Vibration-based energy harvesting via a bistable system: experimental study

Sandra Chiacchiari*, Francesco Romeo*, D. Michael McFarland**, Lawrence A. Bergman** and Alexander F. Vakakis**
Dipartimento di Ingegneria Strutturale e Geotecnica, Sapienza University of Rome, Rome, Italy
**College of Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA*

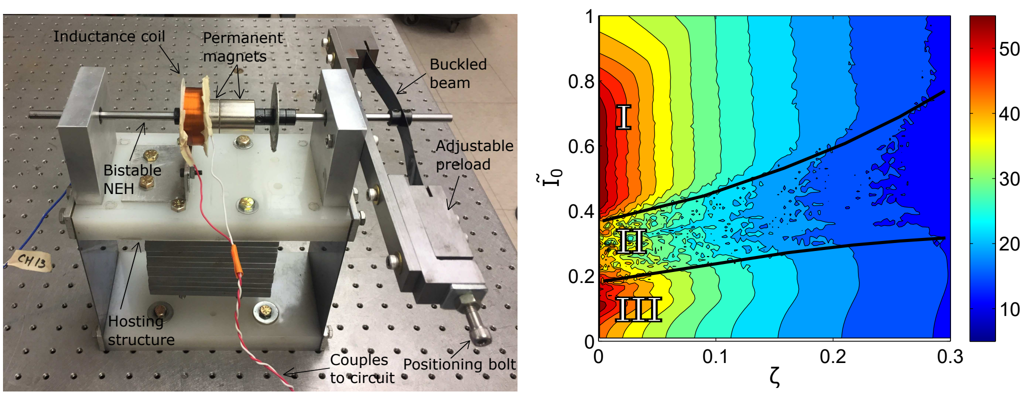
Summary. A vibration bistable nonlinear energy harvester coupled to a directly excited host structure is experimentally examined. The aim of the work is to study the effect of the bistability on the energy harvesting capability of the system under low-level ambient vibration. The investigated system consists of a weakly damped linear oscillator coupled to a lightweight damped oscillator by an element which provides cubic nonlinear and negative linear stiffness components and electromechanical coupling elements. Single and repeated impulses with varying amplitude are applied. A preliminary theoretical study reveals the enhancement in energy harvesting for low levels of vibration provided by the addition of the negative stiffness component in the coupling. The bistability enables the attachment to exploit efficient dynamical regimes, depending on the initial energy level.

Abstract

A vibration-based bistable nonlinear energy harvester (BNEH) coupled to a directly excited host structure is experimentally examined. The principal aim of the study is to investigate the positive effect of the bistability in the mechanical coupling on the energy harvesting capability of the system under low-level ambient vibration.

Although incorporating bistable nonlinear harvesting devices into primary systems has not been fully explored in the literature, several research works show the advantage of a BNEH in harvesting energy because of its capacity for high output power when it snaps through from one stable equilibrium state to the another, providing large-amplitude motions across a wide range of input frequencies and input energy levels. To mention a few, Erturk et al. [1] proved that a piezomagnetoelastic harvester driven by harmonic base excitation can produce power output over an excitation frequency range an order of magnitude larger than the case without magnetic buckling. Cottone et al. [2] theoretically and experimentally investigated a piezoelectric axially loaded beam under wideband random vibrations; the buckled configuration enabled a significant amplification of displacement and output voltage compared to the unbuckled case.

The system investigated in the present work consists of a grounded, weakly damped linear oscillator coupled to a lightweight damped attachment. As shown in Figure 1a, the mass of the linear sub-system is mainly given by an high-density polyethylene mounting mass supporting additional steel plates, the steel buckled beam support and the aluminum shaft's support. The primary structure is grounded to an optical table via two thin blue-tempered spring steel flexures, which provide for the linear stiffness and light viscous damping. The mass of the BNEH is provided by two neodymium permanent magnets and the shaft that sustains them; most of the linear viscous damping in the coupling arises from the interaction of the rod with the linear roller bearings, embedded in the aluminum uprights. The mechanical coupling between the two sub-systems is realised by a blue-tempered spring steel beam, oriented perpendicular to the direction of motion of the attachment. Its resulting transverse deflection provides a dominant third-order stiffness nonlinearity whereas the negative linear stiffness component arises from its buckled configuration. The electromechanical coupling uses the electromagnetic induction as transduction mechanism for kinetic-to-electrical energy conversion, which exploits the relative motion between a conductor (a copper inductance coil), which acts in this case as the stator, being fixed on the mounting mass, and a static magnetic field produced by the permanent magnets, acting as the driver. The electromagnetic force which arises as a result of the relative motion is proportional to the current and hence the relative velocity; thus it



(a) (b)

Figure 1: (a) experimental apparatus; (b) contour plot of the efficiency measure $\eta_{\%}$ resulting from the application of a single impulse, as function of the inherent viscous damping of the coupling ζ and the amplitude of the initial velocity $\tilde{I}_0$. Regions I, II and III refer to different energy transfer mechanisms.

can be described as linear, electromagnetic damping. The coefficient of proportionality, or electromechanically induced damping coefficient, is related to the transduction factor which, in turn, depends on the magnetic field flux density and coil size, and both the coil and load resistances. Enamelled AWG 30 copper wire is used to maximize size while minimizing coil resistance, which adds additional linear viscous damping to the system without the benefit of contributing to energy harvesting output. Such a transduction technique allows low to high frequency applications based on a variety of system configurations and it is particularly recommended for low frequencies (2-20 Hz) [3]. Moreover, it turns out to be easily tunable as the coupling term depends only on design parameters (strength of the magnetic field, number of turns and size of the coil). The main limitation of electromagnetic transducers is the difficulty in micro-fabrication: minimization in scaling leads to vast efficiency reduction, since the induced electromotive force decreases rapidly as the device size scales down. They are, in general, preferable on condition that there are no severe restrictions on the dimensions of the harvester. The described system is first investigated under an impulsive force, applied to the linear oscillator by use of an instrumented modal hammer with the system initially at rest. The analysis is then extended to the case of a train of identical impulses, applied by use of a long-stroke electromagnetic shaker.

A preliminary theoretical study [4] has revealed that the bistable nonlinear system outperforms its monostable counterpart, for low level vibrations. The existence of an impulse magnitude threshold for the purely cubic configuration, below which no significant energy absorption or harvesting occurs, has been, in fact, proven [5,6,7,8]. It is shown in [4] that the presence of the negative stiffness in the coupling enables the nonlinear attachment to exploit different dynamical regimes, depending on the initial energy level input into the system. Effective mechanisms for passive energy transfer from the directly excited primary system to the bistable nonlinear attachment, and therefore for energy harvesting, have been numerically explored for this system. It has been found that for the system optimized in terms of stiffness and damping parameters of the coupling, cross-well oscillations (that is, jumps from one of the two stable equilibrium positions to the other one) for sufficiently high magnitudes of the input excitation and nonlinear beats caused by internal resonance taking place in an in-well motion (i.e., fully evolving around one stable equilibrium), for very low energy levels represent the main energy transfer mechanisms. In the range of intermediate energy level, a chaotic motion with aperiodic cross-well oscillations is still capable of a satisfactory energy harvesting. According to the numerical results, under single impulse the optimized device is able to harvest above $40\,\mathrm{mJ}$ at the highest energy level, 90$\%$ of which in the first 0.4 seconds, whereas energy of the order of mJ can still be harvested at very low input energy regime. The same study conducted on the system subjected to periodically repeated impulses reveals the greater robustness of the bistable configuration resulting from a lesser dependence upon the inter-arrival time of the impulses when compared to the monostable configuration, for which narrow, high-performance ranges of impulse period exist. Energy harvesting capability greater than $400\,\mathrm{mJ}$ per applied impulse is achievable for the highest energy input considered and for optimal impulse periods.

The mechanical parameters governing the dynamics of the experimental system were initially identified. The damping in the coupling was the most sensitive parameter and difficult to calibrate. On the one hand, as known, a small value of the overall damping in the coupling is required to trigger the aforementioned energy transfer mechanisms. On the other hand, as shown in Figure 1b, high damping significantly decreases the efficiency of the energy harvesting system. Moreover, small mechanical damping drastically reduces the dependency of the energy harvesting performance on the electromechanical induced damping, allowing a simpler coil construction. The built experimental setup turned out to be stiffer and more damped than the theoretical optimized system. As a result, the energy harvested by the apparatus, albeit in agreement with the theoretical predictions, is found to be significantly less than the maximum achievable by the same system with optimized parameters. Nevertheless, the system's capability remains significant, with energy levels on the order of several tens of mJ experimentally harvested.

References

[1] Erturk A., Hoffmann J., Inman D. (2009) A piezomagnetoelastic structure for broadband vibration energy harvesting. *Appl. Phys. Lett.* **94**(25):254102.

[2] Cottone F., Gammaitoni L., Vocca H., Ferrari M., Ferrari V. (2012) Piezoelectric buckled beams for random vibration energy harvesting. *Smart Mater. Struct.* **21**(3):035021.

[3] Vocca H., Cottone F. (2014) Kinetic Energy Harvesting, ICT - Energy - Concepts Towards Zero - Power Information and Communication Technology *InTech* http://www.intechopen.com/books/ict-energy-concepts-towards-zero-power-information-and-communication-technology/kinetic-energy-harvesting

[4] Chiacchiari S., Romeo F., McFarland D.M., Bergman L.A., Vakakis A.F. (2016) Vibration energy harvesting from impulsive excitations via a bistable nonlinear attachment. *Int. J. Non-Linear Mechanics* (submitted).

[5] Barton D.A., Burrow S.G., Clare L.R., (2010) Energy harvesting from vibrations with a nonlinear oscillator. *J. Vib. Acoust.* **132**(2):021009.

[6] Daqaq M.F., Masana R., Erturk, A., Quinn D.D. (2014) On the role of nonlinearities in vibratory energy harvesting: a critical review and discussion. *Appl. Mech. Rev.* **66**(4):040801.

[7] Remick K., Quinn D.D., McFarland D.M., Bergman L.,Vakakis A. (2016) High-frequency vibration energy harvesting from impulsive excitation utilizing intentional dynamic instability caused by strong nonlinearity. *J. Sound Vib.* **370**:259-279.

[8] Remick K., Quinn D.D., McFarland D.M., Bergman L.,Vakakis A. (2016) High-frequency vibration energy harvesting from repeated impulsive forcing utilizing intentional dynamic instability caused by strong nonlinearity. *J. Intell. Mater. Syst. Struct.* 1-20.