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A bistable electromagnetic micro-power generator using FR4-based folded arm cantilever☆

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ABSTRACT

This paper discusses a wideband, bistable vibrational micro-power generator using a folded cantilever beam. At an acceleration of 0.5 g (35 Hz frequency) the device generated a peak power of 22 μW across an optimum resistive load of 1 kΩ. The half-power bandwidth of the nonlinear bistable device was increased by 5 Hz (15% of the peak power frequency) with respect to the linear counterpart. The choice of FR4 as the structural material and the utilization of a folded cantilever design are aimed at achieving a low operational frequency within a relatively small footprint. The bistable mechanism which is introduced into the system by means of a magnetic force between a pair of repulsively positioned NdFeB permanent magnets was analytically modelled, numerically simulated and successfully validated with experimental results. The wideband frequency response is further experimentally modified by adjusting the gap between the repulsive magnets. The effect of the depth of the bistable potential well on the performance of the vibration energy harvester at low to medium accelerations is also validated numerically and experimentally.

1. Introduction

Low power electronic devices and wireless sensor nodes (chemical, mechanical, optical, environmental and biological sensors), wearable electronic devices and medical biosensor chips will have momentous impact on the development of smart buildings, smart cities, environmental monitoring, surveillance and security systems and healthcare [1,2]. The realization of the full potential of such systems requires these devices to be autonomous and self-reliant regarding power, which necessitates the exploration beyond conventional limited lifetime energy sources such as batteries. Mechanical vibrations, due to their ubiquity in the modern urban and industrial landscape, provide a viable energy source to power the wireless sensor nodes perpetually. Hence, the generation of electrical energy from the ambient mechanical vibrations to power such low power devices is an attractive option [3]. Whilst the topic of vibrational energy harvesting (VEH) has been extensively investigated over the last few years, most of the reported linear resonance based VEHs have a very narrow range of operational frequency [4–6]. However, real vibration sources (cars, washing machines, HVAC systems, motors, industrial machinery, human movements, etc.) usually produce vibrations across a wide range of frequencies. To harness energy from the broad spectrum of vibration frequencies, Hu et al. [7] discussed the possibility of broadening the frequency response of VEHs by utilizing inherent material and geometric nonlinearities effected by large deformations. Later, a micro-electromagnetic VEH, proposed by Beeby et al. [4], demonstrated a nonlinear response for certain excitation frequency ranges. While the nonlinear behaviour reported by Hu et al. [7] and Beeby et al. [4] was due to inherent mechanical and material properties, Burrow and Clare [8] and Barton et al. [9] intentionally introduced a nonlinearity by interaction of moving magnets and a high permeability core. This configuration gave a broad frequency response. Subsequently, several other researchers have proposed novel methods of introducing nonlinearities into vibrational energy harvesters [10–13]. Mann and Sims [10] exploited the nonlinear forces due to magnetic levitation and demonstrated bandwidth widening through a hardening frequency response, and, Masana and Daqaq [11] used an axially loaded piezoelectric beam to achieve an increase in power and bandwidth. In another approach of intentionally introducing nonlinearities, Marinkovic and Koser [12] and Mallick et al. [13] explored a cubic nonlinear restoring

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force as a result of the large deformations of clamped–clamped beams.

The VEHs investigated in [7–13] were monostable, i.e. the oscillator possesses only one stable state. Another type of nonlinear VEH systems widely studied are bistable oscillators, which possess two stable states. Some of the earliest bistable energy harvesting systems, based on bistable Duffing oscillators, were reported by Cottone et al. [14] and Erturk et al. [15]. Cottone et al. exploited the dynamical features of a stochastic nonlinear bistable oscillator activated by noise and evaluated the performance to be superior to that of the linear counterpart [14]. A piezomagnetoelastic device consisting of a ferromagnetic cantilever and piezoceramic laminates was developed by Erturk et al. [15]. They observed large amplitude periodic oscillations for excitations over a range of frequencies. The piezomagnetoelastic generator achieved a 200% increase in the open-circuit voltage amplitude in comparison to the conventional case where no magnetic buckling was applied. Following the initial works by Cottone et al. and Erturk et al., bistable VEHs have been investigated by several other researchers [16–26]. While most of the studies suggest an improvement in performance of bistable VEHs over their linear and monostable counterparts, it is also noted that this performance enhancement occurs only under certain types or levels of harmonic excitation. Stanton et al. [16] and Erturk and Inman [17] observed that bistable VEHs are advantageous over their linear counterpart when they can perform large amplitude inter-well oscillation. In this scenario, the bistable VEHs can generate substantially larger power output over a wider bandwidth in comparison to an equivalent linear VEH. Generally, the large amplitude high energy branch of frequency response is accompanied with small amplitude low energy branches. Similar findings were also reported by other groups for different system configurations [18–20] emphasizing the complicated nature of voltage response generated by bistable VEHs. While working on a bistable piezoelectric buckled beam, Masana and Daqaq [21] noted that a much higher level of harmonic excitation was needed to induce the high energy cross-well oscillation when the potential wells are deep. In a later study, Sneller et al. [22] reported that with the addition of a lumped mass at the centre of the buckled beam, the cross well dynamics of the beam could be excited at a much lower level of acceleration. Cottone et al. [23] compared the performance of an electromagnetic VEH configured as an unbuckled and buckled beam. They demonstrated while the power generated by the unbuckled beam was higher than that of the buckled beam, the bandwidth associated with the buckled beam was much wider than the unbuckled configuration. MEMS based bistable VEH systems were developed and studied by Ando et al. [24] and Cottone et al. [25,26], reporting improvements in the harvested power and frequency bandwidth in comparison to the linear counterparts.

In this work, we study the effect of the depth of the potential well on the performance of an electromagnetic bistable VEH in a low frequency (10–40 Hz) and low acceleration (0.2–0.6 g) vibration environment. In order to harvest vibration energy from low frequency vibrations FR4 (PCB material, Young's modulus ∼21 GPa) has been chosen as the structural material for the oscillator. A folded-arm cantilever structure is designed for the oscillator, reducing even further the linear resonance frequency, while keeping the device footprint (11 mm × 22 mm) relatively small. Piezoelectric transduction is the most widely employed transduction mechanism for the reported bistable energy harvesting devices. However, due to the very high internal impedance of piezoelectric materials the resulting output current is very low. Also, the brittleness and degradation of piezoelectric materials over time adversely affect the long-term performance and reliability of piezoelectric transduction. The reported device circumvents the issues posed by piezoelectric transduction by implementing electromagnetic (EM) transduction. The device has been analytically modelled and numerically simulated across a range of excitation conditions. The simulation results have been validated against experimental results from extensive measurements using the fabricated device. In particular, we study the dependence of the power–frequency response and Q-factor of the device on the potential well profile to demonstrate that under low to medium excitation levels, a shallower bistable potential well is preferable from an energy harvesting point of view.

The paper is structured into sections as outlined here. Section 2 deals with the design and fabrication of the bistable electromagnetic vibration energy harvesting device. Section 3 describes the mathematical model of the device, where analytical expressions for the bistable potential well and nonlinear restoring force, due to the experienced magnetic repulsive forces, are obtained. Also, the expressions for voltage and power generated by the device are presented in Section 3, along with a brief description of the simulation procedure for the mathematical model of the device. Beginning with an outline of the experimental set up and methods, Section 4 discusses the results of the simulations and experiments. Finally, Section 5 presents the concluding remarks.

2. Device design and fabrication

The device, shown in Fig. 1, consists of an FR4 suspension, neodymium (NdFeB) magnets and a copper wire-wound coil. A folded-arm cantilever structure was carved out by the CNC (Computer Numerical Controlled) machining of a low Young's modulus FR4 sheet (300 μm thick). The central area of the folded cantilever is fixed, while the rest of it is free to move. A slot is made on the free side of the folded arm cantilever and four sintered NdFeB magnets (4 mm × 2 mm (a) × 1 mm) are bonded on both sides of the slot in an anti-parallel orientation. This arrangement results in a high flux gradient in the region within the magnet assembly [4,5]. Fig. 2(a) shows the simulated deflected device structure using COMSOL finite element analysis tool. A copper wire-wound coil (32 μm wire diameter, 2500 turns, 1.2 mH inductance, and 770 Ω resistance) is placed in the slot within the magnets. The magnet orientations and magnetic flux lines passing through the coil are depicted in Fig. 2(b). The magnetic flux linkage in the coil changes its direction periodically when the magnet assembly moves vertically with respect to the coil. At the free end of the folded-arm cantilever, a fifth NdFeB magnet (4 mm × 1 mm (a) × 1 mm) is bonded, with one of its poles facing the outward direction. Another magnet (4 mm × 2 mm (a) × 1 mm) is mounted on a micro-positioning stage and placed in front of the cantilever in such a way that it exerts a repulsive force on the magnet at the end of the cantilever. This repulsive magnetic force, which can be controlled by adjusting the gap between the magnets, introduces a nonlinearity into the system. The overall volume of the device is 2.97 cm^3 (35% of a standard AA size battery) including the clamped repulsive magnet at the front of the cantilever.

3. Analytical modelling and numerical simulation

The device can be modelled as a spring-mass-damper system combined with a bistable potential well created by the magnetic repulsion force. The equivalent mass of the system, linear spring constant and total damping coefficient is denoted by m, k and D respectively (Fig. 3). The distance between the centres of the repulsively positioned magnets is denoted by d. A periodic external force F due to the external vibration is applied in the vertical direction. The resulting displacement of the mass m from the initial equilibrium position is denoted by $z(t)$ and the distance between the centres of the repulsive magnets becomes r.