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Experimental and theoretical investigation of a nonlinear vibrational energy harvester

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Abstract

It has been demonstrated that, under the proper conditions, nonlinear configurations can provide better performance, compared to linear resonant oscillators, in terms of the amount of energy extracted from environmental wide spectrum mechanical vibrations. Recently, the authors presented the results of investigations on a system for energy harvesting from wideband vibrations, using a nonlinear snap-through-buckling (STB) configuration and two piezoelectric transducers. The device was shown to be capable of providing sufficient electrical energy to power an RF transmitter. However, in order to optimize the system, an analytical model is necessary. In this paper, a comparison between two different theoretical models for the STB beam is discussed. In addition, preliminary simulations demonstrating the possibility of exploiting the stochastic resonance phenomenon (SR) to improve the performances of the harvester are reported.

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Keywords: Nonlinear Energy Harvesting; Bistable Systems; Snap Through Buckling; Wideband Vibrations; Piezoelectric Materials, Stochastic Resonance.

1. Introduction

The development of systems aimed at powering electronic devices by exploiting the energy scavenged from their operating environment is an important line of research as witnessed by the efforts of researchers worldwide.
Recent progress in low power electronics and sensors, as well as suitable electronics for power harvesting, make

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possible new solutions to scavenge energy from different sources [1-4].

In particular, environmental mechanical vibration sources [5] have gained much attention because of their ubiquity and the availability of new high-performance materials that can be used to convert mechanical vibrations to a suitable electrical response. Linear resonant mechanical structures exploiting piezoelectric, macro-fiber composites (MFC), electromagnetic or electrostatic [6] conversion mechanism comprise traditional solutions able to efficiently harvest energy when stimulated very close to their resonance frequency [7]. Different solutions, for increasing their operating frequency range, 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. [8]. On the other hand, we know that the exploitation of new harvesting configurations based on nonlinear mechanisms [9, 10] such as bistable systems [11], can outperform traditional (linear) energy harvesters under the right set of operating conditions.

Recently, the authors investigated the mechanical and electrical behaviour of buckled beam based nonlinear energy harvesters [12-15]. One of the main advantages of this system, over traditional linear harvesters, is the possibility of accessing the energy contained in low amplitude wideband vibrations. In particular, in [13] 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 Snap Through Buckling (STB) configuration was presented. In [15], the use of rapid prototyping techniques for the realization of a nonlinear energy harvester exploiting the benefits of bistable dynamics and a screen printed piezoelectric layer electrically connected using InterDigiTed electrodes (IDT) realized by the inkjet printing of a silver based solution on a flexible PET (PolyEthyleneTerephthalate) substrate was presented. In [16] the authors presented preliminary experimental results showing the capability of the nonlinear bistable energy harvester discussed in [13] to power (without batteries) a Commercial Off-The-Shelf (COTS) wireless transmitter @ 2.4 GHz.

The advantages of the proposed harvesters stem, mainly, from the intrinsic nonlinear nature of the conversion process. 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, the bistable dynamics yields enhanced device behaviour in terms of an extension of the frequency band where the device is able to scavenge energy from vibrations [7].

However, in order to understand the system behaviour and optimize its performance, both in the mechanical and electrical domains, an analytical model is necessary. In this paper, a comparison between two different theoretical models for the mechanical behaviour of the STB beam is discussed and supported by experimental evidences. In addition, preliminary simulations demonstrating the possibility of exploiting the stochastic resonance phenomenon [17] to improve the performances of the harvester, under some specific operating conditions, are reported.

2. The models for the STB beam

A schematization of the nonlinear bistable harvester is shown in Fig. 1. It consist of a clamped-clamped cantilever beam with pre-compression along the Y axis (in a STB configuration), a proof mass placed in the middle of the beam and two lateral piezoelectric transducers. The beam exhibits a bistable behavior in response to stress applied perpendicular to its surface.

In this paper a first order dynamical model to fit the dynamic nonlinear mechanical behaviour of the system of Fig 1 is presented:

$$\tau\dot{x} - \Psi(x) = F(t) \tag{1}$$

where τ is the system time constant, $\dot{x}$ is the velocity of the beam, $F(t)$ is a stochastic source characterizing the external mechanical vibrations, and $\Psi(x) = -\partial U(x)/\partial x$ is the restoring force, with *U(x)* the potential energy function. In this paper, we compare the model performance with two different nonlinear potentials:

$$U_q(x) = \frac{1}{4}a \cdot x^4 - \frac{1}{2}b \cdot x^2 \tag{2}$$

$$U_h(x) = \frac{1}{2}x^2 - a'\ln\cosh\left(b'x\right) \tag{3}$$

3. Experimental results and conclusions

Fig. 2 shows the experimental displacement of the beam in response to a sinusoidal stimulation at 6 Hz, compared to the displacement predicted by the two models (2) and (3), while Fig. 3 shows the fitting with the hysteretic relationship of the accelerations *vs* displacement. The coefficients (a,b) and (a',b') were determined via the fitting algorithm. A reconstruction of the potential by using the parameters identified for the two models is given in Fig. 4. The results show a good fitting of both models with real data; however the model (3) shows a slightly better fit than the model (2). This difference stems from the (different) topologies of the potential energy functions in (2) and (3). Actually, potential (3) better describes the non-linearity of the device under investigation.
Preliminary simulations of the system response in the presence of band limited noise and a subthreshold sinusoidal force at 1 Hz, were carried out in Simulink®. The results in Fig. 5a and 5b show the typical peak in the output Signal to Noise Ratio (SNR) due to the stochastic resonance phenomenon. Further investigations on the possibility of exploiting this phenomenon to enhance the performance of the system are ongoing.

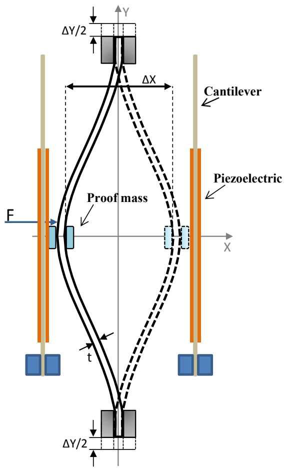

Fig. 1: Schematization of the bistable nonlinear harvester

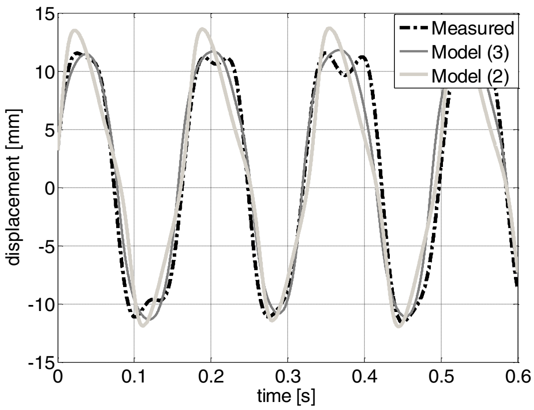

Fig. 2: Fitting of the displacement of the beam predicted by (2) and (3) with the real displacement measured in case of a sinusoidal stimulation at 6 Hz.

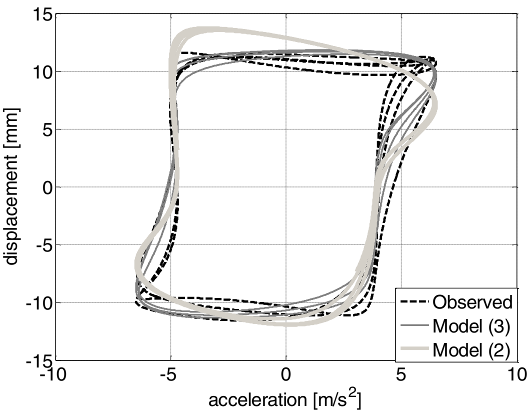

Fig 3 The observed and predicted hysteresis of displacement vs acceleration.

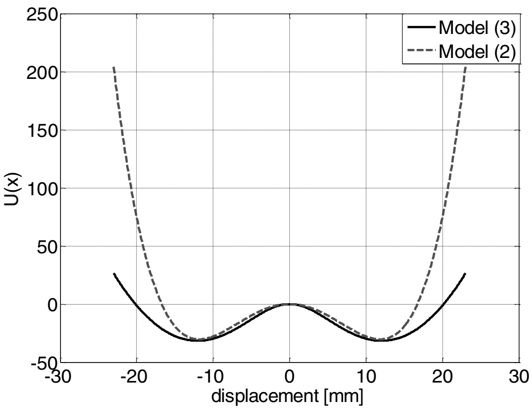

Fig. 4 Double-well potential reconstruction by using the parameters identified for the two models investigated.

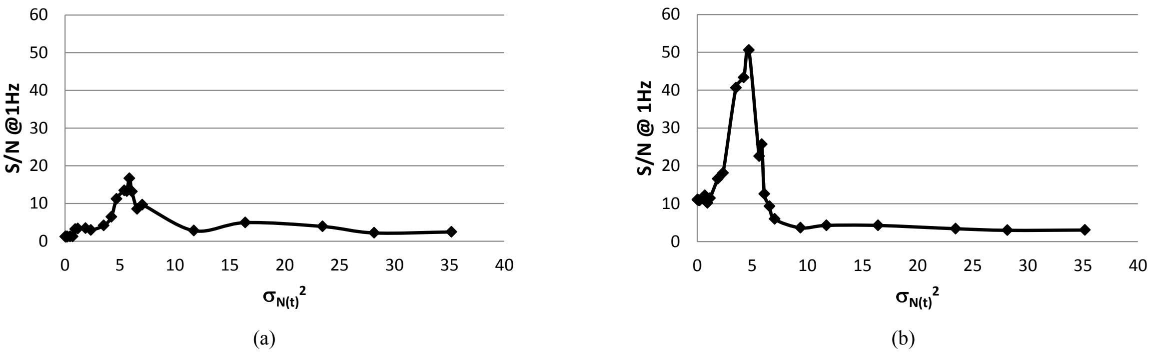

Fig. 5: The S/N ratio for different values of the variance of the added noise in case of the (a) model (3) and (b) model (2).

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