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# A Nonlinear Energy Harvesting with Asymmetry Compensation †

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**Abstract:** A Nonlinear Energy Harvester designed to scavenge energy from wide-band mechanical vibrations is presented. The harvester exploits the advantages of a flexible beam in a Snap-Through-Buckling configuration and a novel magnetic repulsion mechanism to compensate for the asymmetric behavior of the device, in the vertical direction, due to the effect of the proof mass load. The device is demonstrated to be capable of scavenging energy in the range 0.5–10 Hz, which is compatible with many vibration sources, and to generate power up to 120 μW in case of an impulsive input at 5 Hz.

**Keywords:** nonlinear energy harvesting; Snap-Through Buckling; piezoelectric conversion; characterization; magnetic repulsive force

## 1. Introduction

The possibility of harvesting unused energy already present in the environment with the aim of powering sensor nodes or electronics has been, recently, of considerable interest [1]. In particular, environmental mechanical vibration sources, because of their ubiquity, have inspired many efforts to provide more efficient solutions [2]. Generally, ambient mechanical vibrations occur in a wide frequency spectrum, a feature that makes vibrational energy harvesters based on resonant structures, e.g., cantilever beams, unsuitable. Under these operating conditions, harvesters based on nonlinear mechanisms [3,4], e.g., bistable systems [5], can outperform resonant energy harvesters. The Snap-Through Buckling (STB) configuration is a possible suitable solution to implement nonlinear energy harvesters. Recently, the authors investigated the mechanical and electrical behavior of a buckled beam based nonlinear energy harvester [6–8]. The advantages of this system, over traditional linear harvesters stem, mainly, from the intrinsic nonlinear nature of the conversion process which allows for rapid switching (between the two stable states) and large displacements, both of which are crucial to enhancing the efficiency of the power conversion process. In [9,10] a harvester exploiting the STB configuration has been demonstrated, experimentally, to be capable of scavenging energy from both deterministic and random vibration sources in the range 0–15 Hz; it generates power up to 160 μW with an average conversion efficiency of about 15% in case of horizontal operation. Moreover, a nonlinear dynamic model fitting the behavior of the STB device has been presented.

In case of vertical operation (vibrations along the vertical direction, a typical scenario of stimulation by wide band vibrations) the STB configuration suffers for asymmetry caused by the proof mass load on the beam. The proof mass load introduces an asymmetry in the accelerations required to switch the beam between its two stable states (top and bottom). Actually, if the weight of the proof mass is higher than the static force required to switch the beam from the bottom to the top stable state, as in the case of the device discussed here, the STB beam dynamics become monostable with the bottom state being the only stable state. To cope with such a drawback, in this paper the novel configuration shown in Figure 1 is suggested; it uses a magnetic repulsive mechanism. The basic idea is to exploit the magnetic repulsive force between a (suitably placed) permanent magnet, and the proof mass (which also consists of a permanent magnet). The device is demonstrated, after the asymmetry compensation, to be capable of scavenging energy in the range 0.5–10 Hz which is compatible with many vibration sources (e.g., the case of a running human). The device is seen to generate power up to 120 μW in case of an impulsive input at 5 Hz.

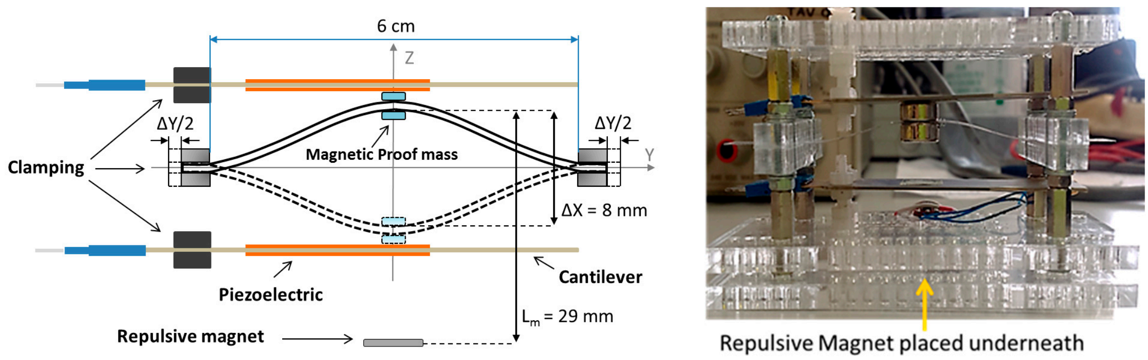
## 2. The Nonlinear Energy Harvester: The Experimental Setup

A schematization of the nonlinear bistable harvester is shown in Figure 1a. It consists of a beam of flexible PET (PolyEthylene Terephthalate) of dimensions 6 cm by 1 cm, with thickness 140 μm, in a STB configuration obtained by a pre-compression ΔY = 1 mm along the *y* axis, a proof mass placed in the middle of the beam and two piezoelectric transducers Midè Volture V21BL placed at the two stable positions [9]. A real view of the harvester is shown in Figure 1b.

A proof mass of 4.77 g composed by two identical disk shaped permanent magnets S-10-04-N [11] with diameter 10 mm and height 4 mm has been used to optimize the trade-off between the range of frequencies in which the beam can follow the input signal dynamics and the minimum force that allows the switching [7,9].

The behavior of the lab prototype has been experimentally investigated through a dedicated setup including a vibration exciter TIRA GmbH TV 51110, a reference accelerometer, model MMA7331L by Freescale Semiconductor with a nominal sensitivity S = 83.6 mV/g (configured in the operating range of ±12 g), to perform an independent measurement of the input signal and a distance measurement module, model QTR-1A by Pololu, including a very small reflectance InfraRed (IR) sensor and the conditioning electronics, to continuously monitor the displacement of the proof mass.

A neodymium permanent magnet Q-10-10-01-N [12], has been placed underneath the bottom harvester support at the optimal distance Lm = 29 mm from the upper state position. The position of the repulsive magnet has been experimentally fixed by a load cell Transducer Techniques GSO-10 in order to restore the beam's upper state position [7].




(**a**) (**b**)

**Figure 1.** (**a**) The schematization of the nonlinear energy harvesting with a repulsive magnet for vertical asymmetry compensation (lateral view); (**b**) a real view of the device.

## 3. Experimental Characterization of the STB Harvester

In order to assess the proposed strategy for the compensation of the asymmetry introduced by the proof mass load and to investigate the dynamic behavior of the device with and without the repulsive magnet, several repeated cycles of mechanical stimulation were applied by the dedicated experimental setup. Figure 2 shows the normalized number (*N*/*N*th) of complete switches vs. the root mean square (RMS) acceleration, $Acc_{RMS}$, in both the cases (a) without and (b) with the repulsive magnet. Here, *N*th represents the expected theoretical number of switches. The normalized number of switches increases with the acceleration, and decreases with the frequency.

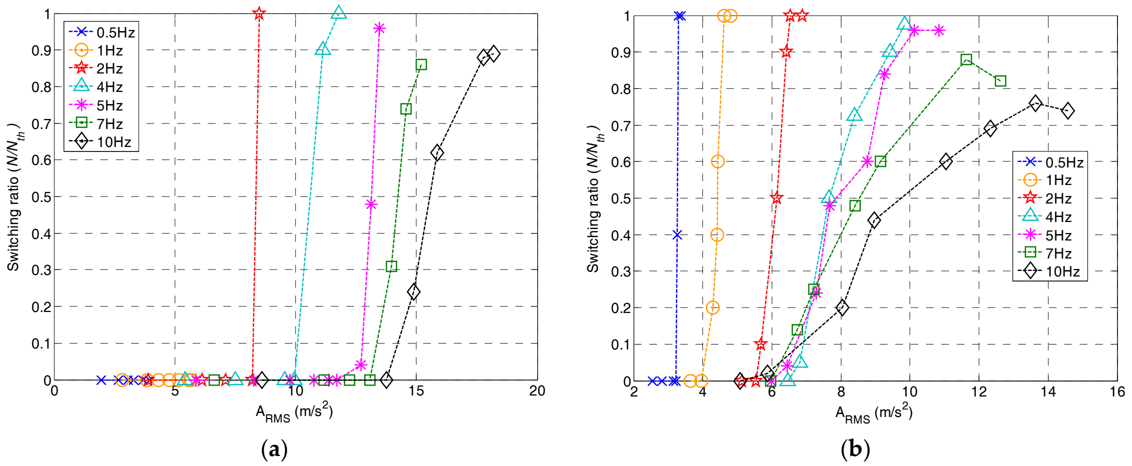



**Figure 2.** The normalized number (*N*/*N*th) of switches vs. the root mean square (RMS) acceleration, *Acc*RMS, for the frequency range 0.5–10 Hz in cases (**a**) without and (**b**) with the repulsive magnet.

Figure 2 shows that the range of frequencies in which the beam can follow the signal dynamics, extends to about 4 Hz, but can be exploited up to higher frequencies (10 Hz) in case of higher input accelerations, with an acceptable loss of efficiency. Figure 3 shows some examples of the measured acceleration, of the displacement of the STB beam between the two stable states and of the output voltage from the two piezoelectric transducers, without and with the repulsive permanent magnet, in case of the same impulsive input accelerations at 1 Hz (Figure 3a,b), and 4 Hz (Figure 3c,d), respectively. As evident from Figure 3, the repulsive magnet enables beam switching at lower frequencies and acceleration values.

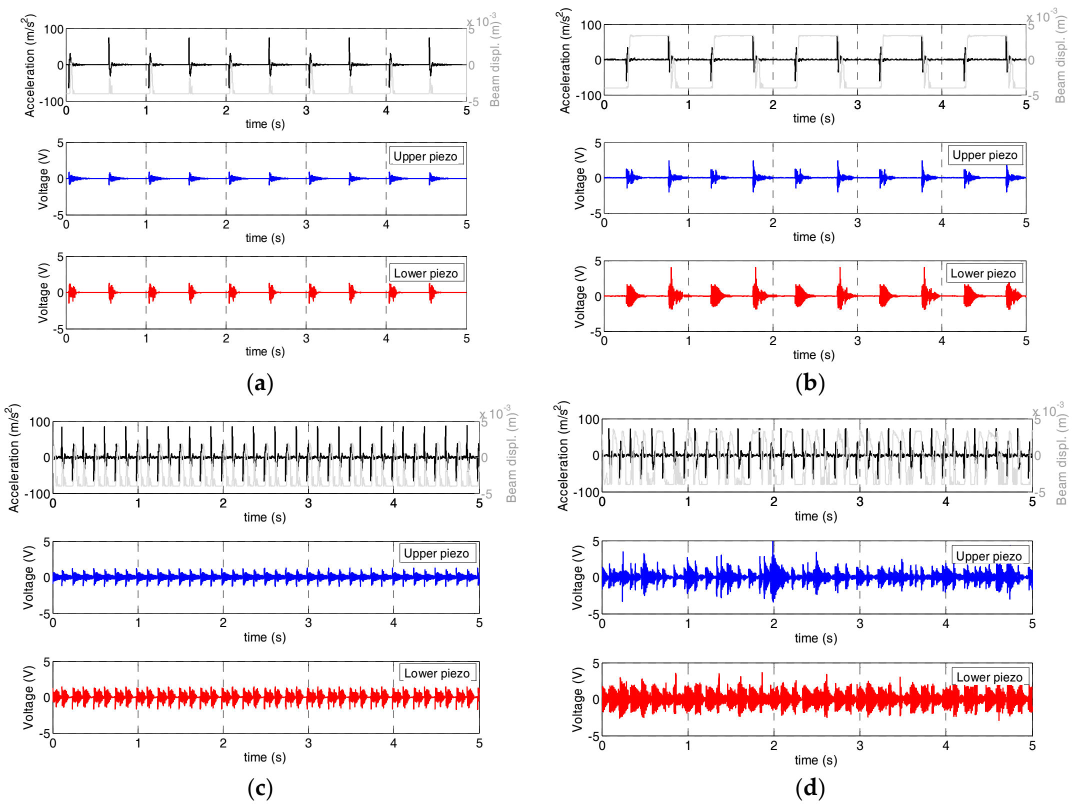



**Figure 3.** Examples of the measured acceleration, displacement of the beam and output voltage from the two piezoelectric transducers, without (**a**,**c**) and with (**b**,**d**) the repulsive permanent magnet, in case of (**a**,**b**) $Acc_{max}$ = 71.1 m/s² at 1 Hz, (**c**,**d**) $Acc_{max}$ = 80.4 m/s² at 4 Hz, respectively.

The electrical power for increasing frequencies of the impulsive stimulus in the range 0.5–10 Hz was evaluated as $P_e = V_{RMS}^2 / R$, where $R$ = 15 kΩ is the resistive load assuring the optimal power transfer [10]. Examples of the amount of power generated by the prototype are shown in Table 1.

**Table 1.** Performance of the harvester with compensation mechanism in case of the minimum acceleration assuring the maximum switching ratio.

| Frequency (Hz) | $Acc_{RMS}$ (m/s²) | Power (μW) | Efficiency |
|---|---|---|---|
| 1 | 4.81 | 20.2 | 4.3 |
| 2 | 6.88 | 38.9 | 5.5 |
| 5 | 10.8 | 120 | 7.7 |

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**Author Contributions:** Bruno Andò, Salvatore Baglio and Adi R. Bulsara conceived and designed the device and the experiments; Vincenzo Marletta and Antonio Pistorio performed the experiments and analyzed the data.

**Conflicts of Interest:** The authors declare no conflict of interest.

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