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Modeling and experiment of bistable two-degree-of-freedom energy harvester with magnetic coupling

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ABSTRACT

The operating bandwidth of energy harvesters is one main concern in vibration energy harvesting due to the random and time-varying nature of most vibration sources. Recent research efforts have been made to address this issue including exploiting multimodal structures and nonlinear dynamics. These ideas have yielded some exciting results to leverage the broadband performance. Hybrid configurations combining these ideas are expected to provide an even better operating bandwidth and yet to be studied. In this paper, a bistable two-degree-of-freedom (2-DOF) piezoelectric energy harvester (PEH) with magnetic coupling is proposed, in which a linear parasitic oscillator attached to the main energy harvesting beam is used to generate two resonant peaks and the magnetic coupling is used to generate nonlinear dynamics, thus to achieve broadband electrical outputs. A nonlinear electromechanical model of the proposed harvester is established and the parametric study is conducted for various parasitic oscillator configurations. Experiment is subsequently performed to validate the theoretical analysis. The results indicate that nonlinear responses can appear at any of the two peaks or at both. One strong nonlinear peak in addition to a quasi-linear peak can be achieved by adequate adjustment of the parasitic oscillator. This is advantageous over the optimal linear 2-DOF PEH in terms of wider bandwidth thanks to the involved nonlinear dynamics. In addition, the load resistance has significant influence around the peak with strong nonlinear responses, resulting in evident peak shift. The best power output is accompanied with a shrunk bandwidth due to the peak shift.

1. Introduction

With the increase in the interest of self-sustained wireless sensor networks and portable electronic devices, harvesting vibration energy from ambient environments provides an exciting solution to resolve the costly and tedious battery replacement issue for these devices. Vibration energy can be converted into electricity via electrostatic mechanism, electromagnetic induction, or direct piezoelectric effect. Regardless of the vibration-to-electricity conversion mechanisms, conventional vibration energy harvesters are designed as linear one-degree-of-freedom (1-DOF) resonators, which are only efficient near resonance. The random and time-varying nature of most practical vibration sources, however, demands the vibration energy harvesters to work in a wide operating bandwidth.

In order to overcome the bandwidth constraint of the conventional 1-DOF energy harvesters, researchers have considered the use of the linear multimodal energy harvesting structures to achieve two or more resonant frequencies for wider bandwidth. Multimodal

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structures were extensively studied in the literature, such as L-shaped beam-mass structure harvester [1], 2-DOF "cut-out" beam harvester [2], dual mass or multi-mass harvesters [3–5], energy harvesters with dynamic magnifiers or dynamic oscillators [6–9], and 2-DOF hybrid piezoelectric-electromagnetic energy harvester [10]. Other designs including the plate structure [11] and fractal-inspired structure [12] were also proposed for wideband energy harvesting. It has been demonstrated that with properly selected parameters, it is possible to achieve two or more close resonant peaks with significant output at each peak.

Exploring nonlinear dynamics is another way for broadband energy harvesting. The nonlinearity can be introduced by magnetic interaction or geometric nonlinearity, such as buckled beams. Monostable [13,14] and bistable [15–19] structures were investigated extensively after the nonlinear dynamics concept was first introduced in energy harvesting area. Structures and magnetic interaction are easy to implement and tune to achieve monostability and bistability. The superior performances of these structures have been demonstrated theoretically and experimentally, under both harmonic and random excitations in the aforementioned literature. Tristable [20,21] and quadstable configurations [22] were investigated recently. As more potential wells were introduced and the barriers between the multiple potential wells might be lower than the one in the bistable configuration, the inter-well oscillations could occur more easily, resulting in a lower frequency threshold in harmonic excitations and a lower excitation density in stochastic excitations for jumping between potential wells [20]. However, the magnetic field arrangements for tristable or quadstable structures are much more complex than that for monostable or bistable structures. The aforementioned nonlinear structures are all based on a 1-DOF structure. Very recently, by introducing an additional DOF to 1-DOF nonlinear structures, the possible internal resonance was exploited by researchers to promote wide-bandwidth harvesting performances due to energetic saturation vibrations and enhanced energy transfer between modes. Chen and Jiang theoretically studied this internal resonance mechanism in a snap-through electromagnetic energy harvester [23]. Engela et al. [24] attempted to implement this idea experimentally but the internal resonance behavior became noticeable only for very large excitations.

Inspired by the recent advances in multimodal and nonlinear techniques, this paper proposes a bistable 2-DOF piezoelectric energy harvester (PEH) with tunable magnetic coupling, which combines the concepts of multimodal technique and bistable dynamics to widen the operating bandwidth of energy harvesting systems. A linear parasitic oscillator attached to the main structure aims for two resonant peaks and the magnetic coupling engages bistable dynamics. The nonlinear electromechanical model of the proposed bistable 2-DOF PEH is established. The effect of the parasitic oscillator configuration on the resonant peaks of the bistable 2-DOF PEH is investigated theoretically and experimentally. The nonlinear responses are obtained and compared with their optimal linear 2-DOF counterpart. The effect of the load resistance on the nonlinear response and power output is also investigated.

2. Theoretical model

The bistabe 2-DOF PEH is designed by adding the magnetic coupling into the conventional linear 2-DOF PEH. In this section, we first briefly introduce the model of the conventional linear 2-DOF PEH. Subsequently, we establish the nonlinear electromechanical lumped parameter model of the bistabe 2-DOF PEH with magnetic coupling. Parametric studies are performed to evaluate their performances in terms of the resonant frequencies and electrical outputs.

2.1. Linear 2-DOF PEH

Fig. 1 shows a conventional linear 2-DOF PEH model [9]. The harvester comprises two moving masses (m_1 and m_2) connected in series with their respective springs (k_1 and k_2) and dampers (η_1 and η_2), and a piezoelectric element placed between the base and m_1. The mass m_1, spring k_1, damper η_1 and the piezoelectric element form the energy harvesting component of the system. The mass m_2,

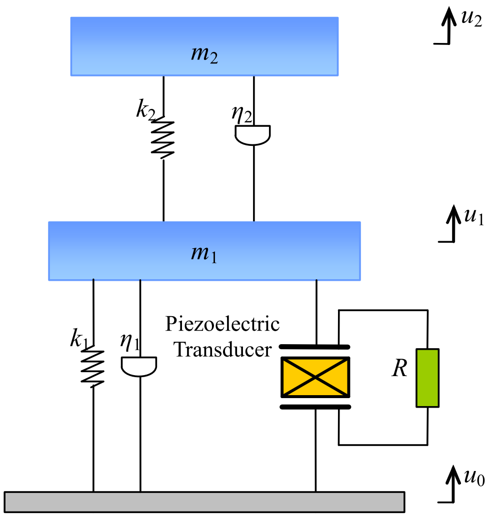

Fig. 1. Linear 2-DOF PEH model [9].