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Piezoelectric Energy Harvesting under Air Flow Excitation

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Abstract

This study focuses on the numerical analysis of a high efficiency Energy Harvesting device, based on piezoelectric materials, for the sustainability of smart buildings, structures and infrastructures. Before that, a comprehensive literature review on the topic takes place. The device consists in an aerodynamic fin attached to a piezoelectric element that makes use of the air flow to harvest energy. The principal utilization of this device is for energy autonomous sensors, with applications in bridges, transportation networks and smart buildings. The results are corroborated by advanced analytical and numerical analyses (in ANSYS®) that demonstrate the energy harvesting capacity.

1 Introduction

There is a strong consensus in the engineering community and the society for the realisation of enhanced structures and infrastructures. In addition to safety and functionality requirements, collectively addressed by the so-called “Performance-Based Design” (SEAOC, 1995; Spekkink, 2005), one of the pillars of contemporary structural engineering, today the attention focuses on the most broad and profound notion of “sustainability” (Ehrenfeld, 2008). In this sense, the modern construction industry embraces the concept of smart structural systems that behave optimally with respect to the human needs, being at the same time coherently collocated in the environment (Srinivasan & McFarland, 2001) and inserted in a context of resilient cities (Rose, 2011). Smart structural systems combine their primary function with additional capabilities. For instance, a bridge can pair its primary function of carrying vehicular traffic with several secondary features, such as an embedded set of sensors that constantly monitor the structural condition, or devices able to provide power to the bridge itself and make it (partially) self-sufficient, more sustainable and environmentally friendly. This study investigates this latter type of smart features, with focus on structural and mechanical models for piezoelectric energy harvesting devices under airflow excitation.

Energy Harvesting (EH) can be defined as the process of collecting energy from the environment or from a surrounding system and converting it to useable electrical energy. The idea of harvesting freely available energy is not new, and dates back to the invention of windmills and watermills. Modern wind turbines can be considered the direct and straightforward evolution of ancient windmills. However, today EH is performed with a much broader set of devices and techniques, and has become a prominent research topic also in the field of civil engineering, with several promising applications to structural and infrastructural systems. For instance, current popular areas of application extend from powering small autonomous wireless sensors (thus eliminating the need for wires) up to large auxiliary systems (e.g., road lights, signs or information panels, in the case of transportation infrastructure), thus contributing towards the pursue of sustainable structures and infrastructures (Gkoumas, 2012).

From this point of view, EH in civil engineering is part of a global clean energy trend that encompasses several aspects and disciplines, and focuses on the use of renewable sources and the reduction of fossil fuel usage for a more sustainable development (Adams, 2006).

Several proposals and applications can be found in literature and practice, mostly using solar and wind energy. The latter is of particular interest for high-rise buildings and long span bridges, due to the superior characteristics of the wind field.

2 Energy harvesting for smart buildings, structures and transportation infrastructures

So far, EH for smart buildings, structures and infrastructures has been focusing mostly on the production of small amounts of energy for powering SHM (Structural Health Monitoring) systems, so the topics of EH and SHM are strictly related in the literature. Some more recent applications, still mostly at a conceptual level, aim at supplying power to auxiliary systems (e.g. road lights or information panels), thus, contributing to the development of sustainable and self-sufficient infrastructure systems. More recently, EH is implemented in devices for smart building automation.

Spencer & Cho (2011) reviewed the recent developments in SHM technologies, including an energy harvesting options for sustainable operation. The same paper reports on a number of recent full scale implementations of EH for SHM networks. Gkoumas (2012) provided a literature review and a framework for the optimal implementation of EH applications in transportation networks. A review of the EH applications on this topic can be found also in Park et al. (2008). The authors, after providing an overview of SHM, focus on the energy generation from mechanical vibrations as a powering option. In the same paper, the power requirements of existing and emerging sensing modalities are discussed, and future directions are given.

In the field of piezoelectric material modelling, several alternatives have been proposed in literature. Erturk and Inman, 2008, provide a critical review and identify the principal issues in the mechanism of piezoelectric coupling and the basic excitation relation. Numerical (Finite Element) modelling of piezoelectric material presents many challenges for what regards the coupling between the deformation and diffusion in the piezoelectric material. De Miranda et al. (2009) studied the coupled piezo-diffusion in elastic solids and provided indications and examples for the accurate modelling, overcoming simplistic assumptions of displacement and concentration of the material as independent variables in the model.

Focusing on the specific application proposed in this research (piezoelectric benders), recent developments seem promising in terms of EH capacity. In a recent study by Weinstein et al (2012), the EH potential is investigated, both analytically and experimentally, in heating, ventilation and air conditioning flows. The energy effectively harvested is augmented by means of an aerodynamic fin attached at the end of the piezoelectric cantilever and the vortex shedding downstream from a bluff body placed along the airflow in front of the fin/cantilever assembly.

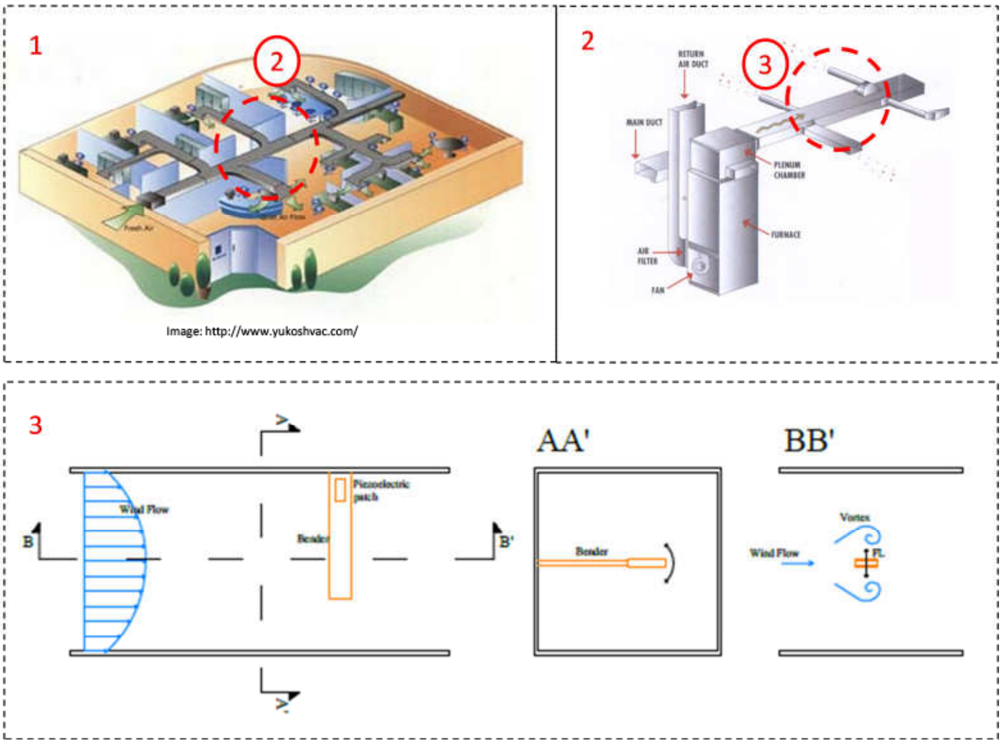

Figure 1. The device for EH (in orange in the figure) and its collocation inside a HVAC duct.

Figure 1 provides a schematic representation of a possible application of the EH device, object of this study. The EH device, could harvest the airflow powered inside Heating, Ventilation and Air Conditioning (HVAC) systems, using a piezoelectric component and an appropriate customizable aerodynamic appendix or fin that takes advantage of specific air flow effects (principally Vortex Shedding), and can be implemented for optimising the energy consumption inside buildings. The possibility to implement autonomous sensors inside a building that monitor relevant parameters (temperature, humidity, chemical agents concentration etc.), and transmit intermittently data to a central unit is a recent and rapidly grown business, helped by the standardisation of wireless (wi-fi) data transmission.

3 Numerical modelling

The proposed research focuses on the numerical modelling of different configurations of a piezoelectric bender and an attached fin (Figure 2).

The ANSYS® numerical code is used for the analyses (ANSYS, 2011). In the analysis, different air-flow intensities are considered.

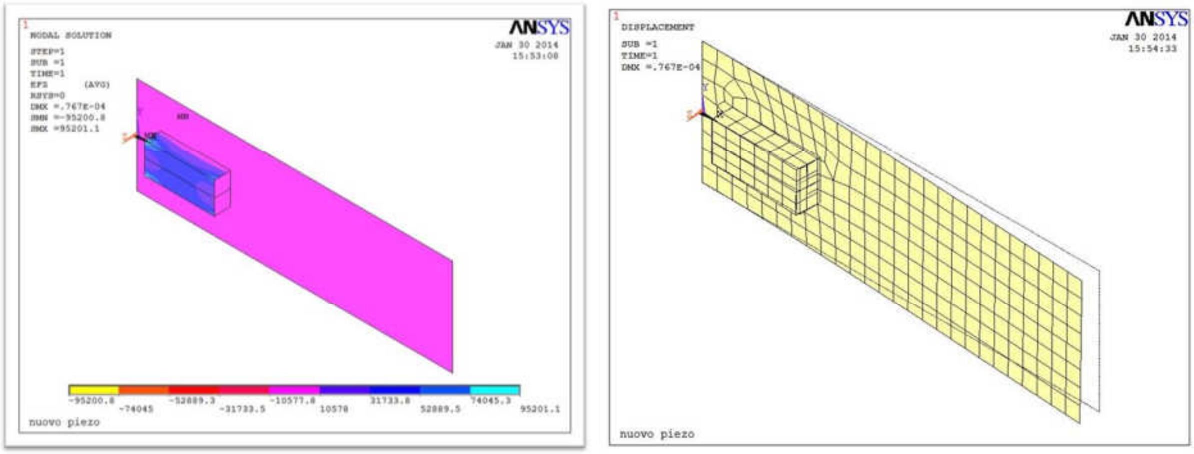

Figure 2. Numerical model of the piezoelectric bender and the fin (left); deformed shape of bender and the fin under air flow excitation.

A performance-based parametric analysis is conducted in order to assess the optimal values of some design and operating condition parameters, including length, width, thickness, constitutive material of the bender and velocity and turbulence intensity of the incoming airflow. The response parameters used for evaluating the performances include:

- The bender max tip displacement;
- The bender vibration frequency;
- The rms of the voltage generated by the device.

Considerations are made for the harvested energy potential and possible applications in structures, infrastructures and smart buildings.

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