

Modeling and experiment of a broadband energy harvester for concurrent energy harvesting from base vibrations and wind flows

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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 the resonance frequency. The proposed energy harvester consists of a D-shape-sectioned bluff body attached to a piezoelectric cantilever, and a mechanical stopper fixed at the bottom of the cantilever to introduce frequency up-conversion through impact with the bluff body. The experimental results show that at the stopper-harvester distance of 19.5mm, the proposed harvester effectively harnesses energy from both vibration and wind from 17.3Hz to 19.1Hz with a power level from 3.0mW to 3.8mW at the wind speed of 5.5m/s and the base acceleration of 0.5g.

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 by eliminating the dependency of batteries which are with limited lifespans and require cumbersome replacements. Available energy sources surrounding the electronic systems include solar energy, mechanical vibrations, electromagnetic radiation, thermal gradients and wind flows. Considerable research efforts have been devoted to piezoelectric energy harvesting from base vibrations with various techniques to broaden the operational frequency bandwidth and improve the energy conversion efficiency (Liu et al., 2011; Zhou et al., 2013; Harne and Wang, 2013; Yang and Zu, 2016). These efforts include developing energy harvesters with close multiple modes, introducing nonlinearity, such as stiffness nonlinearity, to achieve monostability, bistability or tristability, employing frequency up-conversion technique, and so on. Besides the pre-existing mechanical vibrations, the bulky kinetic energy in

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the ambient wind flows provides an alternative on-site power source. Researchers have employed various aeroelastic instabilities to harness the kinetic energy in wind flows, including vortex-induced vibration (VIV) (Akaydin et al., 2012), galloping (Sirohi and Mahadik, 2011; Zhao et al., 2014; Zhao and Yang, 2015), aeroelastic flutter (Bryant and Garcia, 2011), wake galloping (Abdelkefi et al., 2013), and turbulence-induced vibration (Hobeck and Inman, 2014).

Most studies in the literature have considered one type of energy source, either pre-existing base vibrations or wind flows. However, there are many circumstances where wind flows and base vibrations are coexisting, such as on the heavily travelled bridges, ships, aircrafts, supporting structures of offshore infrastructures, and the numerous buoys in the ocean. These two types of energy sources can be simultaneously harvested to power the sensors or other microelectronic devices. Recently, concurrent wind and vibration energy harvesting has been studied with a flutter energy harvester (Bibo and Daqaq, 2013a; 2013b), with a VIV energy harvester (Dai et al., 2014), and with a galloping energy harvester (Yan et al., 2014; Bibo et al., 2015). However, a major problem with these traditional energy harvesters is that they can only effectively harness energy from the combined excitations around the harvesters' fundamental frequencies. There is only a narrow bandwidth around the resonance where the two energy sources can efficiently lock in and 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 resonance.

In this paper, we propose a novel broadband energy harvester to concurrently harvest energy from base vibrations and wind flows based on galloping. By utilizing a mechanical stopper, the quasi-periodic oscillations will be converted to periodic vibrations when the base frequency deviates from resonance. The bandwidth for effectively harvesting energy from both vibration and wind is greatly widened.

2. PROPOSED DEVICE CONFIGURATION

The configuration of the proposed broadband energy harvester for concurrent base vibration and wind energy harvesting is shown in Fig. 1. A piezoelectric element is bonded to a cantilever near its root area. A D-shape-sectioned bluff body is attached to the free end of the cantilever to induce the wind-induced galloping instability. The flat surface is adjusted to be facing the wind flow. Another cantilever is fixed at a certain distance above the cantilever as a mechanical stopper. An energy harvesting interface circuit is connected across the electrodes of the piezoelectric element to further transfer the generated electrical charge, which is resulted from the piezoelectric effect during the alternating deformation of the energy harvester.

The resonance frequency of the stopper is chosen to be much higher than the energy harvester. When the oscillation amplitude of the energy harvester is sufficiently

high, the bluff body will impact with the stopper, resulting in a sudden increase in the effective stiffness (Liu et al., 2011). Such piecewise linear stiffness brings an extension of the resonance to a wider range of frequencies, within which the harvester can effectively harness the concurrent energy from both base vibration and wind flow. The stopper cantilever will oscillate at its own high resonance frequency when the bluff body departs from the contact in each cycle, achieving a frequency up-conversion. If a piezoelectric element is bonded to the root area of the stopper, this part of strain energy can be further harnessed and transferred to electricity. In this study, we focus on the power generation performance of the galloping energy harvester without adding piezoelectric materials on the stopper.

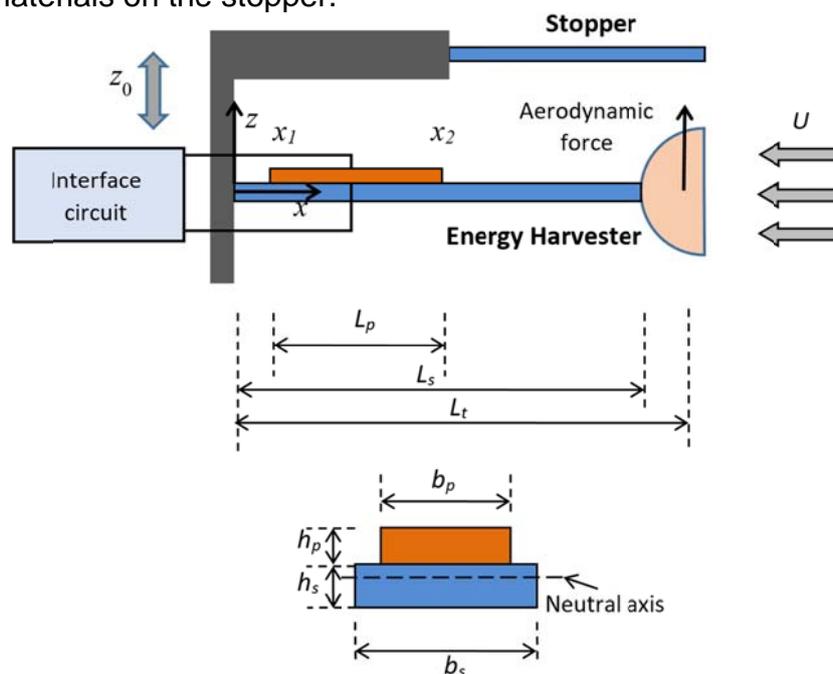


Fig. 1 Configuration of the proposed broadband energy harvester for concurrent base vibration and wind energy harvesting

3. AERO-ELECTRO-MECHANICAL MODEL

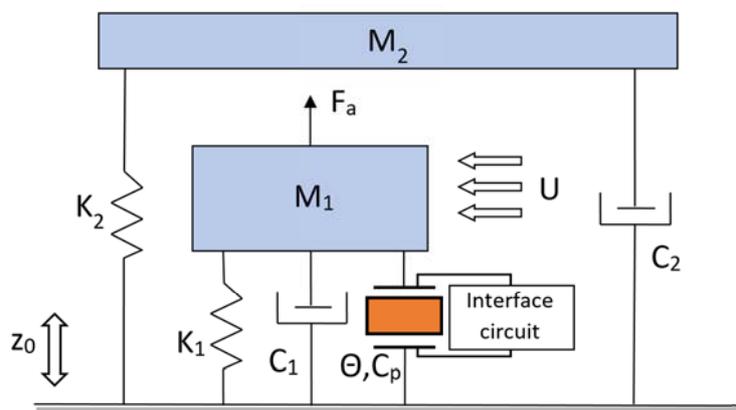


Fig. 2 Schematic of the lumped parameter model

The analytical model for the proposed energy harvesting system is established by considering the aero-electro-mechanical coupling behaviors between the structure, piezoelectric material and airflow. A lumped parameter model is established of which the schematic is shown in Fig. 2. The electromechanically coupled equation of motion of the system is given by

$$\begin{cases} M_1\ddot{u}_1 + C_1\dot{u}_1 + K_1u_1 + \Theta V = F_a - f_1M_1\ddot{z}_0 \\ M_2\ddot{u}_2 + C_2\dot{u}_2 + K_2u_2 = -f_2M_2\ddot{z}_0 \end{cases} \quad (u_1 < D) \quad (1)$$

$$\begin{cases} (M_1 + M_2)\ddot{u}_1 + (C_1 + C_2)\dot{u}_1 + (K_1 + K_2)u_1 - K_2D + \Theta V = F_a - (f_1M_1 + f_2M_2)\ddot{z}_0 \\ u_2 = u_1 - D \end{cases} \quad (u_1 \geq D) \quad (2)$$

where M_1 , C_1 and K_1 are, respectively, the effective lumped mass, damping and stiffness of the energy harvester; M_2 , C_2 and K_2 are, respectively, the effective lumped mass, damping and stiffness of the stopper; f_1 and f_2 are the correction factors for the forcing function for the energy harvester and the stopper, respectively (Erturk and Inman, 2008); θ is the electromechanical coupling coefficient; V is the generated voltage across the piezoelectric element; F_a is the aerodynamic force for wind-induced galloping instability; D is the distance between M_1 and M_2 ; and u_1 , u_2 and z_0 are, respectively, the relative vibratory motions of M_1 and M_2 to the base, and the external base motion. It should be noted that in order to ensure the resonance frequency of the stopper to be much higher than that of the energy harvester, it is chosen that M_1 is much larger than M_2 , while K_1 is much smaller than K_2 . The circuit model with coupling is given by

$$I + C_p \dot{V} - \Theta \dot{x}_1 = 0 \quad (3)$$

where I is the output current, and C_p is the piezoelectric capacitance.

The aerodynamic model for F_a is established based on the quasi-steady hypothesis (Païdoussis et al., 2010), given by

$$F_a = \frac{1}{2} \rho h L U^2 \sum_{i=1}^3 \left[A_i \left(\frac{\dot{u}_1 + \dot{z}_0}{U} + \beta u_1 \right) \right]^i \quad (4)$$

where ρ , h , L and A_i are the air density, frontal height and length of the bluff body, and empirical aerodynamic coefficients, respectively; U is the wind speed; and β is the ratio of the rotation angle to the vertical translation of at the bluff body, which is calculated by $\beta = \phi'(L_t) / \phi(L_t)$ with $\phi'(L_t)$ and $\phi(L_t)$ being the slope and amplitude of the mass normalized fundamental mode shape of the energy harvester at the position of the bluff body center, i.e., at $x=L_t$. The oscillation frequency under galloping is always close to the fundamental frequency of the energy harvester, which has been validated experimentally in previous studies (Zhao et al., 2013).

4. EXPERIMENTAL SETUP

Table 1. Properties of cantilever and piezoelectric material of energy harvester

Properties	Cantilever substrate	Piezoelectric element
Length (mm)	135.5	28
Width (mm)	20	14
Thickness (mm)	0.6	0.3
Mass Density (kg m^{-3})	2700	5440
Young's Modulus (GPa)	69	30.336
Capacitance (nF)	--	25.7
Piezoelectric constant (pm/V)	--	-170

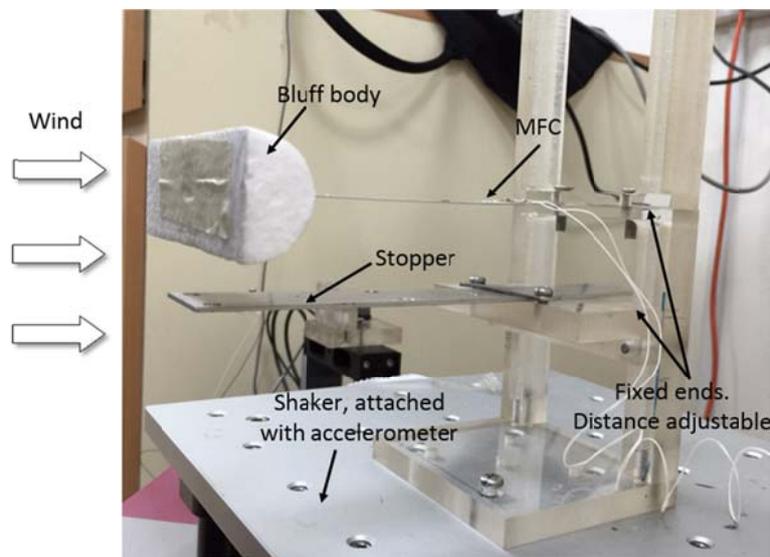


Fig. 3 Schematic of broadband energy harvester for concurrent vibration and wind energy harvesting

Experiment with a fabricated prototype is carried out to investigate the performance of the proposed design and verify the analytical model. The experimental setup is shown in **Fig. 3**. The energy harvester consists of an aluminum cantilever of dimension $135.5 \times 20 \times 0.6 \text{ mm}^3$, with a D-section-shaped tip body of dimension $107 \times 32 \times 16 \text{ mm}^3$ made of foam being connected at the free end as the bluff body. The weight of the bluff body is 2.0g. Near the fixed end of the cantilever, a piece of piezoelectric sheet (MFC M2814-P2 from Smart Materials Corp.) is bonded to its top surface to convert the strain energy to electrical charges. The properties of the cantilever substrate and the piezoelectric element are listed in **Table 1**. An aluminum cantilever is fixed at the same frame with the energy harvester as the mechanical stopper. The width and thickness of the stopper are 40mm and 1mm, respectively. The stopper-harvester distance D is 19.5mm. The prototype is then mounted to a vibration shaker and placed in front of an axial fan which provide the external base vibration and wind flow. The base vibration acceleration is monitored by an accelerometer. The base vibration frequency and amplitude are controlled by a function generator and an

amplifier. The wind speed is measured using a hotwire anemometer. The short circuit damping factors of the energy harvester and the stopper are measured using logarithmic decrement technique to be 0.011 and 0.03, respectively. The interface circuit is simplified to be with a resistive load R only, thus in Eq. (3), I is calculated by $I=V/R$. The generated voltage V is measured by the NI 9229 DAQ module (National Instruments) together with LabVIEW.

5. RESULTLS AND DISCUSSION

The experimental and predicted results for the variation of average power as a function of base vibration frequency at a constant wind speed of 5.5m/s and different acceleration levels are shown in Fig. 4. When the base vibration frequency is away from the resonance, the average power is almost equal to that from pure galloping, which means that the base vibration energy is barely harnessed by the energy harvester. In this range, the response of energy harvester is quasi-periodic due to the interaction of the two different frequencies. As the base vibration frequency sweeps up to approach the harvester's fundamental frequency, the power first decreases, then increases sharply until the bluff body impacts the stopper. The harvested power gradually increases over a wide range of frequency, achieving a broadened bandwidth where both the base vibration energy and wind energy are effectively harnessed. As the base vibration frequency further sweeps up, the energy harvester stops impacting the stopper and the harvested power drops to the level from pure galloping. The bandwidth of effective concurrent energy harvesting increases with the base vibration acceleration. At a base acceleration of 0.5g, the power extracted from the concurrent excitations increases from 3.0mW at 17.3Hz to 3.8mW at 19.1Hz. Overall, reasonable agreement is obtained between the experimental and theoretically predicted results.

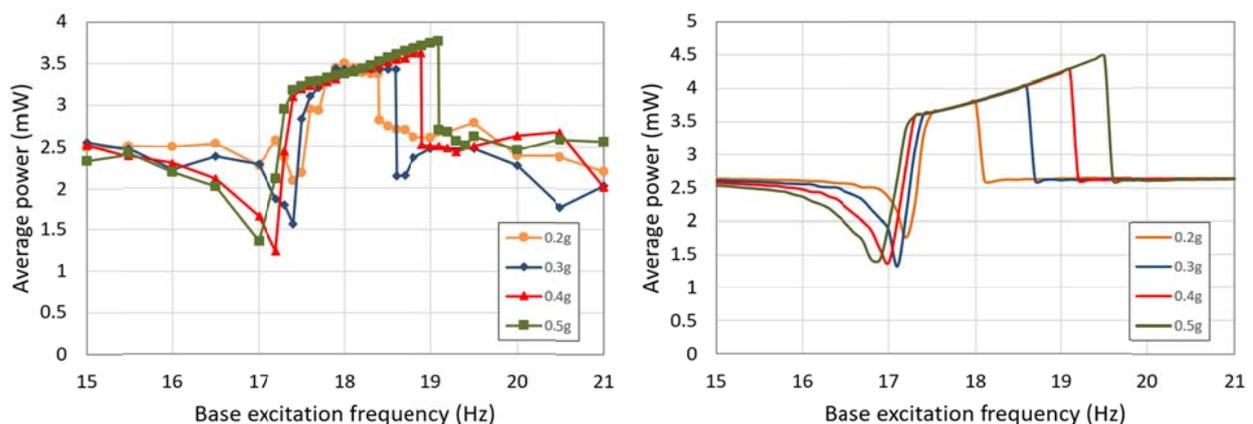


Fig. 4 Variation of average power with base vibration frequency at a constant wind speed of 5.5m/s and different acceleration levels: (a) experiment, (b) model prediction

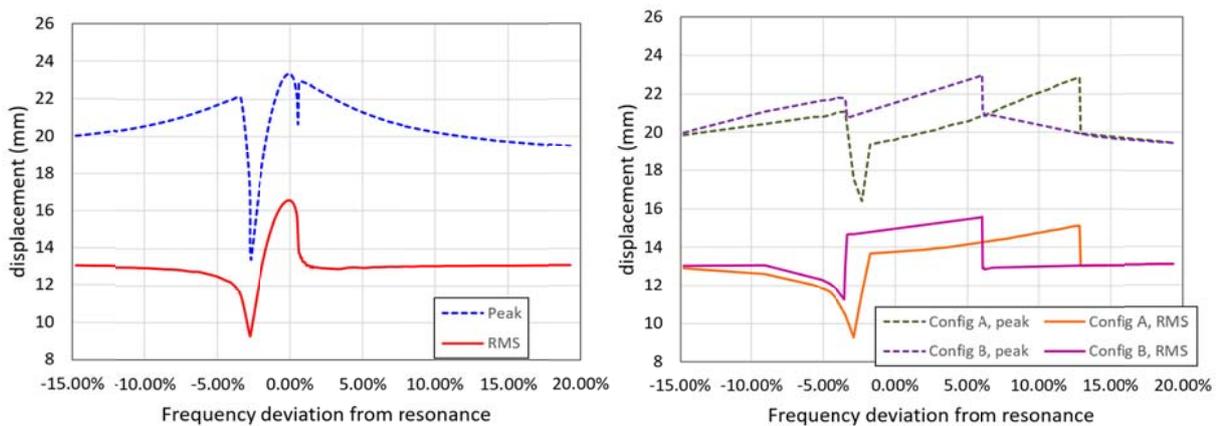


Fig. 5 Variation of displacement of the bluff body with frequency deviation from resonance: (a) conventional energy harvester, (b) proposed energy harvester incorporating a stopper

To further compare the performance of the proposed design with that of the conventional linear energy harvester, the predicted variations of the displacement of the bluff body with the frequency deviation from resonance for the conventional energy harvester and the proposed energy harvester with a stopper are shown in Fig. 5. Two stopper configurations are considered. For configuration A, it is chosen that $D=20\text{mm}$, and $M_2=8.0\text{g}$; while for configuration B, it is chosen that $D=19\text{mm}$ and $M_2=2.9\text{g}$. For both configuration, K_2 is 2956.53N/m . The base acceleration is fixed at 0.3g , and the wind speed is fixed at 6m/s . It is shown from Fig. 5(a) that for the conventional energy harvester, when the base vibration frequency slightly deviates to the right of the resonance, the root mean square (RMS) displacement of the bluff body quickly drops to the value from pure galloping. This will make the average power quickly drops to the level from pure galloping as well. However, the peak displacement stays high in a much wider range of frequency. The high peak displacement is not fully utilized in such a case. Moreover, high peak displacement is undesired in energy harvesting since it will cause fatigue problems. By incorporating a stopper, it is shown in Fig. 5(b) that the bandwidth of RMS displacement is greatly broadened. Moreover, the peak displacement is reduced in most range within the bandwidth, which beneficially protects the energy harvester from large amplitude vibration.

6. CONCLUSION

In this paper, a novel broadband energy harvester which concurrently harvest energy from base vibrations and wind flows is proposed by utilizing a mechanical stopper. The quasi-periodic oscillations are converted to periodic vibrations through impact of the bluff body with the stopper. The bandwidth where both vibration energy and wind energy are effectively harnessed is greatly widened. An aero-electro-mechanically coupled model is established. Experiment is carried out with a fabricated prototype. At a wind speed of 5.5m/s and a base acceleration of 0.5g , the proposed harvester can effectively harness energy from both vibration and wind from 17.3Hz to 19.1Hz with a power level from 3.0mW to 3.8mW . Moreover, in most range within the

broadened bandwidth, the peak displacement of the bluff body is beneficially reduced to protect the energy harvester from large amplitude vibration.

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