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Energy harvesting prospects in turbulent boundary layers by using piezoelectric transduction

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ABSTRACT

Thin flexible cantilever beams with patches of piezoelectric materials or surrogate beams with attached strain gages have been electromechanically characterized for energy harvesting inside turbulent boundary layers. A turbulent boundary layer carries mechanical energy distributed over a range of temporal and spatial scales and their interaction with the immersed piezoelectric beams results in a strain field which generates the electrical charge. This energy harvesting method can be used for developing self-powered electronic devices such as flow sensors. In the present experimental work, various energy harvesters were placed in the boundary layers of a large scale wind tunnel with Re_θ between 2000 and 7500. The orientation of the beam relatively to the incoming flow and the wall was found to be critical parameters affecting the energy output. "Power maps" are presented for various roll and pitch angles as well as external flow velocities. The role of large instantaneous turbulent boundary layer structures in this rather complex fluid–structure interaction is discussed in interpreting the electrical output results. The forces acting on the vibrating beams have been measured dynamically and a theory has been developed which incorporates the effects of mean local velocity, turbulence intensity, the relative size of the beam's length to the integral length scale of turbulence, the structural properties of the beam and the electrical properties of the active piezoelectric layer to provide reasonable estimates of the mean electrical power output.

1. Introduction

The field of harvesting energy from the ambient environment on the macroscale (order of cm^3) (Anton and Sodano, 2007) or microscale (order of μm^3) (duToit et al., 2005) is an emerging technology which is being extensively studied by various scientific disciplines. The objective in the development of these harvesting methods is to design low profile systems which can provide power to small electronic devices for a wide range of applications including: monitoring environmental processes in remote areas with wireless sensors, structural health monitoring of ground and airborne vehicles, or charging consumer electronics products. Recent developments and progress in energy harvesting is being led by advances in synthesis and chemistry of smart materials, structural mechanics, computer science and electronics. In this context, harvesting energy from the environment which otherwise will be wasted can offer several benefits to existing sensors and sensing systems, such as reduced maintenance, extended lifetime, and smaller onboard weight (Sodano et al., 2005a, 2005b). While extracting energy from mechanical vibrations is a reasonably well-established field, whereby active materials are incorporated into vibrating structures to convert part of their mechanical energy into usable electrical charges, the study of energy harvesting from fluidic environments using different classes of smart materials has only been recently initiated.

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The first application of piezoelectric materials to extract energy from fluid motion is described in the conference paper by Schmidt (1992). He proposed the concept of an oscillating blade generator and emphasized the importance of incorporating mechanical and electrical resonance in the design of the system. Allen and Smits (2001) studied the behavior of long and very flexible piezoelectric beams made of Polyvinylidene Fluoride (PVDF) in the wake of a flat plate normal to the flow stream. This concept was then applied to harvest energy from ocean waves in (Taylor et al., 2001). Aside from the flow tank testing and optimization study, this work attempted to couple the flow and structure to simulate the interaction between the piezoelectric material and the surrounding fluid. Pobering and Schwesinger (2004) targeted kinetic energy extraction from flowing rivers. Flag-like membranes similar to those used in the water-based application of Taylor et al. (2001) and Giacomello and Porfiri (2011) were used by Robbins et al. (2006) to harvest energy from wind.

Vibration caused by aeroelastic effects have been also studied (Tang et al., 2009). Vibrations at the linear flutter speed (neutral stability condition) are an idealized scenario for linear wind energy harvesting (De Marqui and Inman, 2010) but the effective power generation performance is limited above a specific airflow speed. Akcabay and Young (2012) identified critical non-dimensional parameters that governed the response of piezoelectric beams fluttering in a viscous flow.

It has been demonstrated in the work of Akaydin et al., (2009, 2010a, 2010b, 2012) that it is possible to generate large voltage outputs (up to 30 V) from piezoelectric harvesters placed inside flows with high or low degree of spatial and temporal coherence. These flows are characterized by a large number of temporal and spatial scales with significant kinetic energy distributed over them. The available power in the fluid flow is proportional to U_f^3 where U_f a characteristic velocity which is proportional to a length scale L_f and a strain rate and thus frequency scale f_f. In that respect the available flow power is proportional to L_f^3 and f_f^3. This feature creates a unique opportunity to generate a substantial amount of energy by using piezoelectric materials to convert fluid kinetic energy to electrical energy. Piezoelectric materials generate electricity when exposed to a change in mechanical strain and, conversely, change shape when exposed to a change in electric field. The flow unsteadiness can produce fluctuations in mechanical strain energy in the piezoelectric material that in turn generates an electrical charge. This converted energy can readily be used for the continuous powering of small electronic devices or it can be stored for intermittent use. Such a small electronic device could be a sensor to measure unsteady characteristics of the flow such as turbulence levels and vortex shedding frequency. Of particular importance is the design of energy harvesting devices to work in remote environments which are not easily accessible or under conditions which do not facilitate the use of classical powering methods such as batteries or photovoltaic devices.

The work of Akaydin et al. (2009, 2010a) has shown that full coupling of the flow scales with those of the vibrational modes of the piezoelectric structures is a challenging problem which involves not only the classical fluid structure interaction with moving boundaries but also the additional coupling of the electrical field of the piezoelectric materials, thus classifying it as a truly *three-way* coupled interaction problem. Our previous experimental work involved testing of short-length flexible piezoelectric cantilever beams in a large-scale wind tunnel under resonant, self-excited or random forcing. In the first case resonant forcing between the flow and the vibrational motion of the beam resulted in maximum electric power extraction. This was achieved by placing the piezoelectric beam in vortex streets formed behind circular cylinders (Akaydin et al., 2010a). In this work the efficiency of the energy (or power) conversion was estimated and analyzed. The conversion of fluid kinetic energy to vibration energy appears to be the least efficient among the partial efficiencies of the processes contributing to the overall conversion into electrical power. Typically the conversion from vibrational to electrical energy has an efficiency of about 10–14%, the efficiency of the fluid to vibrational energy is below 0.72%. Akaydin et al. (2012) described a configuration with self-excited forcing in which a low aspect ratio circular cylinder is attached to the tip of a vibrating cantilever beam. This configuration is appropriate for uniform flows without disturbances where Karman vortices initiate the vibrational motion of the beam. The aeroelastic energy conversion efficiency of this configuration was shown to be approximately a factor of 4 times greater than behind the wake of a circular cylinder. While the operation of fluidic harvesters in resonance forcing in vortex street experiments is reasonably well demonstrated, their behavior under random forcing in various turbulent flows is yet to be fully explored. The first reported energy harvesting study in turbulent boundary layers was published in Akaydin et al. (2010a). The maximum power measured was 0.06 μW which is rather low in comparison to the 4 μW measured in the vortex dominated near wake of a cylinder or the 1 μW harvested in the turbulent far-wake of the same cylinder (see Akaydin et al., 2010b). Hobeck and Inmann (2012) subsequently investigated the performance of harvesting arrays of piezoelectric (PVDF) elements in a grass type configuration placed in the three-dimensional turbulent wake/boundary layer of a rectangular block mounted on a wind tunnel wall. The harvested power was about 1 μW per element which is close to the value measured in the cylinder's far wake in Akaydin et al. (2010b).

In the present contribution we report results of experimental work in which various types of piezoelectric beams under random excitation by turbulence have been tested. Most flows are turbulent, and the performance of harvesters in such environment is not known. Cantilever beams have been placed within a nominally 2-dimensional boundary layer flow which has been previously fully characterized and described in Andreopoulos and Agui (1996) and Andreopoulos and Honkan (2001). Fig. 1 shows a sketch of the investigated flow with a beam of length L, width b and thickness t_b placed inside the boundary layer of thickness δ in various orientaions relatively to the incoming flow. The large eddy size of turbulence is characterized by the scale L_c.

In Section 2, we provide theoretical considerations leading to normalization of the relevant quantities involved in the present three way interaction and the partial efficiencies in the energy conversion processes. The experimental setup and techniques are described in Section 3. Our experimental results are presented in Section 4, while the effects of the beam's orientation on harvested energy are shown in Section 5. Details of the fluid structure interaction are described in Section 6,

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