A Miniature Coupled Bistable Vibration Energy Harvester

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Abstract. This paper reports the design and test of a miniature coupled bistable vibration energy harvester. Operation of a bistable structure largely depends on vibration amplitude rather than frequency, which makes it very promising for wideband vibration energy harvesting applications. A coupled bistable structure consists of a pair of mobile magnets that create two potential wells and thus the bistable phenomenon. It requires lower excitation to trigger bistable operation compared to conventional bistable structures. Based on previous research, this work focused on miniaturisation of the coupled bistable structure for energy harvesting application. The proposed bistable energy harvester is a combination of a Duffing's nonlinear structure and a linear assisting resonator. Experimental results show that the output spectrum of the miniature coupled bistable vibration energy harvester was the superposition of several spectra. It had a higher maximum output power and a much greater bandwidth compared to simply the Duffing's structure without the assisting resonator.

1. Introduction

Vibration energy harvesters collect ambient vibrations in the environment around the device and convert them into electrical energy [1]. The main hurdle preventing linear vibration energy harvesters from widespread use is that they only harvest energy efficiently when the device's resonant frequency matches the frequency of the vibration. Significant research has been done to increase the operational bandwidth of vibration energy harvesters and multiple approaches have been created [2]. One of the most promising ways to widen the bandwidth is to use a bistable structure [3].

A bistable structure is a type of nonlinear structure that consists of two potential wells. These two potential wells enable the inertial mass to jump between the two equilibrium positions under external mechanical vibrations regardless of their frequencies. It can be realised with a pre-stressed structure or by applying an external nonlinear force to a linear structure. Conventional bistable structures have been found to have broader operating frequency ranges than linear structures and harvest more energy than linear structures under white noise excitation [4]. Zhu and Beeby [5] proposed a coupled bistable structure consisting of two cantilevers with a repelling force created by permanent magnets between them. An energy harvester [6] based on the coupled bistable structure was later realised and proved that such harvester require lower excitation to trigger bistable operation and to operate significantly better than conventional bistable harvesters and linear energy harvesters under wideband vibrations.

This paper presents miniaturisation of a coupled bistable vibration energy harvester. The operational principle is first introduced followed by the design and experiment of a prototype device. Test results are then presented and discussed.

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2. Proposed miniature coupled bistable energy harvester

Figure 1 shows the cross-section view of the proposed cylinder miniature coupled bistable energy harvester. It consists of two parts, i.e. a Duffing's nonlinear structure and an assisting resonator. A plastic tube is located in the middle of the energy harvester. Magnets are fixed to both ends of the tube. A shuttle magnet in the tube can move freely vertically. These three magnets are oriented so that the two end magnets repel the shuttle magnet. This forms a typical Duffing's nonlinear structure. The assisting resonator consists of a ring spring with a pair of magnets attached. The two end magnets and those on the assisting resonator generate two potential wells and the shuttle magnet is always trapped in one of them. It is also used to reduce the threshold acceleration that triggers the bistable operation. Two coils are placed above and beneath the assisting resonator. When the shuttle magnet moves vertically, voltage can be induced in both coils. Figure 2 shows the integration concept of the harvester. Please note that magnets on the assisting resonator are not shown.

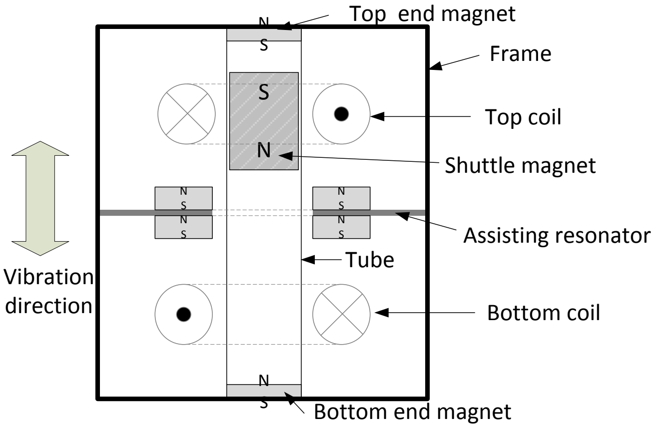


Figure 1. Structure of the miniature coupled bistable energy harvester.

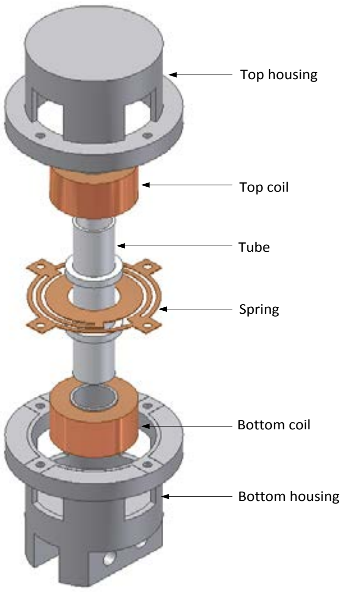
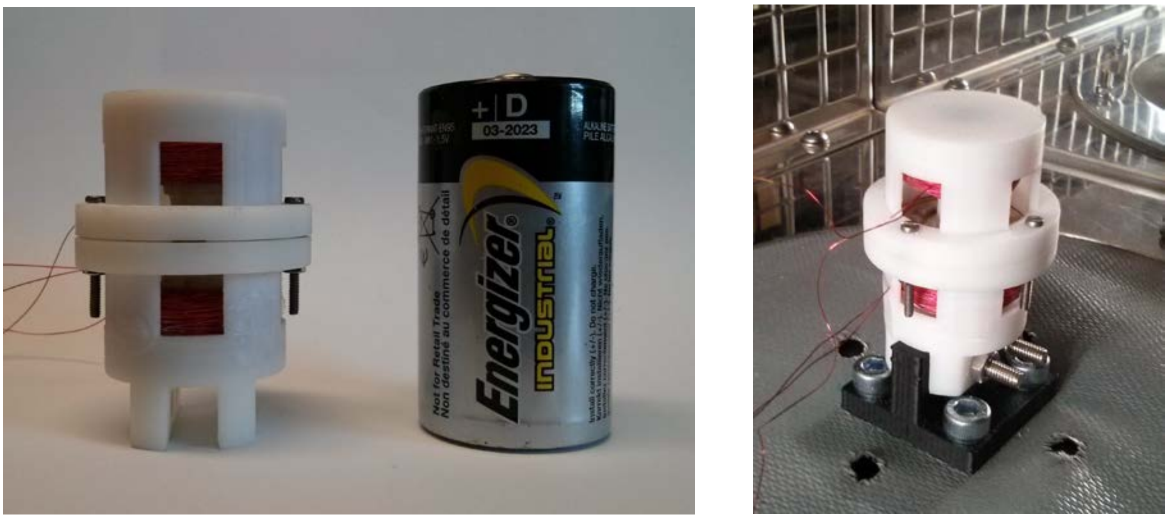


Figure 2. Integration concept of the harvester.

3. Experiment

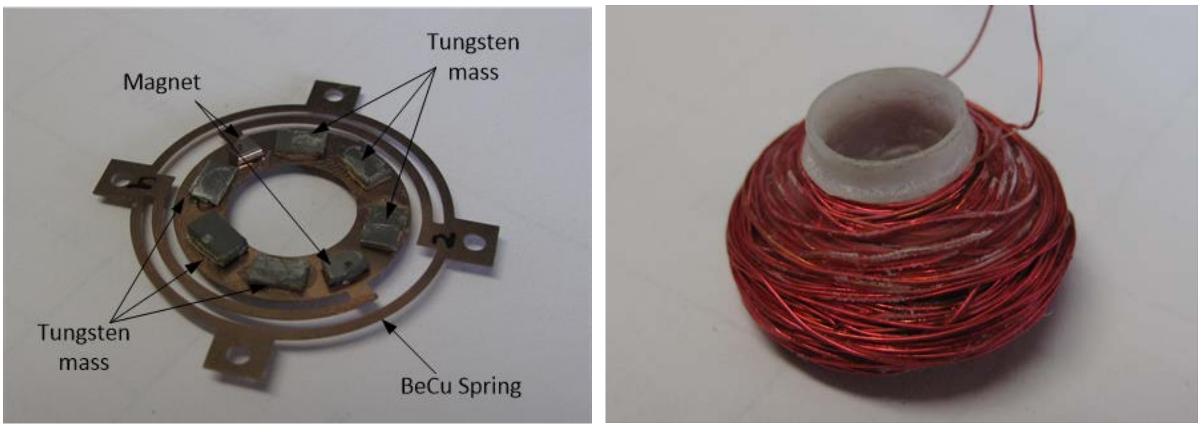
3.1. Test setup

The proposed energy harvester is a cylinder device. It has a diameter of 40 mm and a total length of 56 mm including the section for mounting the harvester on the shaker. It has a similar size to a D battery as shown in Figure 3(a). The plastic tube is 44 mm long and has outer and inner diameters of 8.5 mm and 9.6 mm respectively. The two end magnets are both 1 mm thick and 8 mm in diameter. The shuttle magnet has a diameter of 8 mm and thickness of 4 mm. All magnets used in this device are NdFeB. The ring spring as shown in Figure 4(a) is 100 μm thick and made of BeCu. Two sets of magnets are attached to the spring. Apart from magnets, twelve tungsten pieces are also attached to the spring to decrease the resonant frequency of the assisting resonator. The total mass on the spring is 2.66 g. Each magnet has an area of 2×2 mm^2 and is 1 mm thick. Two coils as shown in Figure 4(b) were hand wound around plastic holders. Each coil has 500 turns of 254 μm thick copper wire. Resistances of the two coils were measured as 12.4 Ω and 12.6 Ω respectively. All plastic components in this device are 3D printed ABS plastic. The assembled harvester was attached to a Data Physics V55 shaker for testing as shown in Figure 3(b).



(a) Assembled energy harvester (b) Harvester mounted on the shaker

Figure 3. The energy harvester.



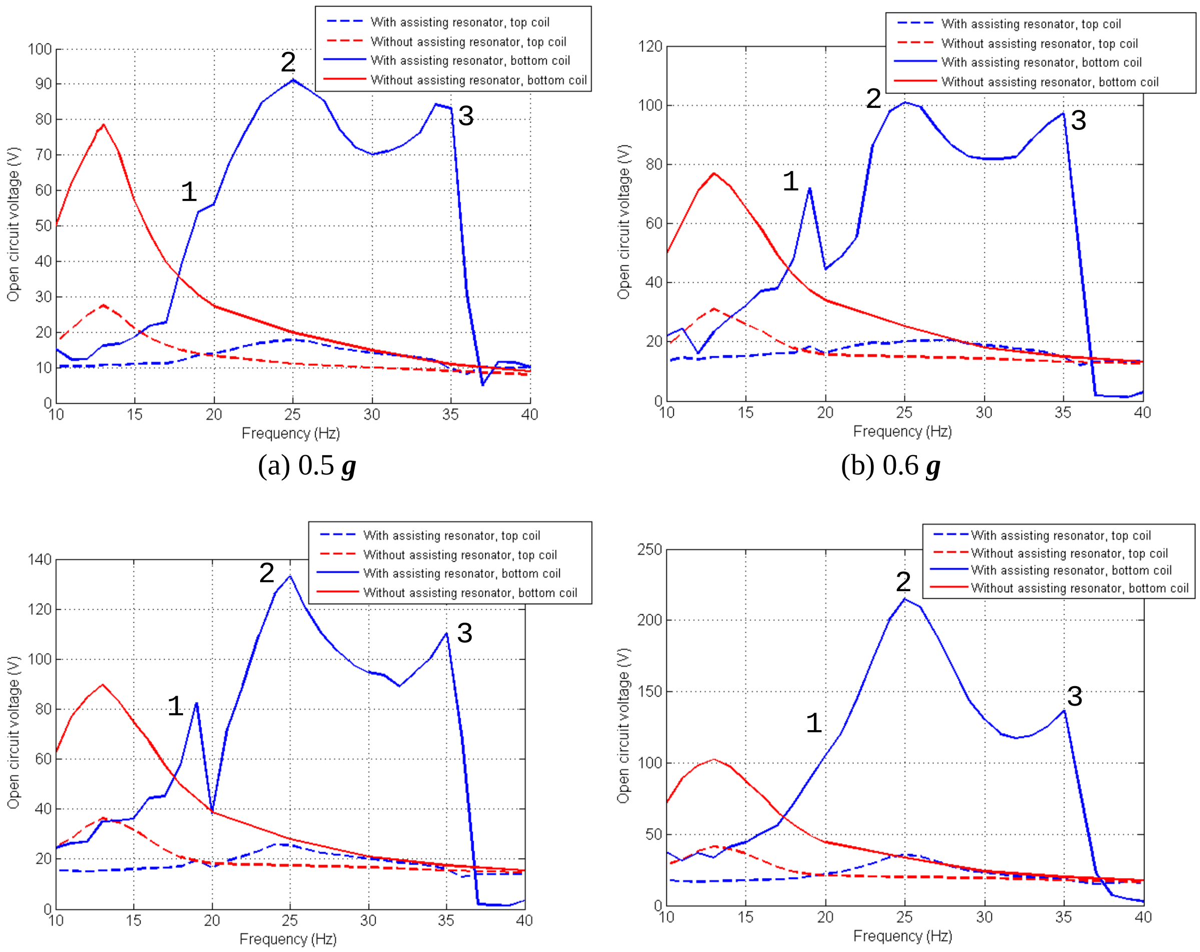
(a) Assisting resonator (b) Coil

Figure 4. Components.

3.2. Results and discussion

The energy harvester was tested under sinusoidal excitations with various frequencies (10 to 40 Hz) and accelerations (0.5 to 0.8 $\boldsymbol{g}$, 1 $\boldsymbol{g}$ = 9.81 m·s^{-2}). Two sets of tests were carried out. In the first test, the assisting resonator was removed so that the energy harvester is purely a Duffing's nonlinear structure. In the second test, the assisting resonator was in place, which formed a coupled bistable energy harvester. Both up-sweep and down-sweep tests were carried out and results were found identical in both tests.

Figure 5 shows the open circuit voltage of the two coils under various excitations. It was found that both maximum output voltage in the bottom coil and bandwidth were higher in the case with the assisting resonator, i.e. the coupled bistable harvester, compared to the case without the assisting resonator, i.e. Duffing's nonlinear energy harvester. However, the maximum output voltage in the top coil is lower in the coupled bistable harvester although its bandwidth is still larger. Furthermore, it was found that there are three peaks in the spectrum of the coupled bistable energy harvester. Peak 1 was the result of the resonance of the Duffing's nonlinear structure at 19 Hz, i.e. magnetic spring formed by the two end magnets. In this case, the shuttle magnet only moved within one of the potential wells. Therefore, the output voltage was low compared to other two peaks. Peak 2 was caused by the resonance of another Duffing's nonlinear structure at 25 Hz which was formed by one of the end magnet and magnets on the assisting resonator. During this resonance, bistable operation was triggered. Thus the output voltage was higher. Higher excitation generated higher force that enabled bistable operation to occur more frequently. Therefore, amplitude of this peak increased more than other two peaks with increasing accelerations. Peak 3 occurred at the resonant frequency of the assisting resonator at 35 Hz. Bistable operation was also triggered in this case. It is worth mentioning that due to the gravity, the shuttle magnet preferred to stay in the bottom potential well. Therefore, output voltage in the top coil was much lower than that in the bottom coil and the advantage of the coupled bistable harvester was not obvious.



(a) 0.5 ***g*** (b) 0.6 ***g***

(c) 0.7 ***g*** (d) 0.8 ***g***

Figure 5. Comparisons of open circuit voltage under various accelerations.

Figure 6 compares maximum output power in the bottom coil of the Duffing's nonlinear harvester and the coupled bistable harvester when connected to an optimal resistive load of 13 Ω. It can be found that maximum output power of the coupled bistable harvester increased more significantly than that of the Duffing's nonlinear harvester. This is because the shuttle magnet travelled more frequently between two potential wells when the excitation amplitude increased.

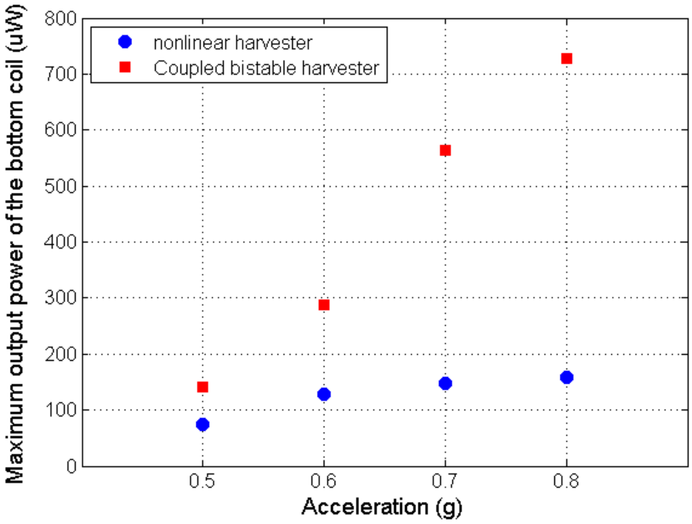


Figure 6. Comparisons of output power under various accelerations.

4. Conclusion and future work

This paper reports a miniature coupled bistable energy harvester that has a similar size of a D battery. Experimental results showed that the output spectrum of the miniature coupled bistable vibration energy harvester was the superposition of several spectra and the harvester had a higher maximum output power and much greater bandwidth compared to the Duffing's structure without the assisting resonator. The next step forward will be to investigate the performance of this harvester under wideband excitations such as white noise.

5. Reference

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Acknowledgments

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