A triboelectric wind turbine for small-scale energy harvesting

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Abstract. This paper deals with a rotational energy harvester including a Horizontal Axis Wind Turbine (HAWT), a cylindrical stator covered by several electrodes, and thin Teflon dielectric membranes hung on the rotor. The sliding contact of the Teflon membranes on the stator provides simultaneously large capacitance variations and a polarization source for the electrostatic converter by exploiting triboelectric phenomena. 1µW has been harvested at 4m/s; 130µW at 10m/s and 550µW at 20m/s with a 40mmØ device. In order to validate the energy harvesting chain, the airflow energy harvester has been connected to a power management circuit implementing Synchronous Electric Charge Extraction (SECE) to supply a wireless sensor node with temperature and acceleration measurements, transmitted to a computer at 868MHz.

Introduction
Converting the kinetic energy present in an airflow into electrical energy requires an intermediate mechanical energy converter turning this kinetic energy into a relative movement between two elements, for example a relative movement of rotation between a stator and a rotor. This kinetic-to-mechanic conversion can be achieved thanks to a Horizontal Axis Wind Turbine (HAWT) or a Vertical Axis Wind Turbine (VAWT). The mechanic-to-electric conversion is finally achieved thanks to an electromagnetic, a piezoelectric, an electrostatic or a triboelectric converter. Over the past two decades, many researchers have investigated the airflow energy harvesting field and, as a consequence, many configurations have already been tested: HAWTs have been coupled to electromagnetic [1-3], piezoelectric [4] and electrostatic converters [5-6]; VAWTs have been coupled to piezoelectric [7] and triboelectric converters [8]. This paper focuses on a HAWT using a triboelectric converter implementing a free-standing triboelectric conversion scheme with flexible dielectric membranes so as to insure large capacitance variations and a self-polarization.

1. Micro wind turbines design
HAWTs are driven by the lift force \( F_L \) and limited by the drag force \( F_D \) (Figure 1). Here, we want to develop small devices (\( \Omega=4\text{cm} \)) able to work at relatively low speeds (\( U<10\text{m/s} \)). These two constraints imply a Reynolds number lower than \( Re<3\times10^4 \). At these Reynolds numbers, the viscous drag is significant and the lift is limited by early detachments of the boundary layer. Consequently, the specific speed \( (\lambda=\omega R/U) \) of micro-turbines is very limited, as well as the power coefficient \( C_p \). Yet, it appears that the best aerodynamic profiles to maximize the \( F_L/F_D \) ratio are simple thin flat plates, which greatly simplifies the fabrication of the devices.
2. Triboelectric conversion
Triboelectricity is a fascinating phenomenon of electric charges exchange that occurs when two materials of different triboelectric natures are brought into contact (Figure 2). The strength of the triboelectric effect depends on many parameters such as the materials’ nature, surface roughness, friction conditions (intensity and speed), moisture, temperature... In most cases, triboelectricity is damaging and must be avoided (overvoltage, electric shock, fuel ignition...), but it can also offer interesting possibilities in several applications including tactile sensors [9], and electrostatic energy harvesters to ensure a stable polarization source through time [10,11].

As presented in Figure 2, representing the free-standing triboelectric conversion scheme implemented here, triboelectricity enables to generate and to store negative charges on the dielectric layer. Then, as the dielectric moves from an electrode to another, positive charges are able to move freely from a conductive electrode to another, thus creating an electric current through a resistive load.

3. Experimental results
The blades of the rotor are made of 750µm-thick ABS. Several films (N) of 50µm-thick Teflon FEP are attached to the rotor and slip inside the multi-electrodes copper stator. When the rotor starts to turn, the centrifugal force drags the membranes away, entering in contact with the stator’s electrodes on N angular sectors θ (Figure 3a). As a result, the Teflon layers are negatively charged and the copper electrodes positively charged by triboelectric effects. By linking wisely the different electrodes (Figure 3a), a flow of electric current is generated through an external load.
Figure 3. Triboelectric wind turbine: (a) schematic view with N=4 membranes and θ=45°, (b) Picture of prototypes with respectively β(R)=20°, θ=90° and N=1

Various rotors with a constant diameter of Ø=40mm, a depth of H=10mm and different pitch angles β(R) have been designed. Several membranes (N) have also been fixed to the rotor’s rim (Figure 3b). The stator is located 3mm away from the point of connection, so there is no need to use very precise manufacturing techniques to obtain high electrostatic couplings with this concept [4]. Experiments have shown that the membranes tend to increase the start-up speed from 1m/s to 5m/s (Figure 4a). The friction of the membranes on the stator also decreases the rotational speed of the rotor from 7300rpm@10m/s without membranes to 3700rpm@10m/s with N=1 membrane and 1200rpm@10m/s with N=2 membranes (Figure 4a). Yet, the sliding contact of the membranes turns FEP layers into 300V-triboelectrets as expected, ensuring the polarization of the electrostatic converter for long. 1µW has been generated at 4m/s; 130µW at 10m/s and 550µW at 20m/s (Figure 4b).

Figure 4. (a) Reduction of the rotational speed by the membranes (θ=90°). (b) Output power of the best prototypes between 0 and 20m/s (θ=90°).

4. Self starting battery-free power management circuit

So as to validate the viability of this approach, a power management circuit implementing SECE (Synchronous Electric Charge Extraction) has been designed (Figure 5a) to supply a wireless sensor node. This circuit was already presented in [12] and tested with a flutter electrostatic energy harvester in [13]. It uses two energy paths, a passive one and an active one, to start the system from scratch without battery, and then to perform a SECE conversion scheme with a flyback converter.

Our circuit has been tested with a triboelectric wind turbine at 12m/s and it turned out to be very efficient with a first measurement of temperature and acceleration and its RF emission after 30 seconds followed by other measurements and RF emissions every 6 seconds (red curve in Figure 5b). This active circuit was compared to a passive strategy with a diode bridge rectifier directly connected to the buffer capacitor Cb (blue curve in Figure 5b). In this case, the first measurement is performed...
after 3 minutes and 37 seconds (7 times as much time) followed by the other measurements every 1 minute (10 times as much time).

Figure 5. (a) Schematic of the SECE circuit. (b) Evolution of the voltage $V_{Cb}$ during the measurements ($R=20\text{mm}$, $\beta(R)=20^\circ$, $N_p=4$, $N_m=2$ and $U=12\text{m.s}^{-1}$, $C_b=100\mu\text{F}$).

Conclusions
We have presented an airflow electrostatic energy harvester exploiting flexible membranes to ensure large capacitance variations and a stable polarization by taking advantage of triboelectric phenomena. Up to 550µW have been generated at 20m/s. The device has been connected to a self-starting SECE power management circuit to supply a temperature and acceleration sensor node and its RF data transmission. Research actions are now focused on the reduction of friction losses to improve the efficiency of the turbine and its cut-in speed.

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