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# Aeroelastic energy harvesting: A review

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ABSTRACT

Energy harvesting is the process by which light, thermal, solar, and kinetic energy can be converted to a usable form of energy with the ultimate objective of developing self-powered sensors, actuators, and other electronic devices. Each of these sources of energy can be used to power remote sensors, however, many researchers have emphasized on vibration-based energy harvesting. Converting ambient and aeroelastic vibrations can be achieved using either electromagnetic, electrostatic or piezoelectric transduction mechanisms. The piezoelectric option has attracted significant interest because it can be used to harvest energy over a wide range of frequencies and the ease of its application. Many researchers have used the piezoelectric transducer to develop simple and efficient energy harvesting devices from vibrations. In this paper, we review recent literature in the field of energy harvesting from aeroelastic vibrations during the last few years. Various types of aeroelastic vibration mechanisms and representative mathematical models are also reviewed. Qualitative and quantitative comparisons between different existing flow-induced vibrations energy harvesters are discussed. Limitations and future recommendations are also presented.

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## 1. Introduction

The ultimate objective of many researchers is how to use the natural energy sources to generate inexhaustible electric energy and to operate self-powered devices including microelectromechanical systems or actuators (Gurav et al., 2004; Muralt, 2000; Zhou, Liao, & Li, 2005), heath monitoring and wireless sensors (Inman & Grisso, 2006; Roundy & Wright, 2005), cameras (Abdelkefi & Ghommem, 2013), pacemakers (Karami & Inman, 2012), cell phones (Sharpes, Abdelkefi, & Priya, 2014, 2015), or replacing small batteries that have a finite life span or would require hard and expensive maintenance (Capel, Dorrell, Spencer, & Davis, 2003; Magoteaux, Sanders, & Sodano, 2008; Priya, Popa, & Lewis, 2006). Therefore, the target of energy harvesting is to operate autonomous powered electronic devices over their life time. A number of alternative energy sources include thermal energy (Abdelkefi, Alothman, & Hajj, 2013a; Huesgan, Woias, & Kockmann, 2008), chemical, light energy (Norman, 2007), and mechanical energy (Abdelkefi & Barsallo, 2014, 2015; Abdelmoula & Abdelkefi, 2015; Beeby, Tudor, & White, 2006; Javed, Dai, & Abdelkefi, 2015; Tang & Yang, 2012). For powering electronic devices, mechanical energy has received the most attention (Abdelkefi, 2012; Anton & Sodano, 2007; Erturk, 2009; Harne & Wang, 2013; Karami, 2011) because it can be found in many places where thermal or light energy is not suitable. Harvesting mechanical energy through converting wasted vibrations to electrical energy can be achieved using either electromagnetic (Arnold, 2007; Glynne-Jones, Tudor, Beeby, & White, 2004; Karami, 2011; Mitcheson et al., 2004), electrostatic (Anton & Sodano, 2007; Mitcheson et al., 2004), or piezoelectric (Abdelkefi, 2012; Anton & Sodano, 2007; Cook-Chennault, Thambi, & Sastry, 2008; Erturk, 2009; Harne & Wang, 2013; Javed, Abdelkefi, & Akhtar, 2015; Kim, Kim, & Kim, 2011) transduction mechanisms. Of these mechanisms, the piezoelectric transduction is most suitable for MEMS devices

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(Muralt, 2000) and wireless sensors (Inman & Grisso, 2006; Roundy & Wright, 2005) mostly because it can effectively be placed in small volumes and it can be used to harvest energy over a wide range of frequencies. The piezoelectric effect was discovered by Pierre and Jacques Curie in 1880. There are two distinct piezoelectric effects. The direct effect describes the ability of some materials (including quartz, Rochelle salt, tourmaline, and barium titanate) to convert mechanical strain into electrical charge and hence electrical energy. The second piezoelectric effect is the converse effect which describes the ability to convert an applied electrical potential into mechanical strain. In their paper, Anton and Sodano (2007) reviewed the used piezoelectric materials and coupling modes for power generation.

Several studies (Churchill, Hamel, Townsend, & Arms, 2003; Discenzo, Loparo, Cassar, & Chung, 2006; Platt, Farritor, & Haider, 2005; du Plessis, Huigsloot, & Discenzo, 2005; Roundy & Wright, 2004) have been conducted to investigate the possibility of employing the piezoelectric transduction mechanism in order to operate electronic devices. Arms, Townsend, Churchill, Galbreath, and Mundell (2005) designed and fabricated a piezoelectric-powered wireless temperature and humidity sensor. To power the sensor and the wireless data transmission circuitry, a piezoelectric cantilever beam was used to convert ambient vibrations to a usable amount of energy. The wireless sensing node includes a microprocessor, strain sensing gauge, on-board memory, and sensor signal conditioning.

The harvested power depends on the quantity and available form of kinetic energy and the efficiency of the harvester. During the last decade, many studies have been concerned with harvesting energy from base vibrations (Abdelkefi, Najar, Nayfeh, & Ayed, 2011a; Erturk, 2009; Renno, Daqaq, & Inman, 2009; Stanton, Erturk, Mann, & Inman, 2010; Xie, Wu, Yuen, & Wang, 2013). A significant number of review papers have been published to show different techniques and mechanisms to enhance the level of the harvested power (Anton & Sodano, 2007), tune the harvester's natural frequency and design broadband energy harvesters (Tang, Yang, & Soh, 2009b), and report advances in bistable energy harvesters (Harne & Wang, 2013; Pellegrini, Tolou, Schenk, & Herder, 2013). On the other hand, although there is a significant interest in harvesting energy from aeroelastic vibrations in the last few years, to the author's knowledge, no comprehensive review article has been published to report the recent advances in energy harvesting from flow-induced vibrations or aeroelastic phenomena. There is only a short review article (Truitt & Mahmoodi, 2013) which focused on active wind energy harvesting designs with a narrow scope. Our objective in this review paper is to review and consolidate the major research findings in this topic with a particular focus on the considered aeroelastic energy harvesters, used mathematical modeling, and design perspective of these harvesters. Furthermore, qualitative and quantitative comparisons between various existing flow-induced vibrations energy harvesters are presented and discussed. At the end, remaining challenges in terms of modeling, design, and fabrication as well as future recommendations are presented.

## 2. Used aeroelastic phenomena for energy harvesting applications

When a structure is subjected to flow loads, the structure may undergo various responses (Dowell & Tang, 2002; Liu, Wong, & Lee, 2000; Nayfeh & Mook, 1979; Vasconcellos & Abdelkefi, 2015), including bifurcations, limit-cycle oscillations, internal resonances and chaotic motions. Due to aerodynamic phenomena, such as vortex-induced vibrations, flutter, buffeting, and galloping, unwanted and excessive vibrations can occur. In the fields of civil and aerospace engineering, researchers work on avoiding these types of vibrations in large scale systems including buildings, bridges, aircraft, pipelines, transmission lines, and structures to suppress possible failure or damage (Dai, Abdelkefi, Wang, & Liu, 2014; 2015; Librescu & Marzocca, 2005).

In the literature of aeroelasticity, piezoelectric materials (as actuators, converse effect) and other actuators have been used as active and semi-passive controllers to modify the aeroelastic behavior of wings (Brown, 2003; Giurgiutiu, 2000; Lazarus, Crwley, & Lin, 1996; Li, 2012; Lin, Crwley, & Heer, 1996). Furthermore, the effects of passive controllers have also been investigated by several researchers to increase the linear flutter speed (Agneni, Mastroddi, & Polli, 2003; Agneni, Sorbo, Mastroddi, & Polli, 2006; McGowan, Heeg, & Lake, 1996). Researchers have also used piezoelectric materials as actuators for morphing wings or morphing aircraft (Bilgen, Kochersberger, Diggs, Kurdila, & Inman, 2007; Schultz & Hyer, 2004). Moreover, Macro-Fiber-Composite (MFC) actuators have been used to suppress buffeting oscillations on the vertical fins of an F-18 (Sheta, Moses, Huttsell, & Harrand, 2003; Wickramasinghe, Chen, & Zimcik, 2007). From a different perspective, these aerodynamic phenomena associated with structural nonlinearities have been proposed as a new source of power generation in small scale systems. These structural nonlinearities can be classified into either distributed or concentrated based on the region of their existence. Distributed nonlinearities arise generally from deformations of the entire structure. On the other hand, concentrated nonlinearities arise from loose or worn hinges of control surfaces.

From an energy harvesting point of view, the harvester is placed in a flow field and excited to undergo large limit-cycle oscillations that can be converted to electrical energy using piezoelectric and/or electromagnetic transducers. The research findings in this topic have been performed in the following chronological order: flutter in airfoil sections, vortex-induced vibrations in circular cylinders, galloping in prismatic structures, and wake galloping in parallel cylinders. In this section, we briefly introduce these concepts. It should be mentioned that only the most used systems are described in the next sections. Other possible designs of flutter, VIV, galloping, and wake galloping are presented and discussed in details in one of the next sections.

### *2.1. Flutter in airfoil sections*

In the case of flutter energy harvesting, in general, an airfoil section is attached to the end of a piezoelectric cantilever beam, as shown in Fig. 1. As the flow speed increases, there may be a critical speed, named flutter speed, at which self-excited motions take place because the structural damping is insufficient to damp out motions due to the aerodynamic effects. At this critical