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Optimal design of a beam-based dynamic vibration absorber using fixed-points theory

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The addition of a dynamic vibration absorber (DVA) to a vibrating structure could provide an economic solution for vibration suppressions if the absorber is properly designed and located onto the structure. A common design of the DVA is a sprung mass because of its simple structure and low cost. However, the vibration suppression performance of this kind of DVA is limited by the ratio between the absorber mass and the mass of the primary structure. In this paper, a beam-based DVA (beam DVA) is proposed and optimized for minimizing the resonant vibration of a general structure. The vibration suppression performance of the proposed beam DVA depends on the mass ratio, the flexural rigidity and length of the beam. In comparison with the traditional sprung mass DVA, the proposed beam DVA shows more flexibility in vibration control design because it has more design parameters. With proper design, the beam DVA's vibration suppression capability can outperform that of the traditional DVA under the same mass constraint. The general approach is illustrated using a benchmark cantilever beam as an example. The receptance theory is introduced to model the compound system consisting of the host beam and the attached beam-based DVA. The model is validated through comparisons with the results from Abaqus as well as the Transfer Matrix method (TMM) method. Fixed-points theory is then employed to derive the analytical expressions for the optimum tuning ratio and damping ratio of the proposed beam absorber. A design guideline is then presented to choose the parameters of the beam absorber. Comparisons are finally presented between the beam absorber and the traditional DVA in terms of the vibration suppression effect. It is shown that the proposed beam absorber can outperform the traditional DVA by following this proposed guideline.

1. Introduction

A Dynamic Vibration Absorber (DVA), also known as the tuned mass absorber, is a mechanical device designed to be attached to a primary dynamic structure in order to reduce its vibration or sound radiation. A traditional passive vibration absorber consists of a single degree-of-freedom (SDOF) mass-spring-damper system. The DVA can be used to reduce the unwanted vibration due to a resonant mode or the forced vibration of the primary structure. When properly tuned to deal with the vibration at the targeted frequency, the vibration energy can be transmitted efficiently from the primary structure to

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the DVA, leading to a reduction in the vibration of the primary structure. DVAs have been extensively applied in civil engineering [1–3] to strengthen the resistance of slender tall buildings subjected to wind loads or seismic excitation.

Many criteria can be found in the literature for the optimal design of tuning frequency and damping ratios of the DVA to maximize its vibration suppression performance [4–7]. The most commonly used one is the H_∞ criterion to minimize the maximum vibration amplitude of the primary structure. Common ways of achieving the H_∞ optimal design of the traditional DVA is to apply the fixed-points theory proposed by Den Hartog in 1928 [4]. The theory states that there exist two fixed points, independent of the damping, in the frequency response spectrum of an undamped SDOF primary system connected with the traditional DVAs. The optimum tuning ratio is determined by making the two fixed points equally high in the spectrum and the optimum damping ratio is determined by making the two fixed points to be the highest points in the response spectrum. The H_∞ design strategy works well for the narrow band control. To tackle the broadband problem like the random excitation, the H_2 optimization criterion can be applied. Warburton [5,6] derived the optimum tuning ratio and damping ratio in order to minimize the mean square values of the vibration displacement or kinetic energy over a frequency band under various types of external excitations. Asami et al. [7] introduced the damped SDOF primary system and derived the series solution for the H_∞ optimization and the analytical solution for the H_2 optimization of the absorbers parameters. They confirmed that their solution of the optimal absorber parameters could be degenerated to the existing value by Den Hartog's method [4] when the primary system's damping is assumed to be zero.

There are many research works done to extend the fixed-points theory for global vibration control of continuous structures [8,9] and the optimization of variant design of DVA [10]. The limitations of the traditional mass spring DVA are mainly in three aspects. a) Their vibration suppression performance is limited once the mass ratio is fixed. Without sufficient absorber mass, the vibration suppression effect is not significant. Due to physical or practical constraints, the absorber mass is seldom larger than 20% of the mass of the primary structure. b) The stiffness of the spring can neither be too high or too low. The spring stiffness can't be too low or else the static displacement will become very large, rendering it difficult to be implemented in practice. If the spring is too hard it can't achieve vibration control at low frequency. c) Their vibration control performance is undermined if the resonance frequency deviates from the targeted value for which they are designed (also known as detuning effect). The solutions to the last question have been attempted by many researchers. The methods include developing active, semi-active or hybrid control devices [11–14] or adaptive vibration absorbers [15] whose stiffness varies with the excitation frequency. These devices are usually bulky and need external energy input. Acar and Yilmaz [16] developed a adaptive absorber consisting of a string-mass system equipped with negative stiffness tension mechanism. Their design allows the absorber's natural frequency to be varied within a certain frequency range by using a small tuning actuator force. This kind of device provides a solution for the bulky and energy-consuming problem in the design of adaptive absorber. However, most of the adaptive absorbers with other physical mechanisms still have the size and energy problems. Meanwhile, strategies involving multiple tuned vibration dampers (MTVD) [17,18] are also investigated to overcome the detuning effect.

As far as the authors know, there is still a lack of effort to address the challenges in a) and b). A beam type DVA which can have better vibration suppression performance under the same mass constraint as compared to the traditional spring mass DVA is proposed. Moreover, this type of DVA can easily control low frequency vibration by using a long beam as the absorber. Aida et al. [19] has reported the optimization of a beam type DVA connected to the host beam through spring and damping element. Under the same boundary constraints, the beam DVA and the host beam can be reduced to a 2-DOF system, and then the fixed-points theory is used to obtain the optimum tuning ratio and damping ratio. In their optimization method, the vibration control effect of the beam type DVA is still dependent on the mass ratio between the two beams. Moreover, the spring and damping element are required to be accurately manufactured to their optimum value. On the other hand, the proposed beam DVA of this paper doesn't require any extra stiffness element and its vibration control effect is not solely dependent on the mass ratio. The working principle of the proposed beam DVA is described in Sections 3 and 6 of this paper.

The idea of the beam-based dynamic vibration absorber proposed in this paper was inspired by the work of Tso et al. [14] as shown in Fig. 1, in which a hybrid DVA capable of achieving the global control in a broadband vibration of a primary beam structure is established. This hybrid DVA has a passive control part consisting of a rotational beam structure with a lumped

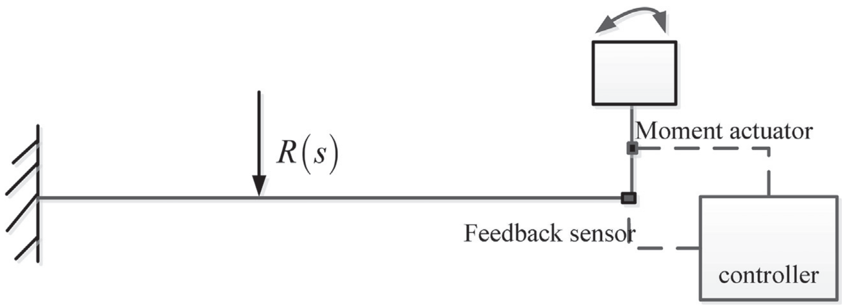

Fig. 1. A cantilever beam carrying the proposed HVA at the end of the beam [14].