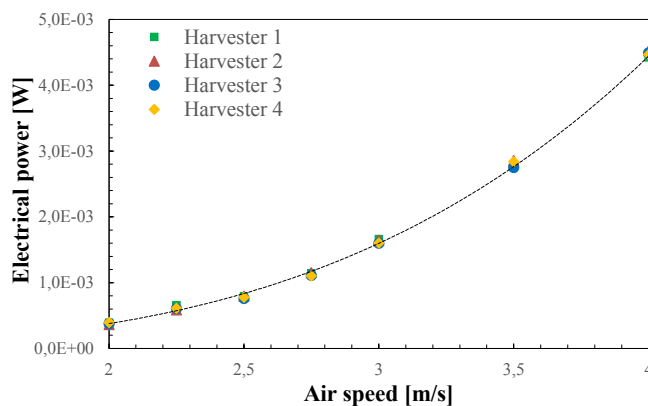


Figure 5. Electrical output power measurements of the 4 harvesters at maximum power point vs air speed at room temperature

4. Comparison to the state of art

Figure 6 shows the power density, i.e the maximum electrical power per unit cross sectional area of the harvester as a function of the air speed. It should be clarified that the two lower velocity values ($v_{air} = 2$ and 2.25 m/s) have been measured after launching the propeller at 2.5 m/s (cut-in speed). Its cut-off speed is around 1.9 m/s. A suggested improvement could be the downsizing of the generator to reduce the influence of the rotor's inertia and the Earth's magnetic field on the cut-in speed of the device.

Regarding the power density, our harvester exhibits the highest performances compared to prior art [2-4,6,7] in the cm-scale ($\varnothing < 6$ cm) and low velocity ($v_{air} < 5$ m/s) ranges. This is moreover the first one to be compatible with harsh aeronautic environments, that is to say high temperature (250°C) and high accelerations (20G).

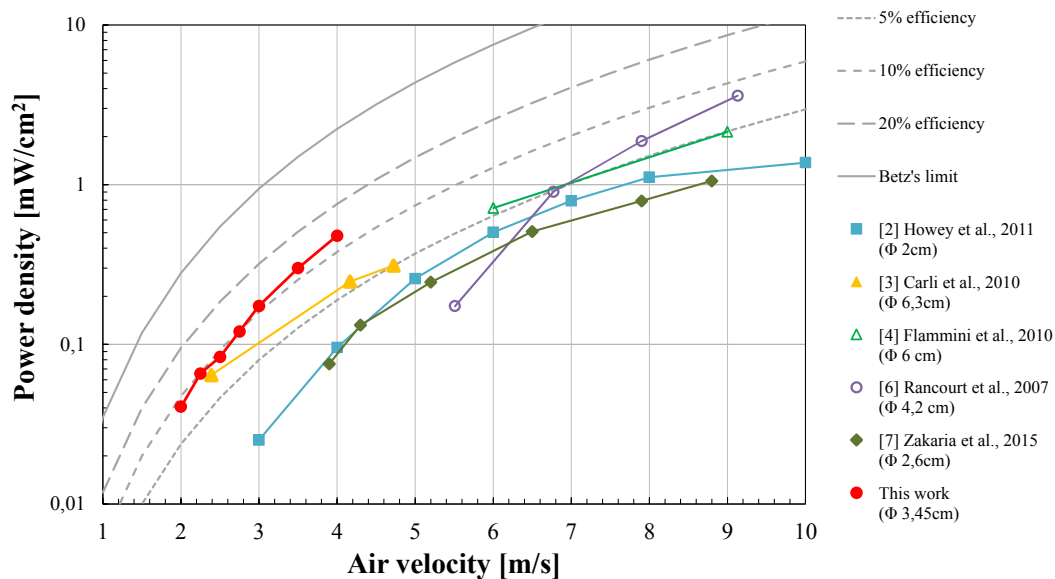


Figure 6. Performance comparison for air flow harvesters reported in the literature

5. Conclusion

This paper presents a cm-scale ($\varnothing=35\text{mm}$), low wind velocity (down to 2m/s) and 250°C compliant airflow-driven harvester dedicated to aeronautic applications. It is based on a horizontal axis propeller coupled to a permanent magnet (magnet – air coil) converter. Its compliance to harsh environments was achieved by the use of dedicated materials (Vespel®, SmCo), thermal/vibration analysis thanks to FEM modelling and specific tests in vibration chamber. In this dimension and flow velocity range, our harvester exhibits the highest performances compared to prior art while withstanding high temperature and high acceleration. It also provides a practical solution to harvest power from low-speed air flows in highly constrained environments where batteries cannot operate, as well as more conventional applications like inside buildings equipped with ventilation (HVAC).

Acknowledgments

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