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Magnetically-Coupled Cantilevers with Antiphase Bistable Behavior for Kinetic Energy Harvesting

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Abstract

This work deals with bistable devices for vibration energy harvesting. We have addressed this subject through MEMS cantilevers and the use of two facing magnets, with opposed magnetization, in order to obtain the desired double-well potential energy function. However the fabrication on MEMS devices of micromagnets placed very close one each other and having non-parallel magnetization is seriously challenging: parallel magnetization would be greatly preferable. Based on this latter consideration, new device architecture is presented here: two parallel cantilevers, with a magnet on each tip, are used. The two magnets are equally oriented and therefore provide repulsive forces that in turn induce antisymmetric bistable behaviors in the two cantilevers. The system has been analytically modeled and an experimental prototype has been realized and tested obtaining very promising results.

Keywords: Energy harvesting, nonlinear behavior, magnetically-coupled cantilevers;

1. Introduction

Energy harvesting is one of the hottest topics in micro and nanotechnology. Several strategies have been proposed to harvest energy from vibrations [1,2]. The kinetic energy associated with these mechanical vibrations (i.e. cars, trains, human-induced vibrations, noisily sources, etc.) represents a potential source of energy for sensors, conditioning circuits, autonomous nodes, and smart systems. In order to generate electrical power from kinetic energy, the generator requires a mechanical system (oscillator) that couples environmental vibrations to the transduction mechanism (i.e. electrostatic, electromagnetic, piezoelectric).

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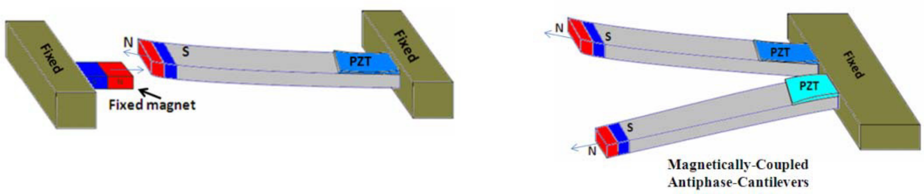
Furthermore several strategies have been addressed in order to optimize the efficiency of the oscillator, the coupling between the external energy source, the transduction mechanism and the bandwidth. In particular it has been demonstrated that for single-tone kinetic sources a linear oscillator (mass-spring-damper device) is particularly suitable to recovery energy but there are several disadvantages: 1) the dominant ambient vibration frequency must therefore be known prior to the design of the resonator, 2) in order to achieve maximum conversion efficiency the dominant ambient vibration frequency must be tuned to the mechanical resonance of the harvester. For this reason literature presents several systems act to compensate the "uncertainly" between the external monochromatic source and the oscillator resonance, such as a tunable-resonance oscillator or multiple oscillators having various mechanical resonances. Furthermore in presence of time-varying resonance or broadband excitations the performance of a linear oscillator decreases drastically. For this reason several ways for optimization have been pursued, in macro and micro-scale, in order to increase the bandwidth of the harvester exploiting the advantages of nonlinear behaviors that typically present a rich power spectrum that arouse interest to save energy from wideband sources (characterized by a wide spectral distribution [3]). Considering the integrated approach, in [4] authors propose MEMS cantilevers and the use of two facing magnets, with opposed magnetization, in order to obtain the desired double-well potential energy function. However the fabrication of micromachined devices having micromagnets placed very close one each other and having non-parallel magnetization increases difficulties in handling and manufacturing [5].

In this context a different device architecture oriented for MEMS prototype and based on parallel magnets-magnetization will be here described through model and experiments obtaining very promising results for integrated energy harvesters from kinetic ambient sources based on coupled bistable systems.

2. Working principle

Several strategies have been proposed to address the issue of recovering energy from low-frequency and large-bandwidth vibrations [1]. Efficient solutions have been reported based on bistable oscillators [3,4] where bistability is obtained by exploiting the repulsive force produced by two facing permanent magnets (see Fig. 1a): one placed on the tip of a cantilever while the other is placed on the device frame. Implementations of this strategy on MEMS devices have been also presented [4,6]. In view of fully integrated bistable MEMS harvesters it must be considered that the realization of very close magnets having opposite orientations is challenging, it is then easier to work with a single orientation of magnetization. The approach presented here is based on the use of two parallel cantilevers each one carrying a magnet on its tip, the two magnets will have identical magnetization (see Fig. 1b). The device is excited by the inertial force *F(t)* coming from environmental vibrations that will act together with the nonlinear elastic force due to the magnetic interaction between the two cantilevers.



(a) (b)

Fig. 1. (a) Bistable mechanism, based on opposing magnets, tipically used to increase the bandwidth response of the harvester; (b) the device proposed based on Magnetically-Coupled Antiphase-Cantilevers.

It results into a bistable behavior for each beam; moreover both cantilevers will behave in antiphase one respect to the other.

The magnetically coupled system has been modeled considering two mass (*m*)-spring (*k*)-damper (*d*) equations.

The magnetic interaction has been modeled via two nonlinear terms: 1) $k_{nl}=\alpha-\beta x_i^2$ correlated with the displacement of the oscillator (x_i, $i=1,2,$), 2) $k_{nlc}=\gamma-\delta(x_2-x_1)^2$ that include the relative displacement between the cantilevers. Furthermore a magnetic damping coefficient (d_m) has been also considered:

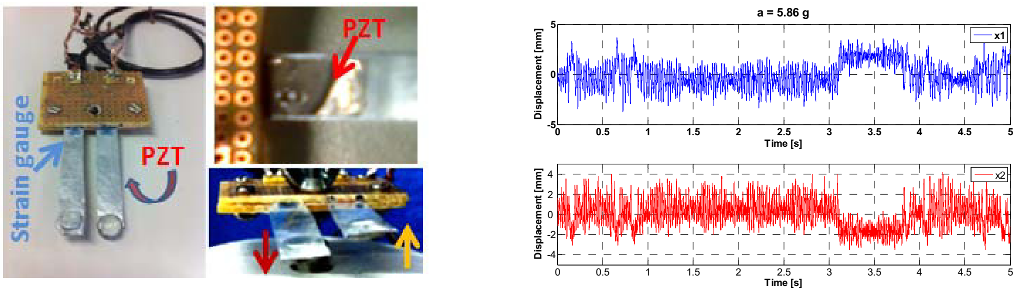
$$\begin{cases} m\ddot{x}_1 = -d\dot{x}_1 - kx_1 + k_{nl}x_1 + k_{nlc}(x_2 - x_1) + d_m(\dot{x}_2 - \dot{x}_1) + F(t) \\ m\ddot{x}_2 = -d\dot{x}_2 - kx_2 + k_{nl}x_2 - k_{nlc}(x_2 - x_1) - d_m(\dot{x}_2 - \dot{x}_1) + F(t) \end{cases} \quad (1)$$

where the shape of the two double-well potentials is related with the terms α, β, γ, δ estimated through measures.

3. Experimental setup and results

The prototype (see Fig. 2a on the left) used to validate the mechanical principle is composed of two aluminum beams having a length of 40mm and a width of 7.5mm. Two permanent magnets with parallel polarities have been used to create the two stables states as shown in Fig. 2a on the right. Both magnetic structures have been fixed on the cantilever tips and the distance between the two beams has been fixed at 4mm.

Two piezoceramic elements (see Fig. 2a) have been used as active material in order to harvest energy from known imposed vibrations and two strain gauges conditioned through Wheatstone bridge followed by a low-noise amplifier have been used to monitor the displacement of both structures. The experimental setup consists of a board to support the Magnetically-Coupled Antiphase-Cantilevers; a shaker has been used as a vibration source driven by a Gaussian white noise generator (low-pass) filtered at 450Hz. Finally an accelerometer has been used as a feedback element. Fig. 2b shows the measured tip displacements in presence of an acceleration (rms) of about 5.8g, where the bistable and antiphase behaviors are evident. In Fig. 3a, the experimental signal has been compared with the model assuming two identical beams having a mass (*m*) of 0.82g and damping (*d*) of 0.0044Ns/m, both experimentally estimated. The linear elastic constant (k = 44 N/m) has been evaluated through the cantilever beam model.



(a) (b)

Fig. 2. (a) The experimental prototype developed: aluminium magnetically-coupled antiphase-cantilevers (on the left). Piezoceramic element used as active material and the two cantilevers in their initial equilibrium positions (on the right); (b) tip-displacement of both cantilevers. Gaussian white noise (low-pass) filtered at 450Hz has been imposed through the shaker. An acceleration (rms) of about 5.8g has been measured through a feedback accelerometer.

The parameters $\alpha, \beta, \gamma, \delta$ of the two nonlinear terms have been estimated through a fitting procedure (Nelder–Mead nonlinear algorithm). Fig. 3b shows the power spectrum: a wide band appears as consequence of the bistable dynamic.

An output power of about 3.5µW has been measured with a resistive load of 500kΩ for an acceleration (rms) of about 5.8g. Harvested energy is 2-times higher compared to a single beam nonlinear oscillator (Fig. 1a) and 10-times more compared to a linear system (single cantilever in absence of magnetic coupling).

4. Conclusions and future developments

In this paper it has been presented a "anti-phase" mechanisms for vibration energy harvesting. Both modeling and experimental results have been reported to show the suitability of what has been proposed. Work is in progress toward optimization of the MEMS design and realization, moreover the proposed bistable antiphase behaviors is currently investigated for further exploitation in "fully mechanical MEMS rectifiers".

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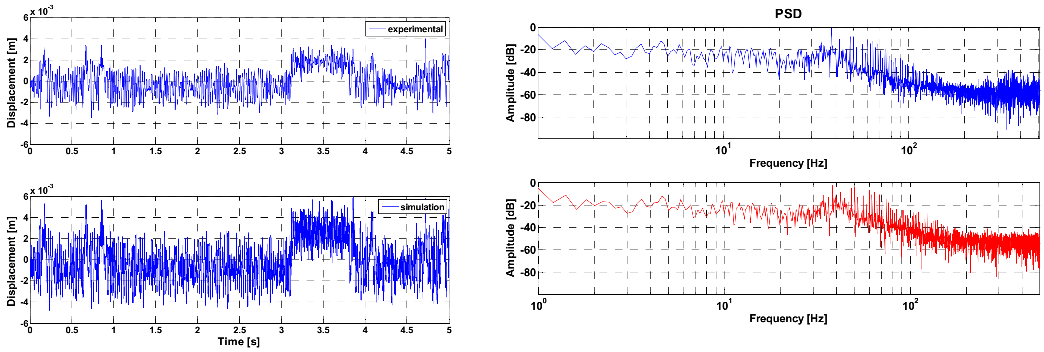

(a) (b)

Fig. 3. (a) Tip-displacement: experiment Vs simulations; (b) spectral analysis, on the top the state-variable x_1 and on the bottom x_2.