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A Single-Magnet Nonlinear Piezoelectric Converter for Enhanced Energy Harvesting from Random Vibrations

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Abstract

Power harvesters from mechanical vibrations are commonly linear mechanical resonators that are most efficient when excited at resonance. Differently, under wideband vibrations, linear converters are suboptimal. A nonlinear converter is here proposed that implements nonlinearity and bistability by employing one external magnet, in order to improve conversion effectiveness while simplifying device fabrication. The converter is composed of a piezoelectric bimorph on a ferromagnetic cantilever which, under proper coupling with the external magnet, bounces between two stable states when excited by random vibrations. According to theoretical predictions, experimental results demonstrate a remarkable improvement of the rms voltage generated by the converter when bistable behaviour is present.

Keywords: Energy harvesting, piezoelectric energy converter, wideband vibrations, nonlinear bistable system

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1. Introduction

In vibration harvesting, energy converters are typically mechano-electrical resonant devices tuned with the dominant vibration frequency [1]. Under frequency-varying or random vibrations this solution is suboptimal because of the narrow frequency bandwidth of the converter. Among different approaches recently emerged [2], nonlinear bistable energy converters have demonstrated to increase the energy conversion effectiveness and widen the useful bandwidth [3-6]. However, most of the bistable converters based on magnetic interactions need a permanent magnet on the resonator. This complicates the design, especially when MicroElectroMechanical Systems (MEMS) devices are considered, due to the dedicated processes required to deposit a permanent magnet of suitably small size. The possibility to create bistability using only external magnets would significantly simplify the design and fabrication of the energy converter. To investigate such a solution, this work proposes a piezoelectric energy converter where bistability is introduced by using a ferromagnetic substrate cantilever placed in front of a permanent magnet. System simulations and experimental results are reported demonstrating the energy conversion improvement of the proposed converter.

2. Single-magnet converter

The schematic diagram of the implemented single-magnet nonlinear piezoelectric converter is shown in Fig. 1a. It is composed of a ferromagnetic cantilever whose free end is placed at a distance *d* from a permanent magnet with vertical

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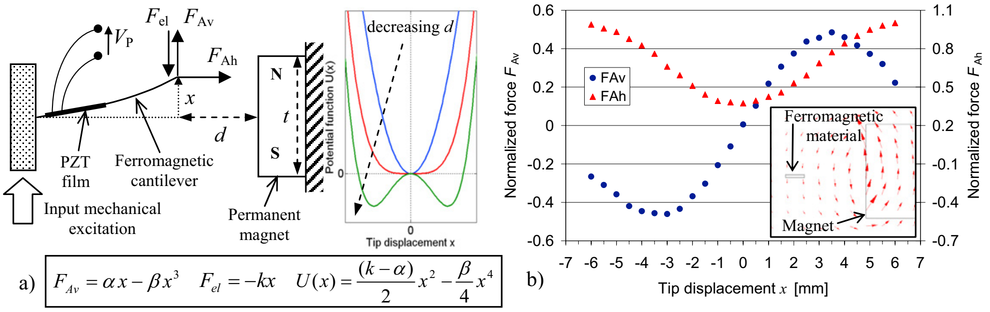
magnetization. On both the cantilever surfaces, piezoelectric films are deposited to perform the energy conversion. The ferromagnetic cantilever is attracted by the magnetic poles with a resultant force F_A whose dependence from the vertical tip displacement x was studied by finite element simulations. The simulations were carried out assuming the ferromagnetic material, having a relative permeability $\mu_r = 5000$, concentrated on the cantilever tip. Vertical and horizontal attractive force components F_{Av} and F_{Ah} were computed varying the vertical position of the ferromagnetic material, simulating a change in the displacement x. The simulation results are shown in Fig. 1b, where in the bottom-right inset the simulated geometry and the magnetic induction field $\boldsymbol{B}$ are reported. It can be seen that the vertical force F_{Av} is a nonlinear odd function of x that can be approximated with a 3rd order polynomial function, while the horizontal component F_{Ah} is a nonlinear even function of x. Combining the vertical attractive force F_{Av} with the restoring linear elastic force F_{el} of the cantilever, with stiffness k, gives a bistable behaviour when d is low enough [6]. The right inset of Fig. 1a shows a qualitative behaviour of the potential function $U(x)$, obtained integrating the total force function. For high d values the potential $U(x)$ has only one stable equilibrium point while, when d is low enough, it has a symmetric double well shape with two stable equilibrium points, implying a bistable characteristic.



$$F_{Av} = \alpha x - \beta x^3 \quad F_{el} = -kx \quad U(x) = \frac{(k-\alpha)}{2}x^2 - \frac{\beta}{4}x^4$$

Fig. 1: (a) Piezoelectric converter made bistable by a ferromagnetic substrate cantilever and a fixed permanent magnet. F_{Av} and F_{Ah} are the components of the attractive force between the cantilever and the magnet; Right inset: qualitative trend of the potential energy $U(x)$ of the cantilever varying the distance d; (b) Simulated trend of the force components F_{Av} and F_{Ah} as a function of the tip displacement x. In the bottom-right inset: simulation of the magnetic induction field $\boldsymbol{B}$ near the magnet.

3. Experimental results

To validate the proposed approach, a piezoelectric bimorph converter was realized by screen-printing low-curing-temperature lead zirconate titanate (PZT) films on a stainless steel cantilever [7]. Typical measured values for parallel resistance and capacitance of the piezoelectric converter are $R_P = 50$ MΩ and $C_P = 750$ pF respectively. A permanent magnet, with vertical magnetization and remanent magnetic induction $B_r = 1.33$ T, was mounted on a micrometric stage and placed in front of the cantilever tip as shown in Fig. 2. A custom made optical triangulator was used to measure the tip displacement x. The fundamental resonance frequency of the converter when the magnet is not present is 189 Hz. The deflection x_{eq} at the static equilibrium positions of the cantilever for two different magnets with thickness $t = 2$ mm and $t = 6$ mm respectively was measured varying the distance d, as shown in Fig. 3a. The equilibrium positions follow a pitchfork bifurcation diagram where monostable and bistable regions can be recognized, with a boundary between the regions at the bifurcation distance d_{bif}. For $d > d_{bif}$ the cantilever has a monostable behaviour with only one stable equilibrium position $x_{eq} = 0$, while for $d < d_{bif}$ the cantilever potential becomes bistable where two symmetric stable equilibrium positions x_{eq} are possible. The bifurcation distance is about $d_{bif} = 7$ mm and $d_{bif} = 4$ mm for the thick and thin magnets respectively. In order to investigate the frequency response of the system, the converter was excited with a sinusoidal acceleration by means of an electrodynamic shaker. A gain-phase analyzer HP4194A was employed to drive the shaker and measure the displacement x. The frequency sweep was performed for both decreasing and increasing frequencies, varying the level of the input vibrations.

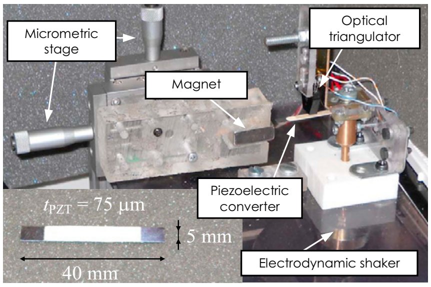


Fig. 2: Experimental setup for the bistable converter characterization. In the bottom-left inset: low-curing-temperature piezoelectric converter and its physical dimensions.

The typical measured frequency response magnitudes are shown in Fig. 3b where the responses are normalized to the higher peak value and a magnet with t = 6 mm is considered. Nonlinear resonances are visible with a soft spring behaviour that bends the resonance peak towards lower frequencies. For high excitation levels a hysteretic response occurs, with a sudden jump in the response.

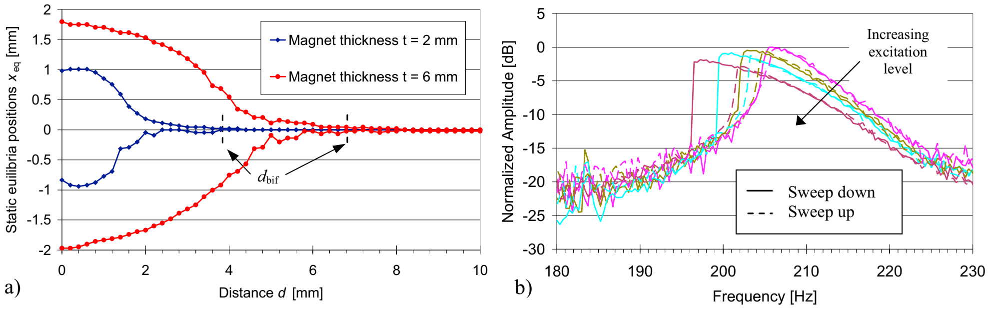


Fig. 3: (a) Bifurcation diagram showing the cantilever tip deflection x_{eq} at the static equilibrium positions respect to the distance d, for different magnet thickness; (b) Frequency responses of the converter for different excitation levels performing a decreasing (solid line) and an increasing (dashed line) frequency sweep, employing the magnet with t = 6 mm.

The converter was then excited by a band-pass filtered white-noise acceleration, whose spectrum is shown in Fig. 4a. The tip displacement x and the open-circuit output voltage V_P generated by the converter were measured at different values of the distance d, employing a magnet with a thickness t = 10 mm. Fig. 4b shows the measured x and V_P under bistability, for a distance value d = 3.5 mm. The cantilever rapidly jumps between the two stable states with a corresponding significant increase in the generated voltage. The rms value V_{Prms} of the open-circuit voltage V_P was computed as a function of the distance d and it is plotted in Fig. 5a. For the given excitation level, the converter has a bistable behaviour for suitably low distance where an increase in the rms output voltage is visible, reaching a value of V_{Prms} = 0.38 V for a distance d = 3.5 mm. With respect to the linear behaviour case, obtained for the highest d values, V_{Prms} has an increase in the order of 400%, demonstrating the potential improvement in the power conversion capabilities of the bistable converter. For powering an electronic circuit the energy generated by the piezoelectric converter has to be suitably extracted and stored using, for instance, a passive rectifier and a capacitor [8]. A full-wave diode rectifier was connected to the converter feeding a storage capacitor C_b = 1 µF. The converter was again excited by a band-pass filtered white-noise acceleration, measuring the time trend of the voltage V_{Cb} across the storage capacitor, for different distance values d and considering the 6 mm thick magnet. The obtained results are shown in Fig. 5b where it is visible that passing from a monostable to a bistable behaviour an increase in the rectified voltage occurs, reaching the maximum when d = 2 mm. For lower distances the voltage V_{Cb} decreases, as expected from Fig. 5a, due to the higher confinement inside each potential well that makes jumps between the stable states less probable for a given excitation level.

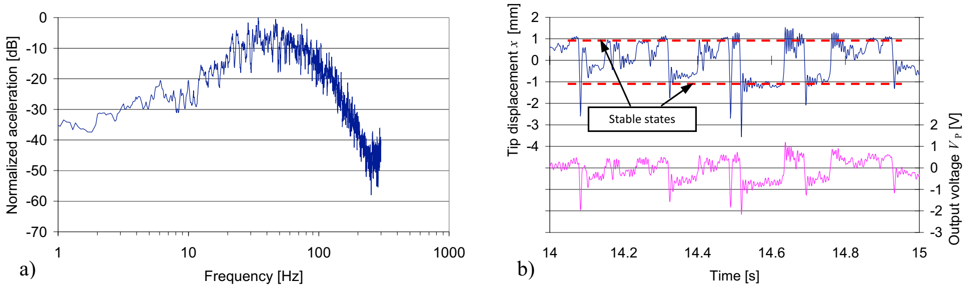


Fig. 4: (a) Frequency spectrum of the band-pass filtered white-noise mechanical vibrations used for the converter excitation. It can be noticed that the excitation bandwidth is at lower frequency than the resonance of the converter; (b) Tip displacement *x* and open-circuit output voltage V_P measured when the converter has a bistable behaviour, for a distance value $d = 3.5$ mm and using a magnet 10 mm thick.

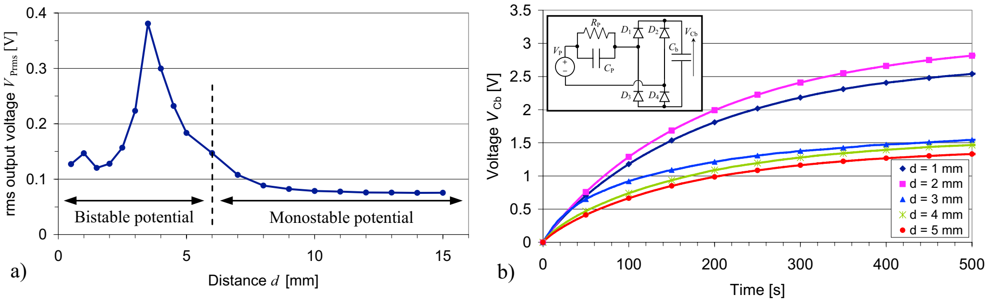


Fig. 5: (a) Measured rms open-circuit output voltage V_{Prms} as a function of distance *d*. It is visible the increase in the rms output voltage in the region where the converter has a bistable behaviour around $d = 3.5$ mm; (b) Measured voltages V_{Cb} across the storage capacitor C_b versus time for different distances *d*, using a magnet with $t = 6$ mm and $C_b = 1$ µF. Upper-left inset: Full-wave rectifier used for energy storage.

Reported results have demonstrated the possibility to implements a bistable energy converter using a ferromagnetic cantilever properly coupled with an external magnet. The improvement in the energy conversion under wideband vibrations has been verified using both the converter alone and an energy storage circuit, extracting a higher amount of energy with respect to a linear converter.

Acknowledgements

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