Mechanical Systems and Signal Processing 85 (2017) 591–600

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Systematic parameter study of a nonlinear electromagnetic energy harvester with matched magnetic orientation: Numerical simulation and experimental investigation

Wei Deng, Ya Wang*

Department of Mechanical Engineering, Stony Brook University, Stony Brook 11790, USA

ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form
26 August 2016
Accepted 1 September 2016

Keywords:
Tristable nonlinear electromagnetic energy harvester
Matched magnetic orientation
Systematic parameter analysis

ABSTRACT

This paper reports the systematic parameter study of a tristable nonlinear electromagnetic energy harvester for ambient low-frequency vibration. Numerical simulations and experimental investigations are performed on the harvester which consists of a cantilever beam, a tip coil, two tip magnets and two external side magnets. The external side magnets are deployed symmetrically along a concave surface parallel to the trajectory of the cantilever tip with a controllable distance so that the magnetic orientation of the tip magnets are matched with that of the side magnets. Therefore, instead of the ternary position parameters (d, h, α), a binary parameters pair (d_0, d) is used to characterize the position of the side magnets and the performance of the energy harvester. The magnetic force and magnetic field on the cantilever tip therefore depend on the relative distance in the tip displacement direction between the tip magnets and side magnets, but is independent of the position of the side magnets on the concave surface. The magnetic force (field)-distance relationship is measured experimentally and curve fitted to obtain explicit expressions, in order to characterize the magnetic force (field) when the side magnets are placed at varied positions along the concave surface. Numerical simulation is, then, performed to predict the electromagnetic voltage output and the bandwidth of the energy harvester. The simulation results coincided with the measured data. Significant broadband response is obtained experimentally and the maximum RMS power output is 40.2 mW at 0.45g of excitation. The proposed structure showcasing the matched magnetic orientation is characterized by the binary parameters pair (d_0, d) and the systematic parametric approach could contribute to the design and study of nonlinear broadband energy harvesters.

1. Introduction

Low-frequency vibrational energy is widely available in an ambient environment and could be harvested to power remote microsystems. The most prolific structure consists of a cantilever metallic beam with harvesting units, such as piezoelectric or electromagnetic transducers. With high voltage but small current output, piezoelectric transducers have been theoretically and experimentally studied over the past couple of decades [1–6]. On the contrary, one may prefer

---

* Correspondence to: Department of Mechanical Engineering, State University of New York, Stony Brook, NY, USA.
E-mail address: ya.s.wang@stonybrook.edu (Y. Wang).

http://dx.doi.org/10.1016/j.ymssp.2016.09.002

electromagnetic transducers when a low voltage but large current output is required in the application [7–9]. In addition to the conversion mechanism, bandwidth limitation is a more pressing issue since the ambient vibrational energy is either distributed over a wide spectrum of frequencies or the dominant frequency slowly drifts away with respect to time. The application of a linear energy harvester (LEH) is thus limited, as its efficiency will drop substantially in the event that the excitation frequency slightly mismatches its fundamental resonant frequency. One promising solution is to apply external design elements that introduces a nonlinear magnetic force to the LEH, modifying the restoring force and the potential energy profile, in order to obtain a broadband response of a nonlinear energy harvester (NEH). For example, the nonlinear stochastic oscillation of a noise activated energy harvester could enhance the power output performance by about 200% compared to its standard LEH counterpart in terms of the power output [10,11]. The performance superiority of a nonlinear piezomagnetoelastic energy harvester (consisting of a ferroic beam with external magnets) as a high-energy large orbit attractor has been experimentally and theoretically proven [12]. A vibrational power flow analysis approach has been adopted to assess the long-time behavior of a nonlinear system exhibiting either periodic or chaotic motions [13]. A thorough investigation of a bistable piezoelectric inertial generator has also been carried out to study the favorable nature of strange nonlinear chaotic motions [14]. It has been revealed that it is possible to define the minimum excitation variance that enhances the harvested energy for a given bistable piezoelectric generator [15].

Another NEH configuration proposed by Stanton et al. consists of two magnets attached at the end of the cantilever beam and two external side magnets deployed symmetrically [16]. With properly designed position parameters (transverse displacement d, and longitudinal displacement h) of the side magnets, the proposed NEH is capable of harvesting energy more efficiently than a LEH from excitations with a slow-frequency drift around its respective dominant resonance in a softening or a hardening configuration. Later on, Zhou et al. introduced another position parameter, angular orientation α, which could be adjusted by rotating the side magnets to achieve broadband response at different center frequencies [17]. The NEH could be designed as bistable or tristable by choosing different values for the position parameters (d, h, α), with the tristable NEH demonstrating a better output performance [18]. With the same configuration, a shallower potential well depth is testified to produce a wider bandwidth and a higher harvesting efficiency under low-frequency excitation [19]. Study also shows that compared with a bistable NEH, the tristable NEH could achieve inter-well oscillations at a lower frequency threshold but create a dense and high output power at a low intensity of stochastic excitation [20]. More recently, this configuration with nonlinear time-varying potential is applied to harvest energy from the walking motion of human beings [21,22].

The typical configuration of the aforementioned NEH could produce a monostable, bistable or tristable response depending on the position parameters (d, h, α) of the side magnets. The position parameters are extremely important because they determine the restoring force and feature the nonlinear magneto-elastic interaction. However, work in the (referenced) literature often investigates the position parameters (d, h, α) independently. Moreover, the restoring force is usually measured from multiple experiments and then curve fitted as polynomial functions [17–19,23] for numerical simulation, which is time-consuming to numerate values for (d, h, α) separately and to measure the restoring force in correspondence to each set of values of (d, h, α). Although theoretical formula of the magnetic force could be derived based on the magnetic dipole model [10,14,24], this approach is difficult to implement when the configuration of the harvester is complex, due to the fact that when applying three dimensional magnetic interactions, the model does not take into account the shape of the magnet as well.

In this paper, the typical configuration is modified to construct a nonlinear electromagnetic energy harvester (EMEH) where the magnetic orientation of the tip magnets matches that of the side magnets by positioning the side magnets along a concave surface parallel to the motion trajectory of the cantilever tip, and the position parameters (d, h, α) are studied interdependently. The transverse displacement d is selected as the primary parameter, the longitudinal position h and the angular orientation α are then determined simultaneously, therefore, a binary parameters pair (d_0, d), instead of the ternary position parameters (d, h, α), is used to characterize the position of the side magnets and the performance of the EMEH, where d_0 is the distance between the concave surface and tip trajectory. The magnetic force and the magnetic field on the cantilever tip only depend on the relative distance in the tip displacement direction between the tip magnets and side magnets due to the matched magnetic orientation in the proposed structure. The corresponding restoring force and the magnetic field at varied values of d are calculated based on the measured magnetic force (flux)-distance relation. A systematic parameter analysis and a numerical study are then performed based on the electromagnetic governing equation and the results coincided with the measured data. The optimal power output (RMS) is also measured to verify the energy harvesting capability of the proposed nonlinear EMEH.

2. Structure of the nonlinear EMEH

The schematic diagram of the proposed nonlinear EMEH is illustrated in Fig. 1(a). It consists of an aluminum cantilever beam with a coil and two magnets (K&J Magnetics, 12.7 mm × 6.35 mm × 6.35 mm) at the tip. Two external magnets (K&J Magnetics, 25.4 mm × 19.7 mm × 12.7 mm) are positioned symmetrically at two sides along an aluminum concave shim. The trajectory of the tip is measured and the aluminum shim is made to have the same curve shape as the tip's trajectory so that the magnetic orientation of the tip magnets is normal to the aluminum shim and it is parallel to the orientation of the side magnets when the tip magnets face the side magnets. A photo representation of the nonlinear EMEH is presented in