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Harvesting ambient wind energy with an inverted piezoelectric flag

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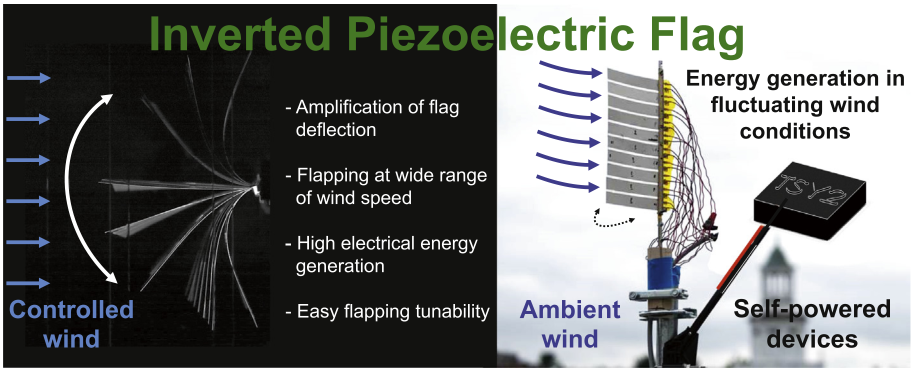
HIGHLIGHTS

- A novel piezoelectric flag orientation with enhanced energy harvesting capability.
- Easy flapping tunability and flapping at a wide range of wind speed.
- High electrical energy generation from ambient wind with fluctuating conditions.
- Self-powered device using ambient wind energy.

GRAPHICAL ABSTRACT



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ABSTRACT

The paper describes an experimental study of wind energy harvesting by self-sustained oscillations (flutter) of a flexible piezoelectric membrane fixed in a novel orientation called the "inverted flag". We conducted parametric studies to evaluate the influence of geometrical parameters of the flag on the flapping behavior and the resulting energy output. We have demonstrated the capability for inducing aero-elastic flutter in a desired wind velocity range by simply tuning the geometrical parameters of the flag. A peak electrical power of $\sim$5.0 mW/cm^3 occurred at a wind velocity of 9 m/s. Our devices showed sustained power generation ($\sim$0.4 mW/cm^3) even in low-wind speed regimes ($\sim$3.5 m/s) suitable for ambient wind energy harvesting. We also conducted outdoor experiments and harvested ambient wind energy to power a temperature sensor without employing a battery for energy storage. Moreover, a self-aligning mechanism to compensate for changing wind directions was incorporated and resulted in an increase in the temperature sensor data output by more than 20 times. These findings open new opportunities for self-powered devices using ambient wind energy with fluctuating conditions and low speed regimes.

1. Introduction

Harvesting ambient environmental energy is an effective approach for sustainable green power for portable and wireless electronic devices, especially those expected to operate for a long time with no human intervention [1,2]. Traditionally, batteries have been employed as the primary power source for such

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devices [3]. However, billions of batteries produced annually are unsustainable, their disposal poses environmental concerns, and their limited operational life challenges long-term/autonomous operations of devices. The fast growing market of solid-state electronics is directing the development of devices with ultra-low power consumption [4] and self-powered devices such as wearable electronics [5], biosensors [6], internet-of-things [7], and remote sensors [8]. Ambient energy from mechanical, thermal, solar, and chemical sources have been harvested using different mechanisms including piezoelectric [9], thermoelectric [10,11], photovoltaic [12,13], triboelectric [14], pyroelectric [15] and combinations thereof. Piezoelectric materials have shown to provide power densities comparable to other regenerative energy technologies such as lithium-ion batteries by harvesting ambient energy in the form of vibration, wind, sound, and human body motion [16–18]. In particular, piezoelectric ceramics have high piezoelectric conversion coefficient and have been used in applications with small amplitude deformation and high frequency oscillatory modes [19]. However, the high brittleness, rigidity and low cyclic life make them unsuitable for applications where flexibility and long-term operations are needed [20]. Alternatively, flexible piezoelectric materials such as piezoelectric polymers (e.g. PVDF [21]) and piezoelectric composites (e.g. soft matrix with piezoelectric nanoparticles and conductive fillers [22]), enable a broad range of applications including smart textiles [23] and sensors for biomedical uses [24,25]. However, for energy harvesting applications using flexible piezoelectric systems, large strain levels from mechanical motions are required, and these are generally unavailable from ambient sources [17].

Wind power is one of the world's fastest growing energy sources that is virtually pollution-free with renewable capabilities [26]. There is a global interest in reducing CO_2 emissions and developing more renewable technologies to produce energy, especially from wind [27–30]. Flexible piezoelectric devices have been utilized to harvest wind energy [31–33]. The continuous oscillatory motion required for piezoelectric harvesters to maximize energy production has been obtained by harnessing aerodynamic instabilities including aero-elastic flutter [34–38], vortex-induced vibrations [34,39–47], turbulence-induced vibrations [48–51], and wake galloping [52–55]. Flutter-based harvesters are typically comprised of cantilever beams bonded with a piezoelectric patch (e.g. MFC) over the high stress regions or fabricated completely with a flexible piezoelectric polymer (e.g. PVDF) [56]. Polymer-based piezoelectric materials are attractive due to flexibility, lightweight, low cost, simple fabrication, scalability, and simplicity in the configuration [57]. Extensive studies have been conducted to understand the dynamics and flutter regimes of flexible plates (i.e. "*regular flag*" defined as the configuration with a fixed leading edge and a free to flap trailing edge) subjected to axial flow as summarized in the review by Shelley and Zhang [58]. In particular, previous studies investigated the influence of parameters such as bending stiffness [59], mass ratio [60], aspect ratio [61], Reynolds number, and gravity [62] on self-sustained fluttering by numerical and experimental approaches. Additional studies exploring energy harvesting performance of flexible piezoelectric flags showed that the dominant vibration mode shapes of the regular flag must be carefully tuned by adjusting the bending stiffness and inertia to achieve the most energetic flutter regime and to maximize energy harvesting [63–69]. Small changes in wind velocity and flag geometry can dampen the "lock-in" self-fluttering regime and reduce the energy harvesting performance significantly. However, such tuned operating conditions are not suitable in a typical ambient environment with low and fluctuating wind speeds (2–5 m/s). In addition, the amount of harvested wind energy utilized by regular flags is limited due to the high critical flow speeds required for self-induced fluttering (>10 m/s), unlikely to be found in typical ambient conditions.

A new concept of a wind harvester was proposed by Li and Lipson [39,70] aimed at inducing self-oscillations of regular flags in slower wind speed conditions by adding a mass (called stalk) at the free end of the piezoelectric membrane. They envisioned a tree-like structure composed of piezo-leaves [71,72] replicating the same orientation of regular flags. Their controlled laboratory experiments showed a maximum harvested electrical power of 0.2 mW/cm^3 by arranging a PVDF membranes hinged with a polymeric triangular leaf (added mass) in cross-flow configuration. Later, McCarthy et al. [41,73–75] investigated the influence of different parameters such as hinge location, leaf geometry, mass, and pitch/yaw angles on power output and critical wind speeds for flutter. Despite the use of the same material/configuration by both groups, there were significant differences in the reported power output attributed to the equipment/electronics used during measurements. Results from both investigations showed that by controlling the harvester properties (leaf shape and size) and wind conditions, it was possible to achieve self-sustained oscillations and operate the device in its most energetic mode shape. Despite the novel design and the increase in the amplitude of deformation and wind velocity range during self-oscillations, the lock-in regime was highly sensitive to the smoothness and unidirectionality of the wind flow, thereby limiting and reducing the robustness of the harvester, especially in fluctuating wind conditions typically found in ambient environment. Most studies on small-scale wind-harvesters have focused on energy harvesting in ideal, laboratory conditions and ignore critical translational challenges such as intermittency of source of energy and potential leakage of electrical charges into the circuit [76–78]. There are recent works showing applications of wind energy harvesters to power remote monitoring systems [79–85]. Yet, to the best of our knowledge, there are no reports on piezoelectric wind-flutter harvesters powering real electronics in ambient environment with fluctuating wind conditions.

In this work, we report a new and robust approach to harvest ambient wind energy using a piezoelectric flag fixed at the trailing edge and the leading edge free to move called "*inverted flag*" (Fig. 1(a)). A previous experimental investigation showed that a flexible membrane fixed in this configuration could induce self-oscillations with large amplitudes via adjustments of the bending stiffness (K_B) [86]. However, the implications of this on energy harvesting have not been investigated. Recent numerical studies revealed that the flapping of an inverted flexible foil can generate ten times more strain energy (i.e. net energy transfer from wind to mechanical energy) in comparison to a conventional flapping foil [87–89]. However, such numerical models did not provide a realistic estimate of the harvested electrical energy, lacked of experimental validation and were limited to 2D simulations. The current study goes beyond the state-of-the-art in this area by conducting experimental studies to characterize the energy harvesting performance of inverted piezoelectric flags under controlled as well as ambient wind conditions. The current study demonstrates the significant benefits of utilizing an inverted flag for wind energy harvesting especially in natural ambient conditions. The study shows that the inverted flag is capable of self-sustained power generation within a desired/tunable range of wind speeds without the need of ideal wind conditions. Moreover, by conducting outdoor experiments and powering a temperature sensor using the harvested ambient wind energy without storing electricity, this study represents the first actual application of the harvester in ambient conditions. Our approach addresses major challenges and limitations from previous investigations and demonstrates a new concept of ambient wind energy harvesters that could be employed in fluctuating conditions.