Broadband Rotational Energy Harvesting with Non-linear Oscillator and Piezoelectric

Transduction

You may also be interested in:

Broadband Rotational Energy Harvesting with Non-linear Oscillator and Piezoelectric Transduction

H Fu and E M Yeatman

Department of Electrical and Electronic Engineering, Imperial College London, Exhibition Road, London, SW7 2AZ, UK

E-mail: `h.fu14@imperial.ac.uk`

Abstract. Rotational energy is widely distributed in many industrial and domestic applications, such as ventilation systems, moving vehicles and miniature turbines. This paper reports the design and implementation of a bi-stable rotational energy harvester with wide bandwidth and low operating frequency. The rotational energy is converted into electricity by magnetic plucking of a piezoelectric cantilever using a driving magnet mounted on a rotating host. The bistable condition is achieved by introducing a fixed magnet above the tip magnet at the cantilever's free end. The repulsive magnetic force between the magnets creates two equilibrium positions for the piezoelectric beam. The harvester is designed to operate in the high energy orbit (interwell vibration mode) to extract more energy from the rotational energy source. Harvesters with and without bistability are compared experimentally, showing the difference of power extraction on both the output power and bandwidth. The method proposed in this paper provides a simple and efficient way to extract rotational energy from the ambient environment.

1. Introduction

Compared with vibrational energy, rotational energy is also readily harnessed for powering low-power electronics. This energy source also widely exists in many scenarios, including heating, ventilating and air conditioning (HVAC) systems, vehicles and wrist watches [1, 2]. However, rotational energy harvesting is less investigated and developed than vibration energy harvesting. Similar to vibrational energy, rotational energy in daily life also has the characteristic of low frequency and wide bandwidth [3]. Therefore, the harvesters should be low-frequency and broadband to harness rotational energy efficiently.

Generally, for large-scale rotational harvesters, such as wind turbines, gear trains are adopted to increase the rotation frequency of the turbine rotor, but for micro-scale energy harvesters, it is costly and complicated to fabricate gear trains. We developed an airflow energy harvester using miniature turbines and piezoelectric transduction [4]. In this design, a mechanism called frequency up-conversion was employed to replace gear trains. This mechanism was achieved by plucking the piezoelectric beam using a driving magnet mounted on the turbine rotor. The beam vibrates freely at its resonant frequency after each plucking. However, the output power has a significant drop when the driving frequency is high due to the interference between the vibrating beam and the coming driving magnet [5]. This phenomenon was also observed in other vibration energy harvesters using frequency up-conversion [6, 7].

Bi-stability is widely used in vibrational energy harvesting to increase bandwidth. This mechanism is generally achieved by applying magnetic force or external mechanical load to the motion direction of proof masses [8]. Zhou *et al.* presented a nonlinear piezoelectric harvester for vibration energy harvesting [9]. Two rotatable magnets and one tip magnet were used to generate the bistable condition. The harvester had a wide low-frequency operating range by adjusting the magnet orientation. In order to enhance the performance of the rotational energy harvester over a wide bandwidth, we combine the bistable method with frequency up-conversion in this paper. The operating principle is illustrated firstly and experiments were carried out to verify the idea. An improved output power was obtained over a wide bandwidth.

2. Operating principle of the harvester

The schematic of the harvester is shown in Fig. 1. It consists of a driving magnet mounted on a rotating host, a piezoelectric beam, a tip magnet and a fixed magnet. The fixed magnet is above the tip magnet, and the driving magnet is below the tip magnet. The driving magnet is mounted on a rotating host. The beam is plucked once per rotation cycle by the repulsive magnetic force between the driving magnet and the tip magnet.
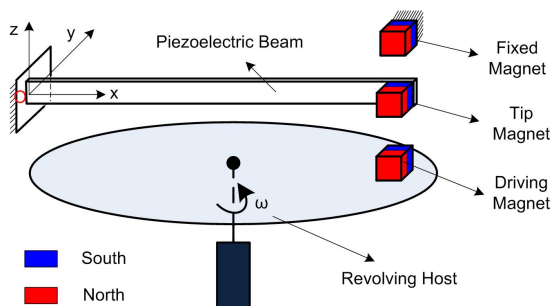

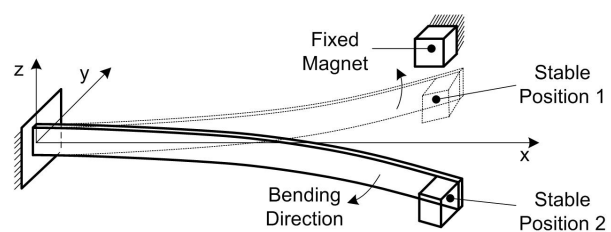**Figure 1.** Schematic of the nonlinear piezoelectric rotational energy harvester.

Figure 2. Bi-stability of the energy harvester, showing the nonlinear characteristic of the design. Two equilibrium positions are created by the repulsive magnetic force.

In terms of bi-stability, it is achieved by the repulsive force provided by the fixed magnet. The force pushes the beam to bend towards either side of its original position, introducing two equilibrium positions, as shown in Fig. 2. There are three modes of vibration for the bistable beam, i.e. intrawell vibration, chaotic interwell vibration and periodic interwell vibration. These modes are determined by the driving force provided by the rotating magnet and the restoring force provided by the fixed magnet and the bended beam.

3. Experimental set-up

The experimental set-up is shown in Fig. 3. The piezoelectric beam was clamped on a beam holder at one end. The holder was fixed on an adjustable platform which is capable of precisely controlling the position of the piezoelectric beam in three directions. A high speed stepper motor (Phidgets 3303) with a step angle of 1.8° was placed underneath the beam with a revolving plate mounting on the motor's shaft. The motor is driven by a bipolar motor control circuit (Phidgets 1067) which has a position resolution of ¹/₁₆ step. The acceleration is also programmable to achieve any desired rotational speed.

A magnet was mounted on the revolving plate as the driving magnet. Magnet plucking is formed by the driving magnet and the tip magnet at the beam's free end. For bistability, a fixed magnet was also employed and placed on a magnet holder above the piezoelectric beam. The magnet holder was also fixed on an adjustable platform. Therefore, the gap between the tip magnet and the fixed magnet can be adjusted as well. A laser displacement sensor was
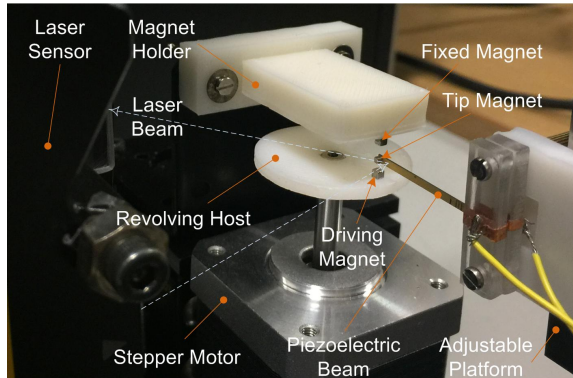
Figure 3. Experimental set-up. The rotational motion is provided by a stepper motor. The rotational frequency can be accurately controlled by the management circuit.
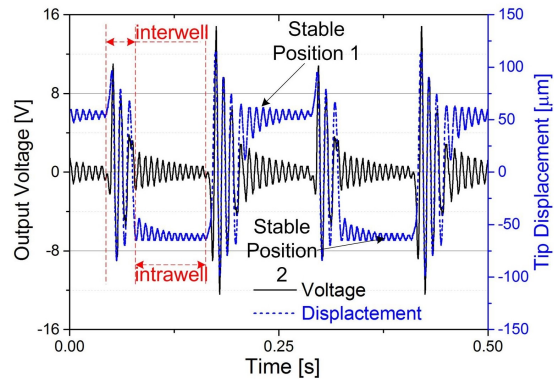

Figure 4. Output voltage and tip displacement of the nonlinear energy harvester, showing the bi-stability of the system under tip excitation (Rotation speed: 9.8 Hz; load: 180 kΩ).

adopted in the experiment to measure the vibration of the piezoelectric beam. The output of the piezoelectric beam was directly connected with a 180 kΩ resistive load.

4. Results and discussion

Fig. 4 illustrates the output voltage and tip displacement of the harvester operating in the high energy orbit (periodic interwell vibration). Due to the limited input energy from each plucking, the beam does not purely vibrate in the interwell mode during one cycle. The beam vibrates in the interwell vibration mode first for several oscillations and then settles into the intrawell mode during one excitation cycle. The output voltage in the interwell mode is much higher than that in the intrawell mode. Two equilibrium positions are clearly observed on the tip displacement curve.
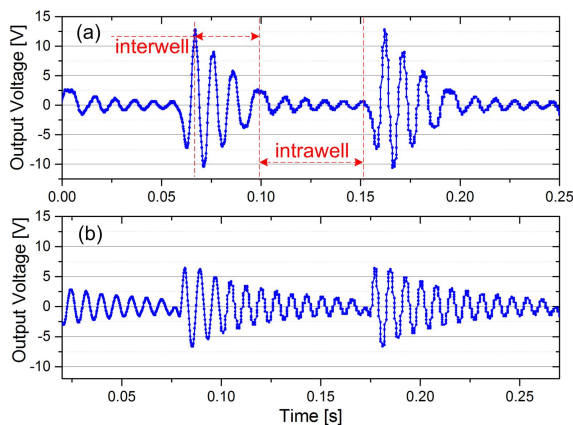

Figure 5. Output voltage of the harvester at 11.2 Hz with and without the nonlinear characteristics. (a) with the fixed magnet (Gap in z-axis: 1.2 mm) and (b) without the fixed magnet.
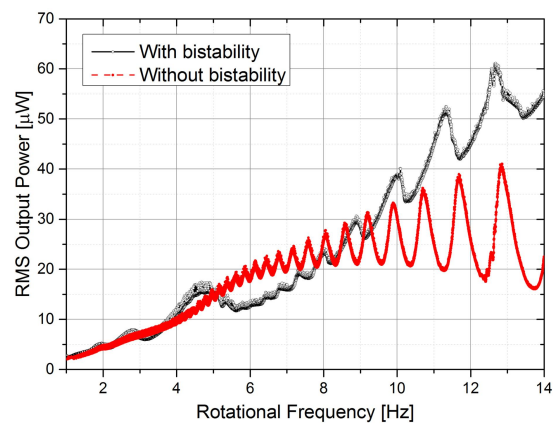

Figure 6. Frequency response of the harvester with and without bistability, showing the wide bandwidth of the bistable device and the improved output power at high frequencies.

Fig. 5 depicts the output voltage of the harvester with and without the nonlinear characteristics. Without bistability, the maximum output voltage is much lower than the maximum voltage from the bistable harvester. The improved voltage in the bistable case will add even greater benefit after rectification. Meanwhile, the output voltage is damped more slowly than that in the bistable case. Therefore, the beam is still in motion when the driving magnet returns in a new cycle, causing interference between plucking cycles and loss of power.

Fig. 6 shows the frequency response of the harvester with and without bistability. The nonlinear harvester has similar performance to the linear harvester at low frequency, but the output power is much higher at high frequency. The improved output power at high frequency is achieved by avoiding the interference between the vibrating cantilever beam and the coming driving magnet. As shown in Fig. 4, for each excitation, the beam finally gets into the intrawell vibration mode with limited oscillating amplitude. Therefore, the beam does not have significant impact on the driving magnet, whereas in the harvester without bistablity, the beam is not damped quickly enough. At high frequency, the beam is still vibrating with a quite large amplitude when the driving magnet comes. Negative work is done on the piezoelectric beam, when the beam vibrating direction and the rotation direction of the driving magnet are opposed.

The quickly damped motion in the bistable case provides a possibility of using 2 or more driving magnets on the rotor to improve the power generation capability at even lower frequencies.

5. Conclusion

This paper presents a bistable rotational energy harvester with low operating frequency and wide bandwidth. A piezoelectric cantilever beam with a tip magnet was employed as the transducer. A bistable beam was achieved by adding a fixed magnet above the tip magnet. Two equilibrium positions were created by the repulsive magnetic force. In terms of the excitation mechanism, the beam was plucked by a rotating driving magnet mounted on a revolving host. The beam vibrated at its natural frequency after each plucking.

An experimental validation was carried out. The bistable beam had higher output voltage and tip displacement, when it vibrated in the interwell vibration mode. Compared with the harvester without bistability, the bistable harvester has a wider bandwidth and improved output power. The proposed nonlinear rotational energy harvester provides a practical solution to harness ambient rotation energy for low-power electronics.

Acknowledgments

References

[1] Briand D, Yeatman E and Roundy S 2015 *Micro energy harvesting* (John Wiley & Sons)
[2] Mitcheson P D, Yeatman E M, Rao G K, Holmes A S and Green T C 2008 *Proceedings of the IEEE* **96** 1457–1486
[3] Yeatman E M 2008 *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **222** 27–36
[4] Fu H and Yeatman E M 2015 *Applied Physics Letters* **107** 243905
[5] Fu H and Yeatman E M 2015 *Journal of Physics: Conference Series* **660** 012058
[6] Tang Q C, Yang Y L and Li X 2011 *Smart Materials and Structures* **20** 125011
[7] Jung S M and Yun K S 2010 *Applied Physics Letters* **96** 111906
[8] Harne R L and Wang K W 2013 *Smart Materials and Structures* **22** 023001
[9] Zhou S, Cao J, Erturk A and Lin J 2013 *Applied Physics Letters* **102** 173901