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A frequency and bandwidth tunable piezoelectric vibration energy harvester using multiple nonlinear techniques

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HIGHLIGHTS

- An ultra-wide bandwidth vibration energy harvester was built with tunable frequency and bandwidth.
- Multiple nonlinear tuning mechanisms were realized by tuning the gap between spring-plate and stopper.
- The theory models and numerical simulations were presented with experimental verification.

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ABSTRACT

This article presents a compact piezoelectric vibration energy harvester (VEH) using multiple nonlinear techniques to tuning the resonant frequency and broadening the bandwidth. The device was designed as a parallel-plate structure consisting of a suspended spring-plate with proof mass and piezoelectric transducers, a tunable stopper-plate, and supporting frames. By mechanical adjusting the vertical gap between the spring-plate and the stopper-plate (GBSS), the VEH can realize tuning of the resonant frequency and the bandwidth by multiple nonlinear effects. Experimentally, the piezoelectric VEH was assembled as a metal prototype that can be operated in three kinds of work states corresponding to the configurations of large-GBSS, small-GBSS, and over-GBSS. The sweeping-frequency measurement results show that the work frequency, bandwidth, and output-voltage of VEH depend on tuning of GBSS and excitation levels, indicating that the multiple nonlinear effects, such as Duffing-spring effect, impact effect, preload effect, and air elastic effect, have significant influence on the dynamic behaviors of VEH. The comparisons of numerical simulations with the experimental results were used to verify the validity of mathematical modeling on VEH with multiple nonlinear tuning techniques.

1. Introduction

The rapid growth of wireless sensor networks and mobile electronic platforms have led to the developments of self-powered devices using energy harvesting techniques. Energy harvesting is a method to generate electrical power from external energy sources such as solar, thermal, wind, vibration, radio frequency (RF) energy, human body heat, and human movements, and so on. Among these energies, vibration-based energy harvesting has received significant attention in recent years. As a typical example of wasted energy that may be harvested, vibrations can be available easily in our surroundings, such as different types of commercial and industrial machines, vehicles, buildings, various structures (bridges, railways), home appliances, and motion of biological systems [1]. The idea of vibration-to-electricity conversion was proposed by Williams and Yates in 1996 [2]. From then on, vibration energy harvesting has been an attractive technique for charging or powering low-power micro-electronics [3].

Typical vibration energy harvesters (VEHs) may be viewed as a simple oscillator (mass-spring system), excited by an external vibration source, with one electromechanical transducer used for vibration-to-electricity conversion [4]. The principal transduction mechanisms in VEHs are piezoelectric, electromagnetic, and electrostatic transductions [5]. While each of techniques mentioned above can provide a useful amount of energy, the piezoelectric technique has gained most attention due to their abilities to directly convert applied strain energy into usable electric energy

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and the ease to be integrated into a system [6]. From the power output viewpoint, actually the piezoelectric materials were not popular as an energy harvester due to its small power output. However, modern electronic devices are getting tiny and consume less power than before. Therefore the most recent developments of piezoelectric applications are related to energy harvesting [7]. Regardless of the transduction mechanisms, a primary issue in VEHs is that the maximum energy output usually occurs in its fundamental resonance frequency. The power output will be decreased significantly when the resonant frequency of VEHs do not matches the ambient vibration, this will seriously restrains the applications of VEHs [8]. There are two possible methods to optimize the output power under random vibration source: tuning the resonant frequency and broadening the bandwidth [9]. In principle, frequency tuning can be realized by controlling the mass and the spring constant of oscillator [7]. Some possible methods are: adding a tip mass [10], moving the center of gravity [11], changing the dimension [12] or shape of cantilever [13], or altering the stiffness [14] or damping [15] of the harvester. As it is impractical to change the dimensions or shape of cantilever, most of methods are to change the mass, damping or the stiffness by manual or autonomous tuning [7]. According to the practicable methods in application, our literature investigation on the frequency tuning focus on four kinds of tuning strategies: resonant frequency tuning, multimodal energy harvesting, nonlinear energy harvesting, and electrical damping tuning [16].

Resonant frequency tuning can be based on active or passive actuators for tuning frequency [17]. The active tuning actuators provide a continuous force proportional to displacement, acceleration, or velocity to alter effective stiffness, effective mass, or effective damping accordingly in a mass-spring system [17]. In contrast, the passive tuning actuators exert force only during altering the resonance frequency and no force occurs while maintaining the new resonance frequency [18–20]. Regardless of active and passive actuators, they need external energy (that is often larger than the harvesting energy) to generate the applied forces [17]. The multimodal energy harvesting is a potential effective-bandwidth-increasing approach. In practice, multimodal systems can be realized by exploiting multiple bending modes of a continuous beam or by an array of cantilevers [21,22]. The multimodal VEHs can achieve an energy harvesting by a multi-frequency resonance with an add advantage of requiring no tuning and thus the external energy. However, the effective bandwidth of multimodal systems are usually discrete, which may only be helpful when the vibration source has a rather wide frequency spectrum [16]. Furthermore, in order to avoid the mode-shape-dependent voltage cancelation in a continuous beam or the voltage cancelation caused by the phase difference between cantilevers in array configurations, multimodal VEHs usually requires complex interface circuit [16]. Nonlinear energy harvesting has shown a tremendous potential for the design of broadband VEHs in recent years. Nonlinear configurations for broadband energy harvesting focus on the generation of nonlinear force by a Duffing-type oscillator or a piecewise-linear impact oscillator. Duffing-type oscillators include monostable [23], bistable [24], and tristable [25] nonlinear configurations with nonlinear stiffness typically introduced by using magnets. Such a mechanism is applied to perturb and drive the system from a low-energy vibration branch into a high-energy orbit, resulting in a much higher output power. Piecewise-linear impact is another type of nonlinear vibration which can be introduced by adding a mechanical stopper to make a piecewise linear stiffness in vibration system [26]. It was found that the tuning configuration using mechanical stopper generates jump phenomenon and results in the increase of bandwidth during frequency sweep. However, the bandwidth is increased at the expense of lowering output power in comparison with the configurations without mechanical stopper [27]. The frequency tuning using electrical damping was investigated previously by Muriuki [15]. It is found that the stiffness and natural frequency of the beam can be adjusted when a capacitor is added in parallel to the piezoelectric element. Electrical damping can be varied by adjusting the electrical load. As the resistive load reduces the efficiency of power transfer while the inductive load is difficult to be varied, the varying of a capacitive load is preferable [7].

It is noted that above-mentioned broadband harvesting techniques are only preferable in specific conditions. Anyway the most suitable method for frequency tuning depends on the intended application. For example, the car-tire vibration spectrum spreads from 300 Hz to 700 Hz [28] and the railway tunnels vibration spectrum is distributed from 200 Hz to 600 Hz and 1200 Hz to 2000 Hz [29]. In these vibration environments, the wireless sensor nodes (WSN) powered by VEHs with a single adjusting configuration cannot be sufficient to tune over such a wide frequency range. Therefore the VEHs using multiple nonlinear tuning mechanisms in a device are considered to be a suitable solution due to its large tunability over work frequency range. According to the requirements of frequency matching over a wide frequency range, VEHs with multiple nonlinear tuning mechanisms are capable of tuning the resonant frequency with the accompaniment of broadening the bandwidth. Up to now there are few reports on the VEHs using multiple nonlinear tuning mechanisms.

In this work, we present a compact piezoelectric VEH using multiple nonlinear tuning mechanisms to tune the resonant frequency and broaden the bandwidth synchronously. The device was designed and fabricated as a metal prototype with compact parallel-plate structure consisting of supporting frames, a suspended spring-plate with proof mass, a tunable stopper-plate. The piezoelectric sheet was integrated on one of the beams of spring-plate. This device can be assembled and adjusted according to the requirements of flexible study options. The multiple nonlinear effects, including the Duffing-spring effect, impact effect, preload effect, and air elastic effect can be achieved in this device by mechanical tuning the stopper-plate. Furthermore, this device has high reliability and repairability due to the high-reliable and interchangeable metal parts and the amplitude-limiting stopper, making this device a strong shock-resistibility for practical engineering applications.

2. Design and modeling of the VEH

The targeted piezoelectric VEH is designed as a parallel-plate spring-mass system as schematically shown in Fig. 1(a), which consists of a suspension spring-plate with a proof mass, a rigid stopper-plate above the spring-plate, three structural frames, and connecting bolts. The spring-plate is designed as a hooked-cross-shaped suspension configuration with four identical doubly clamped L-type beams (see Fig. 1(a)) by hollow-cutting a 0.2 mm thick and 45 mm long square bronze plate, such design brings about a compact structure as well as a nonlinear Duffing-spring effect. A 0.4 mm thick, 3 mm wide, and 24 mm long piezoelectric ceramic sheet is attached to the top surface of the L-shaped suspension beam. The prototype can be assembled by connecting all parts with four bolts, and the vertical gap between the spring-plate and the stopper-plate (GBSS) can be changed by adjusting the number of spacers in the bottom center of the stopper-plate. By varying the GBSS, the VEH can be operated in three kinds of work states, namely large-GBSS, small-GBSS, and over-GBSS, as shown in Fig. 1(b–d).

The electromechanical model corresponding to the case of small-GBSS is schematically shown in Fig. 1(e). In this model, the proof mass M oscillates with the relative displacement $z(t)$; K_m,