Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 3444–3449

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Piezoelectric vibration energy harvesting from airflow in HVAC (Heating Ventilation and Air Conditioning) systems

Konstantinos Gkoumas*, Francesco Petrini, Franco Bontempi

Sapienza University of Rome, Via Eudossiana 18, 00184, Rome, Italy

Abstract

This study focuses on the design and wind tunnel testing of a high efficiency Energy Harvesting device, based on piezoelectric materials, with possible applications for the sustainability of smart buildings, structures and infrastructures. The development of the device was supported by ESA (the European Space Agency) under a program for the space technology transfer in the period 2014-2016. The EH device harvests the airflow 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 airflow phenomena (vortex shedding and galloping), and can be implemented for optimizing the energy consumption inside buildings. Focus is given on several relevant aspects of wind tunnel testing: different configurations for the piezoelectric bender (rectangular, cylindrical and T-shaped) are tested and compared, and the effective energy harvesting potential of a working prototype device is assessed.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: piezoelectric, energy harvesting, vibration, airflow, HVAC

1. Introduction

Energy harvesting (EH), i.e. the process of extracting energy from the environment or from a surrounding system and converting it to usable electrical energy, is a research topic with many promising applications nowadays. Its areas of application currently focus to the powering of small autonomous wireless sensors (thus eliminating the need for wires), in structural health monitoring and building automation applications. Regarding the latter, the prospect to

*Corresponding author. Now at: European Commission Joint Research Centre, Via E. Fermi 2749 -I- 21027, Ispra (VA), Italy.
Tel.: +39 0332 786041. *E-mail address:* konstantinos.gkoumas@ec.europa.eu

Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.496

implement autonomous sensors inside a building that monitor relevant parameters (temperature, humidity, chemical agent concentration etc.), and transmit intermittently data to a central unit is a recent and rapidly growing business, helped by the standardization of wireless (Wi-Fi) data transmission.

Research on EH in the last decade has been substantial for what regards technology, materials and implementation issues. Harb [1] and Gkoumas [2] provide an overview of energy harvesting applications in civil and infrastructure engineering, while an extensive review of methods, technologies and issues is found in Priya and Inman [3]. Gkoumas et al. [4] and Petrini et al [5] proposed a classification for EH integrated systems both in micro- and macro- scale [6] for the potential consideration of EH capabilities as an important design factor of buildings, to be considered in the well-known recent framework of Performance-Based Engineering [7]. Gibson [8] provides a review of multifunctional materials, some of which can be deployed in energy harvesting applications. Belleville et al. [9] lay a framework for the functioning of energy autonomous systems, and provide estimated power output values for different harvesting principles. Chalasani and Conrad [10] provide a survey of different energy harvesting sources for self-powered embedded devices. Gilbert and Balouchi [11] review the characteristics and energy requirements of typical sensor nodes, indicate possible applications, provide potential ambient energy sources and highlight the usefulness of having an EH device able to generate few hundreds of µWs of power as a minimum target. Bowen et al. [12] review energy harvesting technologies associated with piezoelectric materials.

On top of that, the concept of “Smart Building” has evolved and is nowadays closer to reality. It requires buildings equipped with additional subsystems for managing and controlling energy sources and house appliances, and minimize energy consumption, often using wireless communication technology [13]. Among these, typical examples are Building Automation Systems (BAS), or centralized, interlinked networks of hardware and software that monitor and control the environment in commercial, industrial, and institutional facilities. One of the objectives of Building Automation is to automatize the systems present in the building through the monitoring of ambient parameters using sensors installed in the structure. These sensors can be powered through the mains or in alternative, can be self-powered. The latter is advantageous because it makes their installation easier and it reduces the cost of cabling. An alternative is the use of batteries, which, however, considering their limited lifetime, need to be replaced at regular intervals. Therefore, in addition to having a high environmental impact, their use affects maintenance costs in the long term. As a consequence, the best solution is to employ Energy Harvesting wireless autonomous sensors.

In building automation, one of the prominent research fields is in the use of piezoelectric EH devices inside HVAC (Heating, Ventilation and Air Conditioning) systems. These devices make use of different aerodynamic instability phenomena (principally vortex shedding and galloping) inside tubes with a typical airflow that for residential applications are in the range of 2 to 6m/s, while in industrial applications the upper value can be increased.

Flow-induced energy harvesting is not new. Abdelkefi [14] performs a review of major research findings in energy harvesting from aeroelastic vibrations, including galloping and VIV (Vortex Induced Vibrations). In general, in galloping harvesters, the presence of a bluff body that oscillates in the direction normal to the incoming flow due to galloping, leads to the necessary vibration of the piezoelectric material. The bluff body has usually a rectangular or prismatic shape. In vortex-induced harvesters, a cylinder is immersed in a fluid that produces the necessary vortices, usually due to the presence of a bluff-body immediately upstream.

Several researches can be found in literature that explore piezoelectric flow-induced energy harvesting, analytically, in simulation and in experimental conditions. In a comparable study, Weinstein et al. [15] investigate experimentally the possibility to extract energy by means of piezoelectric materials from the airflow in HVAC. In their study they focus on flow speeds of 2.5 and 5.0 m/s, and on using the vortex shedding effect from a bluff body placed in the airflow ahead of piezoelectric fins.

This study focuses on the numerical and experimental testing of a harvester for a wireless temperature sensor. The sensor has been developed for implementation in HVAC systems. The harvester uses a piezoelectric bender and an appropriate customizable aerodynamic appendix (fin) that takes advantage of specific airflow effects (vortex shedding and galloping) for producing energy. The harvesting potential has been demonstrated analytically, experimentally and in wind tunnel testing (accounting also for conditions close to those inside HVAC tubes, not considered in this study for the sake of brevity).

While this study focuses on the prototype development and the wind tunnel testing at the CRIACIV wind tunnel facility in Florence, the development included also extensive numerical analyses, optimization of the EH circuit, operation and integration in HVACs aspects and industrial design.

2. Studies and experimental testing

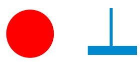
For the design of the EH device, a series of steps has been planned, spanning from the theoretical conception to the final design. The steps include: i) the shape and the geometry of the device, ii) the integration of the piezoelectric bender in the aerodynamic fin, iii) the electric circuit and iv) the final testing in HVAC operating conditions. This paper will focus on steps i and ii. Steps iii and iv (refinements for the representation of the environment and electrical design) are omitted for the sake of brevity.

These design steps are arranged in Table 1, highlighting the focus given in each phase on different design aspects (design values – DVs), using different methods (analytical, numerical and experimental):

Regarding the aerodynamic shape, initially, the idea was to use a plane shape for the aerodynamic fin, finding inspiration from recent literature on the topic at the time the project started, and in particular from the study by Weinstein et al. (2012) [15]. Soon after that, numerical models were built also with cylindrical section, and after some first results (also experimental) it was decided to assess the performance of other shapes as well (rectangular and T-shape). As the analyses advanced, focus was given to the most performing shape for the aerodynamic fin.

Regarding the numerical analyses, initially a Matlab® model was developed using simplified models (two analytical differential equations) with the aim to assess the energy potential of the cantilever beam configuration under sinusoidal lock-in type forces induced by VIV. After that, different FE electromechanical numerical models were developed in Ansys®. Findings from these first analyses led to a better comprehension of the modelling aspect. The voltage and power output have been calculated for different dimensions and configurations, and it was shown how the aerodynamic critical velocity (i.e. the incoming flow velocity initiating the VIV regime), the natural frequency and the oscillation amplitude vary with the bender dimensions.

Table 1. Design steps taken during the research.

	Design Step (DS)	Design Value (DV)	Method	Prototype cross section (shape)
1	Aerodynamic Design	Shape, Dimension, Mass, Damping	Analytical/Numerical Experimental	
2	Electromechanical Design	Resistance (R)	Experimental Shaking test Wind tunnel	
3	Electrical Design	Energy Extraction Strategy	Analytical	
4	Fidelity Environment	Operating Conditions	Experimental Wind tunnel	

2.1. Prototyping and setup

For the experimental analyses, different prototypes were prepared, consisting in an aluminum fixed end-support, a piezoelectric bender in Kampton and piezo-ceramic material and an aerodynamic fin in balsa wood.

The bender is clamped to the base, while the piezoelectric patch is glued to the fin. For the patch, the PI Ceramic P-876K015 DuraAct Patch Transducer was chosen.

Figure 1 shows the three principal prototypes (cylindrical, rectangular and T-shape) inside the CRIACIV wind tunnel facility. As shown in Figure 1(c), for the T-shape configuration, angular stiffening elements were applied at the angular connection (white element in figure) for the double goal of maintaining the orthogonality between the T components and regulating the mass in order to obtain the target eigen-frequency.

Fig. 1. (a) cylindrical prototype; (b) rectangular prototype; (c) T-shape prototype.

Table 2 provides the characteristics of the three components. The principal configurations consist in a fin 35cm long, while additional fins were tested, with lengths of respectively 25 and 30cm for the cylindrical prototype, and 18.5cm for the T-shape one. This was done to account for the positioning of the harvester inside ducts of different dimensions (typically ranging from 50x50cm to 100x100cm).

Table 2. Prototype data.

Fixed end-support Data		
Density (ρ)	2700	Kg/m^3
Volume	9.65	cm^3
Damping Ratio ζ/ζ_{cr}	0.75	%
Piezoelectric Bender Data		
Density (ρ)	3000	Kg/m^3
Volume	0.275	cm^3
Young Modulus (E)	Anisotropic material Data supplied by the manufacturer	Pa
Aerodynamic Fin data		
Density (ρ)	145	Kg/m^3
Volume	41	cm^3
Young Modulus (E)	Anisotropic material	Pa
Cross-wind/along-wind dimension ratio of the cross section (D/t)	Cylindrical 30 /30 Rectangular 20 / 60 T-shape 20/30	mm/mm

In a second phase, a simple prototype electric circuit was designed and attached to the harvester (Fig. 2), later substituted by a more advanced production-ready one.

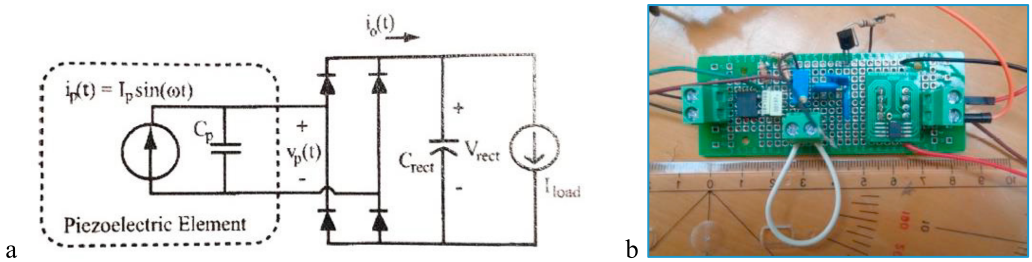


Fig. 2. (a) prototype electric circuit scheme; (b) actual prototype electric circuit.

2.2. Results

The initial tests were conducted without electrical resistance (design Step 1) on all three geometries. Figure 3 reports the normalized dynamic response of the model, varying with the reduced wind velocity, in terms of the equivalent sinusoid (D indicates the cross-wind dimension of the model section). In the graphs (not in the same scale), circles represent the first testing series (increasing values with wind speed), crosses the second testing series (decreasing values with wind speed), and the dotted red line the reduced speed equal to $1/St$, assuming a value of $St = 0.2$ for the Strouhal number St.

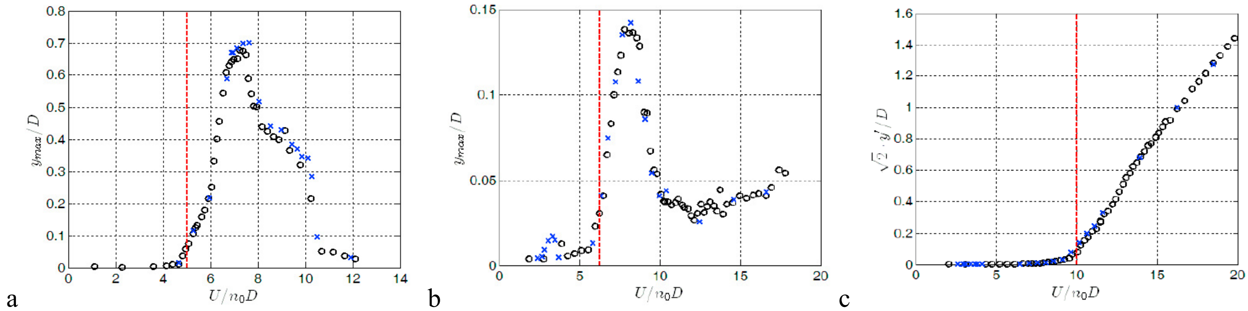


Fig. 3. (a) cylindrical section response; (b) rectangular section response; (c) T-shape section response.

In the design, focus is given to the response, both in terms of peak value and broadness. As can be seen, the cylindrical shape has a much better performance than the rectangular. The performance of both is limited by the VIV (Vortex Induced Vibrations) lock-in phenomenon. The hysteresis is very low for all cases. Regarding the T-shape fin, it is known [16] that for not very high Scruton values, it is subjected to a particular instability due to both VIV and galloping. In this case, the oscillations start at approximately the resonance speed with the vortex shedding velocity $U_r=n_o/St$, where n_o is the natural frequency, St is the Strouhal number of the section, equal to 0.1, and then they increase linearly with the flow speed. Concluding, the T-shape fin has a better performance, which increases with the flow speed, possibly indicating that galloping is occurring before entering in the descending part of the characteristic VIV bell. For this and other practical reasons it was decided to proceed the tests with this geometry.

After that, an electric circuit was attached to the piezoelectric patch. For the test, a flow speed that gave rather high vibrations was chosen (U/U_r=1.47), and different circuit resistances were explored. The vibration damping induced by the energy harvesting (EH) circuit [17] did not influence significantly the dynamic behavior of the system. Figure 3 shows the dynamic response for different circuit resistances and for different flow intensities. The resistance identified as “resistenza 7” (1.5 MΩ) gave the maximum values of power extraction. As can be observed in Figure 4b (and in line with Figure 4c) the dynamic behavior of the harvester, in terms of the amplitude of the equivalent sinusoid (y' is the standard deviation of the time series of the displacements) is linear for flows with $U>U_r$. The power extracted by the T-Shape harvester reaches values of 400 μW.

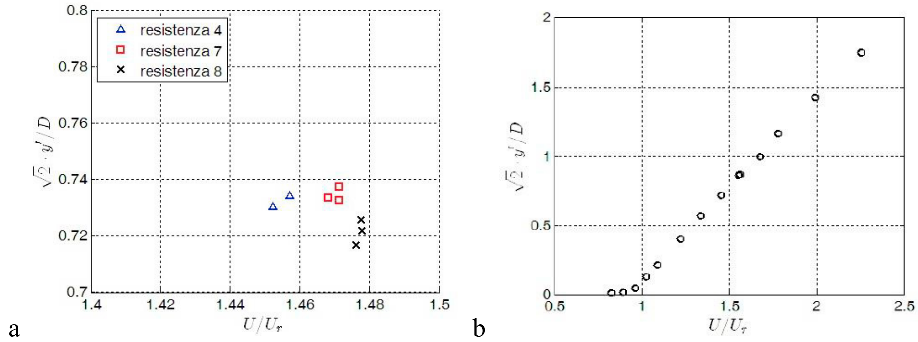


Fig. 4. (a) dynamic response for different circuit resistance; (b) dynamic response for the optimal resistance and varying flow intensity.

3. Conclusions

The experimental testing provided positive results, achieving a power extraction of 400 μW, sufficient for powering a small sensor. The experiments led to the assembly of a prototype temperature sensor (www.piezotsensor.eu).

Acknowledgements

This study was partially supported by BIC Lazio Spa under the ESA Space Technology transfer program. The contributions of Giulio Biscarini, Marco Balsi, and the CRIACIV wind tunnel team are greatly acknowledged.

References

[1] A. Harb, Energy harvesting: State-of-the-art, Renewable Energy 36 (2011) 2641-2654.
[2] K. Gkoumas, Energy harvesting in bridges and transportation infrastructure networks: state of art, recent trends and future developments Proceedings of the Sixth International IABMAS Conference, Stresa, Italy (2012) 1527-1533.
[3] S. Priya and D.J. Inman (eds), Energy Harvesting Technologies, Springer, New York, 2009.
[4] K. Gkoumas K, O. De Gaudenzi, F. Petrini F. Energy harvesting applications in transportation infrastructure networks, Procedia - Social and Behavioral Sciences 48 (2012) 1097-1107.
[5] F. Petrini, O. De Gaudenzi, K. Gkoumas, An energy harvesting application in a long span suspension bridge. Proceedings of the third International Conference on Life-Cycle Civil Engineering (IALCCE 2012), Wien, Austria, October 3-6, 2012.
[6] F. Petrini, S. Manenti, K. Gkoumas, F. Bontempi, Structural design and analysis of offshore wind turbines from a system point of view, Wind Engineering, 34 (2012) 85-108.
[7] M. Barbato, A. Palmeri, F. Petrini, Special Issue on Performance-based engineering, Editorial foreword, Engineering Structures 78 (2014) 1-2.
[8] R.F. Gibson, A review of recent research on mechanics of multifunctional composite materials and structures, Composite Structures 92 (2010) 2793–2810.
[9] M. Belleville, H. Fanet, P. Fiorini, P. Nicole, M.J.M. Pelgrom, C. Piguet, R. Hahn, C. Van Hoof, R. Vullers and M. Tartagni, Energy autonomous sensor systems: Towards a ubiquitous sensor technology Micro electronics Journal, 41 (2010) 740-745.
[10] S. Chalasani and J.M. Conrad, A Survey of Energy Harvesting Sources for Embedded Systems, IEEE Proceedings of Southeastcon (2008) 442–447.
[11] J. M. Gilbert and F. Balouchi, Comparison of Energy Harvesting Systems for Wireless Sensor Networks, International Journal of Automation and Computing 5 (2008) 334-347.
[12] C. R. Bowen, H. A. Kim, P. M. Weaver and S. Dunn, Piezoelectric and ferroelectric materials and structures for energy harvesting applications, Energy & Environmental Science, 7 (2014), 25-44.
[13] B. Morvaj, L. Lugaric and S. Krajcar, Demonstrating smart buildings and smart grid features in a smart energy city, Proceedings of the 3rd International Youth Conference on Energetics - IYCE, 2011, 225-232.
[14] A. Abdelkefi, Z. Yan and M. R. Hajj, Modeling and nonlinear analysis of piezoelectric energy harvesting from transverse galloping, Smart materials and Structures 22 (2013) 12p.
[15] L. A. Weinstein, M. R. Cacan, P. M. So and P. K. Wright, Vortex shedding induced energy harvesting from piezoelectric materials in heating, ventilation and air conditioning flows, Smart Materials and Structures 21 (2012) 10p.
[16] C. Mannini, A. Marra and G. Bartoli, VIV–galloping instability of rectangular cylinders: Review and new experiments, Journal of wind engineering and industrial aerodynamics 132 (2014) 109-124.
[17] H. Shen, J. Qiu, M. Balsi, Vibration damping as a result of piezoelectric energy harvesting, Sensors and Actuators A 169 (2011), 178-186.