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Modeling and experimental verification of an impact-based piezoelectric vibration energy harvester with a rolling proof mass

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ABSTRACT

Impact-based vibration energy harvesters (VEHs) with a rolling proof mass are promising candidates for scavenging ambient low-level, broadband, and low-frequency vibration energy. This paper derives the mathematical model of a VEH with two piezoelectric cantilevers symmetrically located at two open ends of a guiding channel with a rolling steel ball inside as the proof mass. The model includes the equation of motion and coupled electrical circuit equation of the bimorphs under base excitation, the equations of motion of the rolling proof mass under base excitation, and the collision equations between the bimorphs and the proof mass. Simulation results show that the scavenging efficiency of low-level vibration can be improved by introducing the rolling proof mass. The numerical results agree well with the experiments when the harvester prototype is horizontally fixed on the base. Under the base excitation of 1 g(=9.8 m/s^2), the maximum output power of one bimorph is about 511 μW at 18.4 Hz.

1. Introduction

Small or micro scale vibration energy harvesters (VEHs) are serious alternatives to traditional chemical batteries as power sources of wireless sensor nodes and implanted systems [1,2]. In a VEH, the ambient vibration energy is first converted into the vibration energy of a small or micro structure, and then into electric energy by piezoelectric [2,3], electromagnetic [4,5] or electrostatic means [6,7]. Among these mechanisms, piezoelectric VEHs are the most attractive energy harvesting devices as they have the added advantages of high power density and ease of miniaturization [8]. Most piezoelectric VEHs are based on linear resonant mechanism with narrow frequency bandwidth, which means that the energy scavenging efficiency decreases significantly when the frequency of base excitation deviates slightly away from the natural frequency of the devices [2,3]. With reduced volume, the natural frequencies of VEHs are generally higher, as shown by reports that the natural frequency of most resonant-based piezoelectric VEHs are higher that 30 Hz [2,3,8–10]. Unfortunately, the vibration energies that can be captured in normal environments (due to movements of trees, civil infrastructures, and buildings) are typically low-frequency (less than 30 Hz), has broad bandwidth and are weak (lower than 1 g, and with the typical value in the range of 0.06–0.3 g) [11–13]. The resulting scavenging efficiency of resonant-based piezoelectric VEHs is thus very low, which greatly limits the usefulness of these devices in normal ambient settings. Therefore, in recent years, research on VEHs has shifted to and has been concentrated on improving the scavenging efficiency of low-level, broadband and low-frequency vibration energy.

To this end, flexible supporting structures [14–16], magnetic frequency up-conversions [17] and mechanical impacts (mechanical frequency up-conversions) [10,16] have been utilized to improve the scavenging efficiency of low-frequency vibrations. In order to expand the bandwidth, arrays of harvesters [18], harvesters with close natural frequencies [8], impact-based harvesters [16,19,20], and nonlinear harvesters [21–24] have been developed. Nonlinear harvesters are the most well-studied harvesters, however, they tend to suffer from limited bandwidth under low-level base excitations. Impact-based VEHs with a proof mass supported by a flexible spring or a rolling proof mass have also been developed to scavenge low-level vibration energy [16,25]. It should be noted that impact—or the transfer of momentum—is commonly incorporated in energy harvesters to improve their scavenging efficiencies in capturing low-level, broadband and low-frequency vibration

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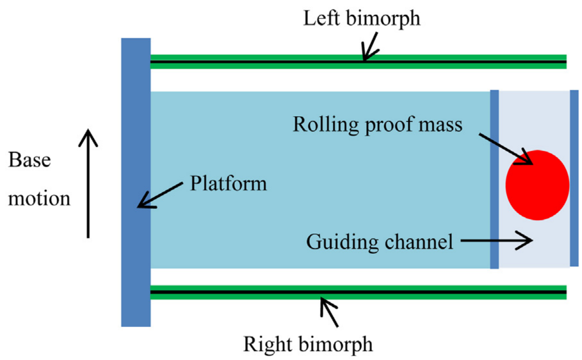

Fig. 1. Schematic of the energy harvester with a rolling proof mass.

energy. Experimental and theoretical analyses have illustrated good performance of an impact-based piezoelectric VEH with a sliding proof in broadband and low-frequency vibration energy scavenging [19]. As rolling friction is typically lower than sliding friction, an impact-based VEH with a rolling proof mass is more energy-efficient for low-level vibration energy scavenging as less kinetic energy is lost through friction. Therefore, VEHs with a rolling proof mass are promising candidates for low-level, broadband and low-frequency vibration energy scavenging.

A robust mathematical model is of significant importance to the optimization of the structures, and understanding of the characteristics of impact-based piezoelectric VEHs with a rolling proof mass. At present, no mathematical model of such impact-based piezoelectric VEHs has been reported. It is somewhat more challenging to establish the model of impact-based VEHs with a rolling proof mass than the model of those with a sliding proof mass. Firstly, to predict the motion of the rolling proof mass, the equations of motion under a base excitation need to be derived, which are more complex than those of a sliding proof mass. Secondly, in modeling the collisions between a rolling proof mass and a piezoelectric beam, more effects (such as the change of the angular velocity of the rolling proof mass) need to be considered. The aim of this work is to establish and experimentally verify the mathematical model of an impact-based piezoelectric VEH with a rolling proof mass. The output properties of the harvester are also theoretically and experimentally analyzed.

2. Operational mechanism of an impact-based piezoelectric VEH with a rolling proof mass

Our group proposed an impacted-based piezoelectric VEH composed of two cantilevered bimorphs, a rolling proof mass, and a platform with an open-ended cylindrical guiding channel, as shown in Fig. 1 [25]. Two cantilevered bimorphs (the left and right bimorphs) are fixed on both sides of the platform, with their free ends covering the open ends of the guiding channel. A steel ball is placed inside the guiding channel and serves as the rolling proof mass. To prevent the ball from dropping out of the guiding channel, the gaps between the ends of the channel and the piezoelectric cantilevers are designed to be much smaller than the diameter of the ball. Under base excitation in a direction parallel to the guiding channel, the ball rolls freely in the guiding channel and collides with the cantilevered bimorphs. Each collision with one of the two bimorphs causes the ball to bounce back, leaving the bimorph to vibrate vigorously. Subsequently, the piezoelectric layers of the bimorph convert the mechanical vibration into electrical energy. This harvester is similar to the work of Renaud et al. [19], with the exception that the sliding proof mass is substituted by a rolling proof mass, which greatly enhances the scavenging efficiency of low-level ambient base excitation as the steel ball can move with much less friction than the sliding proof mass.

Parameters of this piezoelectric VEH, including the radius of the rolling ball and the length of the guiding channel, affect the output voltage. The parameters of the ambient excitation, such as the base excitation acceleration amplitude and the excitation frequency, also affect the electrical output of the harvester. In light of this, a mathematical model of the piezoelectric VEH with a rolling proof mass is required to optimize the structure and is presented in the following section.

3. Modeling of the VEH with a rolling proof mass

Three sets of equations are required to predict the responses of piezoelectric VEHs with a rolling proof mass under base excitation. The first set of equations, developed in Section 3.1, are the equation of motion and coupled electrical circuit equation of the piezoelectric cantilevers under base excitation. Section 3.2 provides the second set of equations which comprise of the equations of motion of the rolling proof mass under base excitation. The third set of equations, presented in Section 3.3, are the collision equations used to evaluate the velocities and displacements of the bimorphs and proof mass after collisions.

3.1. Equations of the piezoelectric cantilevers under base excitation

Erturk and Inman have derived the closed-form analytical solution of the distributed parameter models of the cantilevered piezoelectric VEH with a short proof mass at the free end [26]. By canceling the terms relative to the proof mass, these formulae are also applicable to calculating the responses of cantilevered bimorphs without a fixed proof mass at the free end under base excitations. As the collision between the rolling ball and the cantilevers will be considered here, the model of the cantilevered piezoelectric VEH needs to be simplified before it can be used to model the impact-based harvester. For the purpose of simplification, only the first natural vibration mode is used, which had been shown to be accurate enough in modeling the impact responses of a cantilevered piezoelectric VEH [19]. Only bimorphs that are electrically connected in series are considered here, and the model can be easily adapted for the case of bimorphs with two piezoelectric layers in parallel connection.

It is assumed that the geometrical and material parameters of the piezoelectric cantilever are identical along the neutral x-axis. The length and width of the cantilever are L and b, respectively. The cross section of the cantilever is composed of a structural layer with thickness h_s and two piezoelectric layers with identical thicknesses h_p sandwiching the structural layer [26]. There are two metal electrodes on the top surface and the bottom surface of each piezoelectric layer, respectively. It is assumed that the steel ball impacts $w_b(t)$ with the bimorphs at the point $x = L_i$. The base displacement at time t, due to excitation, is $w_{rel}(x, t)$. The deflection of the bimorph is denoted as $w_{rel}(x, t)$. The equation of motion of a cantilever is given by [26]:

$$YI\frac{\partial^4 w_{rel}}{\partial x^4} + c_s I\frac{\partial^5 w_{rel}}{\partial x^4 \partial t} + c_a\frac{\partial w_{rel}}{\partial t} + m\frac{\partial^2 w_{rel}}{\partial t^2} + \vartheta_s v = -m\frac{\partial^2 w_b}{\partial t^2}, \quad (1)$$

where

$$\vartheta_s = \frac{\bar{e}_{31} b}{2h_p}\left[\frac{h_s^2}{4} - \left(h_p + \frac{h_s}{2}\right)^2\right], \; YI = \frac{2b}{3}\left[Y_s\frac{h_s^3}{8} + \bar{c}_{11}^E\left(\left(h_p + \frac{h_s}{2}\right)^3 - \frac{h_s^3}{8}\right)\right], \; m = b\left(\rho_s h_s + 2\rho_p h_p\right), \quad (2)$$