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# VERTICAL-STALK FLAPPING-LEAF GENERATOR FOR WIND ENERGY HARVESTING

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## ABSTRACT

We study a parallelized flapping piezo-leaf generator for harvesting ambient wind energy and demonstrate an initial design. We fabricated prototypes in various configurations and performed a series of experiments to study performance trends. We propose a novel vertical-stalk L-shape design that exhibits improved output power density over horizontal piezoelectric configurations. While a significant power density performance gap still exists between the current state of piezoelectric devices and commercial wind turbines, their advantage remains in their robust solid-state, low-cost, low-maintenance and scalable construction.

## INTRODUCTION

Renewable and sustainable energy research has attracted much attention with the increasing gap between the demand and supply of fuel in recent years. Researchers have been searching for a practical alternative to petroleum and coal for electrical power. Hydroelectric power stations and wind turbines are two of the most successful solutions in this field; however, even compared to hydroelectric energy, wind power is much more environmentally friendly.

Nevertheless, there are some limitations of traditional wind power generators, namely, that using a large rotational turbine to harvest energy from the air requires significant financial and infrastructure investment, large real-estate area and long term commitment. The focus of our research is to investigate the principles and feasibility of the harvesting energy from the wind in constrained spaces such as around buildings, as an alternative to conventional rotary wind turbines. The central idea is to harvest energy from wind induced vibration instead of wind driven rotation.

Much previous work has focused on using piezoelectric materials to convert mechanical vibration energy into electrical power. Anton, Paradiso, Priya and Sodano *et al*. [1] [2] [3] [4] reviewed recent devices and applications of piezoelectric materials based energy harvesters. Roundy *et al*. [5] [6] developed a vibration based piezoelectric generator with a beam configuration, and provided a model for estimating the output voltage and power with experimental validation. Shen *et al.* [7] developed cantilevered power harvesting prototypes with three types of piezoelectric materials: lead zirconium titanate ceramic (PZT), macro fiber composite (MFC), and Polyvinylidene Fluoride (PVDF). They compared the power generating capabilities of the three materials under large vibration amplitudes. A similar device and mathematic model of piezoelectric cantilevered generators has also been studied by Sodano *et al.* [8].

In order to harvest fluid induced energy, some researchers [9] [10] have designed a novel "energy harvesting eel" using PVDF, which could convert the flow energy to electrical power in oceans and rivers through a flow induced oscillating motion on the PVDF film, which followed bluff body. The model and experimental validations were both studied. Priya and Myers *et al*. [11] [12] designed and optimized a small windmill prototype to extract energy from airflow. They used a wind driven mechanism to bend a series of piezoelectric bimorphs transducers, with the wind driving the rotation of the small windmill. A variety of other piezoelectric and magnet materials based wind energy generation concepts were discussed in


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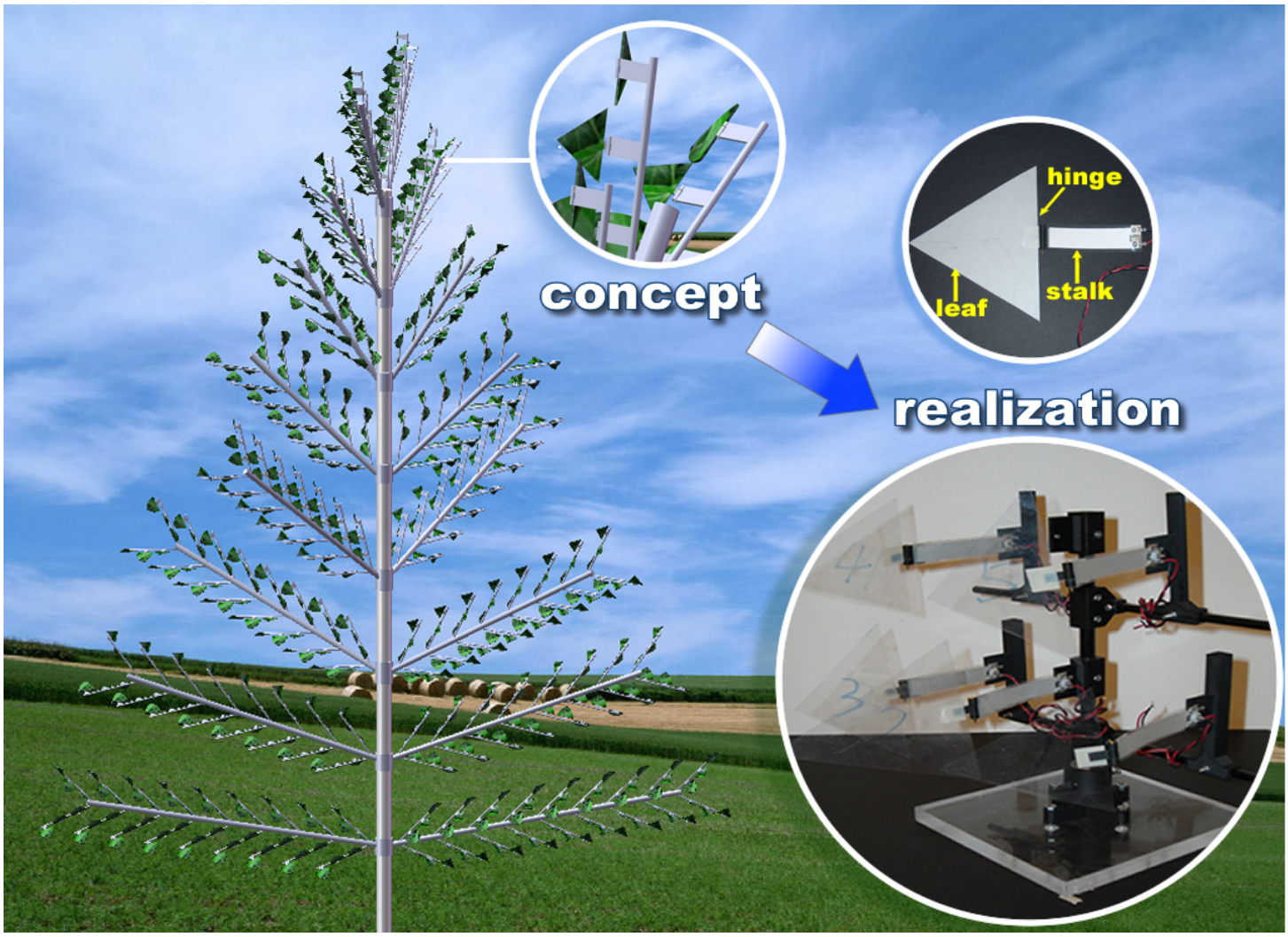



**Figure 1. Conceptual sketch and realization of "piezo-tree" generator, based on Dickson [15]**

previous literatures, media and websites (e.g. [13] [14]). Dickson [15] also suggested a number of leaf-based wind energy harvesting configurations.

Here we study the design of a tree-like generator for wind energy harvesting comprising multiple vibrating elements, as previously proposed by Dickson [15]. Compared to traditional rotary wind turbines and other piezoelectric vibration generators, this parallel vibration generator could have the following advantages:

(1) Light, scalable, robust structure
(2) Low cost
(3) Attractive bio-compatible design
(4) Easy installation, operation and maintenance
(5) Reconfigurable morphology
(6) Usability in a wide range of environments
(7) Broad response band to wind speeds and directions

In this paper, we focus on the "piezo stalk and leaf" which is the essential element of our plant-like generator. We design and implement a single leaf made from piezoelectric materials, which is capable of generating electrical power through wind induced vibrations.

As Figure 1 shows, we have also built a five-leave tree as a wind energy generator prototype. Each vibrating element consists of a polarized PVDF "stalk", a plastic hinge and a polymer/plastic "leaf". The conceptual design and prototype device are both described in the following sections, along with our experimental characterization.

## NOMENCLATURE

| | |
|---|---|
| $P_o$ | Mean output power |
| $V_{rms}$ | Root mean square of output voltage |
| $R$ | Internal resistance of oscilloscope |
| $R_o$ | Optimized matching resistance |
| $f$ | Vibration frequency |
| $C$ | Capacitance of piezoelectric element |


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## CONCEPT, THEORY AND MODEL

### Original Idea

When a fluid passes a bluff body, it will alternately produce a vortex shedding on both sides of bluff body, leading to a classical "vortex street" configuration in the near wake. The fluctuating pressure forces then form in a direction transverse to the flow and may cause structural vibrations [16]. We therefore expect to gain this kind of mechanical vibration energy which we can convert to electrical power afterward. The theoretical background of our design is similar to the aforementioned "eel" [9] [10], however, we propose to harvest energy from wind rather than oceans or rivers.

### Simplified Dynamic System Model

To understand the physical mechanism behind the design, we consider a simplified model of the flapping fluid-structure coupled system which is abstractly treated as an aerodynamic instability driven cantilever-pendulum system (Figure 2). The attachment "leaf" is driven by the vortex induced periodic pressure through the bending force and moment of the PVDF stalk.

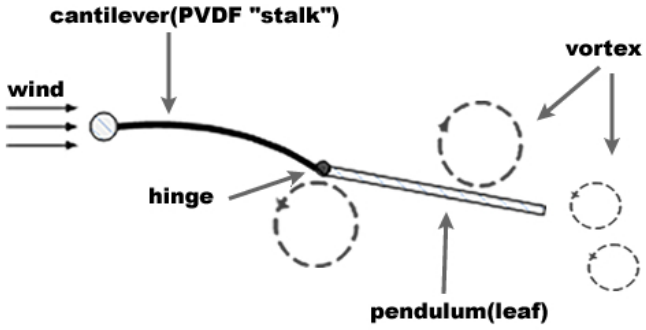



**Figure 2. Top view of simplified system model (horizontal-stalk leaf)**

### Theoretic Background

In our prototype, the flexible plate and film are driven to oscillate just as a flag or leaf might flap in the wind. The flapping motion is attributed to instability of the aero-elastic system. There are two potential excitations that may be responsible for the unstably periodic motion of a flexible body: first is the external harmonic forcing field caused by vortex shedding from leading edge (bluff body); second is the unsteady force and moment induced by the vortex when shedding from the trailing edge of the flexible plate or film, which is called a self-induced effect.

Classical studies predict that the dominant exciter of this oscillation phenomenon should be the vortex shedding from the bluff body. Allen and Smits focused on this type of excitation [10], Shukla *et al.* [18] experimented with the flow over a cylinder with a hinged-splitter plate to investigate the role of the cylinder. The excitation of our device is based on this theoretic foundation also.

Most recent work, however, has ignored or idealized the effect of bluff body at the leading edge, paying more attention to the self-induced aerodynamic instability of trailing edge [19][20][21][22][23][24]. We believe this is still an open question and thus have considered the contribution from both the bluff body and the self-induced effects in this paper.

If we assume both of these aerodynamic effects can be represented as simple harmonic excitations, then the system dynamic model can be simplified to a harmonic excitation cantilever-pendulum system. This system is similar to the physical model of a nonlinear vibration absorber which was introduced by Mustafa, Cuvalci and Ertas [25] [26] [27]. The pendulum could be modeled as an absorber of vibration energy by reducing oscillation amplitude of cantilever when the auto-parametric condition is satisfied. Instead, we prefer to model the pendulum as a cantilevered vibration "amplifier". Previous research [28] indicated that we might design a system with the opposite parametric condition in order to produce a large-amplitude vibration on the PVDF stalk with low-amplitude high-frequency excitation.

## DESIGN AND IMPLEMENTATION

### Basic Design and Experimental Solutions

Considering of the unpredictable wind strength, we choose the flexible and robust piezoelectric materials (PVDF) as the essential component of our device. The basic design is to clamp one edge of PVDF element to the bluff body and leave the other edge free. When the wind crosses this device, it will lead the aero-elastic instability and the periodic pressure difference will drive the piezo-leaf to bend in the downstream of the air wake, synchronously. We collect the AC signal from the flapping piezo-leaf, which is working on a periodic bending model, and store the electrical energy in a capacitor after rectifying it with a full-wave bridge.

We performed a series of experiments with our prototypes in a small wind tunnel (cross-section: 25×25cm; Wind speed: ≤ 15 m/s, experimental range: 2-8 m/s). Wind speed is measured using a small digital wind meter (WindMate 200; Speedtech Instruments). We measure the output voltage simultaneously with digital oscilloscopes (TDS3024B; Tektronix) with 1X (resistance: 1MΩ) and (DSO6014A; Agilent Technologies) with 10X (resistance: 10 MΩ) probes respectively. The wind tunnel experimental apparatus is shown in Figure 3. The Root Mean Square (RMS) of voltage $V_{rms}$ is measured during about 5 seconds on the load resistance $R$. The average output power $P_o$ is calculated using the following formula:

$$P_o = \frac{(V_{rms})^2}{R} \qquad (1)$$


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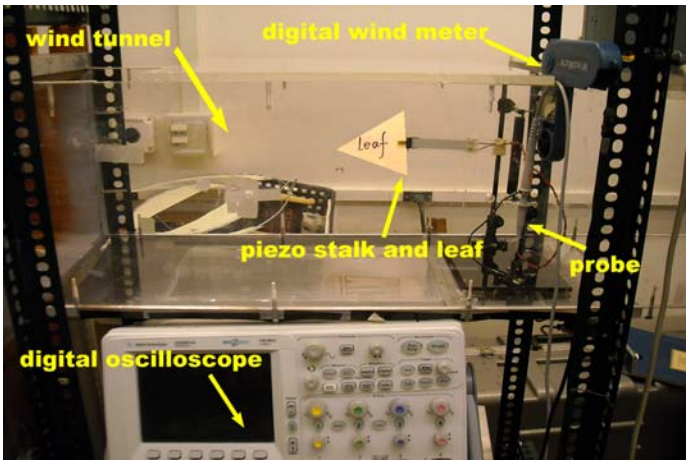



**Figure 3. Wind tunnel experimental apparatus.**

## Original Design

For implementing the prototype device, we fabricated a half circular cylinder (length: 10cm; diameter: 2 cm) for the bluff body using ABS on a 3D-printer (Dimension SST 768; CADimensions, Inc). We clamped one edge of the 28 μm PVDF stalk (DT2-028K/L with rivets, Measurement Specialties, Inc, see Table 1) on the bluff body. We then set the bluff body in the vertical direction by fixing it to a frame with a heavy base. The PVDF stalk is fixed in the same direction of airflow.

**Table 1. Dimension of PVDF "stalks" [17]**

| PVDF stalk | Dimension (Length×Width×Thickness) |
|---|---|
| DT2-028K/L w/rivets | 73mm×16mm×40 μm |
| LDT1-028K/L w/rivets | 41mm×16mm×205 μm |
| LDT2-028K/L w/rivets | 72mm×16mm×205 μm |

Unfortunately, because of the weak piezoelectric strain coefficient of PVDF [7], the preliminary piezo-leaf generator's power level is only a few pW ($10^{-9}$ W), using a 2 cm diameter circular cylinder as the bluff body in 5 m/s wind (unable to drive even a common LED).

## Improved Horizontal-Stalk Leaf

Because of neutral axis is within the lamination instead of in the PVDF, the PVDF film is strained more. We modified the PVDF stalk to a laminated PVDF element (LDT2-028K/L w/rivets and LDT1-028K/L with rivets; Measurement Specialties, Inc, see Table 1) in order to achieve higher output power. Also, we could use multiple PVDF elements to get more output power from one device, but we need to find a tradeoff between higher output and higher total stiffness of the stalks. After some tests of adhering plastic beam (acrylic sheet, thickness: 0.5 mm), metal beam (1095 steel sheet, thickness: 0.3 mm) and two kinds of double-layers stalks, we determined that an air-spaced double layer configuration appears to be the best solution, and made a prototype of this device (Figure 4a).

We chose an isosceles triangle shape polymer attachment (hemline: 8cm, height: 8cm area: 32cm$^2$) as the leaf of our generator (Figure 4b). Based on a design by Bryant and Garcia [34], we fabricated a pair of small ABS hinges to connect the leaf to the end of the laminated stalk. Hereafter we call this configuration the "horizontal-stalk leaf," as in Figure 5a.

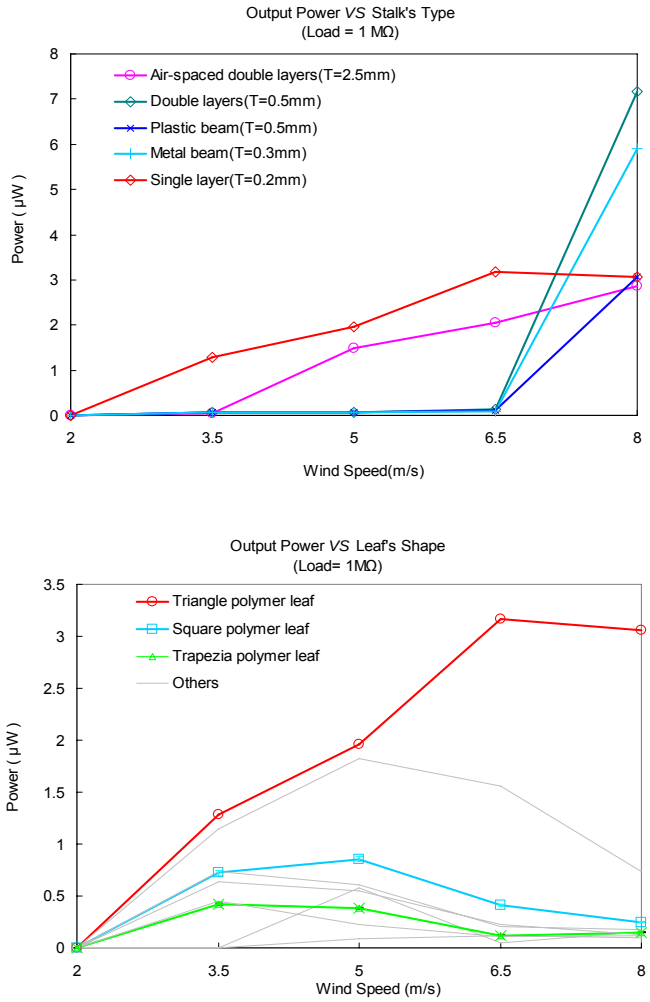



**Figure 4. (a) Output power vs. stalk's type; (b) output power vs. leaf's shape.**

In testing, we encountered an interesting phenomenon whereby the horizontal-stalk leaf could exhibit large amplitude flapping dramatically as a result of increased vibrating amplitude. In this situation the output voltage was several times higher than the original design, which was not a "leaf". Possible reasons for this will be discuss later.

## Vertical-Stalk Leaf

As Figure 5 (b) shows, we also experimented with designs that had no bluff body. The laminated PVDF element (LDT2-028K/L w/rivets) was clamped in the vertical direction


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of airflow, and a triangle shape polymer leaf attaches to the free end of stalk through a plastic hinge. The direction of the leaf is no longer the same as stalk, but it is still in the direction of the airflow, thus the new device looks more likes an "L" shape; we refer to this configuration as the "vertical-stalk leaf" hereafter. In this vertical configuration, the stalk twists as well as bends.

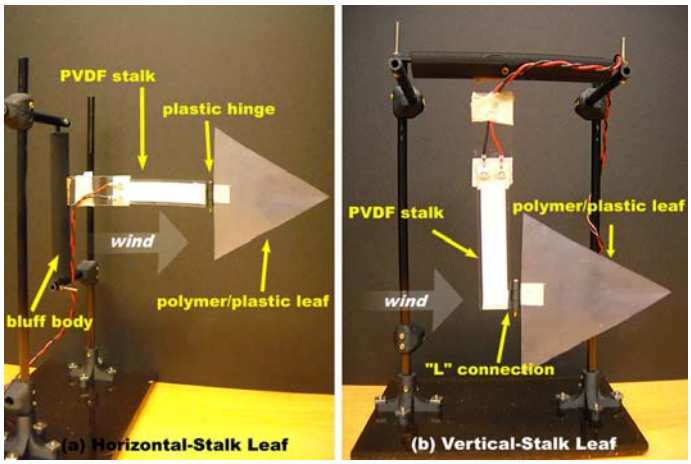



**Figure 5. Different configurations of piezo-leaf.**

Analysis of Results

First we show the output voltage/power of our various designs, both single layer and air-spaced double layers as in Figure 6(a, b). These plots show that there exists a response region of wind speed between 0-8m/s at which both devices could reach a peak value of output voltage/power. However, the trend of output values are also found to decrease as the wind speed increases above the peak value speed. This might indicate that the leaves' flapping frequencies could approach the first natural frequency of the PVDF stalk during this low wind speed range. Thus, we can conclude that both systems will get others peak value of output voltage/power in higher wind speed range again.

Further, the bi-stable response could be observed from the plots of Figure 6(a, b). There exists one critical speed point and region (single layer device: begins around 2 m/s; double layers device: begins around 3.5 m/s.), during these region, the coupled systems keep either flat reposing (might be infinitesimal- amplitude, high-frequency oscillating) or periodically large-amplitude oscillating. Furthermore, if the wind speed is higher than the critical speed, the leaf will flap, but if it is lower, the flapping will stop. Over this region (wind speed ≥ 6.5 m/s), a chaotic oscillation will appear occasionally. This classical fluids-induced bi-stable and chaotic phenomenon was found frequently [23] [24] [29].

The vertical-stalk leaves exhibit much more excitation performance than horizontal-stalk leaves during all experiments. Based on these results, we can conclude that the vertical-stalk configuration of leaf has more potential for wind-vibration devices.

From Figure 6(a, b), we could easily find the difference between single layer and double layers, both two layers devices produce much higher voltage than the single layer device, however, along with a narrowed wind speed response band, they need a higher wind speed to get into large-amplitude oscillation (output voltage ≥500mV). As demonstrated before in Figure 4(a), air-spaced double layers could offer a good trade-off solution between increased strain and added stiffness of multiple layers stalk. A similar experiment was also shown by Wang *et al.* [30].

Previous research suggested an optimized matching resistance for output power of piezoelectric based vibration generator, $R_0$, with neglecting of dielectric loss factor and damping, it could be approximately given as[5][11][31][32]:

$$R_o = \frac{1}{2\pi fC} \qquad (2)$$

Where $f$ is the frequency of vibration, and $C$ is the capacitance of piezoelectric element. For the PVDF stalk of our device, the capacitance of long PVDF stalk is 2.78nF (LDT2-028K/L w/rivets), and of short stalk is 1.38nF (LDT1-028K/L w/rivets) [17]. Wind-induced vibration frequencies are both around 3-10HZ (2-8m/s), so the optimized load should be around 6-19MΩ and 12-38MΩ respectively. Our experimental data validates this by measurement on 1MΩ and 10MΩ internal resistances of the digital oscilloscopes, as shown in Figure 6(c). The 10MΩ load shows a higher output level of power, because it is much closer to the optimized load value than 1MΩ.

We compared the output power of our prototypes (Figure 6(d)). The results reveal that using a short PVDF stalk could get much more output power in the specific wind speed region (6.5-8m/s). We observed the maximum output value 296μW at 8m/s wind during our experiments, however, the response band of the short stalk was more limited, as it was able to oscillate at large-amplitude only when wind speeds reached beyond 3.5m/s. This phenomenon might be attributed to the decrease in external bending moment caused by the shorter element.


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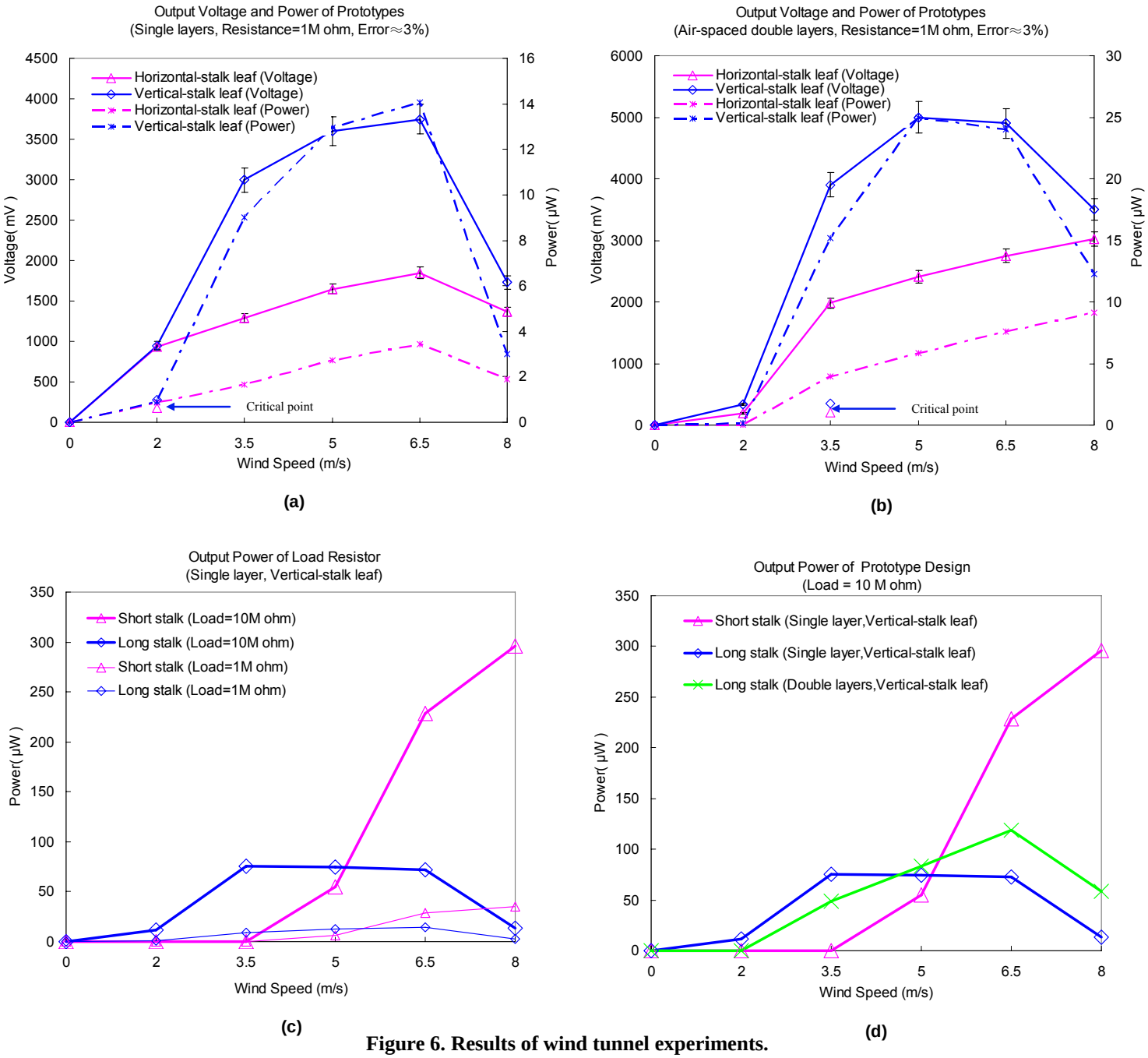



**Figure 6. Results of wind tunnel experiments.**

## DISCUSSION, CONCLUSION AND FUTURE WORK

In this paper we proposed a novel vertical-stalk piezo-leaf generator which could convert wind energy into electrical energy by wind-induced flapping motion.

We designed and implemented a number of prototypes, such as vertical/horizontal-stalk leaf, single /multiple layers stalk and short/long stalk. After a series of wind tunnel experiments, we compared and analyzed all data, and the main conclusions are as follows.

First, we observed the maximum output power (~300μW, 10MΩ load) in 8m/s wind from a single layer vertical-stalk leaf with a short PVDF stalk. The power density approached the peak value: power per device's volume ~300μW/cm$^3$ and power per device's weight ~80μW/g, see Figure 7(a, b) and Table 2. As Figure 7(c) shows, our design's performances are better than previous piezoelectric wind energy harvesters [12]. Also, we must note that we have not tried to use the


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theoretically optimized value (refer to Equation 2) of the load resistor during our experiments, which could allow for even higher levels of output power. As a simple validation, the output power on 1MΩ and 10 MΩ load are shown respectively.

Second, the trade-off between increased strain and added stiffness of PVDF stalk was studied by comparing the experimental results of single layer and air-spaced double layers devices. We observe the bi-stable response of the flapping piezo-leaf in our experiment, and then the critical point and region are shown in our figures.

Furthermore, combining the assumption of a simplified system model and our experimental analyses, we can explain and discuss the dramatically increasing output voltage of horizontal-stalk and vertical-stalk leaf prototype devices for the following two possible reasons:

(1) The attached leaf, like a "sail", could capture much more wind induced force and impact than only a PVDF stalk;
(2) The attachments and hinge could induce the changes of mass distribution and system natural frequency. Possibly, the system natural frequency and subsystem natural frequency approach a region which may amplify the vibration on PVDF stalk.

Finally, we can compared our device and previous piezo-based wind energy harvesters [11] and with the large

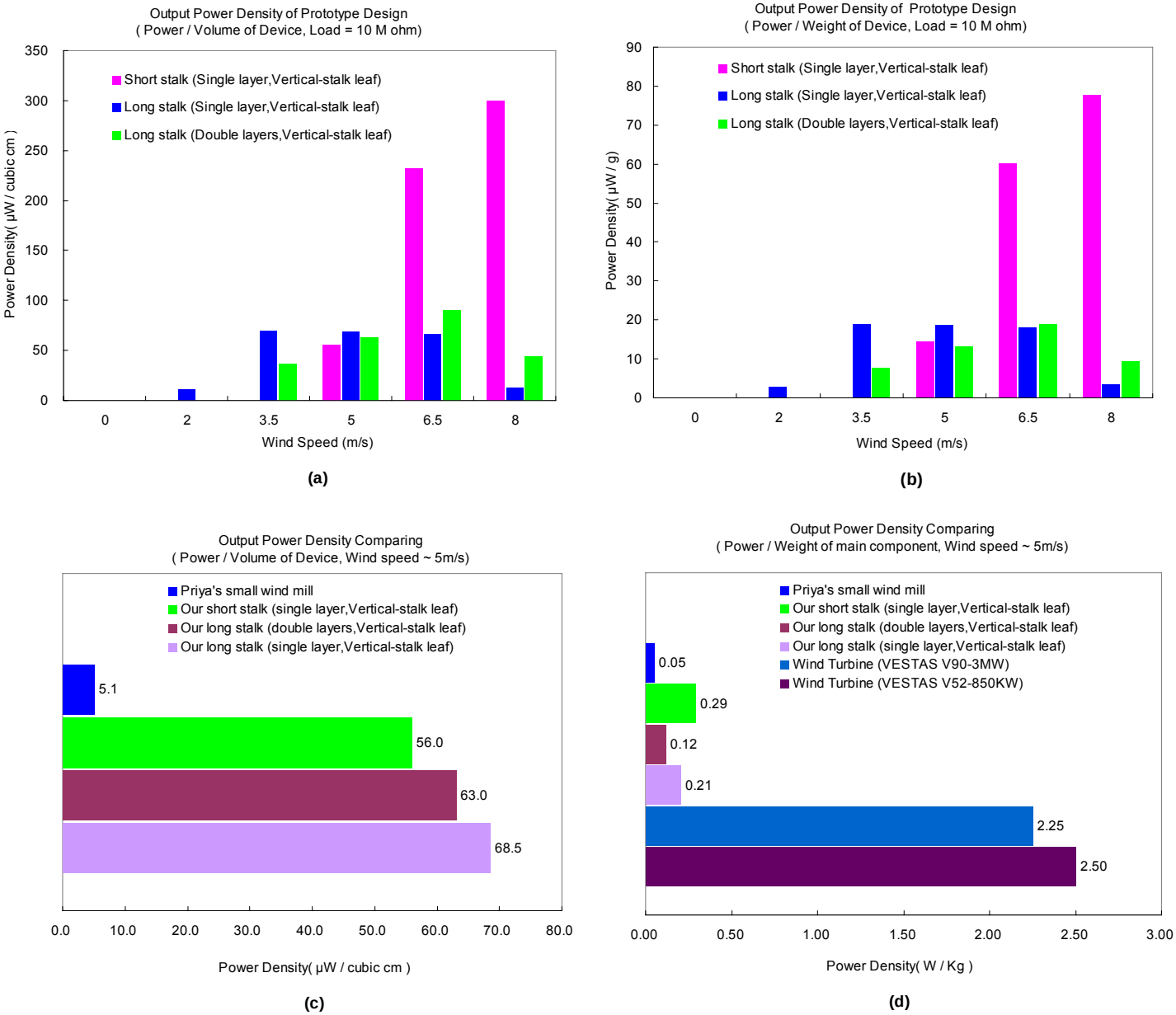
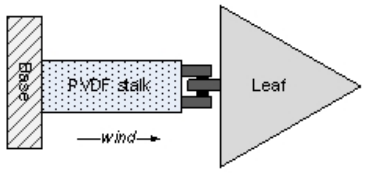
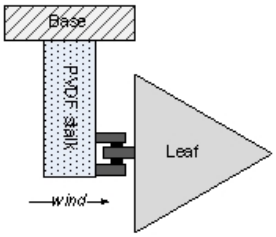



**Figure 7. Comparison of devices.**


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**Table 2. Summary of experimental results on two kinds of devices**

| Configuration of Prototype | PVDF element | Max Output Power (Load=10 MΩ, Deviation ≈ 6%) |
|---|---|---|
| Horizontal-stalk leaf   | Long single layer PVDF stalk | 17 μW (Wind speed = 6.5m/s,) |
| Vertical-stalk leaf   | Short single layer PVDF stalk | 296 μW (Wind speed = 8m/s) |
| | Long single layer PVDF stalk | 76 μW (Wind speed = 3.5m/s) |
| | Long air-spaced double layers PVDF stalk | 119 μW (Wind speed = 6.5m/s) |

commercial wind turbines from VESTAS [33]. This rough comparison focuses on the power density as power per weight of main components (piezoelectric materials of harvesters, rotor and blades of wind turbine). As Figure 7(d) shows, our piezo-leaves have an obvious higher efficiency than the previous piezo-based devices. Nevertheless, both KW and MW class commercial wind turbine clearly lead in power density against all piezo-based wind energy harvesters.

The potential advantage of parallel wind-vibration energy harvesting appears to be in their robust, simple and maintenance-free monolithic construction, their ability to scale from miniature sizes to large scales through parallelization, and their natural blending in urban and natural environments.

## ACKNOWLEDGMENTS

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