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H_∞ optimization of fluid viscous dampers for reducing vibrations of high-speed railway bridges

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ABSTRACT

This work deals with the optimization of fluid viscous damper systems (FVDs) to reduce the resonant dynamic structural response of high-speed railway bridges by algebraic and numerical approaches. The presented method chooses the objective function based on the H_∞ norm over the frequency band of interest. This function allows taking into account structural damping properties and minimizing simultaneously the structural response associated with multiple modes. Especially, the proposed objective function may also be extended to nonlinear problems to determine optimal parameters of nonlinear fluid viscous dampers which may be an interesting solution in applications where high force levels are expected in the dampers. Finally, the proposed method is validated through numerical simulations. The simulation results show that the optimal FVD coefficients obtained by using the presented method are more exact than those by the previous method. Besides, the effectiveness of the method for solving the problems with the contribution of high modes and the consideration of nonlinear FVDs is also proved.

1. Introduction

The fluid viscous damper has been successfully implemented in real structures to improve their dynamic performance under different sources of excitation. It was first used in 1897 in the 75 mm French artillery rifle and after that, in systems of aerospace and military hardware. Since 1990, these devices have been commonly applied to civil structures for seismic protection [1–3]. Numerous experimental and analytical investigations on FVDs have focused on reducing vibrations of high-rise buildings, chimneys, towers, footbridges, etc. Recently, the use of FVDs in high-speed train bridges has received attention from structural engineers.

The first studies documented by Museros and Martinez-Rodrigo [4–6] are concerned with reducing excessive vertical vibrations of high-speed railway bridges experiencing resonance situations by using double beam systems. These systems include auxiliary beams installed underneath bridge decks and FVDs to connect the auxiliary beams to the bridge decks. The solution proposed by the previously mentioned authors could be installed and maintained in existing railway bridges without interfering with everyday rail traffic keeping the lines in operation. On the other hand, FVDs can control the structure vibrations in a wide frequency range, while retrofitting bridge decks with single or multiple tuned mass dampers, proposed by a few authors in the last years [8–11], leads to the structure vibration control at particular frequencies of operation. Furthermore, the above researchers derived analytical closed-form expressions for calculating the optimal

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damper constants of FVDs that minimize the bridge maximum response at resonance. They also analyzed the mitigation of torsional vibrations in double-track and skewed structures. The theory for these studies is based on the feature of "fixed-point" frequency. It means that when structural damping is neglected in the primary system, the family of response curves passes through one invariant point on the amplitude–frequency plane, irrespective of the value of the damping constants. The damping ratio of FVDs is taken to be optimal when the response curves pass through either invariant point with a horizontal tangent. The results indicated that the proposed FVD system could effectively control the maximum response at resonance of bridges, that are subjected to moving loads of trains at high speed. However, it can be seen that the proposed analytical approach did not take the structural damping into consideration.

Recently, researchers have begun to focus on FVDs exhibiting a nonlinear force–velocity relation. Experimental testing by Seleemah and Constantinou [1,12] showed that a suitable mathematical model of the behavior of nonlinear viscous fluid dampers can be described by relating the force and the relative velocity through a fractional power law. For seismic applications, this parameter typically has a value range from 0.2 to 2. Furthermore, the above researchers proved that nonlinear FVDs are advantageous because of their ability to limit peak damper forces at large structural velocities while still providing sufficient supplemental damping. Besides, Symans [1] also suggested a formula to linearize the above nonlinear FVD model. However, it cannot be used directly in the objective functions to find optimal damping coefficients because it depends on the relative displacement amplitude of the main system. This is a challenge about nonlinear FVDs. Recently, to solve this problem, Diotallevi et al. [14] also proposed a method in which a new dimensionless parameter, called damper index, not related to the maximum displacement in Symans' formula, is introduced but only for some particular structures, especially buildings equipped with nonlinear fluid viscous dampers.

For multiple degrees of freedom systems with FVDs, Fabunmi [13] used an extended damping model for analyzing the vibrations of a simple 3-degree-of-freedom spring–mass–damper system with nonlinear FVDs. A formulation expressing the mobility function as a series of modal functions, summed over all the important modes in a given frequency band is proposed. This formulation allows the modeling of general damping behavior by means of a frequency dependent function.

In this article, a new method is established for describing an objective function based on H_∞ norm to find optimal damping ratios of FVDs for reducing resonant response of high-speed railway bridges. Especially, the proposed objective function can include structural damping properties, minimize simultaneously structural response at multiple modes and also be extended to nonlinear problems to determine the optimal parameters of nonlinear fluid viscous dampers.

2. Train and structural system

In general, train loads may be simulated by using three models: the moving force model, the moving mass model and the moving suspension mass system as shown in Fig. 1. Each of them may lead to slightly different structural response and natural frequencies because of the interaction between moving trains and bridges. However, the studies in [15,4] indicate that the use of the different train models leads to a change in resonant frequencies about 2.5 percent. Moreover, on the safety side, it is well known that the train–bridge interaction leads to a smaller reduction of the bridge vertical acceleration response at resonance. For these reasons, the railway excitation will be simulated by means of moving loads in this work, neglecting vehicle–structure interaction effects. In particular, the high speed train model HSLM-A8, one of the high speed passenger train models in accordance with the requirements of the European Technical Specification [16], is used as a prototype of a moving train in what follows. All required properties of the train are given in Table 1 and Fig. 2. The train loads are applied at the centerline of single-track bridges with straight decks and move along the longitudinal direction at a constant speed.

The investigations presented here consider a simply supported bridge and a double-span bridge. The structural parameters and the modal properties of the systems, which were originally suggested by [18,19], are given in Table 2.

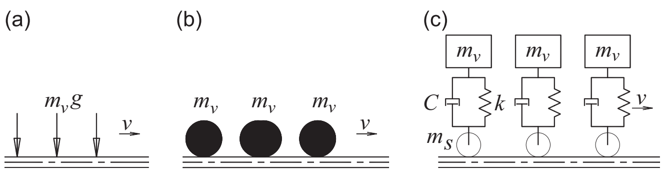

Fig. 1. Train load models: (a) moving load model, (b) moving mass model and (c) moving suspension mass model.

Table 1
Properties of the HSLM-A8 high-speed train [17].

Universal train	Number of intermediate coaches, N	Coach length, D (m)	Bogie axle spacing, d (m)	Point force, F (kN)
A8	12	25	2.5	190