Triboelectret-based aeroelastic flutter energy harvesters

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Abstract. This paper highlights some experimental results on several electrostatic membranes tested in a wind tunnel between 0 and 20m.s\textsuperscript{-1} for airflow energy harvesting. The main idea is to use the aeroelastic behavior of thin flexible films to induce simultaneously the capacitance variations and the polarization required by the triboelectric/electrostatic conversion. This technology provides thin and flexible devices and avoids the issue of electrets discharge. Our prototypes (<16cm\textsuperscript{2}) allowed a quick startup (from 3ms\textsuperscript{-1}), an electrical power-flux density from 0.1µW.cm\textsuperscript{-2} to 60µW.cm\textsuperscript{-2}. In order to complete the energy harvesting chain, we have used a wireless sensor with temperature and acceleration measures coupled to a low power transmission (Bluetooth Low Energy) with reception on a smartphone.

Introduction

Airflow energy harvesting is an area of substantial and growing interest for the energy harvesting community. Indeed, airflows exist in various situations and offer a high density of kinetic power ((60µW/cm\textsuperscript{2})/(m/s\textsuperscript{3})). In order to convert the flow’s kinetic energy into electrical energy, one common option is to go through an intermediary mechanical energy. This mechanical energy can take the form of a rotary or an oscillatory motion of a mechanical element, which can be rigid [1] or flexible [2]. In this paper, we use the fluttering phenomenon as a “kinetic-to-mechanical” energy converter, a triboelectret-based electrostatic transducer as a “mechanical-to-electrical” converter and a self-starting power management circuit to supply low power sensors with a RF communication.

1. Aeroelastic harvesters

A film at rest is more or less flexed by the gravity, according to its orientation and its intrinsic stiffness (Figure 1a). Once a low speed flow appears, the film is able to stretch in the direction of the flow thanks to viscous frictions (Figure 1b). Then, if we increase the velocity up to a critical speed $U_c$, the film starts to oscillate/flutter periodically (Figure 1c). As a consequence, a fraction of the kinetic energy can be converted into mechanical energy of oscillating motion, which can potentially be converted into electrical energy [3,4].

In the state of the art, many aeroelastic harvesters with different converters have been developed during the 10 past years. Overall, it may be noted that electromagnetic converters are not really suited, which explains the small number of publications [4-6]. However, the piezoelectric converters are much more suited to aeroelasticity and have been widely used [7-13]. Indeed, they provide flat and flexible harvesters and do not require any shock/contact to operate.
U=0m.s\(^{-1}\): The film is flexed by the gravity.

U<6m.s\(^{-1}\): The film is stretched in the direction of the flow.

U\(_c\)=6m.s\(^{-1}\): The film starts to oscillate.

**Figure 1.** Behavior of a PVDF film (L=3cm, H=1.5cm and h=25µm) as a function of the airflow speed.

2. **Triboelectric conversion**

The electrostatic conversion requires capacitance variations through relative motion between two elements to operate. In our case, this relative motion occurs thanks to the addition of two lateral walls (Figure 2). This will lead to mechanical contacts between the film and the lateral walls, simultaneously creating strong capacitance variations and the polarization of the structure by triboelectric effects.

**Figure 2.** Functional schematic and parameters associated with the different prototypes.

In this paper, we used Teflon FEP uncharged membranes of various thicknesses, with the aim of using triboelectric effects to turn them into triboelectrets, and several electrodes located around (Figure 2). When the FEP membrane starts to oscillate and collides with the lateral electrodes, electric charges are exchanged by triboelectric effects ([14] and Figure 3). A portion of the negative charges are trapped (<0.25mC/m\(^2\)) in the dielectric membrane, turning the FEP membrane into a triboelectret (V=315V on a 25µm film; 410V on a 50µm film and 570V on a 125µm film at 15m.s\(^{-1}\); with V the surface voltage of the electret), and polarizing the variable capacitor.

**Figure 3.** Polarization of the membrane by triboelectricity.

3. **Experimental results**

Various prototypes with various dimensions and parameters have been tested between 0 and 20m.s\(^{-1}\) (round markers). Whatever the configuration chosen (length, width, thickness, distance between the walls), the power-flux density exceeds 10μW.cm\(^{-2}\) from approximately 10m.s\(^{-1}\) (Figure 4a). At higher speeds (from 15m.s\(^{-1}\) to 20m.s\(^{-1}\)), it is possible to reach larger power-flux densities (from 20μW.cm\(^{-2}\) to 40μW.cm\(^{-2}\)). Overall, thin/flexible films should be favored at low speeds (the brown curve in Figure 4a has been achieved with a thin film of 25µm). In addition, the distance between the film and the
walls must ideally be larger at low speeds and small at high speeds (the blue and green curves have been obtained with 2ε=3mm and all others with 2ε=11mm). Moreover, the high benefit of the multi-electrodes concept was also proven as it has enabled to multiply by three the output power of our devices compared to the two-electrode configuration (Figure 4b – E1, E2, E3 and E4 connected together).

**Figure 4.** Evolution of the power-flux density of our prototypes (round tags) and comparison to the state of the art (triangular tags). (b) Impact of the multiplication of the electrodes on the output power (L=5cm, H=2cm, h=50µm, L₀=1cm, d=1mm, L₁=1cm and U=15m.s⁻¹), the black dashed line represents the case where the four electrodes (E1, E2, E3 and E4) are connected together

4. **Self starting battery-free power management circuit**

For this last reason, we decided to use a MPP (Maximum Power Point) high voltage circuit whose schematic is depicted in Figure 5. Several flutter converters (blue) are connected in parallel to diode bridges (red) and simultaneously recharge a capacitor C₀ (grey). C₀ is in the range of a few dozens of nanofarads in order to reach the optimum voltage V_{opt} (equal to U_{open-circuit}/2) in a few milliseconds. Then, C₀ is connected to a voltage divider to reduce the voltage across R₁ to a few volts (R₀/R₁≈100), and used to measure V_{C₀}, the voltage across C₀. The function of the “Flyback control” is to discharge a part of the energy stored in C₀ in the flyback (purple) as soon as the voltage at its terminal reaches V_{opt} in order to maintain V_{C₀} close to V_{opt}. The electric energy is finally transferred into a buffer capacitance C_b (brown) to power the WSN (orange), as we did in [3] with a SECE circuit. A passive circuit (green) is added to supply the “Flyback control”, through the charge of C_b (pink), at the start-up of the system, as presented in [15].

**Figure 5.** Schematic of the MPP circuit.

Thanks to the device illustrated in Figure 6b subjected to an airflow of 15m.s⁻¹ and with C₀=100µF, the MPP active circuit turned out to be the most efficient with a first measurement of temperature and acceleration after 1 minute followed by other measurements every 9 seconds (green curve in Figure...
The SECE active circuit presented in [3] is less efficient, with a first measurement after 2 minutes followed by periods of 45 seconds (red curve in Figure 6a). However, it is still more efficient than a passive strategy with a simple diode bridge directly connected to the buffer capacitor \( C_b \) (blue curve in Figure 6a). In this case, the first measurement appears after 5 minutes and 35 seconds and every 1 minute and 41 seconds for the other measurements (Figure 6a).

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