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Vibration control of vortex-induced vibrations of a bridge deck by a single-side pounding tuned mass damper

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ABSTRACT

This paper proposes a new method to mitigate vortex-induced vibrations (VIVs) of a bridge deck using a single-side pounding tuned mass damper (SS-PTMD). The SS-PTMD is a passive control device and comprises an undamped tuned mass with a pounding boundary covered with viscoelastic (VE) materials layer. A nonlinear force model for describing impact behavior of VE materials is used to simulate the response of a single degree of freedom (SDOF) system controlled by a SS-PTMD. The free pounding experiments are performed to determine the model parameters of impact force and validate the simulation method. The optimal design of SS-PTMD for SDOF system subjected to sinusoidal excitation is carried out by numerical optimization, and the optimized SS-PTMD is applied to control the vertical VIVs of a bridge deck. The control performance is experimentally examined by elastically mounted section model tests in wind tunnel. In addition, the classical wake oscillator model is used to predict the behavior of the coupled fluid-structure system under VIV and explore the control performance of the SS-PTMD. The experimental results show that the maximum response of the bridge deck model was reduced by 94% when a SS-PTMD with mass ratio of 2% was applied. It is also shown that nonlinearity in vortex shedding forces has little influence on control performance of SS-PTMD optimized under sinusoidal excitation.

1. Introduction

Vortex-induced vibrations (VIVs) of the bridge deck happens if the frequency of vortex-shedding matches with one of the natural frequencies of the bridge [1–4]. It is a resonant-type vibration dominated by a single mode of vibration, and has been observed on many bridges. For the long-span bridges with small damping and more flexible configurations, large amplitude VIV may occur in a relatively low wind speed range about 5–10 m/s. In another word, long-span bridges may suffer from long-term vibration with considerably large amplitudes, which discomforts users and greatly shorten the life of bridges.

Tuned mass dampers (TMDs), as a low-cost and simple passive control device, have been applied to vibration control of flexible and low-damping structures under different excitation inputs, such as vehicle [5–8], wind [9–12] and earthquake excitations [13–16]. The effectiveness of using TMD to control VIVs of flexible structures, such as pipelines [17,18], high-rise buildings [19–21] and long-span bridges [22,23], were reported. The conventional TMD, which is firstly proposed by Frahm [24], only consists of a mass-spring system. When the frequency of the mass is exactly tuned to the frequency of the controlled structure, the vibration energy of the controlled structure will be transferred to the tuned mass. Den Hartog incorporated a linear viscous damper into TMD and the optimal parameters of TMDs to control an undamped system was derived [25,26]. Some other solutions to supply linear or nonlinear damping for TMDs were studied, such as particle dampers [27–29], Magneto-rheological (MR) dampers [30–33], friction dampers and eddy current dampers [34–38].

Recently, Song et al. [39] introduced the pounding damping into a TMD system to enhance the control performance and the combined system is called pounding tuned mass damper (PTMD), as shown in Fig. 1(a). In their design, two pounding boundaries are added in the either sides of the tuned mass and this type of damper is termed as a double-side PTMD. When the relative vibration displacement exceeds the gap between the tuned mass and the pounding boundaries, the tuned mass will pound on the boundary to provide supplemental energy dissipation. To enhance the energy dissipation during poundings, viscoelastic (VE) material layer is attached on the pounding boundary. Several applications of the double-side PTMD for vibration control of a

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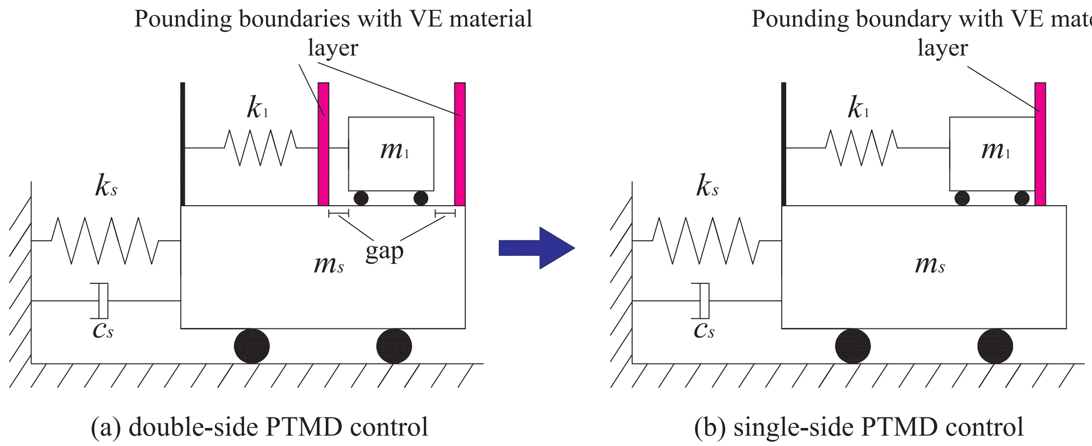

Fig. 1. A SDOF system with conventional PTMD and SS-PTMD.

traffic pole [40,42] and subsea pipelines [39,41,43] showed that the double-side PTMD is more robust and effective than the conventional TMD [42–44]. Furthermore, the effectiveness of the double-side PTMD for the seismic vibration protection of multiple degree of freedom (MDOF) structures was also investigated [45,46]. Based on the double-side PTMD design, Wang et al. [47,48] proposed a novel single-side pounding tuned mass damper (SS-PTMD) to control the free vibration and forced vibration of a low-damping structure, as shown in Fig. 1(b). Compared to the conventional double-side PTMD, only one pounding boundary is added next to the equilibrium position of the spring-mass system to provide additional damping for the TMD system. This modification eliminates the gap between the mass and pounding boundary as shown in Fig. 1(a) and simplifies the parametric design. The optimal design of the SS-PTMD for controlling a SODF system subjected to sinusoidal excitation has been studied [49,50].

In many situations, the installation space and stroke of tuned mass dampers is a practical constraint and the SS-PTMD provides a superior solution. Moreover, the energy dissipation provided by VE materials during poundings is not changed too much even after 350,000 poundings [51]. Although the effectiveness of the novel SS-PTMD to control the free vibration and the forced vibration under harmonic loadings were demonstrated, application to control the VIVs of bridge girders is still an interesting topic and has not been reported yet. Unlike sinusoidal excitation, vortex shedding forces responsible for VIV of bridge deck involves structure-fluid interaction and is highly nonlinear. In this study, the effectiveness of SS-PTMD for control of VIVs of a bridge deck is investigated experimentally and numerically. An impact force model which considers the nonlinear impact behavior of VE materials is used to simulate the response of a single degree of freedom (SDOF) system equipped with a SS-PTMD. The optimal parameters of the SS-PTMD are obtained for a SDOF structure subjected to sinusoidal excitations. Moreover, the optimized SS-PTMD is applied to control the vertical VIV of a bridge girder sectional model. The effectiveness of the proposed SS-PTMD to control VIVs is numerically studied by the wake oscillator model and examined by the wind tunnel experiments.

2. Modeling of single-side pounding tuned mass damper (SS-PTMD)

2.1. Dynamic properties of SS-PTMD

The mechanical model of a single degree of freedom (SDOF) structure equipped with the novel SS-PTMD to suppress vertical vibrations is shown in Fig. 2. The SS-PTMD has a pounding boundary covered by VE material layers beneath the tuned mass when the mass is in the equilibrium position. The natural frequency f_d and the equivalent damping ratio ζ_d of the novel SS-PTMD can be expressed as [48],

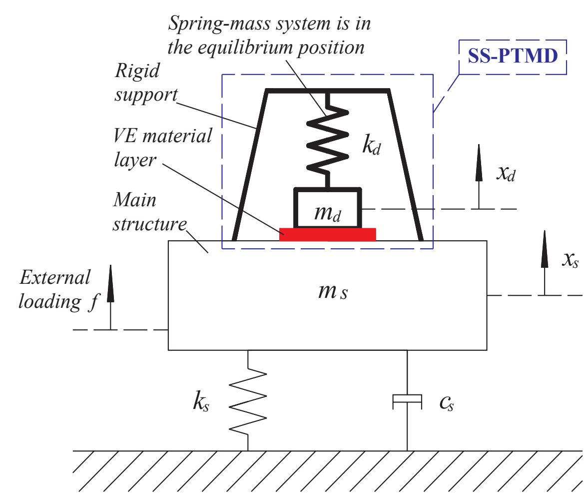

Fig. 2. A vertical vibration system controlled by the proposed SS-PTMD.

$$f_d = \frac{1}{\pi}\sqrt{\frac{k_d}{m_d}} \tag{1}$$

$$\zeta_d = \frac{1}{2\pi}\ln\left(\frac{1}{e}\right) \tag{2}$$

where k_d and m_d are the stiffness and mass of the SS-PTMD, e is the coefficient of restitution (COR) during impacts between tuned mass and the VE material layer. Contrast to a general spring-mass system, it is evident that the frequency of the SS-PTMD is doubled. This is because the pounding boundary prevents the mass move into the lower half stroke, as shown in Fig. 2. Since Eq. (1) ignores the pounding duration, the actual frequency should be slightly larger than that provided by Eq. (1). Moreover, it should be noted that Eq. (2) is an approximate expression for damping ratio calculation and it has good accuracy when e is larger than 0.4 [47].

2.2. Pounding force modeling

The conventional impact theory, employing the impact velocity exchange, neglects the pounding duration and cannot provide the specific value of the impact force [49]. In this paper, an impact force model, which considers the nonlinear behavior of poundings between VE material layer and steel, is utilized to simulate the response of the SS-PTMD. The pounding force between the VE materials layer and steel is given by [49],