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Vibration control for large-span roof structure using pounding tuned mass damper

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ABSTRACT

Large-span roof structures like stadium, airport lobby and exhibition hall are widely used all over the world recently. This type of structures have characters of lightweight, flexibility, low damping ratio and closely natural frequencies. Therefore, they are easy to oscillate when they are subjected to wind load or seismic load, which may lead to component fatigue or even endangers structure's safety. Therefore it is necessary to take some measures to reduce the vibration. This paper utilizes a pounding tuned mass damper(PTMD) installed inside the steel rod of a large-span roof structure for wind-induced vibration control. The PTMD is a combination of the tuned mass damper(TMD) and the impact damper. The spring-mass system can absorb the kinetic energy and dissipate them through the poundings between the mass and viscoelastic materials attached to the boundary surface. In order to evaluate the effectiveness of the damper, the experimental study was performed. In the experiment, a full-sized steel rod of a large-span roof structure with the PTMD installed inside was fabricated on a shake table which can generate external excitation. Both free vibration analysis and forced vibration analysis were performed. The experimental results showed an obvious vibration reduction for the steel rod of large-span roof structure.

1. INTRODUCTION

Large-span roof structures are widely used in public buildings such as stadium, airport, and exhibition centers due to its aesthetically appealing shapes and capacity to provide large spaces without inner columns. However, the parameters like lightweight

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and flexibility, which make them susceptible to external excitations like seismic and wind load. Long-time and persistent wind-induced vibration can cause fatigue and damage of some nodes, support or even the whole structure. Therefore, there is an urgent need to carry out research works for the control of wind-induced vibration for large-span roof structure.

Many researchers investigated the vibration control of large-span roof structures subjected to seismic or wind load. Bao employed a semi-active MR (magnetorheological) damper to control seismically excited vibration of long span structure with an appropriate control strategy(Bao, Huang et al. 2009). But this method is not practical for civil engineering structures. Zhou used multiple TMDs to restrain the vibration of large-span roof structure(Zhou, Lin et al. 2015). However, TMD is a frequency-sensitive damper, when the damper's frequency is detuned from the natural frequency of the main structure, the control performance will deteriorate. As a consequence, the robustness of the damper is a challenging issue to solve. The pounding tuned mass damper(PTMD) was developed to control the vibration for various main structures. The PTMD was first innovated by Song(Song, Li et al. 2012), and then it was applied to a variety of fields, including power transmission tower and subsea jumpers(Zhang, Song et al. 2013, Li, Zhang et al. 2015). The parameters and robustness of the damper were studied then to observe the performance when it was used to control the vibration of the main structures(Li, Zhang et al. 2015, Zhang, Li et al. 2016, Jiang, Zhang et al. 2017). The vibration of traffic signal pole excited by wind load can also be controlled by PTMD(Li, Song et al. 2013). Wang proposed a novel PTMD, which the delimiter covered with viscoelastic material is fixed right next to the tuned mass when the spring-mass system is in the equilibrium position. The natural frequency and the equivalent damping ratio were derived theoretically then(Wang, Hua et al. 2017). Moreover, the advanced impact force model was introduced to simulate the vibration control for the main structures by PTMD(Wang, Hua et al. 2017). The impact fatigue of viscoelastic materials attached to the pounding boundary of the damper was researched, and the result showed a fine property after many times impact(Zhang, Huo et al. 2018).

In order to control the vibration of the large span roof structure, the PTMD installed inside a steel rod of the large-span roof structures are introduced in this paper. And the control performance and the robustness of the damper will be researched. The free vibration and forced vibration load cases will be considered. The PTMD-primary structure will be excited by the shake table which can generate harmonic wave and seismic wave. The frequency of the PTMD will be tuned through adjusting the location of the mass to investigate the robustness.

2. Mechanism of PTMD

The PTMD is a combination of the TMD (Tuned Mass Damper) and the impact damper. Its principle is shown in the Fig. 1. The damper is mounted on the primary structure. The mass of the damper is fixed with the host structure through the spring system. There are two delimiters with viscoelastic materials fixed on both sides of the tuned mass. When the main structure vibrate, the mass of the damper will move due to the inertia force. The spring mass system can absorb the vibration energy from the host structure. However, the natural frequency of the damper must tuned to the natural frequency of the host structures by precise design of spring and damping system. The impact occurred when the vibration amplitude of the mass exceeds a certain level, the tuned mass will pound on the delimiters as an impact damper. And then the energy can be consumed due to the viscoelastic delimiters. As a consequence, the oscillation of the host structure and the damper can be restrained.

The pounding force model is expressed as:

$$F(t)=\begin{cases}\beta\delta^{3/2}+c\dot{\delta} & \text{(approaching period of collision)}\\ \beta\delta^{3/2} & \text{(restitution period of collision)}\\ 0 & \text{(not colliding)}\end{cases} \qquad (1)$$

where δ describes the deformation of the colliding bodies; $\dot{\delta}$ denotes the relative velocity between the primary structure and the damper; β is the pounding stiffness; c is the pounding damping parameter. The determination of the parameters β and c was introduced in a previous study (Zhang, Song et al. 2013).

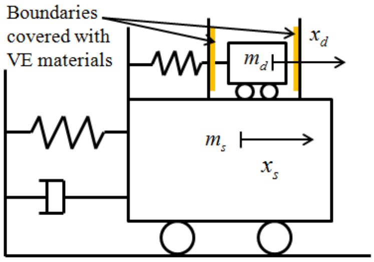

Fig. 1 Schematic of PTMD

3.Experiment setup

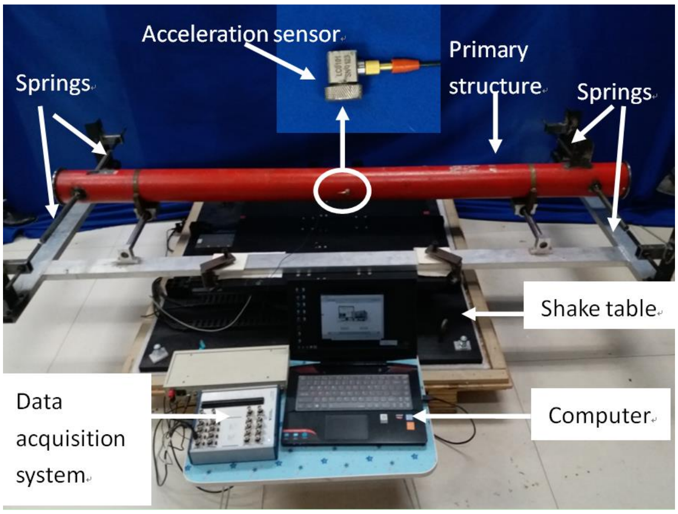

Fig. 2 The experiment setup.

A rod of a large span roof structure was used for experimental investigation. The device was fixed on the shake table, comprising a fixed base, a steel rod, four springs and two sliders, as shown in Fig. 2. The steel rod was linked to the fixed base by four springs which can provide the stiffness of the primary structure. The PTMD was installed in the inner space of the hollow rod. There are two flanges on both sides of the rod which connected with the mass by the spring steel cantilever beam, as depicted in Fig. 3. The boundaries of the damper covered with viscoelastic materials can limit the motion of the mass. The geometrical parameter of the spring steel such as length, width and thickness can be selected to satisfy the frequency of the damper. And after this selection, the position of the mass fixed on the spring steel can be adjusted to change the frequency of the damper in the experiment. An acceleration sensor was mounted on the steel rod to obtain the acceleration signal, and then collected by the data acquisition system shown in Fig. 2. The shake table can provide the external excitation to force the primary structure to oscillate. The natural frequency of the primary structure is 2Hz. And the mass ratio of the damper is 2%.

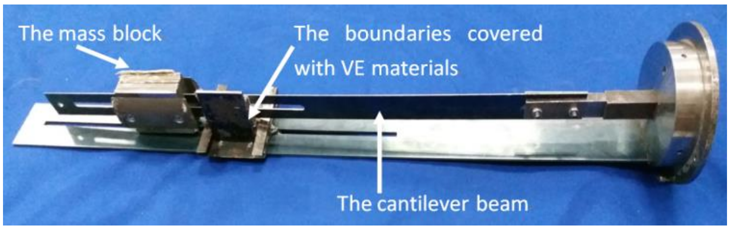

Fig. 3 The PTMD inside the steel rod.

4. Control performance of PTMD

In the experiment, the free vibration and forced vibration was performed. Fig. 4 shows the response of the steel rod with and without PTMD for free vibration. Results of free vibration test show the increase in the effective damping ratio of structure, which was from 1.89% (without PTMD) to 3.88% (with PTMD). Fig. 5 shows the response of the steel rod for forced vibration. The result shows that the reduction of the vibration amplitude of steel rod from 4m/s2 to about 0.3 m/s2, which is reduction of 91.55%.

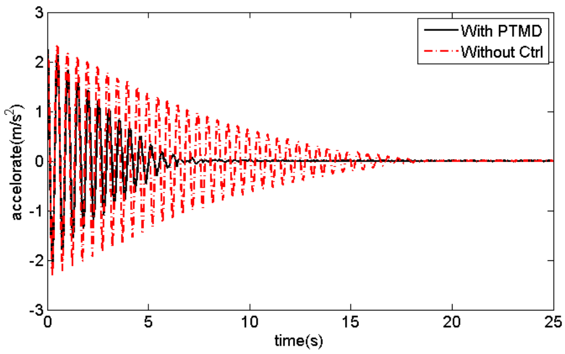

Fig. 4 Response of the primary structure controlled by PTMD in free vibration case

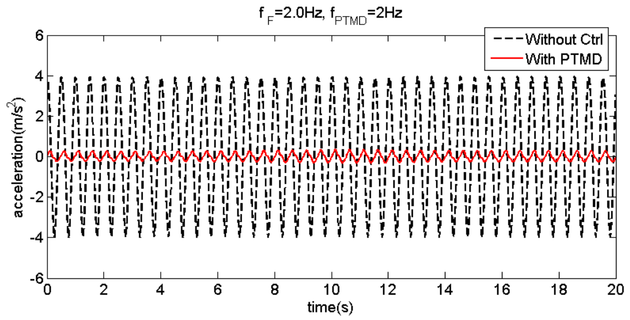

Fig. 5 Results of the forced vibration test

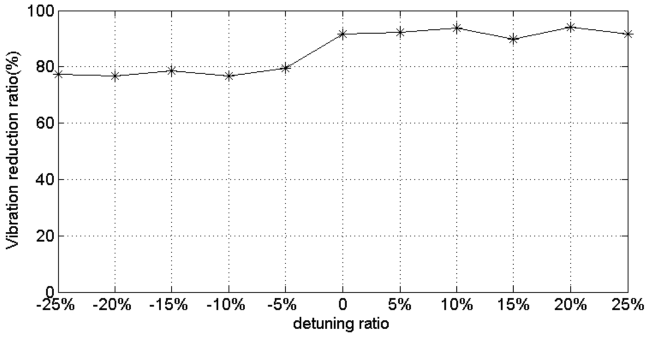

Fig. 6 Reduction ratio of differently tuned PTMDs

5. Robustness of PTMD

The robustness of PTMD against frequency was also investigated. The frequency of PTMD was adjusted through changing the position of the mass, and the frequency ratio of PTMD was changed from -25% to 25%. As Fig. 6 shows, the vibration reduction was over 80%, and the largest reduction ratio was up to 94%. It also shows that the vibration control performance of the PTMD is less deteriorated of positive frequency ratio than the negative frequency ratio. This may because the frequency of the PTMD can influence the energy dissipation ability. When the frequency was lower, the spring steel is more flexible and the pounding force may less than the higher ones and the energy consumption ability is lower.

6. Conclusions

In this paper, the control performance and the robustness of the PTMD installed inside the hollow steel rod of large span roof structure were investigated. Free vibration and forced vibration were considered. The steel rod was fabricated on a fixed base mounted on a shake table.

In the free vibration test, the damping ratio of the primary structure without control is 1.89% and the one controlled by PTMD is 3.88%, which shows a good performance of the introduced damper for the steel rod vibration control. In the forced vibration case, optimally tuned PTMD reduced 91.55% of the acceleration amplitude of the steel rod. And the worst case acceleration reduction is large than 70%. All of those demonstrate the robustness of the PTMD. In the further study, the simulation analysis of the PTMD and the its application in the overall large-span roof structure will be researched.

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