ENERGY HARVESTING FROM FLUID FLOW USING A VERTICAL COMPOSITE PIEZOELECTRIC LEAF-STALK CONFIGURATION

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Abstract

In this paper, energy harvesting using composite piezoelectric beams from fluid-induced flutter was studied. Horizontal and vertical-stalk configurations were examined and the power outputs were recorded. It was found that the vertical-stalk arrangement produced a four-fold increase in power compared to that of the horizontal configuration. High-speed footage of the vertical-stalk configuration was taken to understand the reasons behind the increased power output. The findings are discussed here.

1 Introduction

Flutter of flags, leaves on a tree or automobile antennas are commonplace yet complex engineering and scientific problems involving fluid-structure interaction. These concepts were initially studied only with an academic interest and later was used for practical engineering purposes [1]. There has been extensive work done to understand flutter of plates and membranes [2-5].

Over the past two decades, researchers have shown considerable interest in energy harvesting using piezoelectric patches to convert ambient vibration energy to electrical energy. However, only recently, energy harvesting from ambient fluid flow has gained attention. In 2001, a concept of an energy harvesting 'eel' was introduced [6]. The 'eel' consisted of a Polyvinylelede Fluoride (PVDF) membrane clamped at its leading edge and was placed downstream to a vortex shedding cylinder. The system was immersed in a parallel fluid flow (i.e. zero angle of attack with respect to the PVDF membrane). The vortices shed from the cylinder induced flutter of the PVDF membrane, resulting in an output AC voltage waveform.

In 2004, an array of multiple piezoelectric patches immersed in water was proposed [7]. It was mentioned that these array of energy harvesting piezo patches could help in generating more power than a small wind turbine. However, it was only a theoretical approximation. In 2008, the concept of an artificial tree was proposed [8]. In this concept, the leaves of the tree were attached to composite piezoelectric stalks. Thus, as the wind flowed across the tree, the flutter of the leaves would induce deformations on the piezo stalks, which would result in electrical power. The rationale behind this design was to have a safe, aesthetically pleasing device that could supplement the energy requirement in commercial and household regions by powering Ultra Low Power (ULP) devices such as sensors and LED lights.

In 2009, the artificial tree concept was tested with a single piezo-leaf configuration in parallel smooth flow [9]. Two different configurations, horizontal stalk and vertical stalk were tested. The configurations are shown in figure 1.

The PVDF stalk was connected to a polymeric leaf material with the help of a plastic hinge. It was noted from this work that the vertical-stalk arrangement provided more power output compared to the horizontal stalk arrangement. However, the reason for the increased power output were not clearly explained. It was believed that the vertical
stalk configuration was subjected to coupled bending-torsion vibration modes leading to more power output. In an experiment elsewhere [10], it was shown that a piezoelectric patch subjected to coupled bending-torsion provided about 30% more power than a patch subjected to conventional transverse bending. In [11], a similar energy harvesting device, consisting of a piezo beam connected to a flutter amplifier with a hinge, was investigated.

Composite PVDF patches can be used for energy harvesting from fluid flows due to their high flexibility and low cost. Macro Fibre Composites (MFC) are well engineered piezoelectric materials with energy densities almost an order of magnitude higher than the PVDF materials [12]. However, MFC patches are not capable of handling large amount of strains experienced in fluid-induced flutter. The Lead-Zirconium Titrate (PZT) fibres are brittle and hence crack when the strains are beyond threshold limits. Also, MFC patches are relatively expensive and less flexible and hence do not suit this purpose.

In [13], different leaf geometries were examined and it was shown that the triangular leaf caused the system output the most power. Also in [14], different triangular leaf aspect ratios and areas were examined and its effect on the power output was discussed. Also, the effect of a revolute hinge on a fluttering membrane was explained in [15] and it was clear that the hinge would lower the leaf-stalk’s natural frequency. This caused the system to flutter at a relatively lower wind speed. Thus, from the literature, it is evident that a composite PVDF stalk, coupled with a polymeric leaf with the help of a hinge could be utilised to harvest energy from fluid-induced flutter.

In this work, both the horizontal and vertical stalk configurations are examined and the power outputs from the PVDF are recorded at different speeds. The power outputs are compared and explanations for the increased power output from the vertical stalk configuration are given, following scrutinisation of the high speed camera images; specifically, the aerodynamic forces and coupled bending-torsion modes are qualitatively identified. The results are discussed and the drawbacks are highlighted.

2 Concept of the energy harvester

When a highly compliant plate is immersed in parallel fluid flow, vortices are induced at the trailing edge leading to an adverse pressure gradient. This creates an instability, which causes subsequent plate oscillation. In this case, the PVDF stalk was connected to a triangular shaped polymeric leaf via a revolute hinge. The hinge acted to allow flutter at earlier wind speeds, and permitted greater flexibility of the leaf-stalk. Also, the leaf offered a greater surface area to the fluid and hence amplified the oscillation of the PVDF stalk. The material and geometrical properties that affect flutter characteristics were discussed in [16]. A schematic representation of the device is shown in figure 2.

In the horizontal-stalk arrangement, the system was immersed parallel to the wind direction. Thus, it was suggested that the PVDF stalk was subjected only to transverse bending. In a vertical-stalk arrangement, the PVDF stalk was vertically aligned to the wind while the leaf’s arrangement remained the same as the horizontal case (refer to figure 1). Thus, in the vertical-stalk arrangement, it was believed that the PVDF stalk was subjected to coupled bending and torsion modes of flutter (explained in section 4.3).

A plate undergoing transverse bending due to flutter is governed by the Euler-Bernoulli equation as

\[
m \frac{d^2 y}{dt^2} + EI \frac{d^4 y}{dx^4} = l \Delta P \tag{1}
\]

where \( m = \rho_g h l \); \( m \)- Mass per unit length of the plate; \( \rho_g \)- density of the plate; \( h \)- thickness of the plate; \( l \)- width of the plate; \( E \)- Young's modulus; \( I \)- moment of inertia; \( \Delta P \)- pressure difference across the plate due to the fluid flow. This pressure difference, according to Theodorsen’s approach [3] could be modeled as

\[
\Delta P = P_{nc} + P_y \tag{2}
\]
Where \( P_{\text{nc}} \) - non-circulatory pressure due to the transverse motion of the beam; \( P_{\gamma} \) - circulatory pressure due to vortex shedding at the trailing edge. The stress \( T \) induced by the bending of the piezoelectric beam is given by

\[
T = \frac{Mz}{l} = -zE \frac{\partial^2 y_1}{\partial x^2}
\]  

(3)

Therefore, the strain \( S \) induced is related as

\[
S = -z \frac{\partial^2 y_1}{\partial x^2}
\]  

(4)

Where \( M \) – bending moment, \( I \) – moment of inertia, \( z \) – distance from the neutral axis to the point of interest.

The stress and strain induced due to the beam vibrations are related to the electric field and displacement produced by the piezo in the following coupled equations [17].

\[
\begin{bmatrix} S \\ D \end{bmatrix} = \begin{bmatrix} c & d \\ d' & \varepsilon \end{bmatrix} \begin{bmatrix} T \\ \varepsilon \end{bmatrix}
\]  

(5)

Where \( D \) – electrical displacement; \( c \) – compliance; \( d' \) - direct piezoelectric coefficient; \( d' \) – transverse piezoelectric coefficient, \( \varepsilon \) - permittivity; \( \varepsilon \) - Electric field strength.

In the vertical-stalk configuration, it is suggested that the stalk is subjected to bending and torsional modes of flutter. Then, a system of coupled bending-torsion equations are given as [18]

\[
m \frac{\partial^2 (y-c\theta)}{\partial t^2} + EI \frac{\partial^4 y}{\partial x^4} = l\Delta P
\]  

(6)

\[
m c \frac{\partial^2 (y-c\theta)}{\partial t^2} + R \frac{\partial^2 \theta}{\partial x^2} - R_1 \frac{\partial^4 \theta}{\partial x^4} - \rho_s l_p \frac{\partial^2 \theta}{\partial t^2} = l\Delta P
\]  

(7)

where \( c \) - distance between the centroidal axis of the beam and its shear center; \( I_p \) - polar moment of inertia; \( R \) - torsional rigidity and \( R_1 \) - wrapping rigidity. Thus, by solving the system of equations with the relevant boundary conditions, the stress and strain values could be determined, which would consequently provide the electrical energy through the piezoelectric coupling equations. It is noted that the mechanical and electrical damping were neglected in this mathematical model.

3 Experimental Setup

3.1 Wind tunnel setup

Experiments were carried out in RMIT University aeronautical wind tunnel. The wind tunnel is a closed circuit tunnel having a test section measuring 1.07m in height, 1.35m in width and 2.7m in length. The tunnel consists of a six-bladed fan powered by a 100kW DC motor. The tunnel has a contraction ratio of 4:1. The longitudinal turbulence intensity in the test section is generally less than 0.5%; thus, all the experiments were carried out in smooth flow conditions. A pitot static tube connected to an MKS Baratron® was used for pressure measurements in the tunnel, from which the flow velocities were calculated. The density of air was kept constant at 1.23 kg/m³. An error in the velocity calculation due to standardization of density was determined to be only 0.5%. Thus, a constant air density value was justified in the experiments.

Since the experiment involved recording of electrical output from the piezoelectric patches, a signal to noise ratio in the tunnel was evaluated. At first, shielded cables were placed in the wind tunnel without touching the tunnel walls. The tunnel was turned on to a wind speed of 15m/s and the other end was connected to a 20MHz oscilloscope. Then, the actual piezoelectric element was connected to the terminals of the cable and the signals were recorded. The signal to noise ratio was found out to be as high as 300-400. Hence, no filters or calibrations were required in this regard.

The wind speed range chosen for the experiments was 3m/s to 8m/s. This range was chosen based on the average wind speeds in and around Victoria, Australia [19]. Experiments performed in [9] followed the same test range.

3.2 Specimen configuration

The PVDF patches used for the experiments were LDT1-028K/L (Measurement Specialties, Inc.). The laminated PVDF patch measured 72mm long, 16mm wide and 205µm thick. The patches contained electrodes at the clamping base to which the cable was connected. The leaf used for the experiments was made from 0.35mm thick polypropylene. The material had a density of 995 kg/m³ with an elastic modulus of 1261 MPa. The leaf used was an isosceles triangle with a base and height of 80mm respectively. Previous studies showed that this leaf geometry was the optimum for
the energy harvester [14]. The leaf and the piezo stalk were connected via a plastic revolute hinge. It was ensured that there was no frictional resistance in the joint. The effect of the hinge added mass was evaluated in [14], and it was found that the second modal frequency was reduced by around 15%.

In the horizontal-stalk configuration, the PVDF stalk and the leaf were attached such that both their longitudinal axis were parallel to the wind direction and along the same line. The base of the stalk (the leading edge) was clamped using metal strips having a thickness of 1.75mm (figure 3). In the vertical-stalk configuration, the stalk was placed vertical while the leaf axis was kept horizontal. The base of the stalk was clamped 100mm away from the stand using horizontal metal clamping strips. This clearance was set such that any aerodynamic interference of the base stand with the motion of the fluttering harvester was avoided. The setup of this arrangement is shown in figure 7. The stand was guyed to the walls of the wind tunnel using thin-gauge wires to avoid any stand vibrations during the experiments.

3.3 Load matching and data logging

In order to record the electrical power output from the PVDF patch, the patch was connected to a simple circuit. The power output of a piezoelectric material depends on the external load resistance across which the voltages are measured [20]. The optimal load resistance $R_{L_{opt}}$ for a piezoelectric material in operation for maximum power output is estimated as

$$R_{L_{opt}} \approx \frac{1}{\omega C} \tag{8}$$

where $\omega$ - operational frequency of the piezoelectric material and $C$ - internal capacitance of the piezoelectric material.

In this case, the the patch was tested for its power output from 3-8m/s. Thus, the optimal load resistance was experimentally determined for a velocity of 5.5m/s, the median wind speed. The PVDF patch was connected to different load resistances ranging from 1-60MΩ in parallel. This circuit was connected across a differential probe (Elditest, GE8115) before linking the circuit to the DAQ board (National Instruments, BNC 2110). The use of a differential probe with a very high internal impedance ensured that the AC voltage from the leaf-stalk was measured across the load resistance, and also that the voltage was scaled down to the maximum allowable voltage of the DAQ board. The circuit diagram is shown in figure 6.

The AC voltages were recorded at a sampling rate of 1kHz, for a period of 30 seconds, to ensure good resolution. A LabView® program was written to calculate the RMS voltage at 0.1s intervals, thereby having 300 values of RMS voltages for the recorded time frame. The electrical power output was then calculated for each 0.1s interval as

$$P_i = \frac{V_{RMS}^2}{R_L} \tag{9}$$

where $V_{RMS}$ - root-mean-square voltage from the leaf-stalk. The average power for the 30 second period was calculated as

$$P_{avg} = \frac{1}{300} \sum_{i=1}^{300} P_i \tag{10}$$

The load matching experiments were carried out for the horizontal-stalk configuration. The circuit was setup and the voltage data were recorded after setting the wind speed at 5.5m/s. Different load resistances were connected one by one and their corresponding power outputs were calculated. The output average RMS voltages were plotted against different load resistances and the graph is shown in figure 4.
It is clear that as the load resistance increased from $1\,\text{M}\Omega$, the voltage increased initially and then saturated at resistance of around $20\,\text{M}\Omega$. In order to determine the optimum value of load resistance, the output power was plotted against the load resistance in figure 5.

The optimal load resistance value for this case was found out to be $5.6\,\text{M}\Omega$. Thus, a $5.6\,\text{M}\Omega$ load resistor was used for all the experiments conducted. It is to be noted that flutter frequency would be different for a vertical-stalk arrangement and hence would require a different optimal resistance value. However, in order to have a common ground for comparison between the two different configurations, the same load resistance was used while measuring the voltage output.

3.4 High speed image capture

In order to understand the vibration modes and aerodynamic forces encountered by the vertical-stalk configuration of the PVDF patch, high speed videos were captured for all the tested wind speeds (3-8m/s). A high speed camera (IDT X-Stream XS4) was placed downstream to the specimen facing it with its axis parallel to the wind. A photograph of the setup is shown in figure 7. The high speed footage was captured at 1000 frames/second to ensure good resolution of the leaf-stalk flutter. The specimen was lit with two 300W studio lights from outside the wind tunnel.
times at each wind speed to ensure repeatability. The graph indicating the power output at different wind speeds are indicated in figure 8.

![Graph showing power output vs. wind speed.](image)

**Fig. 8.** Power output of horizontal-stalk configuration vs. wind speed.

The power output from the patch increased as the wind speed increased. This was at first visually connoted in the experiments; as the wind speed increased, the flutter frequency and amplitude of the PVDF patch also increased. Also, it was clear that the patch was subjected to only transverse bending, due to the nature of fluid pressure impinging on the leaf-stalk. The reason for a sharp rise in power output at 5m/s could be attributed to the load resistance. The load resistance was tuned at 5.5MΩ throughout the experiment. The power outputs at different wind speeds are shown in figure 9.

![Graph showing power output vs. wind speed.](image)

**Fig. 9.** Power output of vertical-stalk configuration vs. wind speed.

Noting the scale of the ordinate axes, the vertical-stalk configuration output more power than the horizontal-stalk configuration, for all wind speeds tested. A maximum power of 88.3µW was observed at a wind speed of 8m/s. It is important to note that this power output could have been further increased by tuning the load resistance for this configuration at 8m/s, given its non-optimal load matching as mentioned above. From visual inspection, it was suspected that the PVDF stalk was subjected to coupled bending and torsion. However, due to the high flapping frequencies (8-25Hz), high speed capture of the leaf-stalk was required to confirm the hypothesis. Figure 10 shows a comparison of the power outputs from both the configurations tested at different wind speeds.

**4.3 High-speed video results**

High-speed videos were taken for the vertical-stalk configuration configuration at 1000 frames/second. The camera was programmed to capture two seconds of footage. This was repeated for every wind speed, and the camera captured footage only after limit-cycle oscillatory motion of the leaf-stalk occurred.
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The maximum deformation of the PVDF stalk at a wind speed of 3 m/s is shown in figure 11 (The wind direction is coming out of the page for all the high speed images). In figure 11, it is evident that the PVDF stalk was subjected to large transverse bending. This bending strain was augmented by a torsional strain at this point of maximum deformation. However, the amount of torsion induced in the stalk was considerably less compared to the bending. This behaviour was also observed at the other wind speeds. Thus, the increased power output in the vertical stalk configuration could be attributed to large, and probably, non-linear bending deformations augmented by relatively small torsional deformations.

The larger bending deformations in the vertical leaf-stalk arrangement were caused by the different nature of the aerodynamic forces impinging on the leaf, compared with the horizontal configuration. In the static-stable state (i.e. no flutter), the axis of rotation of the hinge is vertical with respect to the ground plane, for both configurations (see figure 1). However, the disparity in the aerodynamic forces arises once the system begins to flutter. In the vertical-stalk case, the hinge axis of rotation also tilts with the system. Figure 12 is an image of the flapper at 5 m/s, where the hinge axis is virtually horizontal with respect to the ground plane. In contrast, the hinge always remains vertical with respect to the ground plane for the horizontal configuration during flutter. The aerodynamic lift force may be quantified using equation 11:

\[
L = C_L \cdot \frac{1}{2} \rho v^2 A
\]

where \(L\) - aerodynamic lift force, \(C_L\) - coefficient of lift, \(\rho\) - air density, \(v\) - the wind velocity and \(A\) - reference area exposed to fluid flow. Given that the leaf-stalk flutter is mainly driven by the leaf, the leaf geometry did not change between the horizontal and vertical configurations, and the wind speeds tested were identical in both cases, it is proposed that the lift coefficient would have changed throughout the vertical-stalk flutter cycle. That said, it has not been quantitatively determined whether the magnitude of the lift forces were larger in the case of the vertical-stalk case. It can be argued that the changing direction and orientation of the lift forces did indeed act constructively out of phase with the structural deformations occurring in the piezoelectric stalk, with the vertical-stalk case. An in-depth investigation into the unsteady lift forces governing the motion of the vertical-stalk case was not included in the work here.

Due to the large structural deformations, the stalk-leaf system would strike the base clamping strips during every flutter cycle. This behaviour was observed at wind speeds of 5 m/s and higher. The piezo-leaf system would rotate almost 180° and impact the base clamping strips. The interference of the clamping strips on the motion of the flapper could have also been the cause for a marginal decrease in the gradient of the power curve after 4 m/s (figure 9). However, this issue was not resolved simply because the base of the stalk required secure clamping. An image of the flapper at 8 m/s is shown in figure 13, where the base clamp...
is seen to be interfering with the flutter motion of the piezo-leaf system.

Fig. 12. Screen shot at 5m/s. Entire surface of leaf facing the wind with an instantaneous horizontal hinge axis.

Fig. 13. Screen shot at 8m/s. Clamping strip interfering flapper motion.

Although the large deformations result in increased power output, one major drawback is the fatigue life of the PVDF stalks. After the experimental trials, it was found that the piezoelectric patches were cracked at the clamping location. This is primarily due to the combination of excessively large bending displacements and fatigue. However, one way that this issue could be resolved is by increasing the stiffness of the stalk, by stacking the PVDF patches. The patches could be stacked with or without an air gap, which would reduce the large deformations prevalent using a single stalk. At the same time, relatively high power outputs could be obtained since the stalks could be electrically connected in parallel, thus the charge from each piezoelectric patch would be cumulative. It remains to be seen whether the lower deformations of a stacked configuration would trade off with the additional current provided in a stacked configuration. This would form a part of the future work in this configuration.

5 Conclusion

Based on the experiments conducted, it is evident that a composite piezo-leaf system has the potential to harvest energy from ambient fluid flow. Comparison of horizontal and vertical-stalk configurations showed that the vertical-stalk configuration provided relatively higher power outputs. Thus, multiple such vertical-stalk energy harvesting systems could be installed and connected to an energy storage device to power sensors, LED lights and other such ULP devices.

High speed video images indicated that the variable-orientation lift forces acting on the leaf resulted in large deformations. Thus, the reason for increased power output in the vertical-stalk configuration could be attributed to these lift forces acting on the flapping system, along with small amounts of torsional deformations. However, these large deformations resulted in excessive strain at the clamping location, which led to the partial failure of the PVDF stalks over a relatively short period of time. Also, the clamping base system interfered with the flapping motion of the system. Thus, it is essential to overcome these issues to develop an effective energy harvesting system which could be deployed in the outside environment to harvest energy from ambient wind flow.

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References


