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Nonlinear vibration absorption for a flexible arm via a virtual vibration absorber

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ABSTRACT

A semi-active vibration absorption method is put forward to attenuate nonlinear vibration of a flexible arm based on the internal resonance. To maintain the 2:1 internal resonance condition and the desirable damping characteristic, a virtual vibration absorber is suggested. It is mathematically equivalent to a vibration absorber but its frequency and damping coefficients can be readily adjusted by simple control algorithms, thereby replacing those hard-to-implement mechanical designs. Through theoretical analyses and numerical simulations, it is proven that the internal resonance can be successfully established for the flexible arm, and the vibrational energy of flexible arm can be transferred to and dissipated by the virtual vibration absorber. Finally, experimental results are presented to validate the theoretical predictions. Since the proposed method absorbs rather than suppresses vibrational energy of the primary system, it is more convenient to reduce strong vibration than conventional active vibration suppression methods based on smart material actuators with limited energy output. Furthermore, since it aims to establish an internal vibrational energy transfer channel from the primary system to the vibration absorber rather than directly respond to external excitations, it is especially applicable for attenuating nonlinear vibration excited by unpredictable excitations.

1. Introduction

Vibration absorption is a type of effective methods for controlling vibration of the flexible structures and mechanical systems. Generally, one or more vibrating subsystems named the Dynamic vibration absorbers (DVAs) are attached to the primary system to reduce forced vibration excited by external harmonic excitations of a specific frequency.

Due to narrow effective frequency bandwidth, traditional passive DVAs lack enough flexibility and adaptability. Therefore, various measures for tuning the stiffness of DVAs have been developed to extend effective frequency bandwidth of DVAs. These measures include varying effective coil number of a mechanical spring [1], controlling the space between two spring leaves [2], adjusting the length of threaded flexible rods [3], changing effective length of a flexible cantilever beam by moving the intermediate support [4], changing the pressure of air springs [5], and adjusting the curvature of two parallel curved beams [6], etc. Recently, smart materials such as shape memory alloy [7,8], magnetorheological elastomers [9,10] and piezoelectric ceramic [11] have also been used as variable stiffness elements. Moreover, in order to replace those hard-to-implement mechanical designs, some virtual passive approaches are employed to emulate the dynamics of a vibration

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absorber [12,13]. The stiffness, inertial and damping coefficients of the virtual vibration absorber can be readily adjusted by varying the parameters of virtual elements. In particular, the virtual spring is tuned according to the phase difference between the acceleration of primary system and the displacement of virtual mass [13].

Although there are many ways to vary effective frequency, most of aforementioned vibration absorbers are used to deal with linear vibration problem of the primary system. Compared with linear vibration, however, nonlinear vibration of the primary system is much more difficult to control. Since nonlinear terms cannot be ignored any more, many control methods based on the linear model may result in fundamental mistakes. Furthermore, these vibration absorption methods have to depend on the information of external excitations to neutralize vibration of the primary system. As a result, if the external excitations are unclear or unpredictable in such case as the outer space, these methods will deteriorate.

In recent years, active control methods have made remarkable progress. Particularly, various smart material actuators have been put forward to control vibration, such as piezoelectric ceramic and shape memory alloy. However, since they rely on external energy to suppress vibration, it is difficult for them to conquer strong vibration due to limited energy output. Besides, the stability problem is crucial to active control methods. If designed unreasonably, active control forces may excite rather than suppress vibration. Therefore, when dealing with strong vibration, the semi-active vibration absorption method exhibits its own advantages. On the one hand, it absorbs rather than suppresses the vibrational energy. On the other hand, it possesses good stability as the passive methods.

Based on above analyses, it is necessary to investigate an effective semi-active vibration absorption method for reducing strong nonlinear vibration excited by indeterminate external excitations.

Internal resonance is a typical nonlinear phenomenon of the multi-degree-of-freedom nonlinear dynamics system, by which two vibrational modes can be coupled and the vibrational energy can be exchanged between the modes. Golnaraghi [14,15] firstly used internal resonance to reduce vibration of a flexible cantilever. A 1:2 internal resonance state was established between two vibrational modes of the beam and the slider. And vibration of the beam was dissipated by the damping of the slider. Tuer [16] and Duquette [17] conducted numerical simulations and experiments to control vibration of a similar beam using an internal resonance controller. Then Tuer [18] proposed a generalized control strategy for a cantilever beam based on the internal resonance. Afterwards, Oueini [19] built an analog electronic controller to maintain internal resonance and conducted an experiment research. Khajepour [20] examined the possibility of reducing vibration of a flexible beam using the center manifold theory. However, the flexible beam model adopted in above studies is a rigid beam connected by a torsional spring. Obviously, this assumption is not suitable for real flexible arm. Recently, the distributed flexible beam model has been researched. Pai [21] used higher order internal resonance to design a vibration absorber to reduce vibration of a cantilevered plate. Yaman [22] absorbed vibration of a cantilever beam using a pendulum attached to the tip mass. Hui [23] attenuated translational vibration of the source mass by transferring the internally resonant energy from the symmetrical to anti-symmetrical mode.

Nonetheless, new research work on the flexible arm is insufficient. Firstly, since the controlled primary system in the aforementioned studies is a flexible structure without rigid motion, their research results cannot be used to deal with nonlinear vibration problem of a flexible arm with large-scale joint motion. Whether the internal resonance can be established for the flexible arm should be researched. Secondly, the controlled primary system in these studies is viewed as a linear vibration model for the simplicity. However, the flexible arm itself is a complicated nonlinear dynamics system. Therefore, unreasonable linearization may lead to fundamental mistakes. Up to now, there are few theoretical and experimental research works about nonlinear vibration control for the flexible arm based on the internal resonance. Its theoretical correctness and practical feasibility need be examined.

In this paper, a semi-active vibration absorption method is put forward to attenuate nonlinear vibration of a flexible arm based on the internal resonance. To maintain the 2:1 internal resonance condition and the desirable damping characteristic, a virtual vibration absorber is suggested, which frequency and damping coefficients can be readily adjusted by simple control algorithms. Perturbation technique is utilized to study transient and steady-state response of the nonlinear dynamics equations. Through theoretical analyses and numerical simulations, it is proven that the internal resonance can be successfully established for the flexible arm. Finally, experimental results are presented to validate the theoretical predictions.

2. System description

As shown in Fig. 1, a flexible arm is studied in this paper. It can rotate around the joint $o_0(o_1)$, which rigid motion is denoted by θ. $o_0e_1^0e_2^0$ is the fixed coordinate system and $o_1e_1^1e_2^1$ is the moving coordinate system attached to the arm. The arm is simplified as a uniform Euler-Bernoulli flexible beam with the length l, rectangular cross-section of the height h and the width b. Only the lateral deformation $w(x, t)$ about e_2^1 axis in the plane $o_1e_1^1e_2^1$ is considered, where t is time.

In this study, a virtual semi-active approach is adopted in the design of the vibration absorber. It is mathematically equivalent to a vibration absorber, and thus can emulate the dynamics of a vibration absorber. This virtual vibration absorber is implemented by a servomotor, which the stiffness and damping coefficients can be readily adjusted by simple control algorithms. In particular, its virtual spring is tuned via variable position feedback gain and its virtual damping is tuned via variable velocity feedback gain. Therefore, the frequency and damping of the virtual vibration absorber can be altered, and thus play an important role in establishing the internal resonance. As shown in Fig. 1, the servomotor is