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Experimental investigation of non-linear multi-stable electromagnetic-induction energy harvesting mechanism by magnetic levitation oscillation

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HIGHLIGHTS

- A multi-stable electromagnetic-induction energy harvesting system is proposed.
- Detailed device construction and experimental techniques are revealed.
- Bifurcation, high-energy orbits, and chaotic motions are experimentally investigated.
- Algorithm for stroboscopic illustration of bifurcation diagram is elaborated.
- The device delivers a root-mean-square current of 80.15 mA and power of 400.98 mW.

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ABSTRACT

The objective of this study is to present a multi-stable electromagnetic-induction energy harvesting (MEH) system by magnetic levitation oscillation. The MEH system has a non-linear restoring force and a multi-well restoring force potential, offering an improvement upon their linear counterparts by broadening its frequency response. This paper presents the mechanics of the electromagnetic-induction MEH system and describes the multi-stable mechanism by magnetic levitation oscillation. Experimental investigations reveal phenomena of dynamical bifurcation, escape from potential wells, high energy orbits, and chaotic oscillation. Two quad-stable and one tri-stable configurations are experimentally achieved and analyzed by means of phase portraits, Poincaré section, largest Lyapunov exponent, and bifurcation diagram. Algorithm of stroboscopic illustration of bifurcation diagram is elaborated. The results indicate that the electromagnetic-induction MEH system by magnetic levitation oscillation can be utilized to create a multi-well restoring force potential and increase the output current (i.e. electrical load capacity) of energy harvesters.

1. Introduction

A "seismic" energy harvester is designed to generate electrical energy from local variations in ambient vibrations. Amongst a myriad of energy harvesting mechanisms, the most popular ones include electrostatic [1], electromagnetic [2], and piezoelectric energy harvesters [3]. Earlier studies focused mostly on linear oscillators, which work well only when the excitation frequency equals or nears the natural frequency of the system; however, the ambient vibration is always variable and distributed over a wide spectrum [4].

Non-linear energy harvesting studies have therefore been conducted to broaden the usable bandwidth of linear counterparts, including mono-stable [5], impact [6,7], bi-stable [8], and tri-stable [9] oscillator approaches. The bi- and tri-stable oscillators are characterized by the double-well or tri-well restoring force potential and periodic inter-well vibrations (i.e. high energy orbits). It has been recognized that inducement of high energy orbits is a means to dramatically improve energy harvesting performance [10].

The classical concept of bi- and tri-stable oscillators is commonly realized by a magnetic repulsion or magnetic attraction harvester. The device consists of a cantilevered ferromagnetic beam with piezoelectric patches, and the beam carries a permanent magnet at its tip [11–14]. Recently, quad-stable [15,16] and quin-stable [17,18] energy harvesters are presented and their mechanics are also based on the classical form of cantilevered piezoelectric beam with a tip magnet. The quad-stable configuration has three fixed magnets and the nonlinearity is induced by the magnetic repulsion force; whereas the quin-stable one has two fixed magnets and a quin-stable parameter region exists for

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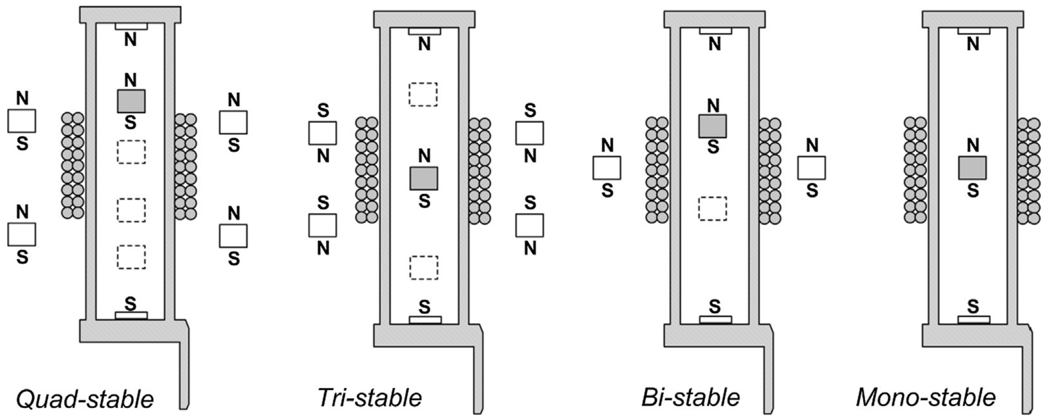

Fig. 1. Illustration of quad-, tri-, bi-, and mono-stable configurations by magnetic levitation.

specific geometry relation between tip magnet and additional fixed magnets.

For above configurations, these additional fixed magnets are placed symmetrically on either side of the beam. The non-linear behavior of the system is determined by the geometry, positions, and properties of these magnets. Although the non-linear restoring force potential is created by the magnetic repulsion or attraction, the system is in essence a piezoelectric energy harvester. The common limitation of piezoelectric energy harvesters is that the piezoelectric materials have a very large internal resistance, that is, it requires a load resistance at the same level (e.g. from 6×10^4 Ω in [14] to 10 MΩ in [18]) to achieve an optimum power output, so the deliverable current is quite low (normally less than 1 mA), while the common electronic circuit or sensors need a workable input current of 10 mA to 50 mA. Therefore, the characteristic of piezoelectric materials limits its electrical load capacity.

Mann and Owens [19] presented an electromagnetic-induction energy generator that directly powers an electrical load. The generator contains a moving suspended magnet and several static outer magnets, whose magnetic interaction created a bi-stable potential well. The advantage of electromagnetic energy harvesters over piezoelectric counterparts is that it can generate enough power at low-frequency range and can be mass-produced with affordable expenses, which fit the requirement in the mechanical industry [20,21].

However, the multi-stable (i.e. tri-stable and quad-stable) electromagnetic-induction energy harvesting has not been studied. First, the multi-stable mechanism of the electromagnetic-induction energy harvesting by magnetic levitation has not been elaborated. Secondly, the detailed device construction and the experimental techniques of the multi-stable electromagnetic-induction energy harvesting system have not been presented. Thirdly, the experimental phenomena and complicate dynamic behavior of the multi-stable electromagnetic-induction energy harvesting system have not been illustrated. Last but not least, the power, electrical loads capability, frequency bandwidth, and application potential of the multi-stable electromagnetic-induction energy harvesting system have not been described. Therefore we cannot make a fair comparison between multi-stable electromagnetic-induction and multi-stable piezoelectric energy harvesting system. These research questions set the main motivations of this paper.

In this paper, we present a multi-stable electromagnetic-induction energy harvesting (MEH) system and conduct an experimental investigation. The novel contribution and features of the present study are: (1) Different from the existing research approaches of multi-stable piezoelectric cantilevered beam energy harvesting system (i.e. use magnetic attraction or repulsion force to create a multi-stable potential well and use piezoelectric patches to harvest energy), this paper proposes a novel electromagnetic-induction energy harvesting system (i.e. use magnetic levitation interaction to create a tri- or quad-stable potential well and use electromagnetic-induction to harvest energy); (2) multi-stable i.e. quad-stable and tri-stable potential wells are realized by different configurations of the proposed MEH, and the tri-stable and quad-stable electromagnetic-induction energy harvesting system are for the first time experimentally achieved; (3) detailed device construction and experimental techniques of multi-stable electromagnetic-induction energy harvesting system are revealed; (4) bifurcation, high-energy orbits, and chaotic behaviors of quad- and tri-stable electromagnetic-induction MEH systems are experimentally investigated; largest Lyapunov exponent is calculated based on the experimental data; algorithm of stroboscopic samples is elaborated, which offers an intuitive illustration of bifurcation diagram; (5) In comparison to the multi-stable piezoelectric energy oscillators, the proposed electromagnetic-induction MEH system can deliver higher output current (i.e. electrical load capacity); a RMS current of 80.15 mA and RMS power of 400.98 mW are obtained, which is suitable for directly powering common sensor nodes.

The work of this paper is organized as follows. Section 2 presents the mechanics of electromagnetic-induction MEH system by magnetic levitation oscillation. It gives a physical description of the multi-stable mechanism and describes the calculation methods that are used to illustrate the non-linear restoring force and potential well. Section 3 gives the methods and setup of the experimental test, including detailed laboratory techniques, geometries, parameters, and configurations of the MEH system. Section 4 shows experimental results that phenomena of bifurcation, periodic inter-well vibrations, and chaotic behaviors are observed. Algorithm of stroboscopic samples is elaborated. Discussions are made and conclusions are drawn thereafter.

2. Design of MEH by magnetic levitation oscillation

2.1. Multi-stable mechanism by magnetic levitation oscillation

Magnetic levitation mechanism is used to present the multi-stable phenomena as shown in Fig. 1. The shaded rectangular stands for the moving magnet that is suspended inside the tube, it could have several stable states as depicted by the dashed rectangular. The rectangular with solid lines represents the outer static magnets, whose quantities and magnetization direction are adjustable to create a MEH system with multi-stable potential wells. The coils are placed between the moving and static magnets; therefore a two-layer con-central tube structure is envisaged by fixing the coils to the inner tube and attaching the static magnets to the outer tube. The advantage of magnetic levitation approach is: (1) up to quad-stable configuration can be easily realized by very compact device design by adjusting the magnetization N-S direction; (2) compared with the setup of cantilevered beams, the magnetic levitation device is much more robust from the viewpoint of mechanical engineering.