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Numerical and Experimental study of a vibro- impact bistable piezoelectric cantilever beam energy harvester

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Abstract

In this paper, in order to increase the frequency bandwidth, a bistable unimorph piezoelectric cantilever beam energy harvester is equipped with a unilateral barrier to limit the oscillation amplitude. This novel design is recognized as a bistable vibro-impact energy harvester. The main objective of this work is to investigate the effects of vibro-impact behavior on the frequency bandwidth of a typical bistable energy harvester. Initially, by employing Euler-Bernoulli beam assumption and energy method, the governing equations of motion were derived. Subsequently, by numerically solving the governing equations, the frequency bandwidth and harvested power of the system in both typical bistable and vibro-impact bistable systems were compared. According to the obtained results, it was clear by exploiting the vibro- impact behavior, the frequency bandwidth of a typical bistable energy harvester could be increased up to 90%. Then, the effects of initial gap between barrier and cantilever beam on the system's frequency bandwidth were investigated. In this study, some experiments were conducted to evaluate the efficiency of the proposed model and to validate the obtained results.

Keywords: Energy harvesting; Vibro- impact; Frequency bandwidth; Bistable energy harvester

1. Introduction

In recent years, with the advancement and development of new technologies, the importance of low-power electronic devices has become more and more evident. Electromechanical systems consist of mechanical and electrical components that interact with each other to convert mechanical energy into electrical energy or vice versa [1]. While small batteries can be a viable solution, they have limitations such as the need for battery replacement, short lifespan, recharge costs, or installation in inaccessible locations. Although the large-scale energy sources such as solar and wind energy are important, harvesting energy from small-scale sources like environmental vibrations has attracted significant attention from researchers. Environmental vibrations are a pervasive and accessible energy source found abundantly in natural environments, making them an appealing option for powering low-power electronic devices [2].

Various methods exist for converting vibrational energy into electrical energy which one of the most significant and effective approaches is the use of piezoelectric materials. Piezoelectric materials can convert mechanical stress into electrical energy, making them particularly suitable for powering small-scale devices [3]. While environmental vibrations encompass a broad frequency spectrum, energy harvesters generally exhibit a narrow frequency bandwidth. This limitation constrains their ability to capture the energy from diverse frequency components of environmental vibrations. To address this issue, researchers and developers in this field are actively seeking methods to broaden the frequency response range of energy harvesters, thereby enhancing their overall energy harvesting capabilities [4]. Due to this constraint, energy harvesters must be excited within their specific frequency range to achieve a suitable energy conversion rate. This requirement often makes many linear energy harvesters inefficient. Linear energy harvesters bear a sharp drop in their performance as the frequency shifts away from their resonance band, leading to reduced energy conversion efficiency.

To overcome the issue of limited frequency bandwidth in energy harvesters, various methods are employed. One of the significant approaches involves adding nonlinear behavior to the harvester. By introducing nonlinearity, the frequency bandwidth can be broadened, allowing for more efficient energy harvesting across a wider range of input frequencies [5]. Many researchers have emphasized bistability methods to increase the efficiency of energy harvesters. Bistable energy harvesters typically consist of one or two layers of piezoelectric material, a cantilever beam, and a pair of permanent magnets. In this method, one permanent magnet is attached to the free end of the beam, while the other is placed on the fixed host structure with the same polarity to make a repulsive force. Erturk et al. introduced a piezo-magneto-elastic device to enhance the power output of a vibration energy harvester [19]. Stanton successfully studied the performance of a bistable energy harvester numerically [6]. Q. Jiang et al. introduced a new bistable energy harvester with improved performance compared to traditional bistable harvesters [7].

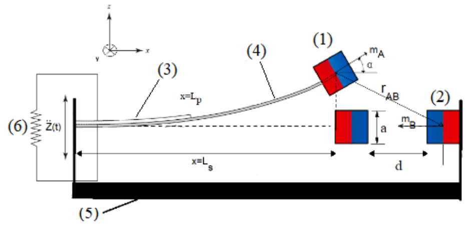
Another method for expanding the frequency bandwidth of an energy harvester is frequency up-conversion technique which is achieved by introducing impacts within the system [8]. This technique involves adding series of impacts to the energy harvester that called vibro-impact phenomenon can effectively broaden the range of frequencies from which the system can extract energy. For the first time, Soliman successfully increased the frequency bandwidth of a vibration energy harvester by employing vibro-impact phenomenon [9].

The main aim of the present paper is to investigate the improvement of a bistable piezoelectric energy harvester's efficiency through using of the vibro-impact technique. To achieve this goal, the electromechanical equations of the problem are derived using the developed Hamilton's principle and Euler-Bernoulli beam assumptions. Subsequently, the governing equations are solved numerically. Furthermore, the effects of initial barrier gap and separation distance on harvested power and frequency bandwidth of the system are investigated. Finally, an experimental test is conducted on the system to evaluate the proposed method, examining energy harvesting and frequency bandwidth under various system parameters.

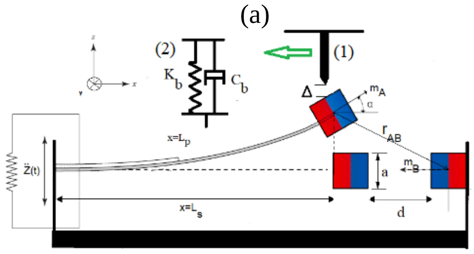
2. Mathematical Modelling

Figure 1(a) depicts a common bistable harvester that has been the focus of many studies. This energy harvester type is comprised of a piezoceramic layer, an aluminum beam, and a pair of magnets.

As shown in the figure, the magnets are positioned with same polarity, inducing a bistable behavior. Introducing a barrier to the system adds a new nonlinear behavior which its frequency bandwidth effects on the bistable system requires further investigation.



(a)



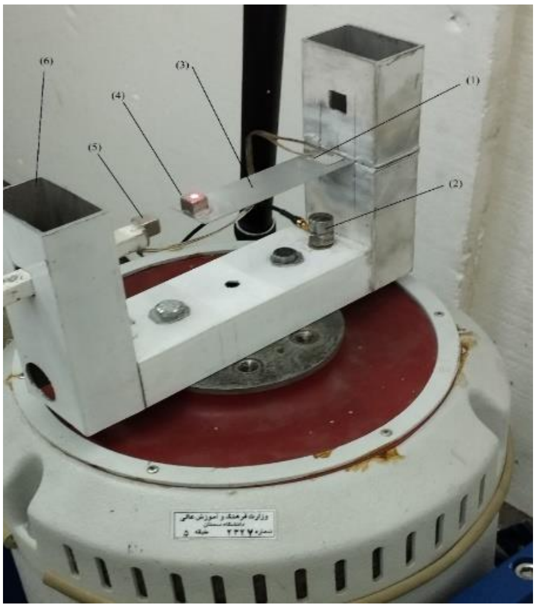
(b)

Figure 1. Schematic of the energy harvester; (a) Common bistable energy harvester, (1) Magnet A, (2) Magnet B, (3) Piezoelectric patch, (4) Aluminum beam, (5) Host structure, (6) Electrical resistance (b) Vibro-impact bistable system, (1) Motion-limiting stop, (2) Mechanical spring-damper model of barrier

3. Experimental setup

In this section, the experimental setup of the system is introduced in Figure 2. The set up consists of an aluminum cantilever beam, a host structure, a piezoelectric patch, and a pair of permanent magnets. An electrical resistance is also connected across the piezoelectric electrodes for completion of the energy harvester circuit. The host structure is also an aluminum U-shaped frame mounted on an electromagnetic shaker TIRA TV5220, which imposes base excitation to the energy harvester. Besides, the velocity of the beam tip is measured via VH300 Doppler laser vibro-meter.

(a)



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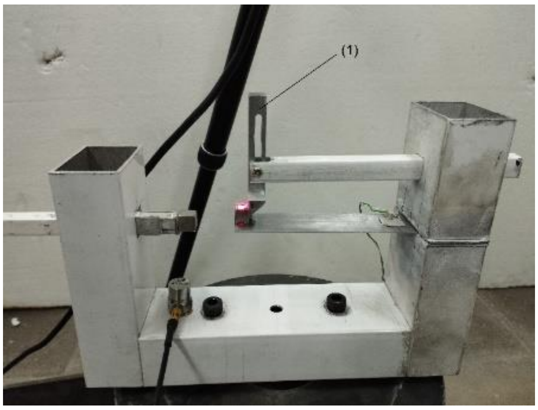
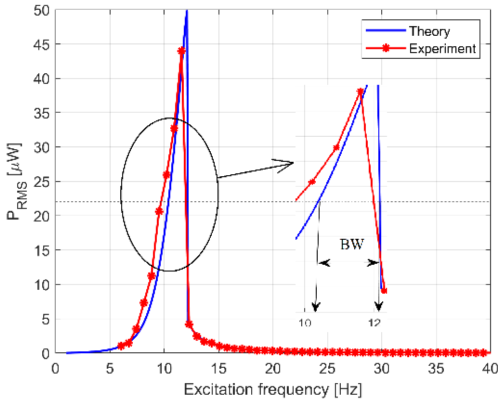


(c)

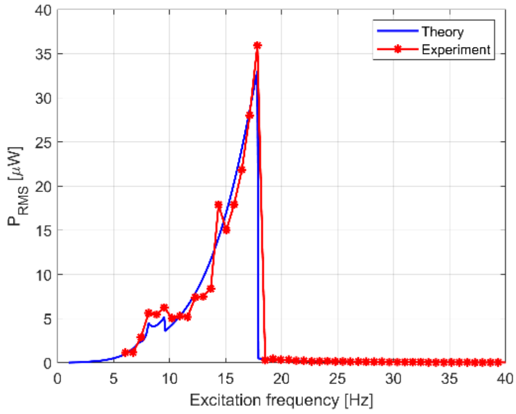
Figure 2. Test set up; (a) (1) Laser vibro-meter (2) Host structure (3) Electromagnetic shaker (4) Analyzer (5) Shaker amplifier (b) (1) Piezoelectric patch (2) Accelerometer (3) Aluminum cantilever beam (4) Magnet "A" (5) Magnet "B" (6) Host structure (c) (1) Barrier

4. Frequency bandwidth analysis

Figure 3 displays the frequency response of the beam's tip velocity in the non-impacting and vibro-impact motion.



(a)



(b)

Figure 3. Half power frequency Response diagram of Theoretical and Experimental Beam Tip velocities in (a) non-impacting (b) vibro-impact motion

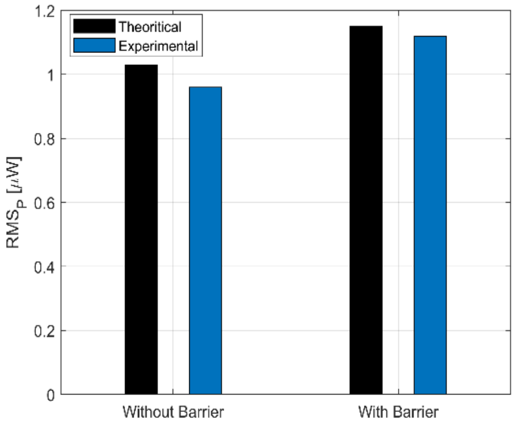
The results of frequency bandwidth and RMS of harvested power is shown in Table 1.

Table 1. Comparison of non-impacting and impacting motion

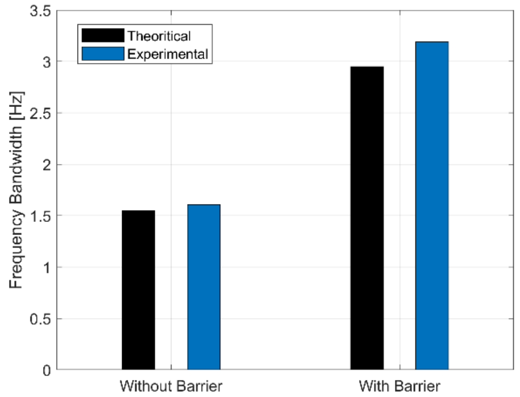
Motion type	FB (Hz)	Max. of RMS of power(μW)
$No - impact$	1.55	44.5
$impact$	2.95	33

5. Designing criteria

Energy harvesters are designed and employed to collect kinetic energy from vibrations present in natural environments. To determine the efficiency level of each set, it is necessary to define a power index which is called the mean RMS frequency response bandwidth of the harvested power and is analyzed in Figure 4.



(a)



(b)

Figure 4. (a) RMS_P and (b) FB comparison of the system in without and with barrier motion

6. Conclusions

This paper presents a theoretical-experimental study of the vibro-impact motion's effect on the frequency bandwidth of a bistable piezoelectric energy harvester. By utilizing vibro-impact motion, the total harvested power within the frequency range of interest and the system's frequency bandwidth have been increased. Utilizing the findings of this study and similar to the prototype developed in this paper, the design of vibration-based energy harvesting systems can be optimized, and industry-efficient energy harvesters can be manufactured. By tracking the proposed set up in this study, researchers and engineers can develop energy harvesters that effectively harness ambient kinetic energy, paving the way for more sustainable and self-sufficient power sources in various applications.

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