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LETTER

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Letter

A wind-induced negative damping method to achieve high-energy orbit of a nonlinear vibration energy harvester

Chunbo Lan[1], **Guobiao Hu**[2], **Yabin Liao**[3] and **Weiyang Qin**[4]

[1] State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, People's Republic of China
[2] Department of Mechanical Engineering, The University of Auckland, Auckland, New Zealand
[3] Department of Mechanical Engineering Technology, Penn State Erie, The Behrend College, Erie, PA, United States of America
[4] Department of Engineering Mechanics, Northwestern Polytechnical University, Xi'an, People's Republic of China

E-mail: chunbolan@nuaa.edu.cn and ghu211@aucklanduni.ac.nz

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Abstract

Maintaining high-energy orbit oscillation of a nonlinear vibration energy harvester (VEH) is the key to achieve high-performance, broadband energy harvesting. Conventional orbit-jump strategies, such as mechanical modulation or electrical control methods, need to consume the limited harvested energy and may unfavourably reduce the energy harvesting efficiency. To avoid the undesired energy consumption, we focus on utilizing the overlooked wind energy to assist a nonlinear VEH to attain the preferred high-energy orbit. The novel orbit-jump method proposed in this letter is based on the wind-induced negative damping mechanism and the resultant self-excited behaviour. Both numerical simulation and experimental results validate the feasibility of the proposed method to efficiently trigger the high-energy orbit oscillations of a nonlinear VEH. Moreover, the required wind energy to achieve self-excited oscillation for different excitation frequencies and acceleration levels, is quite stable and can be easily satisfied, which demonstrates good robustness for practical applications.

Keywords: nonlinear energy harvesting, high-energy orbit, wind energy, galloping, piezoelectric

(Some figures may appear in colour only in the online journal)

1. Introduction

During the past few decades, vibration energy harvesting technology has been extensively explored as a promising way to provide sustainable power supply for small devices [1–3]. Since the ubiquitous environmental vibration energy often spreads over a broad range of frequencies, nonlinearity has been introduced into energy harvesters to enlarge the operational bandwidth and improve the output power [4–6]. Typical nonlinear designs include Duffing-type vibration energy harvesters (VEHs) which can be furtherly classified into monostable/bistable and multi-stable VEHs [7–10], impact-based VEHs [11, 12], internal resonance based VEHs [13, 14], magnetically coupled piezoelectric beams [15, 16], etc.

Through in-depth investigations over the last decade, maintaining high-energy orbit of nonlinear VEHs has been gradually realized as one of the most critical problems and has attracted lots of research interests. Various strategies using mechanical [17–19] or electrical [20–24] methods, have been proposed to obtain the high-energy orbit. Erturk and Inman [17] experimentally demonstrated that using an impact-induced impulse could effectively transform the intra-well oscillation into the inter-well oscillation of a bistable VEH. Yu *et al* [18] proposed a theoretical method based on the stiffness/mass temporary modulation mechanism. Huang *et al* [19] actively adjusted the buckling level by using a piezoelectric actuator to attain the high-energy orbits for both monostable and bistable VEHs. With regard to the electrical methods, Sebald *et al* [20] proposed a fast burst perturbation method for a monostable VEH. Results showed that such a perturbation opened a new opportunity for the nonlinear VEH to jump to the high-energy orbit. Masuda *et al* [21] developed a self-excited control method by using a negative resistance circuit to maintain the high-energy orbit of a monostable electromagnetic VEH. Lan *et al* [22] further pointed out that a high voltage is required to improve the reliability of the voltage perturbation method. To reduce the power cost of orbit jump, two novel methods, namely a load perturbation method and a synchronized-switch stiffness control technique have been proposed by Wang and Liao [23] and Yan *et al* [24], respectively.

Among the aforementioned works, the mechanical methods need an additional mechanical force to generate the impact or modulate the effective mass or stiffness of the system; while the electrical methods require to consume a certain amount of electrical energy which may even contrarily reduce the energy harvesting efficiency. To overcome these drawbacks, there is an urgent need for a novel orbit jump method without consuming the harvested vibration energy. In numerous circumstances, such as aircrafts, bridges, railway, offshore structures and vehicles, both wind and base vibration energy coexist simultaneously. Therefore, we are motivated to employ the overlooked wind energy as a readily existed free source to help the nonlinear VEH attain high-energy orbit. In the past few years, some efforts have been devoted to concurrent energy harvesting (harvesting wind and vibration energy at the same time). Bibo *et al* [25] developed an aero-electromechanical model of piezoelectric cantilever energy harvester under combined galloping and base excitations. The corresponding nonlinear performance was studied by Abdelkefi and Abdelkefi [26] and Yan and Abdelkefi [27]. More recently, nonlinearity has been introduced into concurrent energy harvesting, such as the monostable/bistable GPEH proposed by Bibo *et al* [28] and impact-based GPEH proposed by Zhao [29]. However, all these mentioned studies mainly focus on the energy harvesting performance of the system. An important aspect, how exactly the wind energy affects the physics and dynamics of the nonlinear energy harvester, did not receive much attention. In addition, utilizing the overlooked wind energy as an orbit-jump method has not been reported yet.

Galloping is a wind-induced vibration caused by the aerodynamic force exerted on a structure. The aerodynamic force of galloping is a function of the structural vibration velocity and effectively acts as an aeroelastic damping whose linear component is negative [25–30]. When the wind speed exceeds the cut-in wind speed, the total effective damping of the whole system will become negative, resulting in a self-excited oscillation of the mechanical system. This self-excited oscillation offers another promising way of attaining high-energy orbit of a nonlinear VEH by destabilizing the low-energy orbit of the nonlinear VEH, similar to the mechanism of the negative resistance method. Hence, a novel orbit-jump method is proposed in this letter by exploiting the wind-induced negative damping to achieve orbit-jump.

2. System description and experimental setup

The energy harvester studied in this letter is a monostable piezoelectric energy harvester. To introduce the aerodynamic force into monostable VEH, the tip mass is replaced by a bluff body. Figure 1 depicts the prototype of the proposed VEH and the experimental setups. To obtain the aerodynamic force of galloping, the conventional nonlinear VEH is modified by adding a D-shaped bluff body at the free end of the cantilever beam (figure 1(a)). The nonlinearity is produced by the repulsive magnetic interaction between the magnet attached near the tip of the cantilever beam and the magnet installed on the fixture. A piezoelectric transducer mounted near the fixed end is shunted to an external load resistance. The wind is generated by a fan and an anemometer is used to measure the wind speed. The cantilever beam is mounted on a 3D-printed fixture, and the whole system is installed to a 500 N electromagnetic shaker (E-JZK-50) that can simulate a horizontal base excitation. The vibration controller (VT-9008) together with a feedback accelerometer forms a closed loop to ensure the base excitation at the desired acceleration level. The excitation frequency can be adjusted through the software in the PC. The output voltage of the piezoelectric transducer is measured and recorded by a DATA acquisition system (DH5922D) at a sampling frequency of 2000 Hz.

The aero-electro-mechanical model of the proposed VEH can be formulated as:

$$\begin{cases} m_1\ddot{x} + \left(c_1 + c_2x^2\right)\dot{x} + k_1x + F_{\mathrm{n}} - \theta V = F_{\mathrm{a}} - m_1\ddot{z} \\ C_{\mathrm{p}}\dot{V} + \dfrac{V}{R} + \theta\dot{x} = 0 \end{cases} \tag{1}$$

where, $m_1 = 0.0089$ kg, and $k_1 = 24.11$ N m^{-1}, are the effective mass and stiffness of the VEH, respectively. The effective damping is modelled by the combination of a linear and a nonlinear terms: the linear damping term $c_1 = 2\zeta_1\omega_1 m_1$ is determined by $\zeta_1 = 0.00425$, and the nonlinear term is in proportion to $c_2 = 60$ following [31]; $\theta = 24.75$ μN V^{-1} is the electromechanical coupling coefficient; $C_{\mathrm{p}} = 5.1$ nF is the capacitance of the piezoelectric transducer; x is the displacement relative to the base; z is the displacement of the base excitation; V is the voltage across the electrical load resistance $R = 110$ kΩ; F_{a} is the vertical component of the aerodynamic force acting on the bluff body; and $F_{\mathrm{n}} = k_2x + k_3x^3$ is the nonlinear magnetic force, where $k_2 = -11.0537$ Nm^{-1} and $k_3 = 1.6254 \times 10^{-4}$ Nm^{-3}, respectively.

Under the quasi-steady assumption [30], the aerodynamic force F_{a} can be written as

$$F_{\mathrm{a}} = \frac{1}{2}\rho U^2 LD\left[s_1\frac{\dot{x}+\dot{z}}{U} - s_3\left(\frac{\dot{x}+\dot{z}}{U}\right)^3\right] \tag{2}$$

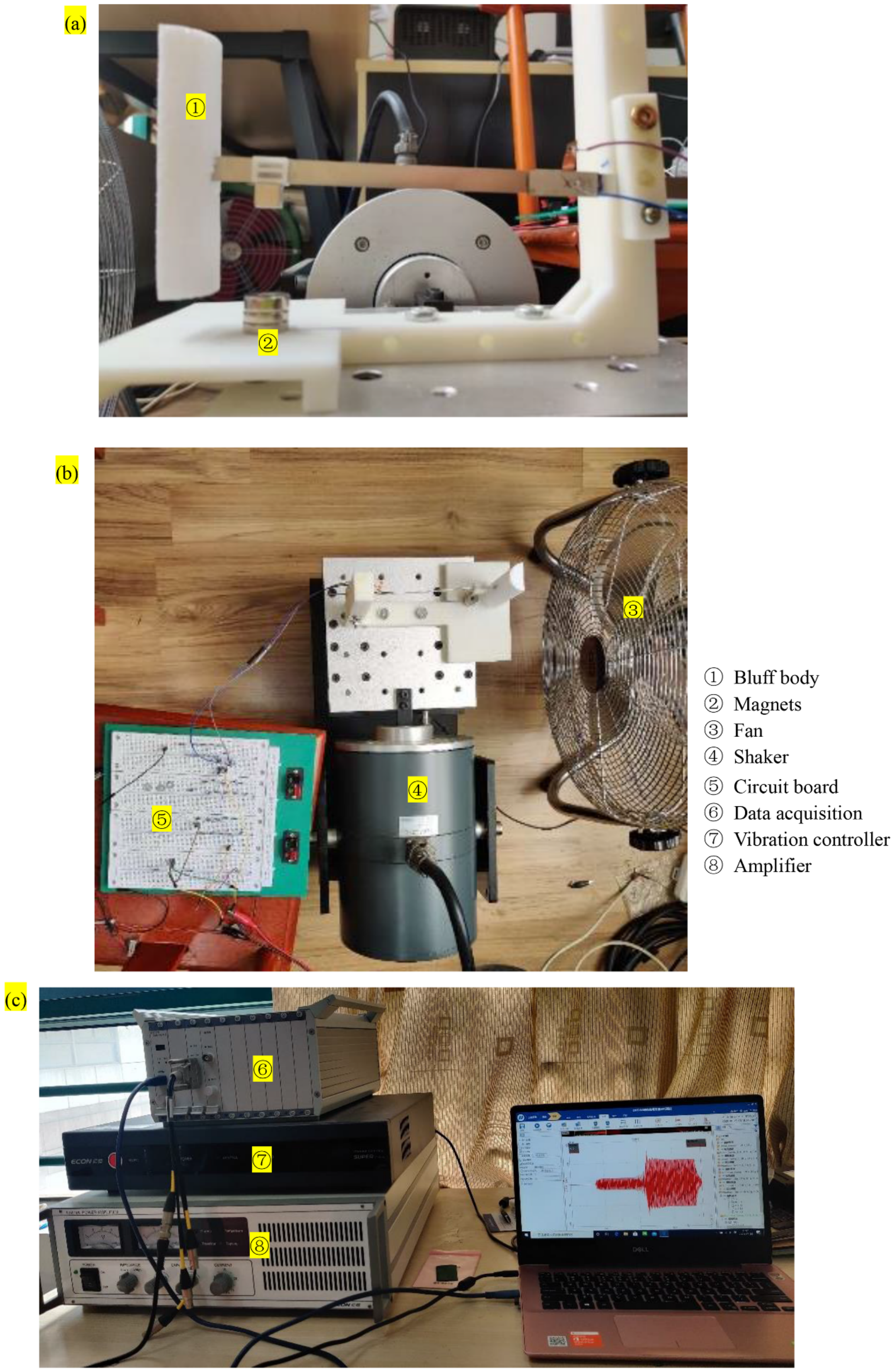

Figure 1. (a) The prototyped nonlinear VEH with a bluff body (b) installation diagram including a shaker to generate base excitation and a fan to produce wind load; (c) auxiliary facilities including the controller, the amplifier and the data acquisition system.

where $L = 107$ mm and $D = 32$ mm are the cross-flow length and width of the bluff body, respectively; $\rho = 1.293$ kg m^{-3} and U are the air density and wind speed, respectively; and $s_1 = 1.56$ and $s_3 = -6.9$ are the empirical linear and cubic coefficients of the transverse galloping force [29], respectively.

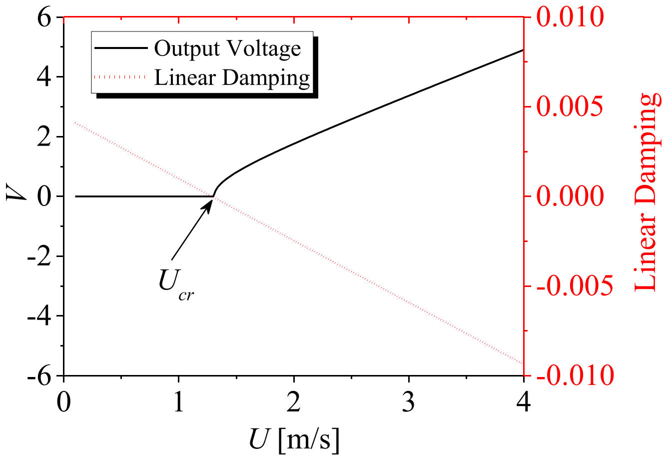

Figure 2. Output voltage amplitude (left *y*-axis) and effective system damping (right *y*-axis) versus the wind speed.

3. Conceptual illustration of galloping-based orbit-jump method

Equation (2) indicates that the aerodynamic force of galloping is analogous to a damping term in the mathematical form. Hence, the effect of wind on the overall system damping is first analysed. As shown in figure 2, the linear damping decreases with the increase of the wind speed and becomes negative when the wind speed is larger than the cut-in wind speed (U_{cr}). As the overall system damping becomes negative, the system will exhibit self-excited oscillation, i.e. galloping. Therefore, given a proper wind load, the system can be self-excited, which can be used to destabilize the low-energy orbit oscillation and provide an opportunity for the whole system to jump to the high-energy orbit.

Based on the wind-induced negative damping mechanism, a novel orbit jump method is proposed and illustrated in figure 3. In the initial state, the system oscillates on the low-energy orbit and the output voltage is very low. Subsequently, the wind speed is increased from zero to a certain level until the overall damping becomes negative and the system loses its stability, e.g. the self-excited oscillation occurs. After achieving the limit circle oscillation, the wind is removed by decreasing the wind speed to zero and the system motion converges to the high-energy orbit oscillation eventually. Note that in this proposed method, the wind is regarded as the action of a control strategy that is injected into the system to initiate and facilitate the orbit-jump process. After achieving the high-energy orbit, the entire system is excited by the base vibration only.

4. Numerical and experimental results

Before proceeding to the demonstration of the proposed orbit-jump method, efforts are devoted to determining the high-energy and low-energy orbits of the nonlinear VEH. Numerical simulations are performed based on the mathematical model (i.e. equation (1)) using Runge–Kutta methods, and experimental tests are conducted for validation. The system parameters used in the simulation are obtained from

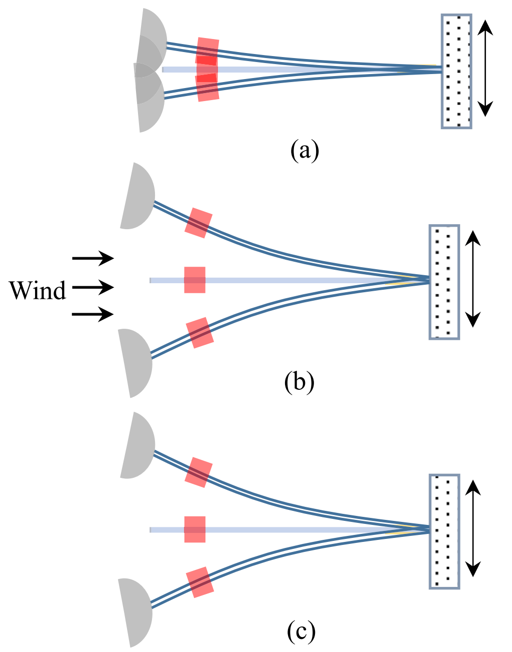

Figure 3. Mechanism illustration of the proposed orbit jump method: (a) low-energy orbit oscillation at the initial state, (b) apply wind load and the system undertakes self-excited oscillation, (c) remove the wind load and the system converges to the high-energy orbit oscillation.

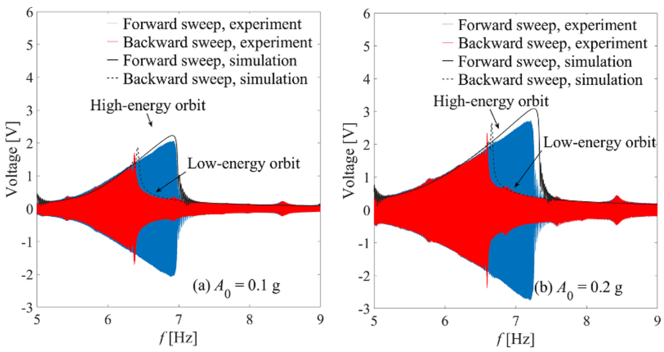

Figure 4. Numerical and experimental results of voltage responses of the nonlinear VEH under the forward and backward sweep excitation: (a) $A_0 = 0.1$g; (b) $A_0 = 0.2$g.

the experimental tests. Linear sweep tests are performed to identify the multi-solution range of the nonlinear VEH. The frequency sweep rate is set to be 1.2 Hz min^{-1} and the base acceleration is first set to $A_0 = 0.1$g then changed to $A_0 = 0.2$g, where g is the gravitational acceleration ($g = 9.8$ m s^{-2}).

Figure 4 shows the forward and backward sweep results from both numerical simulation and experiments. It is found that the numerical simulation and experimental results agree well with each other. According to the experimental results, when $A_0 = 0.1$g, the multi-solution range is [6.38–6.93] Hz. When the base excitation increases to $A_0 = 0.2$g, the multi-solution range becomes [6.59–7.19] Hz. Thus, it is learned that with the increase of the base acceleration, the multi-solution range moves towards higher frequencies and the corresponding bandwidth increases at the same time.

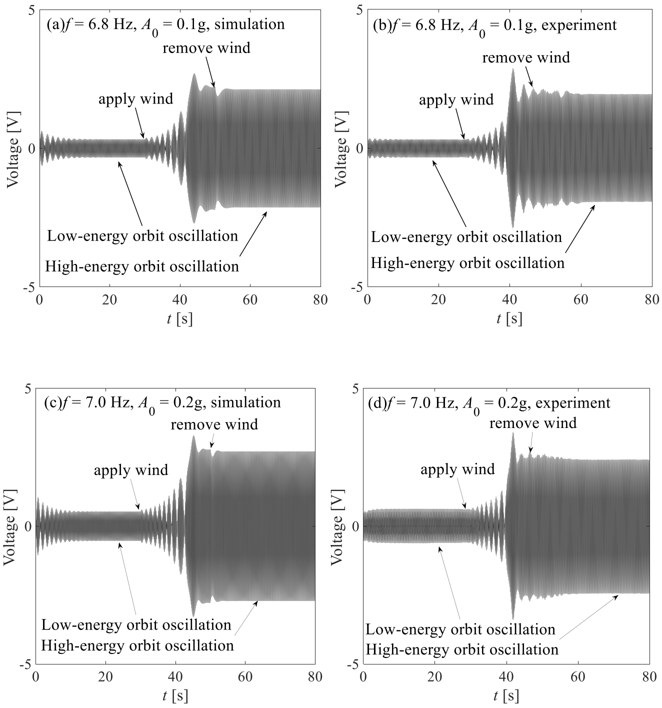

Figure 5. Time-history responses of voltage output from the nonlinear VEH with the proposed method when $f = 6.8$ Hz, $A_0 = 0.1$g (a) numerical results, (b) experimental results; and when $f = 7.0$ Hz, $A_0 = 0.2$g (c) numerical results, (d) experimental results.

Subsequently, the feasibility of the proposed orbit-jump method is explored. Setting the excitation as $A_0 = 0.1$g and $f = 6.8$ Hz to ensure the system operates within the multi-solution frequency range, the numerical and experimental results are depicted in figures 5(a) and (b), respectively. In the simulation, when $t < 30$ s, the system oscillates on the low-energy orbit and the output voltage is low at 0.329 V. The wind load ($U = 2.95$ m s^{-1}) is applied at $t = 30$ s and removed at $t = 50$ s. It is clearly noted that as the wind load is applied, the voltage response starts to increase dramatically and reaches a saturation value eventually, e.g. the limit circle oscillation. After removing the wind load, the system rapidly converges to the high-energy orbit with a large output voltage of 2.13 V. Meanwhile, the experimental results shown in figure 5(b) agree very well with the numerical predictions. It is clearly shown in figure 5(b) that the system undergoes a low-energy orbit oscillation at first. A self-excited oscillation is observed when the wind load ($U = 2.95$ m s^{-1}) is applied at $t = 27.5$ s. After the limit circle oscillation is reached, the wind load is removed at $t = 29.9$ s and the entire system motion converges to the high-energy orbit motion eventually. Based on the numerical simulation and experimental results, it is convinced that the proposed galloping-based orbit-jump method is feasible and effective for nonlinear VEHs to attain high-energy orbit oscillation.

Since the bandwidth of the high-energy orbit changes with the excitation level, to ascertain the applicability of the proposed galloping-based orbit-jump method when the excitation level changes, the same study is repeated by tuning A_0 to 0.2g and f to 7 Hz, while the other parameters are kept unchanged. It is worth noting that as shown in figure 4, this proposed method works more effectively when the excitation frequency is close to the jump-down frequency of the system, where the difference in voltage performance between the high and low-energy orbits is significant. The new frequency $f = 7$ Hz is selected because it falls within the multi-solution range for $A_0 = 0.2$g and close to the jump-down frequency.

The numerical and experimental results shown in figures 5(c) and (d), respectively, are in a good agreement. It is observed that, after applying the same wind load ($U = 2.95$ m s^{-1}), the self-excited oscillation takes place and the output voltage amplitude significantly increases. After removing the wind load, high-energy orbit oscillation is still maintained. From this experiment, it is confirmed that the proposed method works quite well even when the excitation level changes. In comparison with other orbit-jump methods, the proposed galloping-based method does not require to improve the control level when the excitation level increases. Moreover, even when f is close to the jump-down frequency, the proposed method still successfully stimulated the high-energy orbit oscillation, demonstrating good robustness to the variation of the excitation level and excitation frequency. With reference to equation (2), the explanation is that the required wind speed to attain negative damping is principally dependent on the system damping, rather than the excitation frequency nor the acceleration level. Therefore, the required wind speed to achieve negative damping and self-excited oscillation for different excitation frequencies and acceleration levels, is quite stable and can be easily satisfied.

5. Conclusions

In summary, this letter has proposed a novel orbit-jump method based on the wind-induced negative damping mechanism, to enhance the performance of nonlinear energy harvesters in environments where vibration and wind coexist. Both numerical simulations and experimental results indicate that the proposed method is efficient to trigger the high-energy orbit oscillation of nonlinear VEHs. Moreover, the required wind speed of this novel method is insensitive to the external excitation. Besides, the proposed method does not consume the harvested energy, making it more preferable and reliable than the conventional orbit-jump methods.

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ORCID iD

Chunbo Lan https://orcid.org/0000-0001-5959-0488

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