



Design and development of a parametrically excited nonlinear energy harvester



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ABSTRACT

An energy harvester has been designed, fabricated and tested based on the nonlinear dynamical response of a parametrically excited clamped-clamped beam with a central point-mass; magnets have been used as the central point-mass which pass through a coil when parametrically excited. Experiments have been conducted for the energy harvester when the system is excited (i) harmonically near the primary resonance; (ii) harmonically near the principal parametric resonance; (iii) by means of a non-smooth periodic excitation. An electrodynamic shaker was used to parametrically excite the system and the corresponding displacement of the magnet and output voltages of the coil were measured. It has been shown that the system displays linear behaviour at the primary resonance; however, at the principal parametric resonance, the motion characteristic of the magnet substantially changed displaying a strong softening-type nonlinearity. Theoretical simulations have also been conducted in order to verify the experimental results; the comparison between theory and experiment were within very good agreement of each other. The energy harvester developed in this paper is capable of harvesting energy close to the primary resonance as well as the principal parametric resonance; the frequency-band has been broadened significantly mainly due to the nonlinear effects as well as the parametric excitation.

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1. Introduction

Due to increased demands for energy and current limitations of batteries, a future prospective technology is motion based energy harvesters (MBEHs) that convert kinetic energy into electrical energy [1]; this type of energy harvester has the potential to be used in powering electronic devices in hostile or remote environments—another benefit of MBEH devices is that they reduce pollutants in the environment which are left behind when batteries are disposed.

Transduction mechanisms used to convert kinetic energy into electrical power can be grouped into *three* main categories. The first category uses piezoelectric conversion, which converts mechanical strain into electrical energy; for instance, Adhikari et al. [2] numerically investigated motion based energy harvesting under broadband excitation using a stack configuration of piezoelectric energy harvesters—expressions were derived for the non-dimensional time constant, electromechanical coupling coefficient and viscous damping factor. Renno et al. [3] investigated into the

optimised power that can be harvested using a piezoelectric converter; using the Karush-Kuhn-Tucker technique, the power can be substantially enhanced by using an optimal inductor in the load circuit. Fan et al. [4] numerically and experimentally investigated the performance of a bi-directional nonlinear piezoelectric energy harvester; to achieve a nonlinear frequency-voltage curve two embedded magnets were used inducing a nonlinear stiffness—results showed that the bi-directional energy harvester was more effective than its linear counterpart. Fan et al. [5] designed a piezoelectric based energy harvester that could effectively harvest energy from sway and bi-directional motions; using a cantilever beam, frame and roller a frequency-up conversion mechanism was also achieved—results showed that the output voltage could be enhanced by increasing the sway frequency. Guan and Liao [6] recently developed a piezoelectric energy harvester for rotational motion; a theoretical model was developed for the power output and experimental results showed good agreement with the theory. The *second* category of ambient motion energy harvesting transduction mechanisms are electrostatic conversion, where capacitive plates fluctuate inducing a voltage; for example, Bu et al. [7] fabricated a non-resonant wideband micro-energy harvester using electrostatic conversion—to boost low frequency

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excitations, a parallel structure was used to double the output voltage. The *third* mechanism that can be used to convert ambient kinetic energy into electrical power is electromagnetic induction (EMI), where the relative motion between a magnet and coil generates a backward electromotive force (EMF). For instance, Sardini and Serpelloni [8] developed a low frequency energy harvester using polymeric material, due to their low Young's modulus; a theoretical and experimental investigation was conducted—results showed that a small increase in bandwidth could be achieved with this design. Marin et al. [9] fabricated a linear electromagnetic energy harvester with a four Hertz bandwidth using four cantilever beams with closely related natural frequencies. Ooi and Gilbert [10] designed a novel wideband electromagnetic energy harvester using dual resonating cantilever beams; a numerical model was done using MATLAB-Simulink; dual energy harvested peaks were observed resulting in a slight increase in the devices bandwidth. Recently, Siddique et al. [11] presented a comprehensive review of micro-power generators using electromagnetic and piezoelectric energy harvesters; a significant review of recent motion based energy harvesters were compared to each other.

A major drawback with conventional MBEHs is the effective operating frequency range which energy can be harvested; in practical applications, where the excitation frequency is changing or varying with time, precisely matching the natural frequency of a device is crucial for operation and can be achieved with tuning techniques [12]. There are two main classes for MBEH devices based on the core element being used; the first class employs *linear* resonators and the second class uses *nonlinear* resonators.

For the *first* class, i.e. the *linear* energy harvesters, the maximum energy harvested is achieved when the excitation frequency matches the primary natural frequency of the core element in the MBEH device. The literature regarding this class is quite large. For instance, Williams and Yates [13] first investigated the use of external resonating devices for powering micro electrical mechanical systems (MEMS); this work was further theoretically extended by Mitcheson et al. [14] for three different damping based resonators. Stephen [15] theoretically investigated the potential of linear MBEH devices for direct mass and base excitations, including the coupling between mechanical and electrical domains. Shahrz [16] developed a multimodal array based on transversely excited cantilever beams with different geometries and tip masses; the results showed that the combination of these linear energy harvesters could achieve a larger bandwidth, however, the required circuitry was more complex. Tang and Zuo [17] theoretically analysed dual mass linear resonators to widen the bandwidth of MBEH devices; dual mass devices could have two local optimums which can further increase the bandwidth of the device. Erturk and Inman [18] further investigated transversely excited linear cantilever beams with piezoelectric bimorph layers, using Euler-Bernoulli beam theory for use as an energy harvester. Leland and Wright [19] designed a linear MBEH device that could be tuned with compressive axial preloading further extending the operating bandwidth of the energy harvester; other tuneable linear resonators based on preloading mechanisms for energy harvesters have also been developed for example in [20].

The *second* class of MBEHs can be divided into *two sub-classes*, there are: energy harvesters whose core elements are either *transversely* excited or *parametrically* excited; for the transversely excited system, there is a large volume of available literature. For instance, Mann and Sims [21] fabricated a nonlinear energy harvester based on the transverse oscillation of a levitated magnet; a perturbation technique known as the method of multiple scales was employed to derive the theoretical frequency response curve—experimental and theoretical results were within good agreement. Maiorca et al. [22] and Liu et al. [23] fabricated MBEH devices utilising mechanical stoppers in which both devices

showed nonlinear energy extraction near the primary resonance. Sebald et al. [24] analysed the effects of magnetically induced nonlinearities in transversely excited cantilever beams with piezoelectric layers experimentally. In general, bi-stable energy harvesters have a broader bandwidth [25] and the energy harvested is not influenced under white noise [26].

The literature on the *second* sub-group (of the second class), which are *nonlinear* energy harvesters based on *parametric* excitations of their core elements, is not extensive; for example, Abdelkefi et al. [27] theoretically investigated a parametrically excited cantilever beam for energy harvesting purposes using the Galerkin discretisation and the method of multiple scales; the modelling also includes geometric, inertial and piezoelectric nonlinearities. Daqaq et al. [28] investigated the applicability of parametric energy harvesting with large emphasis on the theoretical model using a perturbation technique; experiments were also conducted on a cantilevered beam with a tip mass—this system showed a *weak* softening-type nonlinearity in the vicinity of the principal parametric resonance.

In this paper, for the first time, an energy harvester has been developed and tested experimentally based on the nonlinear dynamical behaviour of a *parametrically excited beam carrying a point-mass* as the core element subject to a magnetic field. The experiments showed that the fabricated device has an *extended bandwidth* for effectively harvesting kinetic energy; in particular, at the principal parametric resonance, the device displays a *strong* softening-type nonlinearity at higher frequencies which is used to further maximise the frequency band-width and hence kinetic energy harvested from the device—the device harvests energy at *both* the primary and principal-parametric resonances. The energy harvester designed based on *parametric excitation* is shown to *harvest energy over larger frequency bands* due to the qualitative and quantitative changes in the *nonlinear dynamical behaviour* of the core element. The paper has been organised as follows: a description of the system including the fabricated device, background theory and experimental procedure are developed in Section 2; the experimentally obtained results for the fabricated energy harvester are acquired and discussed in detail in Section 3. Theoretical verifications are provided in Section 4. Section 5 ends with concluding remarks.

2. System description and experimental procedure

This section describes the specifications of the energy harvester fabricated using a parametrically excited beam carrying a concentrated mass as the core element as well as the experimental setup and data recording and analysing system.

2.1. System description

The system shown in Fig. 1 is the core element of an energy harvester with a parametrically excited beam carrying a point-mass as the core element; one of the clamps is fixed while the other is a moveable support in the longitudinal direction. An aluminium beam with length L , width b and thickness h has dimensions of 160, 12, 0.6 mm, respectively; a magnet has been attached to either side of the centre of the beam with a net weight of 0.0196 kg (m) (as the concentrated mass). A coil was used as the transduction method to convert the dynamic motion into the electrical energy through electromagnetic induction (EMI); the coil consisted of 600 tightly wound turns and had an internal resistance of 2.7 Ohms. The open-circuit voltage was measured during the experiments when the shaker was exciting the energy harvester (see Fig. 2); the moveable support was achieved by using linear bearings.

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