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Downstream flow structures of a fluttering piezoelectric energy harvester

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ABSTRACT

The flow structures downstream of a fluttering piezoelectric energy harvester are examined, since 40% increases in power output have been noted from a downstream harvester. Smoke wire flow visualisation with a novel bi-lighting technique, and simultaneous voltage measurements are used to understand this phenomenon. The bi-lighting technique helped to confirm the out-of-plane velocity fields caused by the tilted cone vortices shed from the upstream harvester. It was speculated that the time-varying local pressure gradients induced by the propagating vortices coupled beneficially with the free-stream dynamic pressure and flutter instabilities, acting to elevate the flutter amplitude of the downstream harvester. Also, the phase lag between the harvesters showed a nonlinear relationship with the free-stream wind speed.

1. Introduction

1.1. Background and context

The study of flow structures downstream of bluff bodies has been ongoing for many years and is, in general, well understood. The vortices being shed from such bodies have been the principle focus of these studies; whether aiming to suppress them because of adverse vibrational effects on structures, or in the case of more recent investigations, exploit them for energy harvesting purposes. Allen and Smits [1] investigated the feasibility of placing a thin, highly compliant membrane laden with polyvinylidene fluoride (PVDF) piezoelectric patches behind a vortex shedding circular cylinder. The time-varying pressure gradient induced by the von Kármán vortices caused the membrane to deform and output an AC voltage, though the power output was not reported. Since then, there has been much work on examining the exploitation of flutter of piezoelectric materials for energy harvesting purposes.

Naudascher and Rockwell [21,22] introduced a method of identifying types of flow-induced vibrations in a system. Though three distinct types of flutter were established, only two have been of importance in the area of flutter energy harvesting: (1) Movement-Induced Excitation (MIE), where flutter of the immersed structure is instigated by the surrounding fluid exciting a resonant oscillatory mode of the structure; and (2) Extraneously-Induced Excitation (EIE), where flutter is generated by application of an external, time varying pressure gradient, such as those caused by vortices being shed from a bluff body. Thus, the type of flutter studied by Allen and Smits [1] was EIE-type. Similar experiments involving the exploitation of EIE-type flutter were conducted by Taylor et al. [25], though they focused more on optimisation of the energy capture circuitry. Kuhl and DesJardin [15] performed two dimensional DNS simulations of a flexible plate with and without a vortex shedding bluff body placed upstream of the plate.

MIE-type flutter has been studied extensively, whether to understand the dynamics of flag motion ([4,8]), the instability mechanisms of a fluttering plate in a fluid flow ([13,12,10]), or even to mitigate paper flutter in high-speed printing machines ([26,27]). Attempts to utilise this type of flutter for energy harvesting were carried out by Li and Lipson [16], following the conceptual design of a so-called “piezoelectric tree” by Dickson [11]. In their experiments, Li and Lipson [16] took a PVDF patch (considered to be the ”stalk”) and hinged a polymeric “leaf” to it, and placed the system in a parallel, smooth air flow. At a certain wind speed, the leaf-stalk would begin to flutter and would subsequently output an AC voltage; when passed through a circuit with a load resistance, power could be generated. This power output, according to a performance study conducted by Mitcheson et al. [20] was proportional to the vibratory amplitude squared and the frequency of vibrations cubed. A study examining the effect of the revolute hinge on a slender cantilever beam system was also conducted by Deivasigamanai

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et al. [9]. It was found that introducing a hinge into the system altered the vibration-frequency and flutter cut-in characteristics, compared with the uniform beam. McCarthy et al. [17] also performed tests using the same PVDF stalk and triangular leaf shape as Li and Lipson [16]; however, different leaf areas and aspect ratios were examined to determine the effect on power output. Tang et al. [24] analysed the energy fluid–structure energy transfer of a thin plate undergoing flutter, and proposed the concept of a 'flutter-mill' to extract useful energy from the flow.

Flutter of a piezoelectric leaf-stalk immersed in a fluid flow causes vortices to be shed from the leaf. These vortices propagate via advection downstream of the leaf-stalk harvester, and there have been studies based on examining the effect of these vortices on downstream leaf-stalk harvesters. Bryant et al. [5] conducted a parametric analysis on the optimum placement of a second harvester downstream of the first one – the optimum placement being the position that rendered maximum power output from the second harvester. They found that a placement two characteristic lengths downstream and in tandem with the first harvester gave the highest power output, though their harvester utilised a different piezoelectric material and configuration than that of Li and Lipson [16]. More recently, Bryant et al. [6] conducted flow visualisation of the vortices generated by their harvesters, and found that the nominally in-plane wake consisted of two parts: a large, sinusoidally shaped wake structure with smaller counter-rotating vortices within that larger wake structure. This agreed well with soap-film flow visualisation experiments previously performed by Jun et al. [14]. Bryant et al. [6] formulated an analytical model to predict the phase lag[1] between the two harvesters, with the assumption that the tip vortices were advecting at the same velocity as the free-stream flow. It was unclear whether this assumption, and the implicit assumption of constant phase lag, was valid. Choi et al. [7] found that the tip vortex from a two dimensional vibrating cantilever was formed due to the pressure gradient at the trailing edge of the cantilever beam; however, vibrations were applied to their beam (i.e. *active* vibration), whereas in piezoelectric energy harvesting from fluid flows, the vibrations are considered *passive*. This could mean that the vortex formation and propagation is different for energy harvesters than for active vibrating cantilevers.

In our previous work, we demonstrated up to a 40% increase in power output of a downstream harvester in tandem with an upstream one ([18]). In the current study, the flow structures off of a PVDF-stalk, polymeric-leaf energy harvester were investigated using smoke-flow visualisation. In order to understand the increase in power output, simultaneous voltage measurements were taken from the two harvesters, to determine vibration frequencies and phase lag. Upon observation of the first smoke-flow visualisation data, it seemed that the some of the flow structures being shed from the upstream harvester were 'tilting' out-of-plane, unlike in the work by Bryant et al. [6] where they observed in-plane vortical structures forming and propagating from their harvester. The smoke-flow visualisation was performed again, this time with a novel lighting technique that confirmed the out-of-plane vortex behaviour.

1.2. Specific objectives

In any study concerning energy harvesting with the intent of concept realisation, the aim would be to analyse the physical mechanisms in order to permit the system to output maximum power. In this study, the power output was considered important, but the specific objectives were to:

1. Enable the distinction of the out-of-plane flow features without the need for a second camera setup, using a novel yet simple bi-lighting technique for use with smoke-flow visualisation.
2. Develop an understanding of these flow structures, which could lead to more effective exploitation of the flow structures in extracting greater amounts of power from a downstream harvester.
3. Begin to understand the peculiar relationship between the flow speed and the phase lag for these harvesters.

2. Experimental methods

2.1. Flow visualisation

2.1.1. Test-specimen data

The piezoelectric films used here were highly compliant, rectangular PVDF uni-morphs (Measurement Specialties, model LDT2–028 K/L with rivets) measuring 72 mm long, 16 mm wide and 205 μm thick, see Fig. 1. These so-called 'stalks' were identical to the ones employed by Li and Lipson [16]. Coupled to the piezoelectric stalk was an isosceles, triangularly shaped leaf fabricated from 305 μm-thick polypropylene. The base and height of the leaf measured 80 mm by 80 mm respectively; elsewhere it was shown by McCarthy et al. [17] that this leaf size gave the highest power output amongst different leaf areas and aspect ratios tested, therefore it was this leaf shape and size that was utilised for the tests conducted here.

In most previous studies, either PVDF films or Lead–Zirconate–Titanate (PZT) patches have been investigated for their power output from vibrations ([3]). The PVDF films used here differed from the patches used by Bryant et al. [6], where PZT patches were bonded to a thin, relatively low stiffness steel beam (Fig. 2). PZT patches have, in general, a higher stiffness than PVDF films and are capable of comparatively higher power outputs; however, they have a lower fracture toughness and cannot withstand the reasonably large deformations that PVDF films may be subjected to – particularly in the context of aeroelastic flutter.

A simple revolute hinge was used as the interface between the stalk and the leaf, in order that rotation of the leaf was permitted during flutter. The mass of the hinge slightly decreased the lowest flexible bending modal frequency of the system, as expected. The efficacy of a nominally zero-stiffness, zero-mass hinge on the flutter characteristics of a representative low aspect ratio, rectangular, polymeric beam was previously quantified by Deivasigamani et al. [9]. There, it was found that by placing the hinge midway along the beam's length, the beam would flutter in its lowest flexible mode (thus exhibiting higher deformations). Also, from an energy harvesting perspective, and in the absence of an upstream bluff body shedding vortices that would induce motion of the beam, the beam would begin to flutter spontaneously at a lower wind speed – meaning power output at a lower wind speed for a deployed piezo-

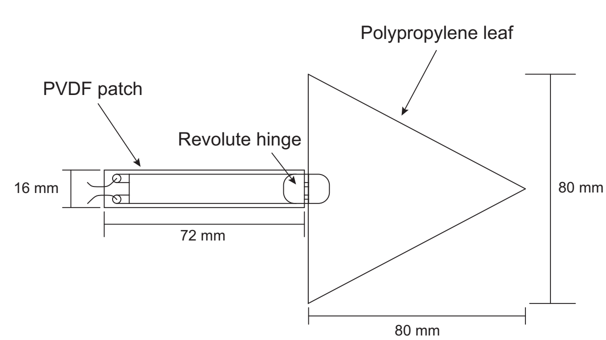

Fig. 1. PVDF-film and leaf dimensions.

[1] The phase lag, in this context, is defined as the phase difference of the downstream harvester, with respect to the upstream harvester as a datum.