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An investigation of fluttering piezoelectric energy harvesters in off-axis and turbulent flows

J.M. McCarthy [a,*], S. Watkins [a], A. Deivasigamani [a], S.J. John [a], F. Coman [b]

[a] RMIT University, School of Aerospace, Mechanical & Manufacturing Engineering, PO Box 71, Bundoora, Victoria 3083, Australia
[b] FCST Pty., PO Box 122, South Carlton, Victoria 3053, Australia

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ABSTRACT

The response of a fluttering piezoelectric energy harvester was studied in smooth flow and in aspects of replicated Atmospheric Boundary Layer turbulence (12.7% intensity, 310-mm longitudinal integral length scale). The harvester was yawed and pitched, and the effects on the power output were examined. Key findings were the following: (1) off-axis flow conditions rapidly degraded the mean output power of the harvester; (2) turbulence, for this specific harvester, acted similarly to a dynamic damping mechanism; (3) for on-axis flow, turbulence degraded the power outputs relative to smooth flow and for off-axis flow, the turbulence enhanced the power outputs relative to smooth flow. Future challenges include determination of harvester efficiencies, and analysis of fatigue-induced performance degradation.

1. Introduction

1.1. Background

Harnessing energy from wind, using various types of wind turbines, has been the focus of research and development for centuries. The vast majority of developments have been in smooth flows (either experimental or computational) with recent work including replicating the effects of Atmospheric Boundary Layer (ABL), where it has been shown that turbulence increases structural loading and decreases power output (Burton et al., 2001). However, there are new wind-energy technologies emerging that show potential for low, local power generation systems (e.g. Fig. 1). Ultra-Low Power generation technologies are moving from the laboratory to the deployable design space (Raju, 2008). Such technologies could be a source of power for low-energy technologies such as wireless sensor nodes or LED lighting in urban-based buildings; the technology could also be considered safer, quieter and more aesthetically pleasing than small-scale, urban-based wind turbines (Webb, 2007; Encraft, 2009).

These technologies involve piezoelectric films fluttering in a fluid stream, and can be grouped into two types: films that self-excite in flutter known as Movement-Induced Excitation (MIE) (Naudascher and Rockwell, 1980, 1994), and those where flutter is induced by a vortex-shedding upstream bluff body, known as Externally Induced Excition (EIE) (Naudascher and Rockwell, 1980, 1994). MIE-type flutter transpires whereby the flow at the critical flutter speed excites a resonant instability of the structure, and negative damping leading to system divergence. This kind of flutter has traditionally been identified in the analysis of divergence and stability analyses of compliant structures in a flow (e.g. Watanabe et al., 2002). Argentina and Mahadevan (2005) reasoned that for a thin beam in a parallel, smooth flow, flutter will initiate approximately when the flutter frequency equals the lowest bending frequency. One of the first investigations into harvesters using MIE was by Li and Lipson (2009), where they examined a single polyvinylidene-fluoride (PVDF) "leaf-stalk" harvester, immersed in a smooth parallel flow without an upstream bluff body. There, they tested the PVDF harvester in a wind-speed range from 3 to 8 ms^{-1}, and with a triangularly shaped leaf (which was found previously to cause the harvester to output the greatest power amongst a range of geometric shapes, see Li et al., 2011) hinged to the PVDF stalk. They found that the harvester performed best when it was fluttering in Limit-Cycle Oscillations (LCOs), and not chaotic-type flutter (Connell and Yue, 2007; Alben and Shelley, 2008).

Energy harvesting utilising EIE-type flutter involves analysis of the structural and fluid-forcing response spectra so that the shedding frequency may be tuned to the resonant frequencies of the structure, resulting in greater deformations and power outputs. Research into EIE-type harvesting had been conducted by Allen and Smits (2001) and Taylor et al. (2001); their work consisted of a thin membrane containing piezoelectric patches, immersed in the flow downstream of a circular cylinder shedding vortices that impinged on the membrane, periodically deforming it and generating power. In an energy harvesting context, EIE-type

* Corresponding author.
E-mail address: jesse.mccarthy@rmit.edu.au (J.M. McCarthy).

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Fig. 1. The artificial "tree" concept, utilising piezoelectric materials to harvester ambient flow energy, as proposed initially by Dickson (2008).

flutter is potentially more beneficial since the vortex shedding frequency may be tuned to the structure's natural frequency. Allen and Smits (2001) found that by using this method of tuning for a given smooth upstream flow, power outputs increased significantly due to large-amplitude vibrations. They also investigated the downstream effects of varying the distance between the bluff body and their harvester, but they did not check the zero-distance case.

Both types of fluttering harvesters need to be held in the fluid stream by a relatively rigid upstream body. The root of the piezoelectric stalk must be clamped so that bending strains are developed, which convert to power output. This negates the possibility of incorporating individual-harvester self-alignment mechanisms at the root of the stalk, which would permit the harvester to align with the mean wind direction. Ideally, for MIE-type harvesters these support structures should be infinitely thin and infinitely stiff, though in practice they are fabricated to be relatively small so as to prevent aerodynamic interference, and stiff enough to prevent transverse oscillations of the harvester base. In the case of EIE-type harvesters, the clamping-base cross-sectional shape is a key parameter, though usually a circular cross-section was envisioned so as to mimic a tree-like appearance (e.g. Fig. 1). The variation in positioning of the harvester, coupled with the variability of wind direction, means that an individual harvester may experience a wide range of wind conditions.

There has been no work done on examining the influence of flow angles, but some on the aerodynamic proximity effects of multiple MIE piezoelectric harvesters positioned close together with smooth upstream flow conditions. Initially, Pobering and Schwesinger (2004) suggested a matrix-like positioning scheme for multiple harvesters, and used simple calculations to estimate that such devices could have power densities greater than conventional wind turbines; however, the calculations were too simplistic and did not account for aerodynamic interference between harvesters. More recently, Bryant et al. (2011) investigated a different type of energy harvester to that of Li and Lipson (2009), and placed two harvesters in tandem within a parallel, smooth flow. At a certain distance, the trailing harvester was found to output nearly 30% more power than the leading harvester. A similar investigation by McCarthy et al. (2013a) using an identical harvester configuration to that of Li and Lipson (2009) found that up to 40% more power could be obtained from the trailing harvester at the same spacing as Bryant et al. (2011). Nevertheless, it was not known why and both McCarthy et al. (2013b) and Bryant et al. (2012) undertook smoke flow visualisation studies to attempt to elucidate the precise mechanisms causing the constructive aerodynamic interference between the tandem harvesters. No solid conclusions could be drawn from either study. More recently, McCarthy et al. (2014) found that two distinct vortical structures were detaching from the leading harvester, but only one – a cone-like horseshoe vortex, was acting to increase the maximum PVDF tip velocity of the trailing harvester through its flutter cycle, thereby increasing its voltage and power output at that particular downstream placement distance.

Efforts thus far have been focused on smooth flows rather than turbulent replication of the ABL, which can include static and dynamic flow directional changes. The only study of these energy harvesters with turbulence in the upstream flow appears to be the study by Hobeck and Inman (2011), where they examined the concept of piezoelectric "grass" immersed in a turbulent boundary layer; however, the integral length scales and turbulence intensity values were significantly different to those found in the ABL (e.g. Watkins et al., 2005, 2006), where these leaf-stalk harvesters are envisioned to be deployed.

1.2. Objectives and scope

In the work here, two distinct gaps in the field of piezoelectric flutter energy harvesting were addressed, namely, how do harvesters perform:

1. When the wind may approach from a direction other than parallel to the harvester?
2. In replicated ABL turbulence as compared to nominally smooth flow?

The performance of a harvester experiencing EIE flutter was analysed given variations in yaw and pitch angles, with respect to the prevailing wind direction. The first tests were conducted in nominally smooth flow, and the second tests in well-mixed turbulent flow with 12.7% intensity and 310-mm longitudinal integral length scales. The interest here lies in the micrometeorological turbulent peak, where temporal scales are around 30 s–2 min (Van Der Hoven, 1957). Since the harvester is a point-like structure, and the tests are carried out with 1:1 scaling of the harvester and test rig, the low-frequency wind fluctuations are considered to be quasi-static and no attempt to replicate the low-frequency part of the spectrum is made, aside from the static changes of yaw and pitch.

2. Methods and instrumentation

Two wind tunnels were used for this study, one for smooth flow and the second for turbulent flow.

2.1. Aeronautical wind tunnel

The smooth-flow work was conducted in the RMIT University Aeronautical Wind Tunnel (AWT). This tunnel is a closed-circuit design consisting of a 100-kW DC motor driving a six bladed fan. The test section is octagonally shaped and is 2100-mm long, 1070-mm high and 1320-mm wide. Upstream of the test section there is a 4:1 contraction ratio and anti-turbulence screens conditioning the flow, such that across a wide range of wind speeds the average longitudinal turbulence intensity component is less than 0.3%