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Improving the performance of auto-parametric pendulum absorbers by means of a flexural beam

S. Mahmoudkhani

Aerospace Engineering Department, Faculty of New Technologies and Engineering, Shahid Beheshti University, GC, Velenjak Sq., Tehran, Iran

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ABSTRACT

Auto-parametric pendulum absorbers perform well only in a very limited range of excitation amplitudes, above which their efficiency would be substantially degraded as a consequence of spillover effects or appearance of quasi-periodic and chaotic responses. For improving the performance against this drawback, the rigid pendulum is replaced in the present study with a low-stiffness viscoelastic beam. An additional one-to-three internal resonance between the almost non-flexural rotational and the first flexural modes of the beam is also introduced. With the aid of this internal resonance, the energy that has been transferred to the absorber due to the one-to-two internal resonance would be avoided from being transferred back to the primary system by faster dissipation of vibrations at a higher-frequency mode thereby leading to lower spillover effects. For modeling purpose, the tracking frame with the rigid-body constraint and also the third-order nonlinear beam theory are employed to account for arbitrarily large rotation angles coupled to moderately large elastic deformations. The assumed-mode method is also used to obtain discretized equations of motion. The numerical continuation of periodic solution is performed and the bifurcations with detrimental effects on the performance are determined. Various parametric studies are also conducted which show that by proper setting of the system parameters, higher efficiencies at much wider range of excitation amplitudes could be achieved.

1. Introduction

There have been growing interests in recent years on exploiting the nonlinearity for enhancing the performance of vibration mitigation devices such as dynamic vibration absorbers. Different features of nonlinear dynamical systems have been considered for this purpose leading to different types of nonlinear vibration absorbers (NLVAs). Among these features, the variation of natural frequencies with vibration amplitudes and the resulted hardening or softening behavior is one of the most common properties of nonlinear systems that was first exploited by Roberson [1] using a mass-spring absorber with a softening and hardening spring. It was shown that a wider suppression bandwidth could be achieved using this nonlinear absorber in comparison to its linear counterpart. A similar absorber named as a nonlinear tuned vibration absorber (NLTVA) has also been recently proposed by Habib et al. [2], where its optimal parameters were obtained using a nonlinear generalization of Den Hartog's equal-peak method. The study showed that the device would be most efficient when the restoring

E-mail address: s_mahmoudkhani@sbu.ac.ir.

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force of the absorber has the same mathematical function as the restoring force of the primary system. The performance and robustness of the absorber attached to a Duffing oscillator were also investigated by Detroux et al. [3] and were shown to be superior to the performance of the linear absorber especially in terms of sensitivity to the excitation level. Mass-spring-dampers with nonlinear springs have also been used in another type of nonlinear absorbers called the nonlinear energy sink (NES). The spring used in this type of absorber is nonlinearizable and thus it has no preferential resonance frequency. As a consequence, the device could engage in nonlinear resonances at different frequencies and with different modes of the primary system leading to broadband vibration suppression [4,5]. The quasi-periodic responses under harmonic excitations were also shown in this system to act in favor of higher suppression efficiencies [6].

Another property of nonlinear systems that have been used for vibration absorption is the bistability. The existence of multiple stable equilibrium states and the resulting snap-through behaviors of bistable systems would cause large amplitude vibrations between different stable positions, which could damp out the vibration of the primary system. The performance of bistable NLVAs has been investigated by Avramov and Mikhlin [7], and more recently by Manevitch et al. [8], Godoy et al. [9], and Remeo et al. [10].

The internal resonance, which may happen in nonlinear dynamical systems with (nearly) commensurable frequencies, is yet another possible mechanism that has been exploited in a different type of NLVAs called the auto-parametric absorber (AVA). The most common internal resonance condition considered for this purpose is the one-to-two resonance, which would benefit from the saturation phenomenon for vibration absorption. This was first implemented by Haxton and Barr [11] using a cantilever beam vertically attached to a linear oscillator. Other various mechanical and electrical realizations of the AVA with one-to-two internal resonance have also been investigated in the literature. Golnaraghi [12] used a sliding mass-spring-damper, and Cuvalci and Ertas [13] and Gumus and Ertas [14] used a pendulum for vibration suppression of a cantilever beam. The vibration control of the first symmetric mode of a curved beam using the energy transfer to the axisymmetric mode was also suggested by Hui and Ng [15]. Digital AVAs were studied by Pai et al. [16], Queini et al. [17], and Queini and Nayfeh [18]. Among different mechanical implementation of AVSs, the pendulum hinged to an oscillator has been gained more attention due to its simple practical realization. It was initially considered in a series of studies by Hatwal et al. [19–21] for vibration suppression of a linear oscillator under harmonic excitation. The nonlinear dynamics of the system was further investigated by Bajaj et al. [22] using the first-order averaging method and later by Banerjee et al. [23] using the second-order averaging method. The numerical simulation of the equations was also performed and it was found that as the excitation level grows, the response could become chaotic through a cascade of period-doubling bifurcations. These chaotic responses were not, however, favorable for vibration absorption. Other studies have also been carried out by Warminski and Kecik [24] on the dynamics of an auto-parametric pendulum attached to a nonlinear oscillator and by Kecik et al. [25] on the effect of the pendulum damping on the efficiency of the absorber.

Although AVAs have shown in the above mentioned studies to exhibit a desirable performance at a specific excitation amplitude, but they would remain efficient only in a small range of excitation amplitudes. In fact, for lower excitations outside this range, the AVA may not be even activated or does not effectively reduce the peak response amplitude. For excitation amplitudes above this range, the response would also become quasi-periodic or chaotic, which would again significantly impair the performance of the absorber. Moreover, AVAs would perform well only in a narrow frequency band and as the excitation amplitude increases, the nonlinear response peaks with growing amplitudes would appear at off-resonance points. This phenomenon is referred to as the spillover effects and would reduce the efficiency when the excitation is broadband [26]. These drawbacks have been partially eliminated using different methods suggested in the literature. Cartmell and Lawson [27] employed a controllable sliding mass on the pendulum to reduce the spillover effects by changing the internal tuning values according to the variation of the excitation frequency. Vyas and Bajaj [28] and Vyas et al. [29] introduced an array of slightly mistuned pendulums and showed through comprehensive analytical and numerical analyses that it could significantly increase the effective bandwidth. Another modification was also suggested by Pai and Schulz [26] for enhancing the performance of a digital AVA by using a quadratic velocity coupling term instead of a quadratic position coupling term, and also adding a negative velocity feedback to the system.

Besides the one-to-two internal resonance employed in the above studies, other types of resonance have also been examined for designing AVAs, such as the one-to-one internal resonance, which was considered by Queini et al. [30] in an active digital AVA possessing a cubic nonlinear term. The one-to-two-to-four and three-to-one AVAs were also examined by Pai and Rommel [31] and Ji [32] respectively. In a recent study [33], the author also investigated a system with one-to-one-to-zero internal resonance, which was realized using a flexural beam attached to a linear oscillator by a weak torsional spring. The performance of the beam as an absorber was investigated in this study and was shown to be effective in a very limited range of excitation amplitudes and frequencies. It is to be noted that although no direct comparison is made in these studies with the more common one-to-two AVAs, but their numerical results show no obvious advantage over the traditional AVA.

In the present study a simple passive method is proposed for enhancing the performance of the pendulum AVA by using a beam with a low bending stiffness and viscoelastic properties. The idea is to use the flexural pendulum with an intermediate lumped mass to introduce a one-to-three internal resonance into the system in addition to the one-to-two internal resonance. This is achieved by adjusting the bending stiffness and the position and mass of the lumped mass such that the frequency corresponding to the mode with dominant elastic deflections (referred to as the first flexural mode) is nearly three times the frequency corresponding to the mode with a dominant rigid body rotation (referred to as the almost non-flexural rotational mode). The frequency of the non-flexural rotational mode would also be nearly half the natural frequency of the primary system and due to the resulting one-to-two internal resonance, the energy would be transferred to the rotational mode of the