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A nonlinear energy sink with an energy harvester: Harmonically forced responses

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ABSTRACT

This study intends to achieve simultaneous vibration suppression and energy harvesting using a variant form of nonlinear energy sink (NES). The proposed apparatus is not a true NES as its spring is not essentially nonlinear. In a previous study [22] (Journal of Sound and Vibration, 333 (20) (2014)), it has been shown that the apparatus demonstrates the transient behaviors similar to those of the NES. As a sequel, the present paper focuses on harmonically forced responses of the system. First, the approximate solutions of steady state responses are derived. Using the approximate solutions, the steady state behaviors are investigated by using the numerical continuation method. This is followed by an experimental study. The study has shown that under harmonic excitation, the proposed apparatus functions similarly to the NES with the typical behaviors such as strongly modulated responses, amplitude jumping, excitation level dependence, etc. Overall, the apparatus meets the design objectives: the vibration suppression and energy harvesting in a broadband manner.

1. Introduction

A vibration absorber or tuned mass damper (TMD) is a common device for vibration suppression. In general the system under consideration is modeled as a linear oscillator referred to as primary or host system. When a TMD is attached to a host system subjected to a harmonic excitation, the host system's vibration can be suppressed if the TMD's natural frequency is tuned to be the exciting frequency. However, the TMD's main shortcoming is a narrow operational bandwidth or poor performance robustness. In recent years, there has been a growing interest in harvesting energy from ambient sources for self-powered devices. Among different ambient sources, vibration sources are suitable for small-scale power generation required by low-power electronics and thus have attracted increasing attention. Current solutions for vibration-to-electricity transduction are accomplished via electrostatic, electromagnetic, or piezoelectric methods. Regardless of the conversion mechanisms, most harvesters are designed as linear oscillators because they provide large amplitude responses at resonance. However, linear resonant harvesters are susceptible to a reduction in performance if the excitation conditions vary from the ideal sinusoidal form and resonant frequency.

Because the basic structure of a linear energy harvester is similar to that of a TMD, naturally it is desirable to use the same device to achieve simultaneous vibration suppression and energy harvesting. The study reported in Ref. [1] proposed to use an electricity-generating TMD to control vibration of tall buildings subjected to wind load. In the proposed apparatus, an

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electromagnetic transducer was used to replace the conventional viscous damper. In Ref. [2], a survey of control strategies for simultaneous vibration suppression and energy harvesting via piezo ceramics was presented. The focus was on using vibration-based piezoelectric harvesters as the main power source in active vibration control applications, such as a multi-functional wing spar for an unmanned aerial vehicle. In Ref. [3], a distributed piezoelectric energy harvesting vibration absorber (EHVA) was proposed. It was shown that the EHVA was capable of suppressing the vibration of structural panels while converting portion of the absorber energy into electricity.

Like the studies in vibration suppression or energy harvesting, how to simultaneously achieve these two objectives in a broadband manner is of importance as ambient vibrations are in general not narrowband in nature. The study reported in Ref. [4] proposed to add a piezoelectric harvester in parallel to the absorber spring and damper with suppression of vibration of the host structure as a primary goal and harvesting energy as a secondary goal. It was shown that with a proper choice of harvester parameters, broadband energy harvesting can be obtained combined with vibration reduction in the primary structure. The concept similar to the one proposed in Ref. [3] was further investigated in Ref. [5]. Two kinds of excitations to the host structure were considered: a broadband random force and a single-frequency harmonic force. It was found that for random excitation, a single device can effectively suppress vibration and harvest energy at the same time, while for a single-frequency excitation, maximizing energy harvesting and minimizing vibration of the host structure cannot be achieved at the same time.

Nonlinear vibration absorbers were proposed to overcome the narrowband problem of linear vibration absorbers. Some early studies on nonlinear vibration absorbers can be found in Refs. [6–8]. Some practical means of realizing nonlinear vibration absorbers were reported in Refs. [9–12]. Most of these studies have shown that a nonlinear vibration absorber can increase effective bandwidth. In the last 15 years nonlinear energy sinks (NES) have received much research attention. The critical difference between an NES and a nonlinear vibration absorber is that the former's spring is essentially nonlinear. The studies on the NES have been motivated to achieve targeted energy transfer (TET) in which vibration energy is irreversibly transferred from the host structure to the NES where it localizes and diminishes in time due to damping dissipation. In Ref. [13] and references therein, the features of the NES were examined. It was shown that the NES can effectively absorb transient vibrational energy from the linear oscillator due to a 1:1 internal resonance in which the oscillating frequency of the NES matches that of the linear oscillator. For periodic (narrowband) excitation, the NES can demonstrate strongly modulated response (SMR) that is the extension of the TET phenomenon.

Recently, there have been reported attempts to employ the NES for simultaneous vibration suppression and energy harvesting. In Ref. [14], the NES was incorporated with a piezoelectric device for vibration control and energy harvesting of a beam. Two configurations were considered: grounded and ungrounded. In the grounded configuration, piezoelectric element was between the NES mass and the ground, while in the ungrounded configuration it was located between the NES mass and the beam. In Ref. [15], energy harvesting from vibration of a nonideal portal frame structural support system under periodic excitation was considered. The system was modeled as a bistable one. An NES was added to the system to improve the energy harvesting by removing the chaotic motion, leading the system to a periodic orbit. It should be noted that the aforementioned studies were purely analytical and numerical and the results were not validated experimentally.

Physical realization of an ideal NES has proved to be challenging. In Refs. [16–20], the essential nonlinearity was achieved through thin piano wires with no pretension. In Ref. [21] the essentially nonlinear stiffness was generated by two coil springs. Again, to produce only the nonlinear spring effect, the springs are not under any pretension or compression when the NES mass is at the equilibrium position. No pretension means that the NES spring cannot be used to support the NES gravity force. The existing solutions included air track [16,20], guide shaft [17–19], and linear rail [21].

In Ref. [22], a variant NES was proposed to achieve simultaneous vibration suppression and energy harvesting. To maximize energy harvesting, mechanical damping must be minimized. The proposed solution is to mount a pair of permanent magnets on an axially preloaded thin steel beam fixed at both the ends. The permanent magnets act as the NES mass while the thin steel beam forms the NES spring. The NES mass is supported by the high vertical rigidity of the beam. The noncontact nature ensures a low mechanical damping. Due to a low lateral rigidity, the beam acts as a hardening spring laterally. Although the beam's linear stiffness can be reduced by preloading it axially, it is not possible to eliminate it. Thus the proposed apparatus is not a true NES. As a result, the setup inevitably introduces both linear coupling and nonlinear couplings between the NES mass and primary mass. In this sense, the proposed design belongs to a nonlinear vibration absorber. The study in Ref. [22] focused on the transient behaviors of the apparatus. It has shown that the developed apparatus possesses the characteristics of an NES and is capable of harvesting energy in a broadband manner. The present paper is sequel that focuses on harmonically forced responses of the system. The steady state responses are investigated both analytically and experimentally. The results show that the proposed variant NES functions similarly to the NES with the typical behaviors such as strongly modulated responses, amplitude jumping, excitation level dependence, etc. Overall, the apparatus meets the design objectives: the vibration suppression and energy harvesting in a broadband manner. To the best of the authors' knowledge, there have been no reports that use such a variant NES device to achieve the stated objectives.

The rest of the paper is organized as follows. Section two presents an analytical study that seeks approximate solutions of steady state responses of the system to a harmonic base excitation. Section three presents an experimental study that intends to verify the analytical results. Section four draws conclusions of this work.