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Sustained high-frequency energy harvesting through a strongly nonlinear electromechanical system under single and repeated impulsive excitations

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ABSTRACT

This work investigates a vibration-based energy harvesting system composed of two oscillators coupled with essential (nonlinearizable) stiffness nonlinearity and subject to impulsive loading of the mechanical component. The oscillators in the system consist of one grounded, weakly damped linear oscillator mass (primary system), which is coupled to a second light-weight, weakly damped oscillating mass attachment (the harvesting element) through a piezoelastic cable. Due to geometric/kinematic mechanical effects the piezoelastic cable generates a nonlinearizable cubic stiffness nonlinearity, whereas electromechanical coupling simply sees a resistive load. Under single and repeated impulsive inputs the transient damped dynamics of this system exhibit transient resonance captures (TRCs) causing high-frequency 'bursts' or instabilities in the response of the harvesting element. In turn, these high-frequency dynamic instabilities result in strong and sustained energy transfers from the directly excited primary system to the lightweight harvester, which, through the piezoelastic element, are harvested by the electrical component of the system or, in the present case, dissipated across a resistive element in the circuit. The primary goal of this work is to demonstrate the efficacy of employing this type of high-frequency dynamic instability to achieve enhanced nonlinear vibration energy harvesting under impulsive excitations.

1. Introduction

Long-lasting self-sustaining energy sources are becoming more important for wireless devices such as portable electronics and sensors. These devices typically rely on batteries, which must be frequently recharged or replaced. Battery charging or replacement can become complicated and sometimes impractical for wireless sensors, which are

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integrated into large structures in difficult-to-reach locations. A device that converts ambient mechanical vibration energy into usable electrical energy fulfills the self-sustaining requirement [1–3]. Piezoelectric materials are commonly used to convert mechanical energy to electrical energy so that ambient vibration can be harvested in a circuit [4,5]. The primary goal of this work is to study a methodology for enhancing the performance of these piezoelastic vibration-based energy harvesting systems through the use of nonlinear passive mechanical systems.

Many vibration-based energy harvesting systems are realized through either linear or weakly nonlinear oscillating systems. Linear systems require specific tuning to efficiently harvest energy when subjected to harmonic excitations, and are designed to match their natural frequency to the external forcing frequency [6,7]. When subject to proper tuning of the device parameters, linear energy harvesting systems efficiently transfer mechanical energy from environmental vibrations to a secondary attachment for subsequent conversion to electrical energy. In addition the electromechanical conversion process can be optimized by proper tuning of the electrical circuit parameters of the harvesting system [8–10,34–38]. This transfer of energy from the primary system to the secondary attachment is more profound for larger vibrational amplitudes and weaker system damping [11]. A sharp resonant peak is a fundamental characteristic of these linear systems with low damping. This is indicative of the narrowband nature of operation of these linear harvesting systems, and therefore their harvesting efficiency is expected to decrease significantly for excitation frequencies that vary only slightly from the tuned resonance frequency of the mechanical system. Harvesting of vibrations with time-varying frequency content using a linear single-degree-of-freedom harvester was theoretically studied in [33], and optimized harvesting strategies for this class of excitations were formulated.

Nonlinear energy harvesting systems have been proposed as a solution to frequency mistuning [10,12,13]. In [27] an analytical study of hybrid linear and nonlinear piezoelectric and electromagnetic energy harvesters was performed, whereas Mann et al. [28] examined the sensitivity of linear and nonlinear single-degree-of-freedom energy harvesters to parameter uncertainties. Erturk et al. [29] explored broadband nonlinear energy harvesting by piezo-magneto-elastic effects through magnetic bucking of an inverted cantilever beam and proved superior performance compared to systems without such buckling effects. Likewise, in recent works [30–32] the enhanced energy harvesting performance of bi-stable nonlinear energy harvesters to broadband excitation was shown. In another series of works it was proposed to use nonlinear mechanical attachments rather than linear attachments to a primary system, in which cubic nonlinearity in the elastic force was utilized to broaden the frequency response range of larger amplitude solutions [14,15]. This class of strong nonlinearity is referred to in the literature as essential (nonlinearizable) nonlinearity. The phenomenon of targeted energy transfer (TET) has been observed in these strongly nonlinear systems, in which TET describes the nearly irreversible passive transfer of substantial energy from the primary system to the nonlinear attachment [16–18]. The capability of the essentially nonlinear attachment to engage in resonance captures with modes of the linear structure over an extensive frequency and energy range results in complex dynamics of these systems [23]. The dynamics of the underlying Hamiltonian system possess highly degenerate eigenstructures with pairs of complex conjugate imaginary and multiple zero eigenvalues, resulting in these complex dynamics. Chaotic motions and dynamic instabilities result from high co-dimensional bifurcations in the nonlinear dynamics. These dynamic instabilities result in large relative displacements, which is ideal for piezoelastic energy harvesting.

It has been shown that nonlinear instabilities occur in highly degenerate systems associated with geometric stiffness [15] or damping [19] nonlinearities. This instability is characterized as a buildup of the response of a nonlinear attachment as it engages in a resonance capture with one of the modes of the linear oscillator. Another interesting dynamical phenomenon described in [19,20] is a peculiar damped transition into a state of sustained nonlinear resonance scattering in a system of two coupled oscillators with essential cubic stiffness nonlinearity. This transition was realized for weak viscous damping and only in the neighborhood of the low-frequency branch of the *impulsive orbit manifold* – (*IOM*) of the underlying Hamiltonian system. For a Hamiltonian system of two coupled oscillators with essential stiffness nonlinearity, an IOM consists of a countable infinity of periodic orbits and an uncountable infinity of quasi-periodic orbits, extending over broad frequency and energy ranges [21]. Impulsive forces applied to the linear oscillator with the system initially at rest enable these transitions, which take the form of nonlinear beats.

The present work seeks to extend the aforementioned results and apply them to the optimization of a nonlinear vibrational energy harvesting system subject to impulsive excitation. We show that sustained high-frequency dynamical instability can be realized in strongly nonlinear systems of coupled oscillators, which is in contrast to previous results in [15,19] where only low-frequency dynamic instabilities were reported. We also show that efficient energy harvesting can result for a single impulse and for a series of periodic impulses by activation of high-frequency dynamic instabilities due to high-frequency transient resonance captures of the dynamics. Finally, we present a strong argument for energy harvesting robustness of this system by investigation of optimal circuit and electromechanical coupling parameters, and studying the sensitivity of energy harvesting effectiveness to parameter variations.

The following analysis is restricted to excitations of the linear (primary) system to represent vibrations in physical bodies in nature, e.g. bridges or buildings. While these physical bodies are truly nonlinear in nature, they are predominantly linear systems, or can be linearized. Strongly nonlinear primary systems are not considered in this work because these physical systems are not the targeted application for this type of energy harvester.