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An analytical approach for predicting the energy capture and conversion by impulsively-excited bistable vibration energy harvesters

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ABSTRACT

Impulsive energies are abundant throughout the natural and built environments, for instance as stimulated by wind gusts, foot-steps, or vehicle–road interactions. In the interest of maximizing the sustainability of society's technological developments, one idea is to capture these high-amplitude and abrupt energies and convert them into usable electrical power such as for sensors which otherwise rely on less sustainable power supplies. In this spirit, the considerable sensitivity to impulse-type events previously uncovered for bistable oscillators has motivated recent experimental and numerical studies on the power generation performance of bistable vibration energy harvesters. To lead to an effective and efficient predictive tool and design guide, this research develops a new analytical approach to estimate the electroelastic response and power generation of a bistable energy harvester when excited by an impulse. Comparison with values determined by direct simulation of the governing equations shows that the analytically predicted net converted energies are very accurate for a wide range of impulse strengths. Extensive experimental investigations are undertaken to validate the analytical approach and it is seen that the predicted estimates of the impulsive energy conversion are in excellent agreement with the measurements, and the detailed structural dynamics are correctly reproduced. As a result, the analytical approach represents a significant leap forward in the understanding of how to effectively leverage bistable structures as energy harvesting devices and introduces new means to elucidate the transient and far-from-equilibrium dynamics of nonlinear systems more generally.

1. Introduction

The conversion of ambient vibrations into a usable electric power resource has motivated a broad range of interests [1,2], where one common goal is to leverage the converted energies to realize self-powered electronics that otherwise rely on less sustainable powering methods. The characteristics of the vibration resources vary considerably, from strongly harmonic motions like those induced by rotating machinery [3], to purely stochastic oscillations [4–7] like the heaving of ocean waves

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[8,9], and transient vibrations like those resulting from moving vehicles on roadways [10,11]. Impulsive motions form an important subset of the ambient, transient vibration resources: they are high-amplitude energies suddenly transmitted in brief durations of time. Oscillations induced due to human activities are oftentimes impulsive: walking or running individuals cause shocks to their portable electronic devices [12,13], automobiles driven over traffic counters or speed bumps induce local impulsive forces on the counters or road surface [14], and extensive research illustrates the impulsive nature of forces exerted upon stairs due to human walking [15]. For the beneficial applications of energy harvesters in impulsive excitation environments (e.g., charging electronics borne and jolted by jogging individuals, self-powered traffic monitoring systems, to name a few), the deployment of a suitable vibration energy harvester is critical to maximize device sensitivity to the impulsive excitations.

Recent research has shown that *bistable* energy harvesters are particularly sensitive to impulsive inputs [14,16–19]. Fig. 1(a) and (b), respectively, show a prototypical bistable, piezoelectric energy harvester and its schematic model for oscillations that strictly exhibit fundamental mode behaviors. In agreement with our experimental system described in Section 5, the inducement of bistability illustrated in Fig. 1(a) is by mutual attractions between the ferromagnetic cantilever substrate and a base-mounted magnet pair. Fig. 1(c) provides an exemplary representation of the vibrations of the bistable harvester when excited by an impulse of initial relative velocity between the tip mass and the base. These numerically simulated results illustrate that the transient oscillations of the bistable harvester are characterized by two distinct regimes: an initial phase of *snap-through* oscillation where the inertial mass vibrates between the two stable equilibria, followed by a period of ring-down-type *intrawell* vibrations at the end of which the bistable device returns to a resting position. The lower inset of Fig. 1 shows that the net converted energy (the integration of instantaneous electrical power in time) is more than an order of magnitude greater for the few cycles of snap-through oscillation than that generated by the long-time intrawell dynamics.

This finding motivates the development of an accurate and efficient predictive tool to determine the power generation performance resulting from the favorable snap-through oscillations induced due to impulsive excitations. Such a tool might then inform and guide design and implementation of bistable vibration energy harvesters excited in impulsive motion environments, so as to enhance device sensitivity to the properties of the anticipated impulsive vibration resource. The aim of this research is to develop such a predictive strategy and thus design tool.

Numerical simulations, for example the Runge–Kutta algorithm-based approach used to generate the representative results in Fig. 1, are one means to estimate the power generation of a bistable energy harvester excited by impulses. However, these strategies are computationally-expensive. In other words, each simulation is an indicator of performance for only one set of design parameters and one prescribed impulsive event. A predictive approach based upon an analytical formulation of the impulsively-excited dynamics of a bistable energy harvester is preferred for the more generalized character of the results and the ease in carrying out the computations of detailed and insightful parametric studies.

In fact, many researchers have devised analytical strategies to predict the transient dynamics of bistable oscillators in the absence of electromechanical coupling. Lakrad and Belhaq [20] developed an approach to approximate the *free, undamped* oscillations of bistable structures, and Yuste and Bejarano [21], Yuste [22], Cveticanin [23], and Al-Shudeifat [24] devised different means to predict the *transient, dissipative* dynamics of bistable oscillators. Although lacking the inclusion of electromechanical influences, these latter approaches are of importance to the current investigation in the broader dynamical sense. On the other hand, these advancements have limitations since the predictions may be accurate for only a few cycles of oscillation and may exhibit severe parameter sensitivity in the fidelity of the estimates.

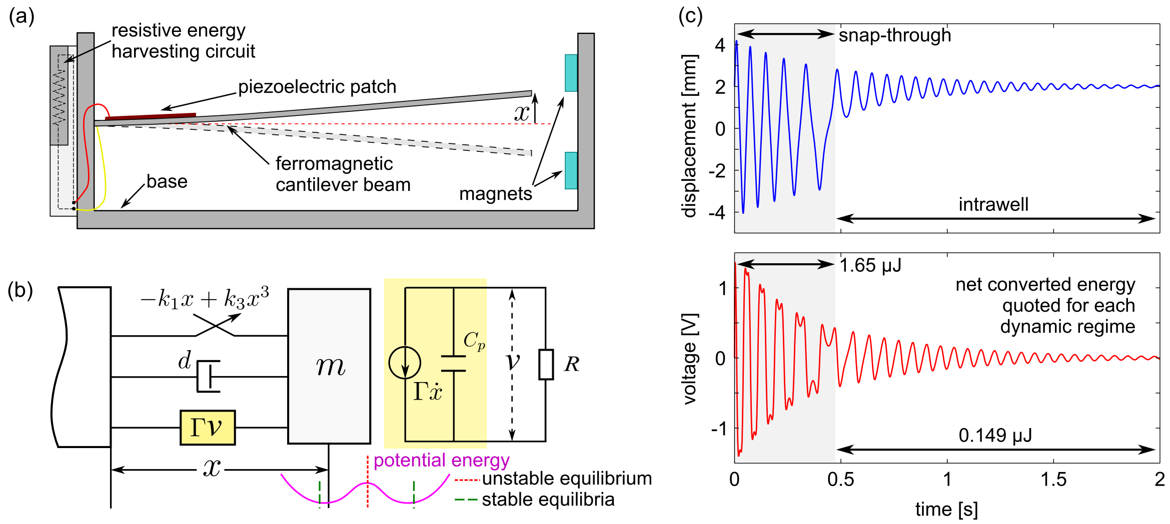

Fig. 1. (a) A prototypical bistable, piezoelectric energy harvesters under impulsive excitation upon the relative motion between beam tip and base; (b) schematic model of the bistable harvester in (a); and (c) an exemplary simulation of the bistable vibration energy harvester beam tip displacement and transduced voltage induced by an impulsive input of relative velocity between the base and harvester beam tip.