BROADBAND ROTATIONAL ENERGY HARVESTING USING BISTABLE MEACHANISM AND FREQUENCY UP-CONVERSION

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ABSTRACT

This paper presents the electromechanical dynamics of a broadband rotational piezoelectric energy harvester using bi-stability and frequency up-conversion. Bi-stability is achieved by the repulsive force between the tip magnet on a piezoelectric cantilever and a fixed magnet above the tip magnet. Frequency up-conversion is realized by the plucking force generated between the tip magnet and a rotating driving magnet below the tip magnet. A numerical model based on the distributed-parameter model was built in Matlab/Simulink. The power extraction capability of different modes of oscillation was analyzed theoretically. The keys to maintain harvester operation in high energy orbit (inter-well vibration) were investigated. The rotational energy harvester was implemented experimentally, showing a significant improvement in output power over a wide bandwidth compared to a harvester without bi-stability.

INTRODUCTION

With the development of micro-electromechanical system (MEMS), wireless communication and semi-conductor technologies, the power consumption of wireless sensing electronics has been reduced to a large extend [1]. The bottleneck of power supply caused by conventional batteries in many wireless sensing networks applications can, therefore, be overcome using energy harvesting technology by converting the ambient wasted passive energy sources into electricity. There are plenty of energy sources, such as temperature gradient, light, motion and fluid low, in the environment where sensor nodes are often installed. Among these energy sources, rotational motion is one of the common energy sources readily available in many domestic and industrial scenarios, including vehicle wheels [2], miniature air turbines [3], and rotation from human motion [4].

In many applications, the rotational frequency of this energy source varies in a wide range, e.g. car wheels. Therefore, energy harvesters should exhibit a wide band-width in order to exploit this energy source effectively. Different strategies for broadening operating bandwidth have been explored extensively in vibration energy harvesting, and these strategies can also be employed in rotational energy harvesting. Frequency tuning and bi-stability are two commonly adopted solutions to enhance the bandwidth. Aboulfotoh *et. al.* demonstrated self-tuning resonator for vibration energy harvesting [5]. The resonant frequency of the harvester was able to be tuned to the excitation frequency in a wide range using an active control method. Therefore, the performance is enhanced in this frequency range due to resonance. However, additional energy is dissipated by this active tuning method. Miller *et. al.* presented a passive frequency tuning method by adding a movable proof mass on a clamped-clamped piezoelectric beam [6]. The position of the proof mass can be self-adjusted according to the excitation frequency. The resonant frequency of the beam can, then, be matched to the excitation frequency over a wide bandwidth.

Bi-stability is another strategy to enhance the band-width. For bistable energy harvesters, the beam can oscillate between two stable positions, which creates higher vibration amplitude and velocity than those of linear harvesters. Therefore, the output power can be significantly increased. In addition, due to the nonlinear characteristics of bistable harvesters, such devices are usually effective over a broad frequency bandwidth. The bistable states are generally created by magnetic force [7], buckled beams by direct external force [8] or residual force from fabrication [9]. Ferrari *et. al.* reported a bistable energy harvester created by repulsive permanent magnets [7]. The harvester showed an improved performance in terms of power output and operating bandwidth compared to a linear harvester. Xu and Kim demonstrated a bistable buckled harvester using the residual stress generated during fabrication [9]. The device showed a wide operating range and a low excitation force requirement.

However, for rotational motions in real life, the operating frequency are generally below 100 Hz, but for energy harvesters on millimeter or micro-meter scale, their resonant frequency is generally more than hundreds of Hz. This issue cannot be addressed simultaneously by bistable mechanisms along with the bandwidth issue. Frequency up-conversion is a mechanism to convert the low excitation frequency to the high vibration frequency (transducer's resonant frequency). The motions between the harvester and energy sources are decoupled by this mechanism. The transducers are plucked by the low frequency motion by direct impact [10] or magnetic force [11]. Once energy is stored in the high operating frequency transducers, the transducers are released and vibrate freely at resonance.

In this paper, we present a piezoelectric rotational energy harvester with low operating frequency and broad bandwidth characteristics. Bi-stability and frequency up-conversion were employed and integrated in the harvester to fulfil the low excitation frequency and broadband requirements. The electromechanical dynamics of the harvester were examined theoretically in Matlab/Simulink using the distributed-parameter model. The dynamics of different oscillating modes of the harvester were analysed and compared. The dominant factors to keep the harvester operating with high power output were explored and discussed. The design was then verified experimentally. For the bistable harvester, the power output was improved over a wide bandwidth when the harvester operated in the periodic inter-well vibration mode.

DESIGN AND OPERATING PRINCIPLE

The schematic of the rotational energy harvester is shown in Fig. 1. A piezoelectric cantilever beam is fixed on a beam hold. A tip magnet is mounted on the free end of the beam as a proof mass. The tip magnet is excited by a driving magnet under the tip magnet. The driving magnet is installed on a rotating host which provides the rotational energy. The driving magnet plucks the piezoelectric beam via the tip magnet at the rotational frequency of the host. After each plucking, the piezoelectric vibrates freely at resonance. Frequency up-conversion is achieved by the tip magnet and driving magnet arrangement.

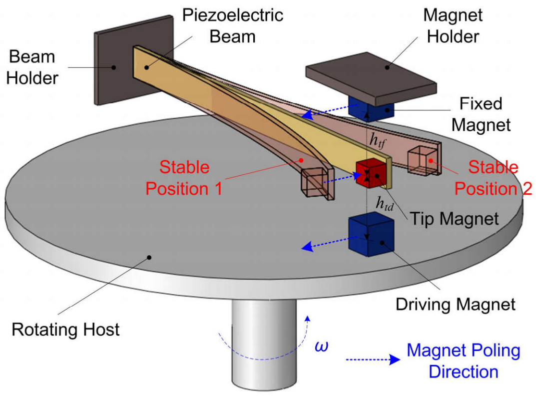

Figure 1: Schematic of the energy harvester with bi-stability and frequency up-conversion.

For bi-stability, another fixed magnet is introduced above the tip magnet. The fixed magnet is rigidly placed on a static host. The blue dotted arrows depict the magnet poling directions. The repulsive magnetic force between the fixed magnet and the tip magnet introduces two equilibrium positions of the piezoelectric beam. The transparent bended beams in Fig. 1 illustrate these stable positions. During operation, when the driving magnetic force is strong enough, the piezoelectric beam oscillates between these equilibrium positions, performing an improved vibration amplitude and velocity.

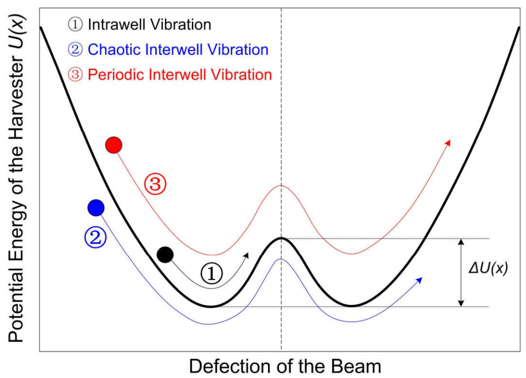

Figure 2: Illustration of different oscillating modes of the bistable energy harvester.

For bistable energy harvesters, there are normally three modes of oscillation, i.e. intrawell vibration, chaotic interwell vibration and periodic interwell vibration, as shown in Fig. 2. The potential wells in this figure are mainly determined by the magnetic coupling between the tip magnet and the fixed magnet. The shape of the function can be adjusted by changing the gap between the tip magnet and the fixed magnet (h_{tf} in Fig. 1). For a fixed gap, h_{tf}, the modes of oscillation can be determined by applying different initial plucking forces to the piezoelectric beam, which is indicated in Fig. 2 (different initial positions of the balls on the slope). This can be achieved by adjusting the gap between the tip magnet and the driving magnet (h_{td} in Fig. 1). Appropriate gaps (h_{tf} and h_{td}) should be chosen for the harvester to operate in the high energy orbit.

ELECTROMECHANICAL DYNAMICS OF THE BISTABLE HARVESTER

In order to understand the electromechanical dynamics of the harvester, a theoretical model was established based on the distributed-parameter model described in [3, 12]. The magnetic forces among these magnets were calculated using the theoretical model provide by Akoun and Yonnet [13]. The model was then solved in Matlab/Simulink.

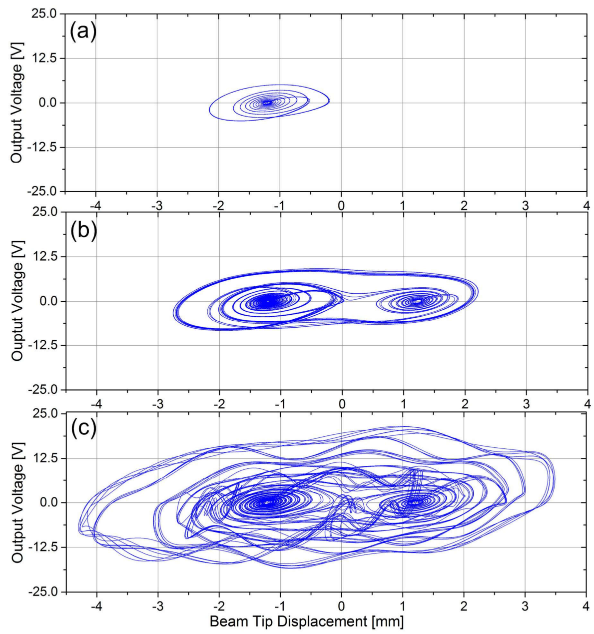

Figure 3: Voltage vs. tip displacement phase portraits of the harvester operating at different oscillating modes. (a) intrawell, (b) chaotic interwell and (c) periodic interwell.

Fig. 3 illustrates the voltage-tip displacement portraits of the harvester operating at different modes of vibration. In this calculation, h_{tf} was fixed and h_{td} was adjusted for different modes. It is evident that in the periodic interwell vibration case, the vibration amplitude and output voltage is much higher than those in the other cases. To achieve the periodic interwell vibration, the gap between the tip magnet and the driving magnet, h_{td}, should be reduced to get a higher driving force. However, the increased driving force would cause a higher stress on the cantilever, which increases the possibility of degradation of the piezoelectric material. Therefore, the gap between the fixed magnet and the tip magnet should be considered to alleviate the driving force requirement for periodic interwell vibration.

In order to further explore the dynamics of the periodic interwell vibration, the beam tip displacement, driving force and force for bistability were calculated and are depicted in Fig. 4. The driving force oscillates dramatically during the interaction between the tip magnet and the driving magnet. This is generated by the complicated relative motion between the vibrating beam and the rotating driving magnet.

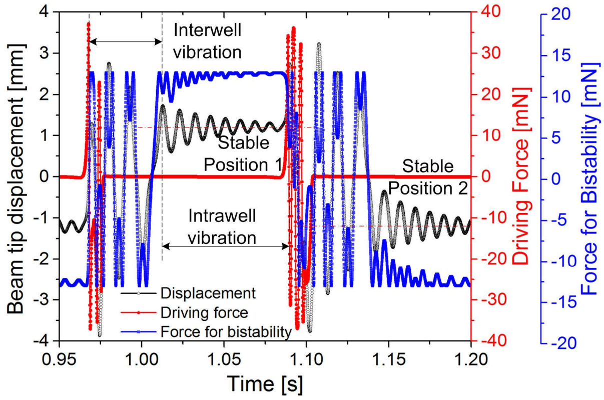

Figure 4: Simulated results: beam tip displacement, driving force and force for bistability in the case of periodic interwell vibration (h_{td}=2.05 mm and h_{tf}=2.7 mm).

From the beam tip displacement curve, we can see that the beam is plucked by the driving force and oscillates in the periodic interwell vibration mode for several cycles and then settles in one of the stable positions during which the remnant energy in the beam is fully dissipated. This cycle is repeated by another plucking from the rotating magnet. This figure clearly shows the combination of bi-stability and frequency up-conversion applied in this harvester.

EXPERIMENTAL VALIDATION

An experimental set-up was built to validate the design and theoretical analysis. The rotating motion was provided by a stepper motor (Phidgets 3303) whose speed can be controlled precisely by a management circuit. The driving magnet was mounted on a revolving host on the motor. A piezoelectric team with a tip magnet was placed above the driving magnet. The beam was clamped on a movable stage that can adjust the vertical position of the piezoelectric beam. Another magnet for bistability was place above the tip magnet on another stage. Then the gaps among these magnets can be all adjusted precisely.

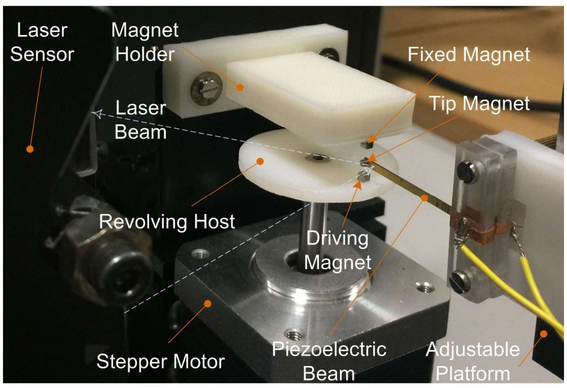

Figure 5: Experimental set-up of the rotational harvester.

A laser detector was installed to measure the tip displacement of the piezoelectric beam. The piezoelectric beam was connected with a 180 kΩ resistive load. Table 1 summarizes the key parameters of the rotational energy harvester.

Table 1: Parameters of the rotational energy harvester.

Symbol	Description	Value
$L \times W \times H$	Piezoelectric beam size	33.5 × 2 × 0.25 mm
$A \times B \times C$	Size: Driving and fixed magnet	1.5 × 1.5 × 1.5 mm
$a \times b \times c$	Size of the tip magnet	1 × 1 × 1 mm
r_m	Rotation radius of driving magnet	12 mm
B_r	Remnant flux density of magnets	1.17 T
$\bar{e}_{31}$	Piezoelectric constant	-22.2 V·m/N

RESULTS AND DISCUSSION

Fig. 6 shows the output voltage and tip displacement of the bistable harvester operating in the periodic interwell vibration mode. The piezoelectric beam is plucked by the driving magnet at a low frequency (10.5 Hz), whereas the piezoelectric beam vibrates at a high frequency (87.5 Hz). This illustrates the operating principle of frequency up-conversion.

During each plucking cycle, the tip displacement varies over two equilibrium positions for the first four vibration cycles periodically (periodic interwell vibration) and then settles into one equilibrium position with the vibration amplitude significantly reduced (intrawell vibration). This means the vibration in each plucking cycle is the combination of periodic interwell vibration and intrawell vibration.

This combined characteristic of periodic interwell and intrawell vibration in one excitation cycle also decouples the connection between the beam vibration and the rotational energy source. The beam is fully damped before for one plucking cycle, before the second plucking force appears. Therefore, there is no interference between the beam vibration and the excitation from the driving magnet at low frequency. The performance variation of bistable beams during frequency sweep-up and sweep-down tests [9] is avoided in this bistable energy harvester design using frequency up conversion.

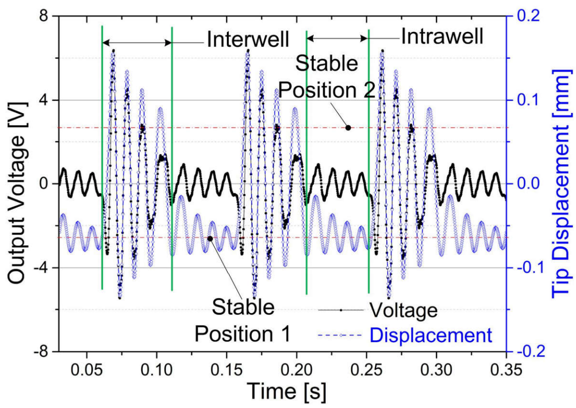

Figure 6: Experimental results: Output voltage and tip displacement, showing the bi-stability of the harvester under tip excitation (load: 180 kΩ).

For bistable beams, the performance of different oscillating modes varies significantly. Fig. 7 shows the RMS output power of rotational energy harvesters for four different operating conditions. It is shown that the performance of the bistable energy harvester is not always better than that of the harvester without bistability. For intrawell and chaotic interwell vibration, the vibration amplitude of the harvester is limited by the repulsive force from the fixed magnet. The 'snap-through' behavior between two equilibrium positions in the periodic interwell vibration does not happen in the other oscillating modes.

However, compared to the linear harvester without bistability, the bistable harvester operating in the periodic interwell vibration mode has an improved output power over a wide frequency range (10 Hz) at low frequency (<15 Hz). Therefore, the bistable harvesters should be designed properly to operate in the periodic interwell vibration mode in order to harness rotational energy effectively.

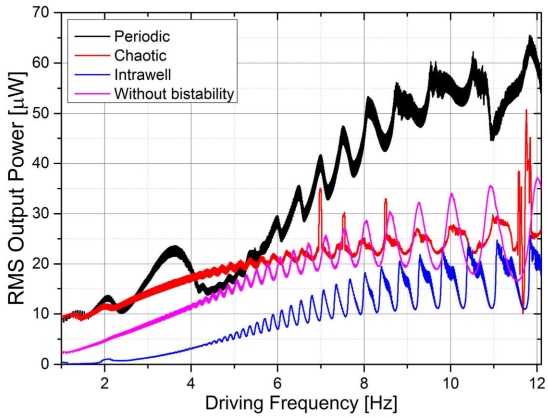

Figure 7: Experimental results: Frequency respond of the harvester under different vibration modes.

CONCLUSIONS

This papers presents a piezoelectric rotational energy harvester with the characteristics of low frequency (<15 Hz) and wide operating bandwidth (> 10Hz). In this design, bi-stability and frequency up-conversion mechanisms are combined in order to increase the bandwidth and to lower the operating frequency requirement.

Frequency up-conversion is achieved by magnetic plucking of a cantilever beam using a rotating driving magnet. Bi-stability is implemented by introducing a fixed magnet above the tip magnet on the beam. The repulsive force between the tip magnet and the fixed magnet creates two equilibrium positions of the beam.

The electromechanical dynamics of the harvester were examined theoretically with the consideration of key design parameters and the harvester's performance. The harvester under periodic interwell vibration has the best performance. The gaps among these magnets are critical to determine the operating modes of the beam.

An experimental validation was carried out, showing the improved performance of the harvester over a wide bandwidth at low frequency. Compared to vibration bistable energy harvesters, this rotational bistable energy harvester is insensitive to frequency sweep-up and sweep-down operation due to the combination of periodic interwell vibration and intrawell vibration during one excitation cycle. This present rotational harvester can be adapted to many wireless sensing applications, including structure health monitoring, tire pressure monitoring, and even human activity tracking.

ACKNOWLEDGEMENTS

The work is supported by the Department of Electrical and Electronic Engineering, Imperial College London and the China Scholarship Council (CSC).

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