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A bistable buckled beam based approach for vibrational energy harvesting☆

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ABSTRACT

This paper presents a low cost solution for vibrational energy harvesting based on a bistable clamped-clamped polyethylene terephthalate (PET) beam and two piezoelectric transducers. Beam switching (between two stable steady states) is activated by environmental vibrations. The mechanical-to-electrical energy conversion is performed by two piezoelectric transducers laterally installed to experience beam impacts each time the device switches from one stable state to the other one. The main advantage of our approach lies in the wide frequency bandwidth of the device; in turn, this leads to improved efficiency at very low cost.

1. Introduction

Many efforts have, recently, been devoted to the development of autonomous solutions aimed at powering electronic devices by exploiting the energy scavenged from their operating environment. This interest stems from the fact that electronic devices, typically, utilize batteries whose limited lifespan (which necessitates their periodic replacement) can be a problem, especially when the devices are embedded into complex structures including (even) the human body. Moreover, energy saving policies increasingly drive the development of new strategies to harvest energy from unconventional sources.

Different solutions for power harvesting from assorted energy sources have been addressed by researchers worldwide. Examples are solar energy conversion [1], thermoelectric power generation [2], the (less well known) radio-frequency (RF) power conversion [3], and power stemming from environmental mechanical vibrations [4]. Among these, environmental mechanical vibrations represent one of the most ubiquitously available sources that can, potentially, deliver a useful amount of energy [5]. Ambient mechanical vibrations come in a large variety of forms such as induced oscillations, seismic noise, vehicle motion, acoustic noise, multitone vibrating systems, and, more generally, noisy environments. Sometimes, the energy to be collected may be confined in a very specific region of the frequency spectrum, as in the case of rotating machines [6]; in practice, though, energy is often distributed over a wide spectrum of frequencies.

Traditional solutions for energy harvesters are typically based on linear resonant mechanical structures, e.g. cantilever beams with inertial masses, and often exploit a piezoelectric, electromagnetic or electrostatic conversion mechanism [7,8]. Such devices are really efficient when stimulated very close to their resonance frequency. Different solutions, for increasing the operating frequency range of vibration energy harvesters, have been proposed in the literature; these solutions present different disadvantages, e.g. complexity, a decrease in the power generated, the need for extra systems and energy, low efficiency, difficulty in implementation, etc. [9]. In practice, though, the need for harvesters able to scavenge energy more efficiently from wideband vibrational sources drives the development of different harvesting solutions exploiting nonlinear mechanisms [10].

Recently, it has been demonstrated that nonlinear bistable systems, under the proper conditions, can provide better performance, compared to linear resonant oscillators, in terms of the amount of energy extracted from wide spectrum vibrations [11–13]. Nonlinear bistable systems are usually realized by a suitable design of the device topology, e.g. the clamped-clamped cantilever beam with pre-compression along the *Y*-axis, as shown

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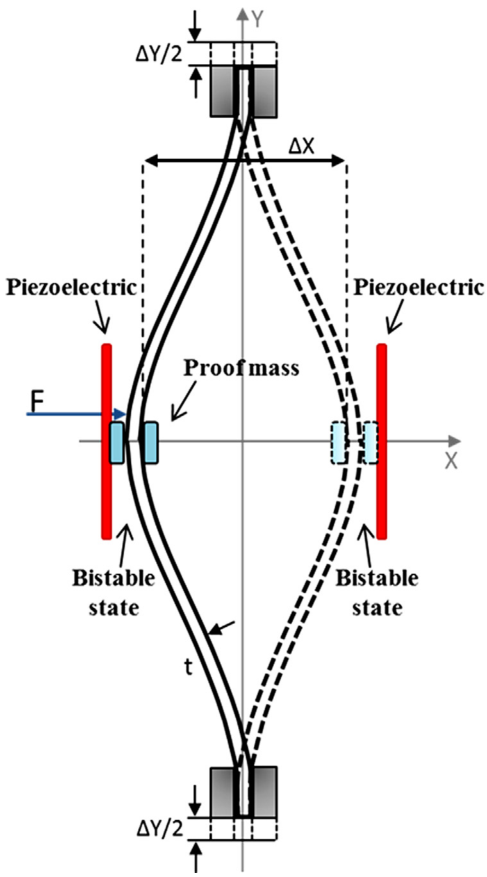

Fig. 1. Working principle of the Double Piezo–NonLinear Harvester (DP-NLH).

in Fig. 1. The clamped–clamped beam exhibits a bistable behavior in response to stress applied perpendicular to its surface. When an external mechanical force, stemming from external vibrations is applied to the bistable beam, it "snaps" between its stable equilibrium states analogous to a credit card fixed and squeezed by fingers at both its ends.

Recently, methodologies to implement nonlinear vibrational energy harvesters, based on the use of low cost technologies and bistable devices have been proposed [10–13]. In particular, in [10] an approach based on a piezoelectric beam converter, coupled to permanent magnets which create a bistable system switching between two stable states, has been proposed. A solution in the micro-scale, exploiting a novel approach involving purely mechanical fully compliant bistable MEMS devices for vibration energy harvesting, has been proposed in [11]. In [12], the use of rapid prototyping techniques for the realization of a nonlinear energy harvester exploiting the benefits of bistable dynamics and assuring a suitable behavior at low frequencies has been addressed. The mechanical-to-electrical energy conversion was performed by a screen printed piezoelectric layer electrically connected using InterDigiTed electrodes (IDT) realized by the inkjet printing of a silver based solution on a flexible polyethylene terephthalate (PET) substrate. A low cost solution for energy harvesting from vibrations based on a bistable clamped-clamped PET beam and two piezoelectric transducers exploiting the benefits of a STB (Snap through Buckling) configuration was presented in [13]. In the Double Piezo-NonLinear Harvester (DP-NLH), the beam switching was activated by environmental vibrations while the mechanical-to-electrical energy conversion was performed by two piezoelectric transducers. The latter convert mechanical energy, collected each time the device switches from one stable state to the other, into electrical energy. In all the above solutions it has been demonstrated that, under proper conditions, a nonlinear bistable configuration significantly improves energy harvesting from wide-spectrum vibrations. A review of research on vibration energy harvesting via bistable systems has been, recently, published [14].

Relative to the work described in [12], in this paper a deep investigation into the device behavior is carried out. In particular, after a more detailed description of the buckled beam based nonlinear harvester, the investigation of the mechanical behavior of the device is presented, together with the analytical representation of the potential energy function underpinning the switching mechanism and experimental validation of the proposed model. For the electrical characterization of the DP-NLH performance, results obtained by a complete experimental survey are shown, including an evaluation of the power produced. It has been demonstrated that the amount of power generated by the DP-NLH harvester is suitable for real applications, e.g. powering wireless sensor nodes. Finally, a case of study where the DP-NLH was connected to a standard electronic circuit for energy harvesting is presented.

The advantages of the DP-NLH stem, mainly, from the intrinsic nonlinear nature of the conversion methodology. In practice, the bistable dynamics implemented by the buckled beam allow for rapid switching (between the two stable states of the bistable configuration) and large displacements, both of which are crucial to enhancing the efficiency of the power conversion process. Moreover, compared to traditional (linear) vibrational harvesters, the bistable dynamics yields an enhanced device behavior in terms of an extension of the frequency band where the device is able to scavenge energy from mechanical vibrations [10]. We reiterate that linear harvesters offer the most efficient energy harvesting alternative when they are tuned to (i.e. resonant with) a particular (in this case, vibrational) frequency in their operating environment.

The low cost of the device, which is intrinsic in the proposed conversion mechanism, is a further advantage.

In the following, a detailed description of the device is presented, together with a characterization of its mechanical behavior and its (experimental) performance as an energy harvester. The paper is organized as follows. Section 2 is dedicated to the mechanical characterization of the buckled beam while Section 3 is devoted to the DP-NLH device and its electrical characterization. A case of study in which the DP-NLH device is connected to a standard electronic circuit for energy harvesting is discussed in Section 4. Concluding remarks are given in Section 5.

2. The buckled beam structure and its mechanical characterization

A schematization of the DP-NLH harvester is shown in Fig. 1. It consists of a pre-compressed flexible PET beam in a clamped-clamped configuration, with only two allowed (i.e. stable) steady states. The PET beam dimensions are 10 cm × 1 cm while its thickness is 100 μm. Under externally induced vibration, the device can switch between its stable states; the switching mechanism is underpinned by a nonlinear (bistable) potential energy function. Two low cost piezoelectric diaphragms are used to convert the beam impacts (in each steady state) into electric charges. The DP-NLH energy harvester, presented here, is able to convert low frequency mechanical vibrations into electrical energy; in particular, this device has been demonstrated to be able to provide enough energy to supply low power electronic devices.

As demonstrated in [15], in order to observe the bistability, the following condition between the beam thickness and the separation (arising from the beam pre-compression along the *Y*-axis) between the stable states must be fulfilled:

$$Q = \frac{\Delta X/2}{t} > 2.31$$