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1 **Self-powered communicating wireless sensor with aero-**
2 **piezoelectric energy harvester**

3 **Julien Le Scornec^{1*}, Benoit Guiffard², Raynald Seveno², Vincent Le Cam¹ and Stephane**
4 **Ginestar²**

5 ¹ Université Gustave Eiffel, COSYS/SII, Route de Bouaye, 44344 Bouguenais, France

6 ² IETR UMR CNRS 6164, UBL University, University of Nantes, 2 rue de la Houssinière, 44322 Nantes Cedex
7 3, France

8 E-mail: julien.le-scornec@univ-eiffel.fr

9

10 **Abstract**

11 This paper presents an ultra-flexible piezoelectric air flow energy harvester capable of powering a
12 wireless sensor. The method to easily adapt the aero-electric generator to the wind is presented. In the
13 wind tunnel, different configurations have been tested to determine the best one for energy harvesting
14 at low wind speed. In particular, the galloping configuration, with the addition of a bluff body at the free
15 end of the cantilever which allows to improve the performance of the micro-generator by coupling the
16 vibrations induced by the vortices and the galloping phenomena. In this study, we also present a method
17 to optimize the energy harvesting without increasing the volume of the device. The effects of mechanical
18 and electrical coupling of several generators on the performance of energy harvesting are presented.
19 Thus, with the electrical parallel coupling of four generators, we obtained a maximum power of 60 mW
20 instead of 30 mW with two generators for a wind speed of about 6 m/s. The mechanical coupling of the
21 micro-generators allowed the device to keep the same volume (z540 cm³), however the threshold wind
22 speed to increase (>6 m/s). The harvested energy was then used to operate a wireless sensor.

23

24 **Keywords:** Aero-electric energy harvester; piezoelectric micro-generator; cantilever configuration
25 ultra-flexible; wireless sensor

26

27

28 1 INTRODUCTION

29 Nowadays, wireless communicating sensors are an integral part of our daily lives, present in industry,
30 transportation, building health, military and space. They are most often scalable and are distributed alone
31 or in a network. They allow the user to physically adapt the instrumentation deployed in the field to the
32 application. For this reason, wireless systems are increasingly demanding energy performance. Micro
33 energy harvesting has many advantages for powering wireless sensors in terms of increased lifetime,
34 reduced maintenance efforts and economic cost. The other advantage is to limit the environmental
35 impact of sensors by limiting the use of batteries that are too polluting. Recent technological
36 developments have allowed the extraction of renewable energy from various sources such as the sun,
37 geothermal energy, wind, vibrations. Naturally, wind energy is of strong interest for its unique
38 properties, such as renewable energy, ubiquitous, freely available and environmentally friendly [1,2].
39 However, the efficiency of the wind energy to electricity conversion system based on remains low. Many
40 researches have been conducted to improve the efficiency of wind energy conversion into electrical
41 energy. To convert this mechanical energy into electrical energy, different transduction mechanisms
42 exist, we can cite electromagnetic [3,4], electrostatic [5], triboelectric [6,7] and piezoelectric [8–10]
43 mechanisms. By their nature, piezoelectric materials are one of the most used means because of their
44 high power density and ease of implementation. Regarding the source of vibration, research can be
45 classified into structural, acoustic, thermoacoustic and aero-elastic energy harvesting vibrations. For
46 example, random excitations [11], flow-induced vibrations [12] or other nonlinear vibrations [13] might
47 be mentioned. Aero-electric energy harvesting exploits the vibrations of elastic structures in an airflow.
48 It is based on the generation of aero-elastic vibrations, which can be obtained from the well-known
49 phenomena of vibration induced by vortex and galloping.

50 In the field of piezoelectric thin films, several materials such as $\text{Pb}(\text{Zr},\text{Ti})\text{O}_3$ (PZT), ZnO, and AlN have
51 been widely studied [14–16]. However, due to its outstanding ferroelectric and piezoelectric properties,
52 PZT is the most attractive candidate for energy harvesting. In our laboratory, piezoelectric thin films
53 were prepared by a chemical deposition process on a commercial aluminum (Al) substrate [17] (low
54 cost and easily transferable in industry). An electrode is deposited on the surface of the PZT to obtain a
55 micro-generator with a Metal Insulating Metal (MIM) electrodes structure. To increase the energy
56 efficiency of the generator, we used the interdigitated electrodes structure (IDE). This structure allows
57 to reduce the linear capacitance of the generator and thus increase the harvested power [18]. To design
58 the IDE structure, the PZT films must be separated from the aluminum foil and transferred onto an
59 insulating polymer in order to remove the ground plane. The solution used by Park et al [19] is to deposit
60 a PZT thin film on a sapphire for the crystallization step. Then, using a laser lift-off (LLO) process, they
61 transferred the film onto a polymer sheet. However, this method may be difficult to transfer to industry
62 for mass production. Another technique [20] consists in depositing PZT on an aluminum foil and
63 transferring this layer to a flexible and insulating polymer. Then, the aluminum foil is chemically etched
64 before finally depositing electrodes on the PZT surface. In this way, the lightness of the micro-generator
65 is preserved and makes it sensitive to air flow.

66 The above studies have made significant progress in the development of piezoelectric wind energy
67 harvesting. However, improving the efficiency of the piezoelectric micro-generator under air flow is
68 still a priority for researchers. In this paper, we present the procedure for obtaining a cantilever-based
69 ultra-flexible micro-generator for wind energy harvesting. The procedure allows the thickness of the
70 beam-shaped micro-generator to be easily adapted to wind source for an energy harvesting application.
71 Thus, changing the thickness directly influences the neutral line, which in turn impacts the energy
72 performance of the generator. The power output and performance of the micro-generator under airflow
73 is improved by adding an obstacle in front of the cantilever or a bluff body attached at the free end of
74 the beam. Comparisons in wind tunnel are conducted between the piezoelectric micro-generator in
75 horizontal, horizontal with obstacle and galloping configurations in terms of output voltages. In this
76 paper, we highlight the mechanical and electrical coupling of an assembly of several generators in order
77 to increase the output energy density without increasing the system footprint. The coupling of the

78 generators allowed powering a wireless communicating temperature sensor during several
79 measurements and temperature transitions.

80 The article is organized as follows. In the first section, the background of this study is introduced,
81 followed by the second section, which describes the design of a micro-generator. The third section
82 reviews the results obtained based on the different configurations (horizontal, horizontal with obstacle
83 and galloping) used in the wind tunnel and the coupling of several generators and conclusions are drawn
84 in the last section.

85

86 2 FABRICATION PROCESS AND EXPERIMENT SETUP

87 2.1 Fabrication process

88 The fabrication techniques mainly involve the preparation of PZT thin films on commercial aluminum
89 foils, the photolithography step, and the transfer onto polymers. Most of the process steps were
90 performed in a standard clean room environment. The basic fabrication process of PZT micro-generators
91 is detailed in previous paper [18].

92 The fabrication process begins with the deposition of a PZT thin film on a commercial aluminum foil
93 by a chemical solution deposition (CSD) process. The precursor solution is prepared by mixing lead
94 acetate trihydrate $[\text{Pb}(\text{CH}_3\text{CO}_2)_2, 2\text{H}_2\text{O}]$, zirconium $[\text{Zr}(\text{O}(\text{CH}_2)_2\text{CH}_3)_4]$ and titanate $[\text{Ti}((\text{CH}_3)_2\text{CHO})_4]$
95 n-propoxides to obtain the optimal composition [21,22], namely $\text{Pb}_{1.3}(\text{Zr}_{0.57},\text{Ti}_{0.43})\text{O}_3$. To reduce the
96 appearance of cracks during the heat treatment of the films, ethylene glycol $[\text{HO}-\text{CH}_2-\text{CH}_2\text{OH}]$ is added
97 to the solution. The resulting solution is deposited on the aluminum foil at 6000 rpm for 20 s by a spin
98 coating process and then annealed for 2 min in an open air oven preheated to 650°C . Each layer has a
99 thickness of 300 nm, to obtain a $3\ \mu\text{m}$ -thick PZT film, the deposition and annealing steps are repeated
100 9 times.

101 On the surface of the PZT, we designed an interdigitated electrodes structure (IDE) by "lift-off"
102 photolithography. This electrodes structure consists of two interdigitated combs, 20 gold fingers of
103 1.3 cm length, $200\ \mu\text{m}$ width and $100\ \mu\text{m}$ space between two fingers. A polymer resin is then deposited
104 on the surface by spin coating process, it allows to create an adhesion layer for the polymer film. The
105 PZT film with the IDE structure is then thermally bonded to a polymer film (Polyethylene Terephthalate,
106 PET) in order to remove the ground plane (aluminum substrate) by chemical etching [23,24]. Finally,
107 the active material is completely encapsulated in the PET. This process allows to obtain a flexible micro-
108 generator at low cost and possibly transferable in the industry. The polarization of the piezoelectric film
109 on a hot plate at 100°C is achieved with a continuous electric field of $100\ \text{kV}/\text{cm}$ applied for about 2
110 hours.

111

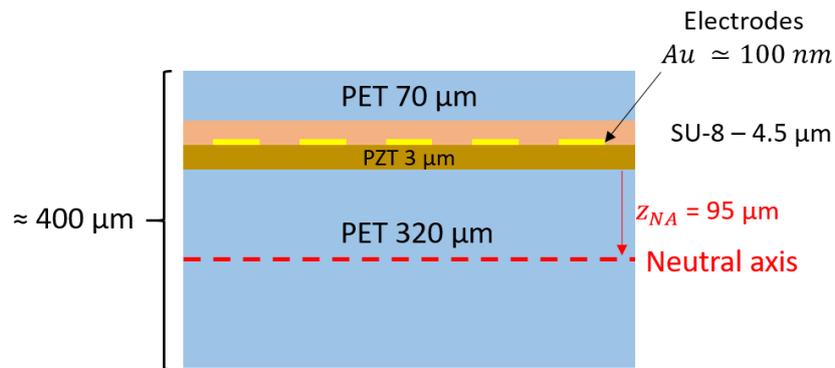
112 The process used in this study to design the micro-generators allows controlling the thickness of the
113 polymer layer that encapsulates the active material. This also allows controlling the position of the
114 neutral line and the flexibility of the micro-generator. For a piezoelectric micro-generator that converts
115 mechanical energy of deformations into electrical energy, the neutral line plays a very important role.
116 When a cantilever beam is subjected to forces that tend to bend it, the upper fibers compress and the
117 lower fibers stretch, while the neutral axis does not change in length. The compression or elongation of
118 the fibers is proportional to their distance from the neutral axis.

119 The position z_{NA} of the neutral axis [25] (taking the free surface of the supporting PET layer as origin
120 $z = 0$) is given by:

$$z_{NA} = \frac{\sum_{i=1}^n \bar{E}_i t_i z_i}{\sum_{i=1}^n \bar{E}_i t_i} \quad (1)$$

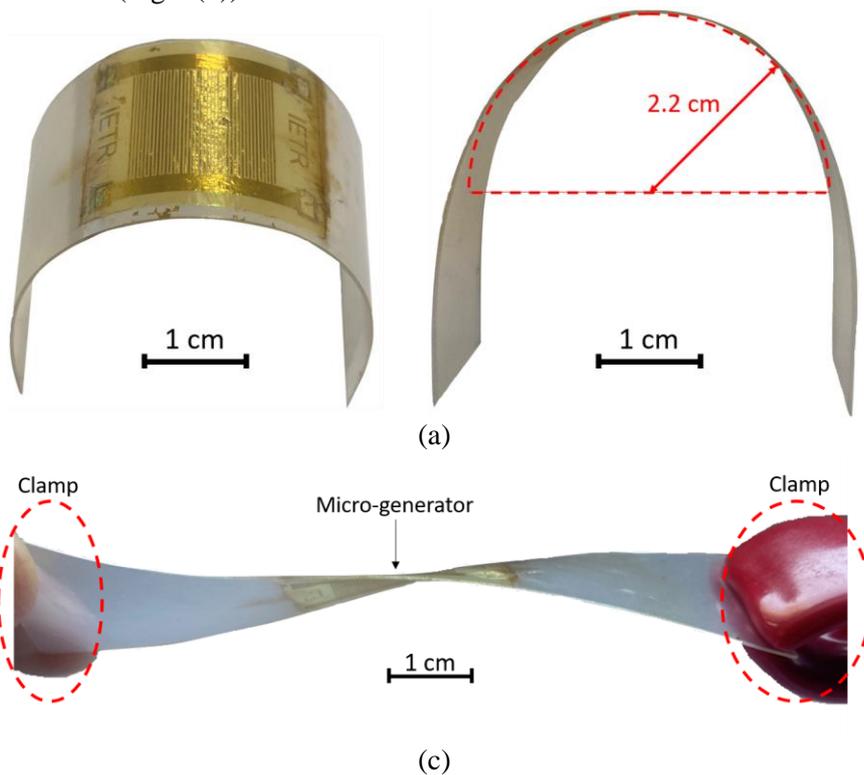
121 With n the number of layers, $\bar{E}_i = E_i/(1 - \nu_i)$ is the plane deformation modulus of the i -layer (E_i and
122 ν_i are respectively the Young's modulus and the Poisson's ratio), t_i the thickness of the i -layer and z_i
123 the position of the median plane of the i -layer.

124 Thus, to optimize the piezoelectric micro-generator, we made a compromise between the neutral line
 125 that must be the farthest from the active material and the flexibility of the micro-generator, which
 126 depends on the thickness of the supporting PET layer.
 127



128
 129 *Fig 1 : Scheme of the cross-section of the micro generator.*

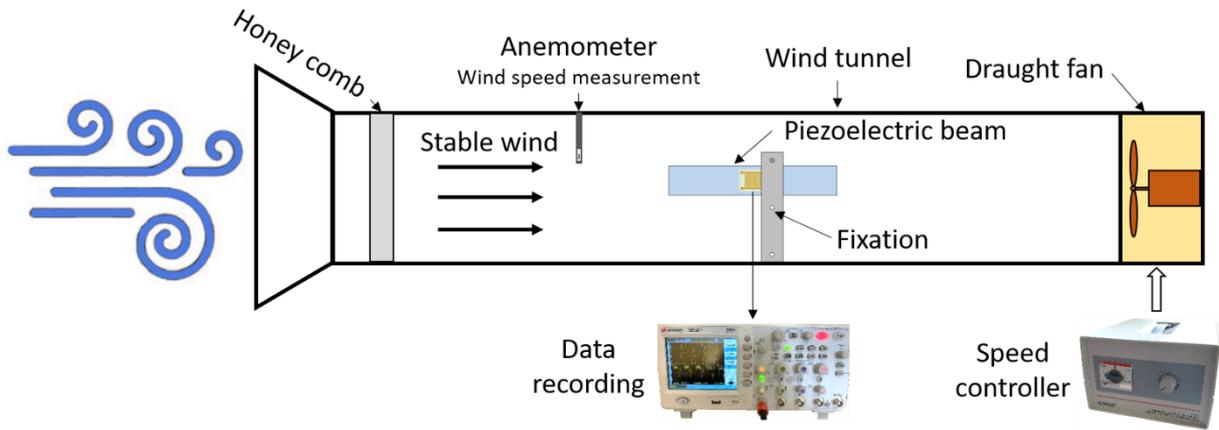
130 In order to keep a high flexibility as well as a high energy efficiency, we used a 320 μm PET sheet as
 131 supporting substrate (Fig 1). Thus, the neutral line is positioned at 95 μm from the active material (PZT).
 132 The encapsulation of the active material in a polymer also allows protecting the micro generator from
 133 large deformations. It can thus tolerate a maximum bending radius of 2.2cm (Fig 2 (a)) and important
 134 transverse deformations (Fig 2 (b)).



135
 136 *Fig 2 : (a) Deformation of the micro generator with a radius of curvature of 2.2 cm and (b) transverse deformations of the
 137 micro generator*
 138

139 2.2 Experimental setup

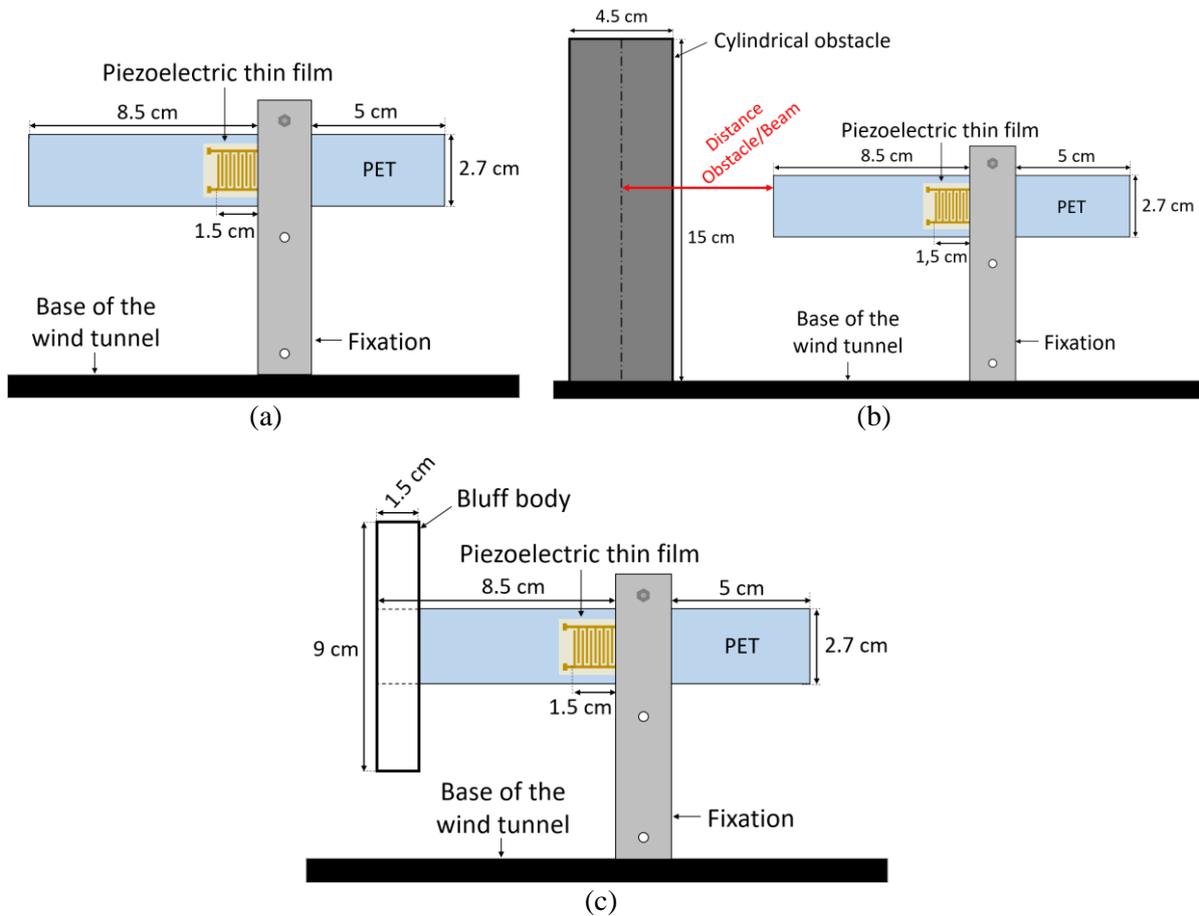
140 The experimental configuration of the micro-generator in the wind tunnel is given in Fig 3. The wind
 141 tunnel is made of plexiglass with a metal honeycomb grille inside to ensure uniformity and stability of
 142 the incoming wind. A draught fan regulated by a potentiometer controls the wind speed in the tunnel. Due
 143 to the properties of the fan controller, we use an anemometer (Testo 425) with an accuracy of 0.1 m/s to
 144 measure the wind speed in the tunnel.



145

146

Fig 3 : Schematic of the wind tunnel experiment setup.



147 Fig 4 : Schematic of the different configurations carried out in the experiment: (a) horizontal configuration, (b) horizontal
 148 configuration with obstacle and (c) galloping configuration.

149 In this experiment, the cantilever beam and the piezoelectric micro-generator (attached near fixed end
 150 of the cantilever beam) are respectively made of Polyethylene Terephthalate (PET) and a PZT thin film
 151 ($3\mu\text{m}$). The energy harvester prototype is firmly clamped by two metal fixings and placed in a wind

152 tunnel. The dimensions of the cantilever beam are $L \times W \times h_b = 85 \times 27 \times 0.4 \text{ mm}^3$. On the Fig 4 is
 153 shown the three tested configurations, horizontal, horizontal with obstacle and galloping. For the
 154 horizontal configuration with obstacle (Fig 4 (b)), a cylindrical obstacle (15 cm high and 4.5 cm in
 155 diameter) is placed at 8 cm between the wind and the micro-generator in order to create turbulences at
 156 the level of the beam. This allows increasing the deformations of the micro-generator. For the galloping
 157 configuration (Fig 4 (c)), the bluff body (polystyrene) (1.5 cm x 1.5 cm x 9 cm) is attached directly at
 158 the free end of the beam.

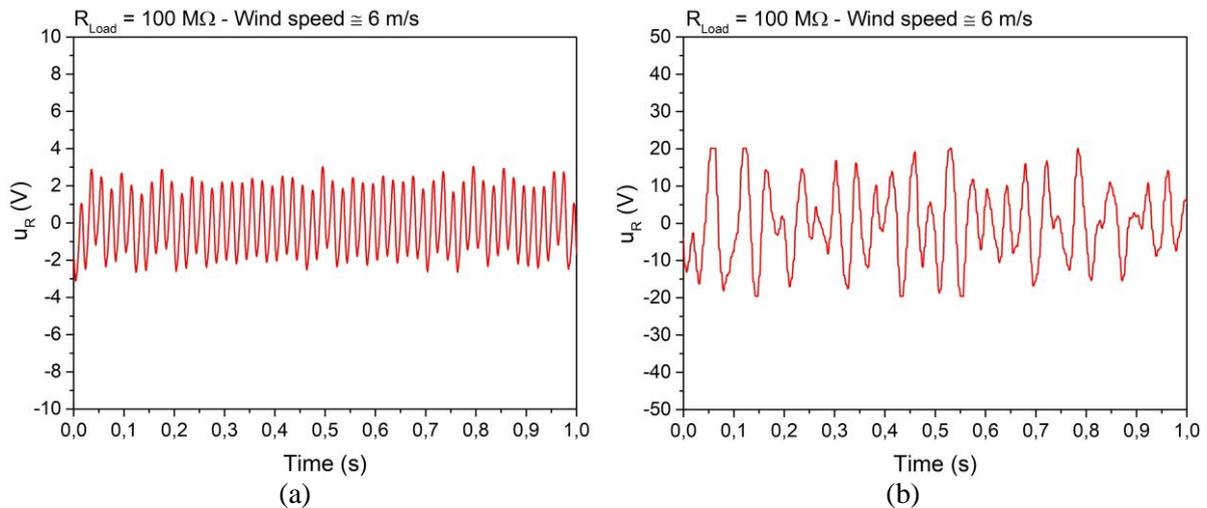
159 For each configuration tested, the voltage across the micro-generator is recorded using a Tektronix TBS
 160 1052B-EDU oscilloscope for different wind speeds (from 2 to 12 m/s). The frequency and voltage
 161 responses were recorded for the distribution of wind speed and load resistances of 1, 5, 10, 50, 100 M Ω
 162 with voltage probe and 200 M Ω and 500 M Ω with voltage divider bridge. Thus, for each wind speed,
 163 the steady-state voltage signal is recorded, and the root-mean-square (RMS) of the response is
 164 calculated. The internal capacitance of the piezoelectric micro-generator is approximately 60 pF.

165

166 3 RESULTS AND DISCUSSION

167 The voltages generated by the micro-generator in horizontal configuration with and without obstacle for
 168 a wind speed of about 6 m/s are presented in Fig 5. The voltage measurements were performed across a
 169 100 M Ω load resistor. The generated voltage is very unstable with a very low amplitude around 2 V for
 170 the horizontal configuration without obstacle and around 20 V for the horizontal configuration with
 171 obstacle. These measurements show that it is possible to recover energy, but that it is difficult to quantify
 172 it as the signals are so unstable.

173



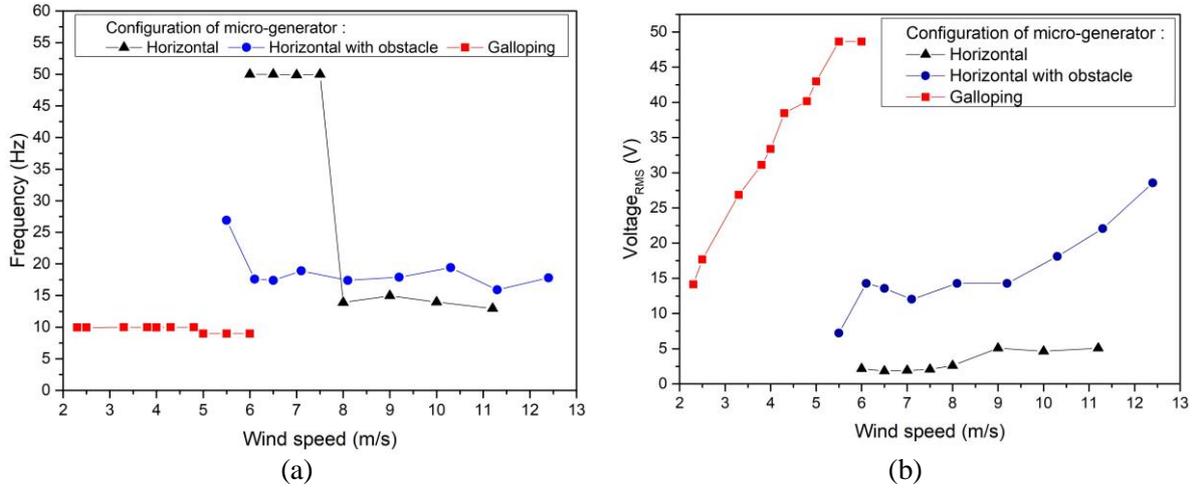
174 Fig 5 : Voltage delivered by the micro-generator in horizontal configuration a) without obstacle and b) with obstacle for a
 175 wind speed of around 6 m/s at 100 M Ω .

176 The recorded signals show excitations at very different frequencies. The observed vibration frequency
 177 for the unobstructed horizontal configuration at 6 m/s ($\approx 50 \text{ Hz}$) is much higher than that observed at
 178 10 m/s ($\approx 14 \text{ Hz}$). With the horizontal configuration with obstacle, the observed vibration frequency
 179 is 27 Hz at 6 m/s and it is about 16 Hz at 12 m/s for the horizontal configuration with obstacle.

180

181 Fig 6 (a) and Fig 6 (b) present the comparisons in frequency and RMS voltage of the micro-generator for
 182 the different studied configurations (horizontal, horizontal with obstacle and galloping) as a function of
 183 wind speed. For the horizontal configuration, the energy harvesting is maximized with a wind speed of
 184 9 m/s (Fig 6 (b)). Between 6 and 8 m/s the voltage delivered by the micro-generator is about 2 V, this
 185 voltage rises up to 5 V at 9 m/s and remains stable. The addition of the obstacle (horizontal configuration
 186 with obstacle) allowed to increase the deformation of the micro-generator and thus to increase the energy
 187 harvesting. The voltage was multiplied by 4, going from 5 V with the horizontal configuration without

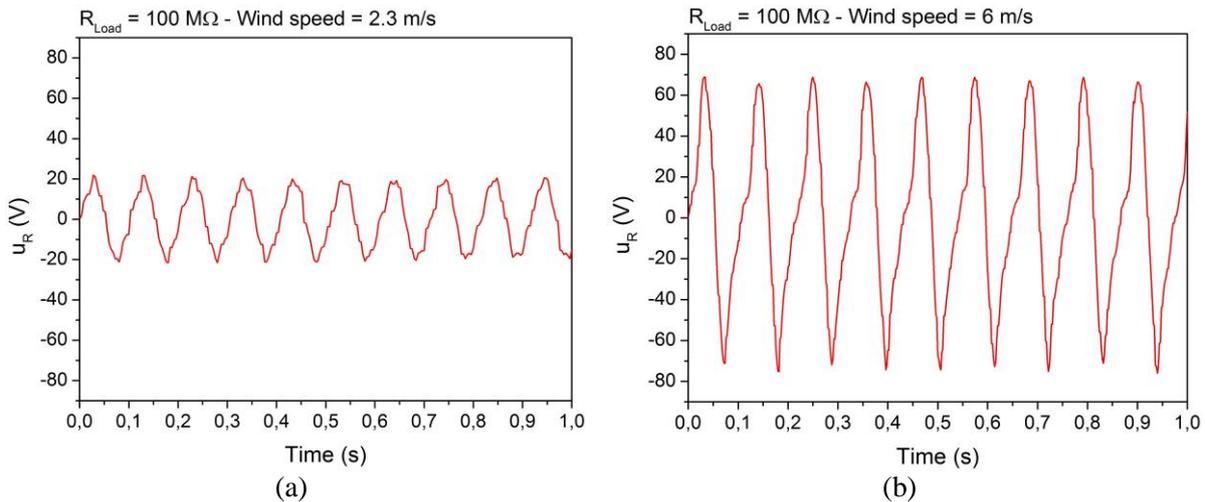
188 obstacle to 22 V for the horizontal configuration with obstacle. However, the voltages generated with
 189 these two configurations are very unstable and low.
 190



191 Fig 6 : Evolution of (a) frequency and (b) RMS voltage delivered by the micro generator across a 100 MΩ load resistor as a
 192 function of wind speed for the different studied configurations.

193 The horizontal configurations without and with obstacle do not allow the micro-generator to have a large
 194 amplitude of deformation despite its high flexibility. With these two configurations, the micro-generator
 195 requires high wind speeds (> 6 m/s).
 196

197 The experimental results of the micro-generator in galloping configuration (Fig 4 (c)) for wind speeds of
 198 2.3 m/s and 6 m/s are shown in Fig 7. The voltage measurements were performed across a 100 MΩ load
 199 resistor. Fig 7 (a) shows that the micro-generator starts to operate efficiently from a wind speed of 2.3 m/s
 200 with a stable voltage and amplitude of 20 V. The amplitude of the voltage generated by the micro-
 201 generator increases with the wind speed to reach 70 V at 6 m/s (Fig 7 (b)). This is explained by the fact
 202 that the amplitude of the mechanical deformation undergone by the PZT thin film increases with the wind
 203 speed.
 204



205 Fig 7 : Voltage signals delivered by the micro-generator in horizontal configuration for a wind speed of (a) 2.3 m/s and (b)
 206 6 m/s at 100 MΩ.

207 The observed vibration frequency for the galloping configuration is stable as a function of wind speed (\approx
 208 10 Hz) unlike the other two configurations. Fig 6 (b) shows that the RMS voltage increases with wind
 209 speed to reach 50 V peak at 6 m/s, while for the same wind speed, the voltage for the horizontal and
 210 horizontal configuration with an obstacle is 2.5 V and 15 V respectively.

211 The galloping configuration is very simple to implement and it allows the micro-generator to deliver
 212 quasi-sinusoidal voltages with higher amplitudes. Contrary to the two other configurations seen
 213 previously (Fig 5), the micro-generator can operate efficiently from 2.3 m/s. This study has also

214 highlighted the mechanical limits of the generator in the wind. Beyond 6 m/s, it undergoes too important
 215 deformations which can damage it.

216
 217 Another characterization was performed by measuring the U_R output voltage amplitude for five different
 218 load resistors at a fixed frequency (10 Hz), corresponding to the resonance frequency of the micro-
 219 generator in galloping configuration (Fig 6 (a)). This experiment was performed for different wind speeds
 220 from 2.3 to 6 m/s.

221 From these measurements, we can deduce the voltage amplitude U_R , the current amplitude I_R and the
 222 generated power P through the load resistance R by using equations (3) and (4), where I_0 is the
 223 piezoelectric current, C is the capacitance of one generator and ω is the angular frequency. Theoretical
 224 curves were obtained by using equations (2) and (4).

$$I_R = \frac{I_0}{\sqrt{1 + R^2 C^2 \omega^2}} \quad (2)$$

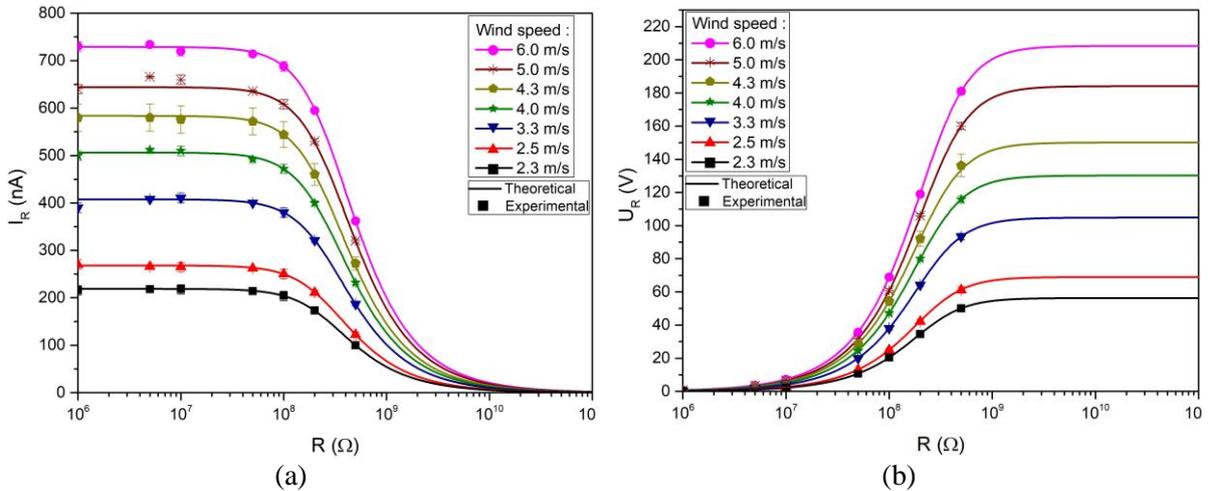
$$U_R = R \times I_R \quad (3)$$

$$P = \frac{U_R \times I_R}{2} = \frac{I_0^2 \times R}{2(1 + (RC\omega)^2)} \quad (4)$$

225 The theoretical and experimental data of voltage, current and power managed by the micro-generator for
 226 different wind speeds are plotted (Fig 8 and Fig 9) with load resistances (1, 5, 10, 50, 100, 200 and
 227 500 M Ω). A good agreement between experiment and theory is observed. Thus, the value of the load
 228 resistance giving the maximum power is consistent with the calculated value $R_{opt} = 1/C\omega$ obtained by
 229 deriving the power expression [Eq. (4)] as a function of R . The theoretical value of the optimum resistance
 230 is $R_{opt} \approx 265 \text{ M}\Omega$ at 10 Hz since the sample has a very low capacitance C around 60 pF.

$$P_{max} = \frac{I_0^2}{4C\omega} \quad (5)$$

231

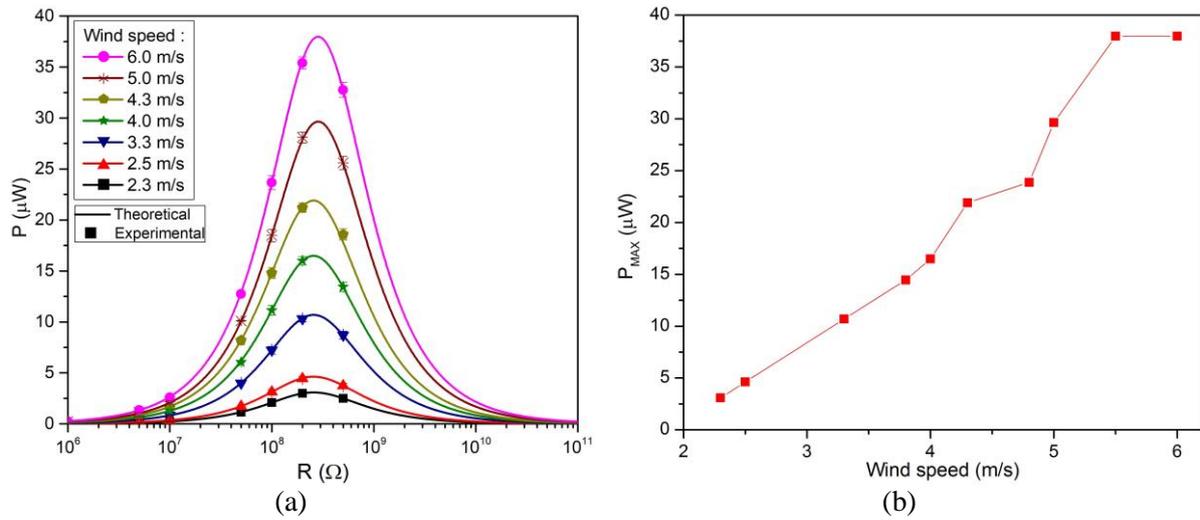


232 Fig 8 : (a) Current and (b) voltage amplitudes delivered by the micro-generator for different wind speeds according to the
 233 load resistance.

234 Fig 8 (a) highlights the influence of the wind speed on the energy harvesting, with a piezoelectric current
 235 I_0 that increases significantly from 215 nA for a wind speed of 2.3 m/s to 730 nA with a wind speed of
 236 6 m/s. The open circuit voltage amplitude delivered by the generator varies according to the wind speed
 237 (Fig.8(b)). It reaches about 200 V for a wind speed of 6 m/s, and drops to 40 V with a wind speed of
 238 2.3 m/s.

239
 240 Similarly, the maximum power (at $R_{opt} = 1/C\omega$) increases with wind speed (Fig 9 (a)). Thus, it
 241 increases from 3 μW for a wind speed of 2.3 m/s to 38 μW for a wind speed of 6 m/s. The evolution of
 242 the maximum power delivered by the micro-generator as a function of the wind speed is plotted in Fig 9
 243 (b). This figure shows the evolution of the maximum power ($R_{load} = R_{opt}$) harvested as a function of

244 wind speed. The increase of the maximum power is mainly due to the piezoelectric current which
 245 increases with the wind speed due to the higher deformation of the beam. With the galloping
 246 configuration, the micro-generator can generate a stable sinusoidal voltage from 2.3 m/s and yields a
 247 maximum power of 38 μW at 6 m/s.
 248



249 Fig 9 : (a) Power delivered by the micro-generator for different wind speeds as a function of load resistance and (b)
 250 evolution of the maximum power delivered by the micro-generator according to the wind speed.

251
 252
 253

254 In the literature, there is a wide range of piezoelectric generators for aeroelectric energy harvesting in a
 255 galloping configuration. However, in the literature very few use an interdigitated electrode (IDE)
 256 structure for aeroelectric energy harvesting. Table 1 summarizes the main characteristics of flexible
 257 piezoelectric micro-generators found in the literature (including polymer/polymer and hybrid
 258 oxide/polymer bilayer structure) with a Metal/Insulator/Metal (MIM) electrodes structure and allowing
 259 a comparison with the micro-generator developed in the present study. It should be noted that the power
 260 density (surface and volume) of the micro-generator depends on the beam shape, active area, thickness
 261 and wind speed. Nevertheless, the data collected for wind speeds between 3 m/s and 8 m/s show that the
 262 surface power density ($21 \mu\text{W}/\text{cm}^2$) with the generator presented in this work is in the average of those
 263 reported in the literature. However, the volume power density ($70185 \mu\text{W}/\text{cm}^3$) of the developed micro-
 264 generator is much higher than those reported in the literature. This is due to the thickness of our active
 265 material which is much smaller than that of the literature, $3 \mu\text{m}$ against $180 \mu\text{m}$ on average.

266

	Piezoelectric material [substrate]	Electrodes	Thickness of active material	Active area	Wind speed	Power max	Power density surface	Power density volume
Zhang and al. [26]	PVDF [metal]	MIM	$28 \mu\text{m}$	6.6 cm^2	8.0 m/s	$50.2 \mu\text{W}$	$7.6 \mu\text{W}/\text{cm}^2$	$2714.2 \mu\text{W}/\text{cm}^3$
He and al. [27]	PVDF [PET]	MIM	$200 \mu\text{m}$	2.3 cm^2	6.0 m/s	$60.9 \mu\text{W}$	$26.5 \mu\text{W}/\text{cm}^2$	$1325.0 \mu\text{W}/\text{cm}^3$
Sun and al. [28]	MFC P2 types [aluminum]	MIM	$300 \mu\text{m}$	3.9 cm^2	6.0 m/s	$74.5 \mu\text{W}$	$19.1 \mu\text{W}/\text{cm}^2$	$636.6 \mu\text{W}/\text{cm}^3$
Yang and al. [29]	PVDF [PET]	MIM	$200 \mu\text{m}$	1.6 cm^2	5.0 m/s	$69.4 \mu\text{W}$	$43.4 \mu\text{W}/\text{cm}^2$	$2170.0 \mu\text{W}/\text{cm}^3$
Sun and al. [30]	PVDF [aluminum]	MIM	$28 \mu\text{m}$	4.0 cm^2	6.0 m/s	$24.8 \mu\text{W}$	$6.2 \mu\text{W}/\text{cm}^2$	$2214.2 \mu\text{W}/\text{cm}^3$
Qui and al. [31]	PZT [aluminum]	MIM	$150 \mu\text{m}$	0.2 cm^2	6.0 m/s	$0.5 \mu\text{W}$	$2.5 \mu\text{W}/\text{cm}^2$	$9.2 \mu\text{W}/\text{cm}^3$
Wang and al. [32]	MFC P2 types [metal]	MIM	$300 \mu\text{m}$	2.0 cm^2	6.0 m/s	$57.8 \mu\text{W}$	$28.9 \mu\text{W}/\text{cm}^2$	$963.3 \mu\text{W}/\text{cm}^3$
Wang and al. [33]	PZT-5 [aluminum]	MIM	$120 \mu\text{m}$	3.9 cm^2	3.0 m/s	$63.2 \mu\text{W}$	$16.2 \mu\text{W}/\text{cm}^2$	$1350.0 \mu\text{W}/\text{cm}^3$
Wang and al. [34]	PZT-5 [aluminum]	MIM	$120 \mu\text{m}$	7.2 cm^2	4.3 m/s	$142.6 \mu\text{W}$	$19.8 \mu\text{W}/\text{cm}^2$	$229.1 \mu\text{W}/\text{cm}^3$
Zhang and al. [35]	PZT-5 [copper]	MIM	$250 \mu\text{m}$	4.8 cm^2	6.0 m/s	$30.2 \mu\text{W}$	$6.3 \mu\text{W}/\text{cm}^2$	$252.0 \mu\text{W}/\text{cm}^3$
Shi and al. [36]	PVDF [PET]	MIM	$28 \mu\text{m}$	1.5 cm^2	6.0 m/s	$4.9 \mu\text{W}$	$3.3 \mu\text{W}/\text{cm}^2$	$1178.6 \mu\text{W}/\text{cm}^3$
Zhang and al. [37]	PZT-5 [copper]	MIM	$250 \mu\text{m}$	6.0 cm^2	8.0 m/s	$99.6 \mu\text{W}$	$16.6 \mu\text{W}/\text{cm}^2$	$664.0 \mu\text{W}/\text{cm}^3$
Hu and al. [38]	MFC P2 types [aluminum]	MIM	$300 \mu\text{m}$	3.9 cm^2	3.5 m/s	$99.4 \mu\text{W}$	$25.5 \mu\text{W}/\text{cm}^2$	$850.0 \mu\text{W}/\text{cm}^3$
This work	PZT[PET]	IDE	$3 \mu\text{m}$	1.8 cm^2	6.0 m/s	$37.9 \mu\text{W}$	$21.0 \mu\text{W}/\text{cm}^2$	$70185.0 \mu\text{W}/\text{cm}^3$

267

Table 1 : Characteristics of flexible piezoelectric generators in galloping configuration.

268

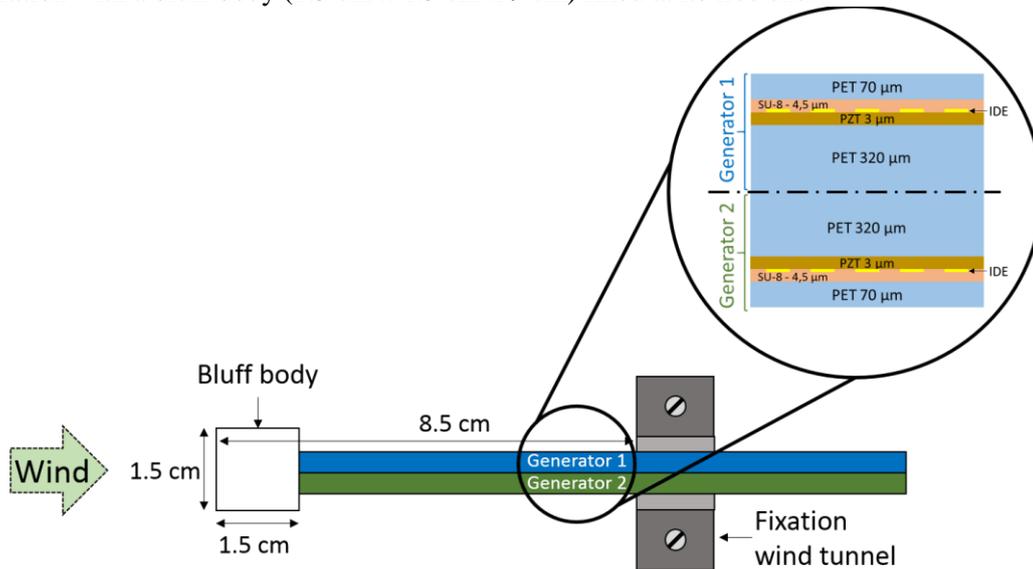
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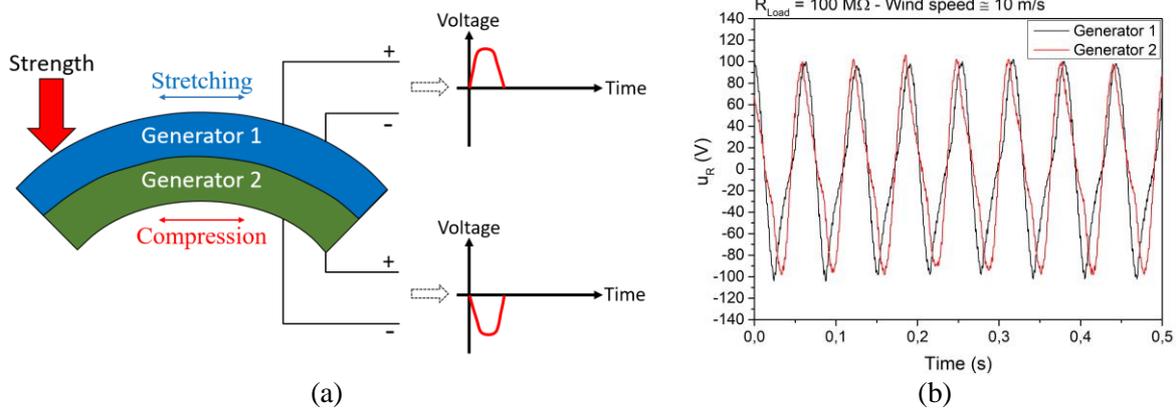
272 3.1 Coupling of micro-generators

273 The objective of this work is to harvest energy from air flows, thus a study on the mechanical and
 274 electrical coupling of two generators with an IDE structure was carried out. For this purpose, the two
 275 generators are glued between each other to form a single beam. Fig 10 shows a schematic of the
 276 association of the two generators. The beam has a width of 2.7 cm and a length of 8.5 cm. The association
 277 of the two generators induces a shift of the neutral line to the center of the beam (320 μm from the active
 278 material) but also an increase the resonance frequency. The previous study on the energy efficiency of a
 279 micro-generator under air flow according to different configurations has highlighted the advantages of
 280 the galloping configuration for energy harvesting. For the coupled generators, we thus use the galloping
 281 configuration with a bluff body (1.5 cm x 1.5 cm x 9 cm) fixed at its free end.



282
283 Fig 10 : Representation of the top view of the bi-generator beam in galloping configuration.

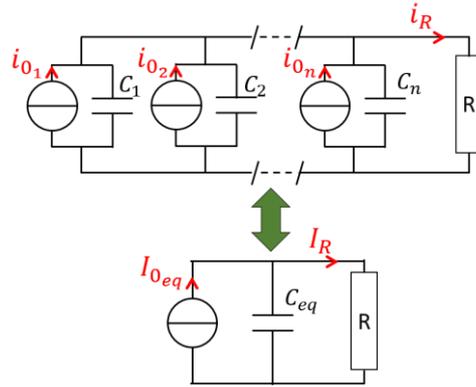
284 The mechanical coupling of the micro-generators allows to double the number of generators without
 285 increasing the dimensions of the device. Thus, the two generators will deform simultaneously, which
 286 makes them electrically coupled (series or parallel coupling). With electrical coupling, it is important to
 287 pay attention to the direction of connection of one micro-generator with respect to the other one. In this
 288 configuration (Fig 10), when a force is applied to the beam, generator 1 becomes stretched while
 289 generator 2 is compressed (Fig 11 (a)). A positive voltage appears at the terminals of the generator when
 290 it stretches and a negative voltage when it compresses. In this study, for the electrical coupling, the
 291 generators were connected in reverse of each other so that their respective output voltages are in phase
 292 (i.e. they do not cancel each other) (Fig 11 (b)).



293 Fig 11 : (a) Representation of the voltages generated during deflection of the bi-generator beam and (b) voltage delivered by
 294 the bi-generator beam in galloping configuration for a wind speed of 10 m/s.

295 The electrical coupling can be designed in two different ways, coupling in series or coupling in parallel
 296 of the generators. In the case of our work and taking into account the results obtained previously (high

297 voltage and low current (Fig 8)), the parallel coupling is the most beneficial. It allows to increase the
 298 current generated while keeping a high voltage level.
 299



300
 301 Fig 12 : Equivalent circuit of n micro-generators connected in parallel.

302 From the equivalent circuit of n micro-generators in parallel (Fig 12), we determine the equivalent output
 303 current:

$$I_{0eq} = \sum_{x=1}^n i_{0x} \quad (6)$$

304 The equivalent capacitance of the model is given by:

$$C_{eq} = \sum_{x=1}^n C_x \quad (7)$$

305 The current I_R across the load R is given by:

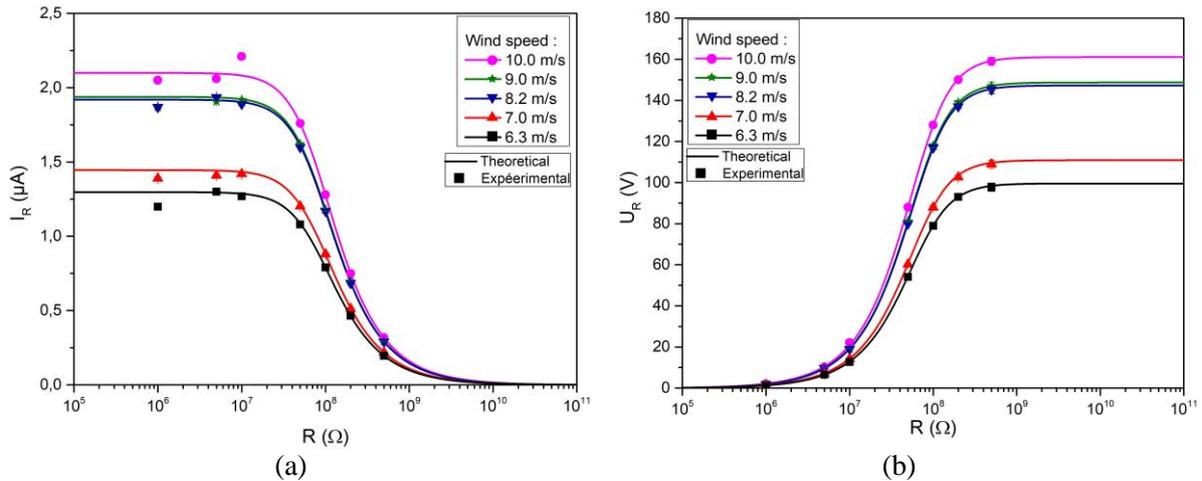
$$I_R = I_{0eq} \frac{\frac{1}{C_{eq}\omega}}{\sqrt{R^2 + \left(\frac{1}{C_{eq}\omega}\right)^2}} = \frac{\sum_{x=1}^n i_{0x}}{\sqrt{R^2\omega^2(\sum_{x=1}^n C_x)^2 + 1}} \quad (8)$$

306 For n identical generators, the maximum power ($R = R_{opt} = 1/C\omega$) is given by the formula:

$$P_{max} = \frac{(nI_0)^2}{4n C \omega_{meca}} = \frac{n I_0^2}{4 C \omega_{meca}} \quad (9)$$

307 with n the number of generators in parallel.
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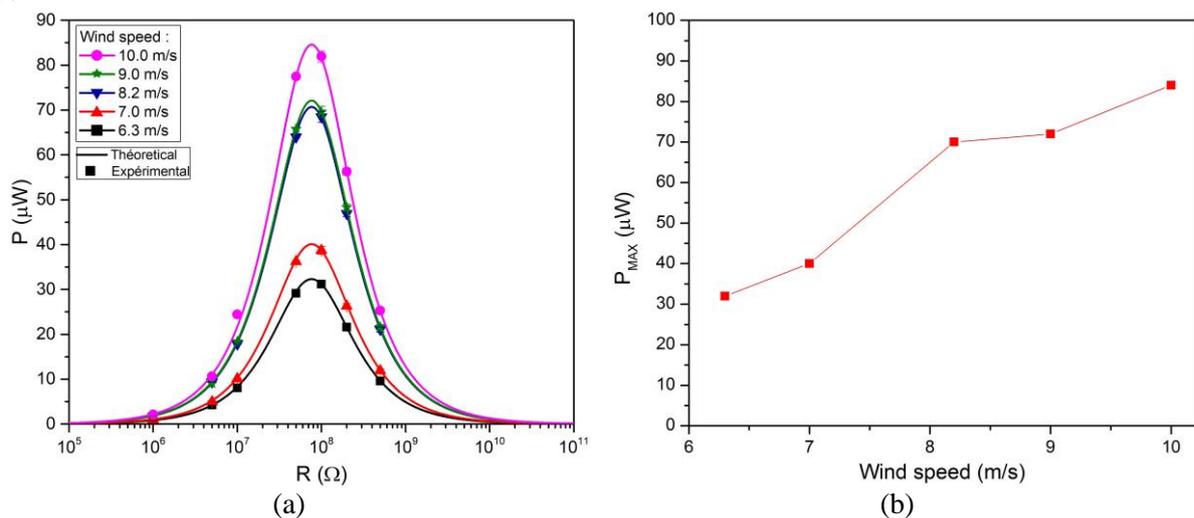
314 Fig 13 shows the current and voltage amplitudes as a function of the load resistance across the external
 315 micro-generator ranging from 1 to 500 M Ω for different wind speeds. The current values gradually
 316 decrease to saturation as the load resistance increases. Conversely, the voltage values gradually increase
 317 to saturation as the load resistance increases.



318 Fig 13 : (a) Current and (b) voltage amplitudes delivered by the two micro-generators in parallel for different wind speeds as
 319 a function of load resistance.

320 Coupling the two generators in parallel doubled the delivered current from 0.7 μA to 1.3 μA at a wind
 321 speed of 6.3 m/s. As for the study with a single generator, the piezoelectric current I_0 also increases
 322 significantly with the wind speed. The same trend is also observed for the maximum power, which
 323 increases with the wind speed (Fig 14 (a)). It increases from 32 μW for a wind speed of 6.3 m/s to 84 μW
 324 with a wind speed of 10 m/s. The evolution of the maximum power delivered by the two-generator
 325 configuration as a function of wind speed is plotted in Fig 14 (b).

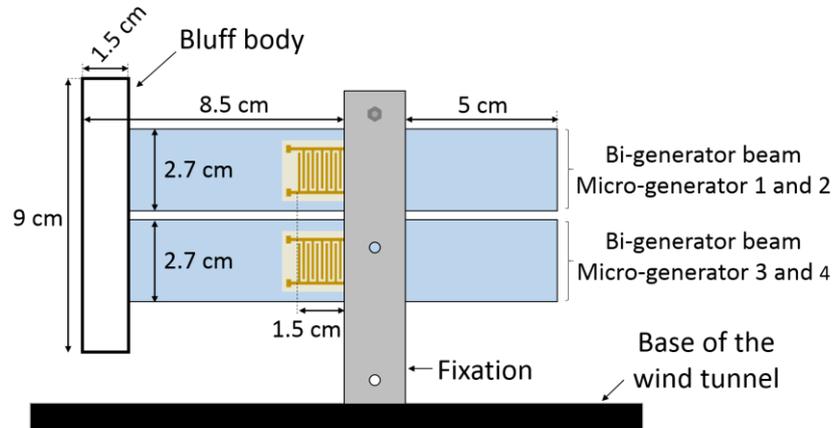
326 However, the mechanical coupling of the two generators, had for consequence to increase the total
 327 thickness of the beam. This increase in thickness has direct consequences on the wind speeds required to
 328 excite the system. The single generator can start to generate energy with a wind speed of 2.3 m/s against
 329 6 m/s for the bi-generator configuration, which can be limiting for the energy harvesting from weak air
 330 flow.
 331



332 Fig 14 : (a) Power delivered by the two micro-generators in parallel for different wind speeds as a function of load
 333 resistance and (b) evolution of the maximum power delivered by the two micro-generators in parallel as a function of wind
 334 speed.

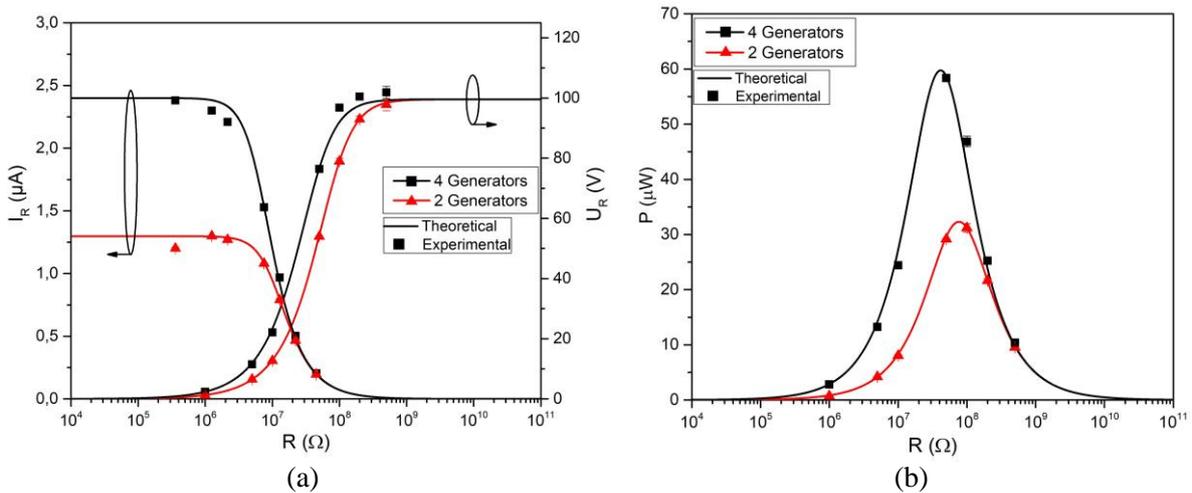
335
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 337

338 In order to increase the energy harvesting, we have arranged two bi-generator beams on the same fixation
 339 and connected them at their ends with the bluff body (Fig 15). The two bi-generator beams being
 340 connected together with the bluff body, the four generators will deform simultaneously. Thus, the
 341 generators can be directly connected in parallel to increase the current and require only one rectifier
 342 circuit.



343
 344 Fig 15 : Schematic of the experimental setup of four generators in in parallel and in galloping configuration.

345 A comparison between the energy harvesting with one and two bi-generator beams was performed in
 346 galloping configuration for a wind speed of 6.3 m/s. The current and voltage amplitudes delivered by the
 347 micro-generators are presented in Fig 16 (a) and the power curves in Fig 16 (b). As expected, the coupling
 348 of the two bi-generator beams has doubled the maximum power [Eq. (9)] from $30 \mu\text{W}$ to $60 \mu\text{W}$. We can
 349 also see that the optimal load resistance has decreased with the paralleling of the four generators. It goes
 350 down from $780 \text{ k}\Omega$ with a bi-generator beam to $410 \text{ k}\Omega$ with the two bi-generator beams in parallel. This
 351 decrease is mainly due to the increase of the total capacitance [Eq. (7)] (from 125 pF to 248 pF for the
 352 two bi-generator beams in parallel) but also to the slight increase of the resonance frequency.
 353

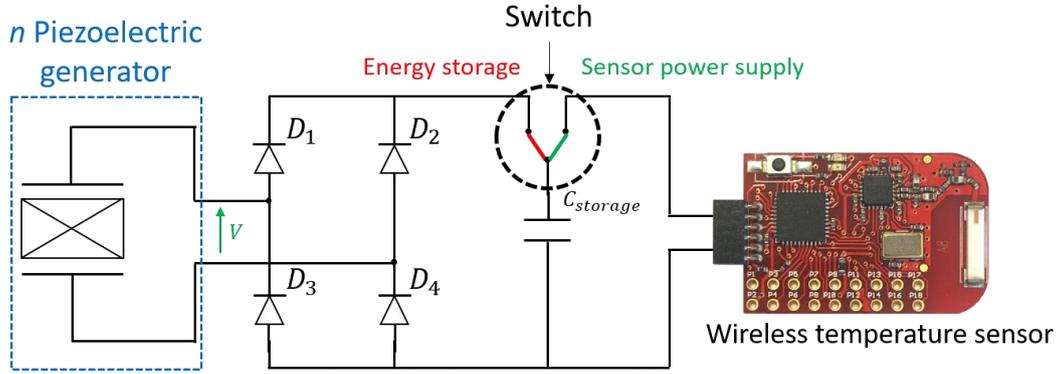


354
 355 Fig 16 : Evolution (a) of the voltage and current amplitudes and (b) the power delivered by the four micro-generators in parallel for a wind speed of 6.3 m/s.

356 To use the micro-generator as a power source for a WSN, the output electrical charge from the generator
 357 must be stored in storage elements such as capacitors and batteries. Piezoelectric micro-generators deliver
 358 an AC voltage that must be converted to a DC voltage by a rectifier circuit to match the electronic systems
 359 to be powered.
 360
 361
 362

363 3.2 Power supply of a communicating sensor

364 In order to demonstrate the potentialities of the developed coupled generators for self-powering a
 365 wireless communicating sensor, we fabricated a complete electronic system consisting of flexible
 366 piezoelectric micro-generators, a rectifier bridge (D1N4007 diodes), a storage capacitor (capacitance
 367 1.2 mF), and a commercially available wireless temperature sensor (eZ430-RF2500T, Texas Instruments)
 368 as shown in Fig 17. The wireless sensor integrates an ultra-low power microcontroller unit with an
 369 internal temperature sensor (MSP430F2274, Texas Instruments), a 2.4 GHz Radio Frequency (RF)
 370 transceiver chip (CS2500, Texas Instruments), and a chip antenna, which requires an overall input power
 371 greater than 20 mW for 20 ms (corresponding total consumption energy greater than 400 μ J).

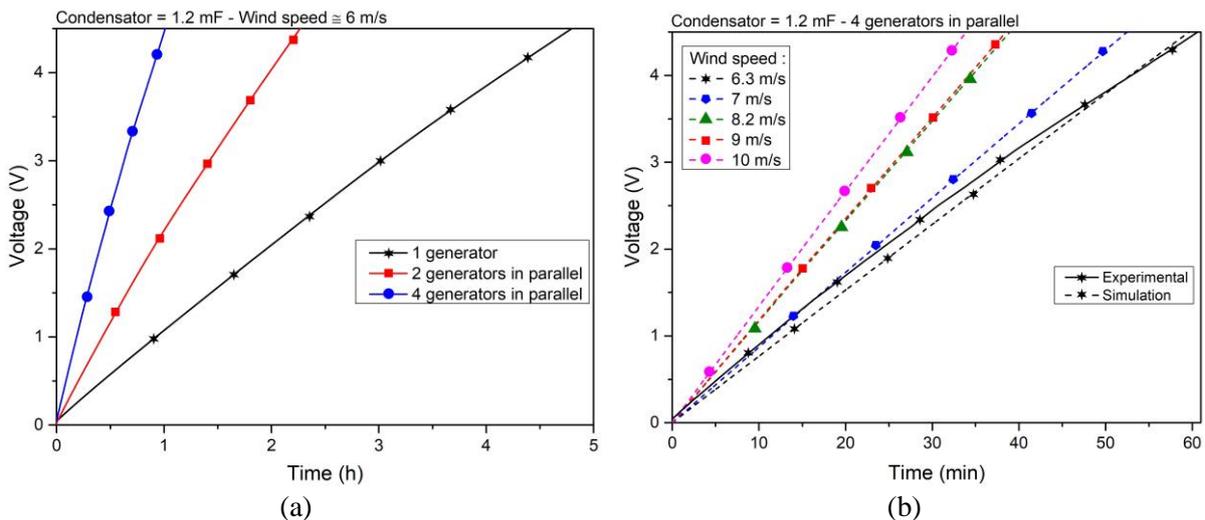


372 Fig 17 : Electronic schematic for the self-powering of the wireless temperature sensor.
 373

374 During the periodic cantilever beam bending, an AC voltage is generated by the piezoelectric micro-
 375 generators connected in parallel and simultaneously converted, via the rectifier circuit, into DC voltage
 376 to charge a 1.2 mF capacitor.
 377

378 Fig 18 (a) shows the charging curve of the capacitor from 0 to 4.5 V using one or more piezoelectric
 379 micro-generators with excitation under constant wind speed (\approx 6.3 m/s). With only one generator, it takes
 380 about 5 hours to charge the capacitor to 4.5 V. Although storing energy with the capacitor by flexible
 381 micro-generators is generally difficult because of the energy loss due to impedance mismatch, coupling
 382 multiple generators in parallel overcomes the energy loss and charges the capacitor. By coupling 4
 383 generators in parallel, the charging time to reach 4.5 V is divided by 5 from 5 hours to 1 hour.

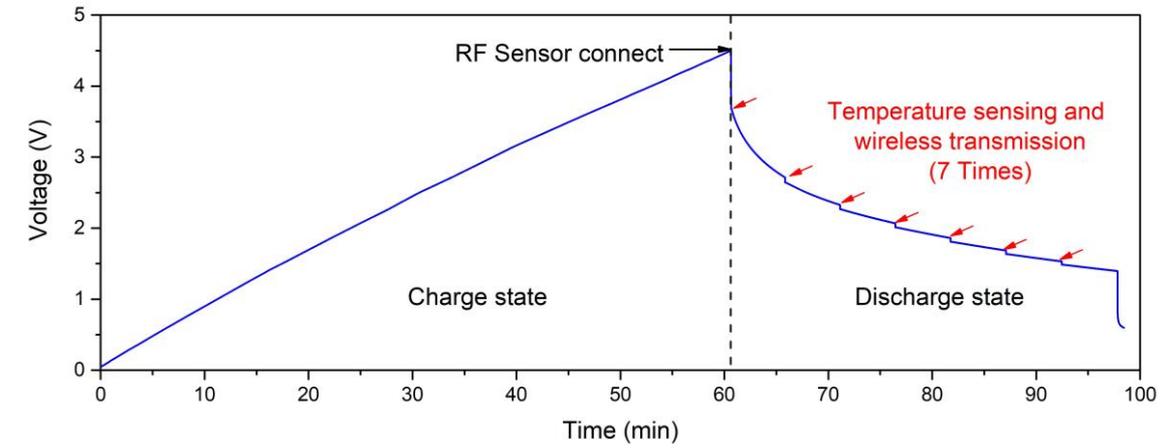
384 Fig 18 (b) shows the capacitor charge with 4 micro-generators in parallel for different wind speeds. The
 385 capacitor charge time decreases with increasing wind speed.
 386



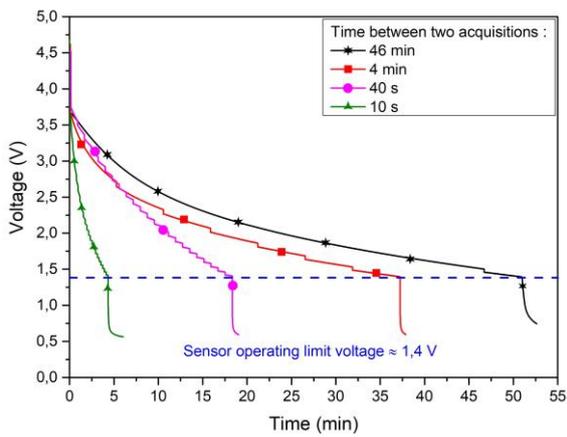
387 Fig 18 : (a) The charging curve of a capacitor (capacitance 1.2 mF) using 1, 2 and 4 micro-generators in parallel for a wind
 388 speed of 6.3 m/s and (b) theoretical and experimental charging curve of capacitor with 4 generators in parallel for different
 389 wind speeds.

390

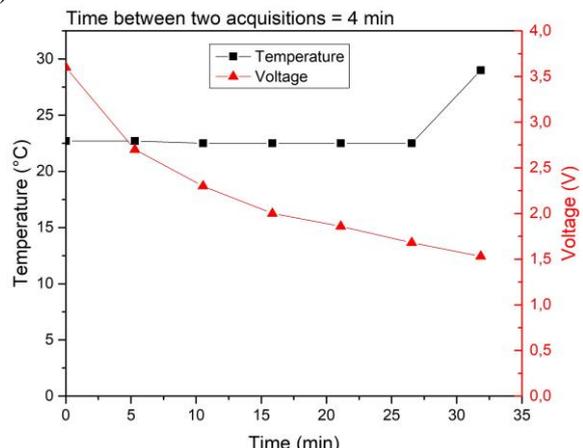
391 Finally, the temperature sensor was powered by the charged capacitor to measure the ambient temperature
 392 and then wirelessly transmit the information to a 2.4 GHz RF receiver connected to a computer. As shown
 393 in Fig 19 (a), the electrical energy from the piezoelectric micro-generators under a wind speed of 6.3 m/s
 394 can be used to charge the capacitor from 0 to 4.5 V in about 60 min, and then it is discharged successively
 395 to operate the wireless temperature sensor 7 times at intervals of about 4 min. The capacitor voltage
 396 immediately dropped to about 3.5 V at about $t = 60$ min when the sensor was initialized for operation
 397 (communication initialization). Another significant voltage drop was observed after the completion of
 398 temperature sensing and wireless transmission cycles. The operating time of the sensor can be varied
 399 according to the programmed measurement interval to suit the target application (Fig 19 (b)).



(a)



(b)



(c)

400 Fig 19 : (a) Charging and discharging curve of a capacitor (capacitance 1.2 mF) for energy storage by the piezoelectric
 401 energy harvester and subsequent operation of RF temperature sensor. (b) Discharging curve of the capacitor in the sensor as
 402 a function of the time interval between transmissions and (c) Temperature and voltage of the microcontroller recorded and
 403 transmitted by the wireless sensor during 32 min.

404 Fig 19 (c) shows the variation of the ambient temperature in a room at 23.2 °C as well as the supply
 405 voltage of the microcontroller as a function of time during 32 min of telecommunication from the RF
 406 temperature sensor in order to verify its proper operation.

407
 408 Finally, this study shows that the flexible aroelectric energy harvester can be used to make the low-
 409 consumption commercial temperature sensor operate in intermittent mode. However, we expect that the
 410 operating efficiency of our self-powered WSN system can be significantly improved, in terms of real-
 411 time monitoring, by adopting advanced conversion circuits [39–41] or very low power sensor design.

412
 413

414 4 CONCLUSIONS

415 In this paper, we have developed and characterized flexible piezoelectric micro-generators for wind
416 energy harvesting. The micro-generator is composed of a thin film of active PZT deposited and annealed
417 on a commercial (low cost) aluminum flexible substrate. The PZT film was then transferred onto a
418 flexible insulate substrate by the chemical process in order to design an IDE structure. Thus, the design
419 steps of the micro-generator are easily transferable to the industry. The flexible PZT micro-generator
420 can convert a maximum output voltage of 100 V and a current signal of 0.7 μ A from mechanical bending
421 motions; these values are comparable to those obtained with a flexible piezoelectric all polymer-based
422 energy harvester. Furthermore, our PZT film is advantageous in terms of production cost and processing
423 time to achieve mass production of flexible harvesting devices compared to piezoelectric single crystals
424 that require an expensive and time-consuming process. The novelty of the study lies mainly in the
425 fabrication technique that has been adapted to achieve an ultra-flexible wind micro-generator with high
426 energy efficiency. For an optimal energy harvesting from an air flow, the galloping configuration made
427 it possible to harvest energy from 2.3 m/s wind speed versus 5.5 m/s for the horizontal configurations
428 with and without obstacle. The mechanical and electrical coupling of the micro-generators allowed to
429 increase the maximum recoverable power without increasing the system footprint. To achieve a
430 maximum power output of 60 μ W, when the system is excited by a wind of 6.3 m/s in a galloping
431 configuration. Through rectifier elements and a storage capacitor, the energy generated by the system
432 was converted to a DC voltage that could be used by an electronic device. The energy generated by the
433 four generators was used to charge a capacitor to 4.5 V in about 60 minutes to operate a wireless sensor
434 for 35 minutes, allowing the sensor to make 7 measurements and wireless transmission of the ambient
435 temperature. This demonstrate the feasibility of our flexible aeroelectric energy harvesting system for
436 self-powering wireless sensor in the context of Internet of Things (IoT) for specific applications such as
437 structural/environmental monitoring, human health, and military/personal electronics. Thus, their
438 mechanical to electrical energy conversion efficiency, combined with their robustness and flexibility,
439 makes these devices very attractive for aero-electric energy harvesting.

440

441 5 ACKNOWLEDGEMENTS

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444

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