Design and performance of a small-scale wind turbine exploiting an electret-based electrostatic conversion

M Perez1,2,3, S Boisseau1,2, and J L Reboud1,3
1Univ. Grenoble Alpes, F-38000 Grenoble, France
2CEA, Leti, Minatec Campus, 17 rue des Martyrs, F-38054 Grenoble Cedex 9, France
3Univ. Grenoble Alpes, G2ELab, F-38000 Grenoble, France

E-mail: matthias.perez@cea.fr

Abstract. This paper reports on a cm-scale wind turbine coupled to an electret-based electrostatic energy converter for airflows energy harvesting. The device we propose is made of a typical axial turbine to convert the wind energy into a mechanical energy of rotation and of a patterned electret-based electrostatic converter to turn this mechanical energy into electricity. This is actually the first time that the mechanical power extracted by a turbine is turned into electricity with an electret-based electrostatic converter. Several prototypes have been tested on a wind tunnel from 0 to 10 m/s; a power of 200 µW has been extracted on a 4 cm-diameter device at 10 m/s.

1. Introduction
Every day, the world is becoming more instrumented and interconnected; sensors become able to communicate without wire by RF, simplifying their installation (Wireless Sensor Nodes). Yet, there remains the energy supply issue, which involves batteries that have to be recharged. Then, the electronic research is directed towards the miniaturization of components, the reduction of their energy consumption, and ideally energy harvesting for an autonomous and long-life operation. Energy harvesting obviously requires an ambient source of energy to convert into electricity; here, we will focus on kinetic energy harvesting from airflows. Such energy harvesters can be placed on buildings, vehicles, in air conditioning system (HVAC), or in any place subjected to free or forced airflows.

We may find in the state of the art some small-scale electromagnetic wind-turbines [1], but also more original ideas such as flow-induced vibration harvesters, exploiting fluttering effects [2]. The transducer we propose here includes a classic windmill coupled to an electrostatic converter. The turbine is driven by wind energy, and its rotational kinetic energy is directly converted into electric energy through capacitance variations between movable and fixed electrodes. An electret is added to polarize the capacitive structure and to enable a direct mechanical-to-electrical energy conversion.

The next sections are devoted to small-scale electrostatic wind-turbines. Section 2 introduces the theory of electret-based electrostatic conversion which will be applied to the specific case of electrostatic wind-turbines (section 3) to end up with experimental results in section 4.

2. Electret-based conversion: models and equations
An electret is a dielectric material in which electrical charges have been implanted, and can be considered as an "electrical magnet" presenting a permanent electrical polarization [3]. Electrets are generally obtained by Corona discharge [4,5], from thin-film materials such as Teflon®, SiO2, Si3N4,
SiN, Parylene, CYTOP... and can keep their charges during several decades [6]. Electrets are currently used to replace charge-discharge cycles [3] in electrostatic converters. They offer the main benefit of simplifying the power management circuit, thus preventing additional energetic losses. Nevertheless, the surface voltage of electrets is limited for stability reasons [5], and the electrets must be kept in a dry environment to avoid their discharge.

The basic electret-based converter is represented in Figure 1a, and its equivalent circuit in Figure 1b. We are dealing here with a capacitive structure made of two electrodes separated by an air gap, with one electrode covered by an electret layer. The constant electrical charges \( Q_e \) present on the electret instantaneously induces the same amount of charges on the counter-electrode \( Q_1(t) \) and the electrode \( Q_2(t) \), to satisfy Gauss’s law:

\[
Q_e + Q_1(t) + Q_2(t) = 0
\]  

Then, the relative motion between the electrode and the counter-electrode induces a reorganization of charges between both electrodes, and thus a current circulation through load \( R \). By implementing Kirchhoff’s circuit laws to the electrical circuit presented in Figure 1b, we can thus deduce the following equation (2). This differential equation provides a link between the electret’s surface voltage \( V \), the load \( R \), the capacitance variation of the harvester \( C(t) \), and the charges on the counter electrode \( Q_1(t) \):

\[
\frac{dQ_1}{dt} + \frac{Q_1}{RC(t)} = \frac{V}{R}
\]  

The average output power \( P_{elec} \) harvested in load \( R \) during a period of time \( T \), can thus be calculated thanks to a finite element analysis (to determine \( C(t) \)) and by calculating the integral of equation (3). More simply, \( P_{elec} \) is directly proportional to the capacitance variation \( C_{max}-C_{min} \), the oscillation frequency \( (f) \) and the electret's surface voltage squared \( (V^2) \):

\[
P_{elec} = \frac{1}{T} \int_0^T R \left( \frac{dQ_1}{dt} \right)^2 dt \propto (C_{max} - C_{min}) V^2 f
\]  

3. Electret-based wind-turbine: theory and simulations

Windmills are clearly the most mature technology for “large-scale” applications (kW-MW). The windmill is composed of a rotating part called rotor, and a fixed part called stator. The most common turbines are Horizontal-Axis Wind Turbines (HAWTs) which have the benefit of being highly efficient and the main drawback of having to be pointed in the direction of the wind. In the majority of cases, the electromechanical converter is electromagnetic, and uses electromagnets or permanent magnets as inductors. For “small-scale” applications (µW-mW), the physical approach is very different but windmills still remain a reference, as well as the electromagnetic conversion [1].

The electret-based windmill energy harvester we propose is a simple HAWT (Figure 2). The operating principle is identical as the one mentioned in section 2: the electrets are positioned on the \( N \) mobile electrodes of the rotor (red layer in Figure 2a), and the stator includes \( 2 \times N \) electrodes to
achieve an optimal energy conversion. Two connection options are possible: (i) the first scheme where one external load is connected between odd and even electrodes of the stator, and (ii) the second scheme where two external loads are connected between the ground (electrodes on the rotor) and respectively odd and even electrodes of the stator.

Figure 2. (a) Solidworks view of an electret-based wind-turbine with \(N=4\) mobile electrodes. (b) Evolution of the capacitance for various air-gaps (COMSOL Multiphysics® simulations)

Contrary to the frequency and the torque that depend on the design of the turbine and wind speed, capacitances variations only depend on the spacing between the stator and the rotor and the number of mobile electrodes \(N\). COMSOL Multiphysics® simulations have enabled us to estimate the capacitance variations for a converter of 40 mm of diameter, with various air gaps. We can note that the capacitance variation is almost triangular (Figure 2b), which makes sense given the triangular evolution of surfaces facing each other. Figure 2b also reveals the impact of the air-gap on the capacitance variation, and thus directly on the output power (equation (3)). We will see in the next section that the air-gap is the most critical parameter and actually very difficult to minimize due to this fabrication process.

4. Electret-based wind-turbine: experimental results

The mechanical part of the harvester has been fabricated by a rapid prototyping machine (Figure 3a). The turbine has a diameter of \(D=40\) mm, and a total depth of \(H=10\) mm (Figure 3a); then the total volume of the prototype is about 12.5 cm³. All the electrodes are covered by a 200 µm-thick copper film, and then by a 127 µm-thick Teflon PTFE layer for mobile electrodes only. The tests were conducted on a wind tunnel. We have decided to fix the number of mobile electrodes at \(N=4\), and the same number of blades to mechanically hold the electrodes (green lines in Figure 3a).

As summarized by equation (3), the power extracted depends on three parameters. First, the air gap thickness which is directly linked to the capacitance variation \(C_{\text{max}}-C_{\text{min}}\), and limited to 500 µm due to the chosen fabrication process. Secondly, the electret's surface voltage \(V\) which should stay under 1400 V for a 127 µm-thick Teflon PTFE electret (Stability issues [7]). Thirdly, as the number of blades has been set to \(N=4\), the operating frequency only depends on the geometry of the blades. Several blade angles \(\alpha\) have been tested (Figure 4a) and it appears that the angle \(\alpha=10°\) configuration enables the highest rotational speed between 0 and 10 m/s. We can notice on Figure 4a a linear relationship between the flow speed and the rotational speed. In Figure 4b, the evolution between the output power and the electret surface voltage is quadratic, as predicted by equation (3).
5. Conclusions
We have presented the first electrostatic windmill exploiting an electret-based converter. The prototypes realized have enabled to extract a maximum output power of $P_{elec}=200$ $\mu$W at 10 m/s. At these sizes, the results are not yet equivalent to what was accomplished with electromagnetic converters, mainly because of the thick air gap which strongly reduces the capacitance and its variation. However, this harvester provides a high voltage, a reasonable amount of power compatible with autonomous sensors application, and a low manufacturing cost. Research is currently underway to improve the harvester’s aerodynamics by replacing the current stator by lateral electrodes, and to increase the output powers by reducing the air gap.

References
[1] Bansal A et al. 2009 Cm-scale air turbine and generator for energy harvesting from low-speed flow Transducers, pp. 529-532
[2] Perez M et al. 2015 An electret-based aeroelastic flutter energy harvester Smart Materials and Structures
[3] Boisseau S et al. 2012 Electrostatic Conversion for Vibration Energy Harvesting Small-Scale Energy Harvesting, ed. M. Lallart, Intech, doi:10.5772/51360
[4] Boisseau S et al. 2013 Stable DRIE-patterned SiO2/Si3N4 electrets Transducers, pp. 1942-45
[5] Sessler G et al. 1998 Electrets 3rd edition, Laplacian Press
[6] Kressmann R et al. 1996 Space-charge electrets IEEE Trans. Diel. Electr. Insul. 3, 5, pp. 607-23
[7] Boisseau S et al. 2011 Cantilever-based electret energy harvesters, Smart Mater. Struct. 20 105013