Applied Energy 212 (2018) 233–243

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

An impact-based broadband aeroelastic energy harvester for concurrent wind and base vibration energy harvesting

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HIGHLIGHTS

- A novel impact-based broadband aeroelastic energy harvester is proposed.
- Broadened bandwidth for concurrent wind and vibration energy harvesting is achieved.
- Quasi-periodic vibration is converted to periodic vibration.
- An aero-electro-mechanically coupled model is experimentally validated.
- Peak beam deflection is slightly mitigated and fully utilized for power conversion.

ARTICLE INFO

Keywords:
Broadband concurrent energy harvesting
Wind energy
Vibration
Piezoelectric
Mechanical stopper
Piecewise-linearity

ABSTRACT

This paper proposes a novel broadband energy harvester to concurrently harvest energy from base vibrations and wind flows by utilizing a mechanical stopper. A problem for a conventional wind energy harvester is that it can only effectively harness energy from two types of excitations around its resonance frequency. The proposed design consists of a D-shape-sectioned bluff body attached to a piezoelectric cantilever, and a mechanical stopper fixed at the bottom of the cantilever which introduces piecewise linearity through its impact with the bluff body. The quasi-periodic oscillations are converted to periodic vibration due to the introduction of the mechanical stopper, which forces the two excitation frequencies to lock into each other. Broadened bandwidth for effective concurrent energy harvesting is thus achieved, and at the same time, the beam deflection is slightly mitigated and fully utilized for power conversion. The experiment shows that with the stopper-bluff body distance of 19.5 mm, the output power from the proposed harvesting device increases steadily from 3.0 mW at 17.3 Hz to 3.8 mW at 19.1 Hz at a wind speed of 5.5 m/s and a base acceleration of 0.5 g. A guideline for the stopper configuration is also provided for performance enhancement of the broadband concurrent wind and vibration energy harvester.

1. Introduction

The field of energy harvesting has received ever growing research interests in the recent years. The ultimate goal is to implement self-powered microelectronic systems such as wireless sensor networks and communication devices by eliminating the dependency of batteries, which are of limited lifespans thus require cumbersome replacements. Available energy sources surrounding the electronic systems include solar energy, mechanical vibrations, electromagnetic radiation, thermal gradients and wind flows. These energy sources can be harnessed and converted into electricity as a substitute or backup power supply. For example, researchers have recently studied energy harvesting from mechanical vibrations for applications in rail tracks or roadways [1–3].

In the past years, considerable research efforts have been devoted to piezoelectric energy harvesting from base vibrations [4,5]. A major challenge for traditional linear resonant harvesters is that when the excitation frequency slightly deviates from the resonance, a dramatic decrease in the power generation efficiency occurs. Various techniques have been proposed in order to broaden the operational frequency bandwidth and improve the energy conversion efficiency of base vibration energy harvesters. These efforts include developing energy harvesters with close multiple modes [6,7], introducing nonlinearity by adding magnets to achieve monostable, bistable or tristable responses [4,5,8,13], employing frequency up-conversion technique [14–16], etc.

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https://doi.org/10.1016/j.apenergy.2017.12.042
Received 30 September 2017; Received in revised form 21 November 2017; Accepted 6 December 2017
0306-2619/

Zhou et al. [10] theoretically and experimentally investigated a tristable piezoelectric energy harvester, which was shown to pass easily the potential wells to achieve wide bandwidth with high energy output compared to a bistable energy harvester with a deeper potential well. Fu and Yeatman [16] recently reported a methodology to harness low frequency rotational energy by utilizing the frequency up-conversion technique, which was achieved by the magnetic plucking between the tip magnet at the piezoelectric tip and the rotating magnet on a revolving host. Besides the above techniques, impact-based energy harvesters have also been studied by employing mechanical stoppers to achieve piecewise-linearity with bilinear stiffness which extends the bandwidth over resonance [17–21]. Soliman et al. [17] proposed the first study on an electromagnetic energy harvester with piecewise-linear restoring force by employing a mechanical stopper. A broadened upsweep bandwidth which was 240% wider than that of the linear counterpart was experimentally demonstrated. Liu et al. [18,19] reported broadband MEMS piezoelectric energy harvesters using both one-sided and two-sided mechanical stoppers. Two mechanical stoppers were employed as synchronous mechanical switches of the optimized synchronous electric charge extraction circuit for a piezoelectric energy harvester in the work of Wu et al. [20]. Recently, Wang et al. [21] reported a compact piezoelectric vibration energy harvester with tunable resonance and broadened bandwidth by integrating a suspended piezoelectric spring-plate with a top stopper-plate, which achieved multiple nonlinear effects such as duffing-spring effect, impact effect, preload effect, and air elastic effect.

Besides the pre-existing mechanical vibrations, the bulky kinetic energy in the ambient wind flows provides an alternative on-site power source [22]. When a properly supported structure is subjected to wind flows, aeroelastic instabilities will give rise to large amplitude limit cycle oscillations, and the vibration energy can be further converted into electricity via specific electromechanical transduction mechanisms such as piezoelectric effect. Researchers have employed various aeroelastic instabilities to harness the kinetic energy in wind flows, including vortex-induced vibration (VIV) [23–27], galloping [28–35], aeroelastic flutter [36–39], etc. Using a VIV-based energy harvester with a piezoelectric cantilevered cylinder, Akaydin et al. [23] obtained a peak power of around 0.1 mW at a wind speed of 1.192 m/s. The driving mechanisms of VIV energy harvesting was subsequently investigated by Goushcha et al. [24] using particle image velocimetry. Galloping occurs to flexibly supported bluff bodies with certain cross-section geometries of which the aerodynamic coefficients satisfy the Den Hartog criterion [40]. With a galloping piezoelectric energy harvester with a square-sectioned bluff body, a peak power of 8.4 mW was achieved at a wind speed of 8 m/s by Zhao et al. [32]. Modal convergence flutter energy harvesters using a cantilevered airfoil with coupled torsion and bending motions were studied by Bryant and Garcia [36] and Wu et al. [39]. Other types of flutter energy harvesters were also reported, such as the flutter energy harvester with an inverted piezoelectric flag recently proposed by Orrego et al. [38], and the electromagnetic energy harvester exploiting the cross flow flutter of a flexible belt proposed by Aquino et al. [37]. Studies on energy harvesting based on wake galloping with paralleled cylinders [41] and turbulence-induced vibrations with piezoelectric grass [42] were also reported. Moreover, efforts have been devoted to enhancing the wind energy harvesting performance from the mechanical aspect with modified structural configurations [31,33–35] and the circuit aspect with optimized power extraction interface [43–46]. For example, Zhao and Yang [34,35] proposed an effective method for aeroelastic energy harvesting enhancement by adding a beam stiffener as an electromechanical coupling amplifier, which was demonstrated to boost the power generation for all three types of energy harvesters based on galloping, VIV and airfoil flutter. Enhanced galloping energy harvesting was also investigated by Zhao et al. [44] using a synchronized charge extraction interface and by Zhao et al. [43] employing a synchronized switching harvesting on inductor interface. Other developments in small-scale wind energy harvesting are available in the recent review works [45–48]. Recently, triboelectric nanogenerators as a new group of energy harvesters have been enthusiastically studied for harnessing ambient mechanical energy from vibrations or airflows based on the coupling of triboelectrification and electrostatic induction. Triboelectric charges and potential differences are induced during the periodic physical contact and separation between two materials with distinct electron affinity. It has been shown to be a cost-effective and robust technique for energy harvesting. Interested readers are referred to the work of Zhu et al. [49], Ahmed et al. [50], Li et al. [51] and Phan et al. [52] for more details.

However, all the above mentioned studies on kinetic energy harvesting have considered only one type of energy source, either pre-existing base vibrations or wind flows. There are many circumstances where wind flows and base vibrations are coexisting, such as on the heavily travelled bridges, subway tunnels, ships, aircrafts, supporting structures of offshore infrastructures, and numerous buoys in the ocean. These two types of energy sources can be simultaneously harvested to power the sensors or other microelectronic de vices. Recently, some researchers have investigated concurrent wind and vibration energy harvesting with an aeroelastic energy harvester [53–57]. It was found by Bibo and Daqaq [53,54] that for a flutter energy harvester under combined aerodynamic and base vibratory excitations, when the wind speed was below the flutter speed, the flow amplified the output power from base excitations, while beyond the flutter speed, enhanced power generation was achieved for base excitation frequencies very close to the resonance. Similar phenomenon was also observed for a VIV energy harvester [55] and for a galloping energy harvester [56,57] under concurrent wind flows and base vibrations. However, a major problem with these traditional aeroelastic energy harvesters is that they can effectively harness energy from the combined excitations only around the harvesters' fundamental frequencies. There is only a narrow bandwidth around the resonance where the two energy sources can supplement each other. This is due to coexistence of two different frequencies resulting from the two types of excitations, making the harvester undergo quasi-periodic oscillations if the base vibration frequency deviates from the resonance. As a result, the peak displacement amplitude is high in a very wide frequency range, yet the effectively harvested average power is low except around the resonance. Nevertheless, while various techniques have been proposed to enhance energy harvesting from pure base vibrations and pure wind flows, performance enhancement of concurrent base vibration and wind energy harvesting has received far less attention. A series of complex mutual coupling behaviors exist in the traditional linear aeroelastic energy harvester, that is, the aeroelectromechanical coupling between the flow, structure, piezoelectric transducer and electric components. Under combined loadings, the responses are further complicated by the interaction between the coexisting base excitation frequency and aerodynamic forcing frequency. Introducing the broadband techniques for base vibration energy harvesting into the concurrent energy harvesting system will bring more complex coupling behaviors and interactions. Therefore, although broadband concurrent base vibration and wind energy harvesting is highly demanded, there is very little effort devoted into this issue.

To fill this gap, in this paper, we propose a novel design of energy harvester to concurrently harvest energy from base vibrations and wind flows with a broadened bandwidth. The device is designed and fabricated by adding a mechanical stopper to a linear galloping piezoelectric energy harvesting system. The proposed system offers several advantages. The quasi-periodic oscillations are converted to periodic vibration by the introduced mechanical stopper which forces the two excitation frequencies from wind and base vibration to lock into each other. Broadened bandwidth for effective concurrent energy harvesting is thus achieved. At the same time, the peak beam deflections are slightly mitigated and fully utilized for power conversion. The proposed design of integrating an aeroelastic energy harvester with a mechanical