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Leveraging nonlinear saturation-based phenomena in an L-shaped vibration energy harvesting system

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ABSTRACT

Trees exploit intriguing mechanisms such as multimodal frequency distributions and nonlinearities to distribute and dampen the aerodynamically-induced vibration energies to which they are subjected. In dynamical systems, these mechanisms are comparable to internal resonance phenomena. In recent years, researchers have harnessed strong nonlinearities, including internal resonance, to induce energetic dynamics that enhance performance of vibration energy harvesting systems. For trees, the internal resonance-like dynamics are evidently useful to dampen swaying motions in spite of the high variation associated with excitation and structural parameters. Yet for dynamic systems, studies show narrow operating regimes which exhibit internal resonance-based behaviors; this additionally suggests that the energetic dynamics may be susceptible to deactivation if stochastic inputs corrupt ideal excitation properties. To address these issues and to investigate whether the underlying motivation of exploiting internal resonance-induced saturation dynamics is truly justified, this research evaluates the opportunities enabled by exploiting nonlinear, multimodal motions in an L-shaped energy harvester platform. The system dynamics are probed analytically, numerically, and experimentally for comprehensive insights on the versatility of internal resonance-based behaviors for energy harvesting. It is found that although activating the high amplitude nonlinear dynamics to enhance power generation is robust to significant additive noise in the harmonic excitations, parameter sensitivities may pose practical challenges in application. Discussion is provided on means to address such concerns and on future strategies that may favorably exploit nonlinearity and multimodal dynamics for robust energy harvesting performance.

1. Introduction

The conversion of ambient vibration energies into electric power has recently been extensively investigated to realize a sustainable energy supply suitable for a wide range of engineered systems [1–3]. A common ambient vibration of high energy density is the swaying of engineered structures, such as tall buildings, due to aerodynamic and seismic excitations [4]. These same forces drive the oscillations of trees [5]. One may then hypothesize that the damping mechanisms which sustain trees may provide guidance towards the development of energy harvesting systems that efficiently convert the same motion- and wind-based excitations into electric power.

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Trees leverage a variety of damping mechanisms for self-preservation when subjected to wind and seismic loads. Some features such as collision effects (e.g., branches rubbing) and aerodynamic phenomena (e.g., leaves flapping) contribute to dampen the swaying vibrations [6]. The remaining energies are dissipated via structural/material factors, about which several interesting hypotheses have been proposed. The nonlinear bending stiffness in numerous tree species led Miller [7] to examine the role of hardening and softening stiffnesses as means for trees to automatically shift the peak frequency of response away from the linear resonance to alleviate damaging stroke amplitudes under high excitation conditions. Spatz et al. [8] found that a tightly confined modal spacing in a Douglas fir was capable of providing substantial damping in the smaller branch oscillations due to efficient energy transfer from the swaying trunk; in the aerodynamically-loaded situation (in which case the branches are the excited members), this phenomenon was described as a means to suppress energy transfer to the trunk. Rodriguez et al. [9] proposed that a scaling law may exist to govern the transmission and dissipation of vibration amongst the trunk and various levels of branches via regularly spaced, but very dense, modal distributions. Later, Rodriguez et al. [10] tested the hypothesis via computational and experimental studies on walnut trees and found clear evidence that dense "mode groups" (such as dense clusters of natural frequencies around 1, 2, and 3 Hz), in contrast to continuously-distributed natural frequencies (such as a continuous spread of natural frequencies from 1 to 3 Hz), are key enablers of the vibration energy transfer and dissipation mechanisms utilized by trees under mechanical loading situations.

Considering such modal spacings in greater detail, Theckes et al. [11] showed that the multimodal dynamics of trees provides for an appreciably enhanced energy dissipation when the hierarchical composition follows certain scales amongst the modal natural frequencies, damping ratios, and masses; for example, a 1:2 proportionality between the two lowest order mode natural frequencies (i.e., $\omega_2 \approx 2\omega_1$, a 1:2 internal resonance) clearly promotes the substantial damping effects when the swaying displacements become large. A thorough and recent review of the structural/material damping strategies of trees may also be found in Ref. [12].

The themes of these studies suggest that nonlinearity and multimodality play critical roles in the dynamical behaviors of trees for the purposes of structural damping. Indeed, the occurrence of an internal resonance suggests that some trees exploit particularly unique energy transfer characteristics. For different purposes altogether, energy harvesting structures are designed to efficiently absorb and electrically dissipate the vibrations to which they are subjected. While to date there have been numerous energy harvesting investigations focused on nonlinearity or multimodality as individual features [13–15], there are few that have considered exploiting both phenomena concurrently to improve energy conversion. Wu et al. [16] showed a broadening of nonlinear "resonant" bandwidths was achieved by employing a two degree-of-freedom (DOF) structure having internal magnetic interactions to induce nonlinear restoring forces. Harne et al. [17] and Wu et al. [18] discovered that the incorporation of bistability – that is, the existence of two statically stable states – in two DOF energy harvesters could be leveraged for enhanced performance. Litak [19] examined two electrically-coupled piezomagnetoelastic harvesters and showed that additive random excitation could assist in activating the bistable "snap-through" behaviors in spite of mistuning between the structures. Karimpour and Eftekari [20] and Chen and Jiang [21] analytically explored the 1:1 and 1:2 internal resonances as bases for inducing large amplitude motions in alternative vibration modes of monostable energy harvesting devices. Nonlinearity and multimodality have also attracted recent attention as tools to advance the performance of vibration absorption [22], vibration isolation [23,24], and sensing systems [25].

In spite of the active explorations on the potential for nonlinearity and multimodality to enhance energy harvesting system performance, there are several important questions which remain to be answered, particularly regarding how these two features are best integrated and exploited via internal resonance. For instance, a prime motivation is to "broaden" the operating frequency bandwidth of the vibration energy harvester by harnessing the large amplitude behaviors near the lower order natural frequency induced in consequence to excitations at approximately twice this frequency via 1:2 internal resonance (the saturation phenomenon). On the other hand, since the common piezoelectric and electromagnetic electromechanical conversion strategies generate an amplitude of harmonic current flow in proportion to the frequency of the excitations, activating nonlinear motions at a lower frequency may not provide advantage. The prior research efforts have not addressed whether the underlying motivation of exploiting internal resonance-induced saturation features is truly justified. Another concern is related to the robustness of activating the large amplitude dynamics when design and/or excitation parameters are known inexactly or undesirably change over time. Established studies on 1:2 internal resonance [26–28] have shown that there can be severely limited operating and design regimes over which large amplitude motions are induced. Such observations are obviously a practical concern for vibration energy harvesting systems unless excessive control is available for device fabrication and the harmonic excitation parameters are sufficiently static. Additionally, while trees are occasionally subjected to harmonic excitations related to seismic or flutter-type phenomena, by and large the excitation form is stochastic [29]. Likewise, energy harvesters may be operated in strongly stochastic environments or be under excitations which vary in the degree to which an individual frequency dominates above a background noise. Although internal resonance shows beneficial results in consequence to purely harmonic excitations on energy harvesters [20,21], the robustness of the phenomena when the significance of the harmonic contribution is reduced is not well understood, thus potentially compromising the viability of leveraging the nonlinear behaviors for energy harvesting enhancements. Indeed, as it relates to purely mechanical systems, the investigations conducted to characterize the stochastic sensitivity of nonlinearly coupled structures possessing 1:2 internal resonance show that the large amplitude dynamic effects may lose their stability due to the stochastic perturbations [30–32].

This research seeks to address these important questions by investigating a prototypical, monostable energy harvesting platform which exploits the 1:2 internal resonance. The justification for utilizing the phenomenon and the sensitivities

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