COMPARATIVE STUDIES ON STRUCTURES WITH A TUNED MASS DAMPER AND A PARTICLE DAMPER

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Abstract

As a traditional passive control device, tuned mass damper (TMD) has been investigated widely and also applied in many practical engineering structures. However, TMDs have some inherent limitations such as narrow effective frequency range, poor durability, and deterioration over time. Hence, some researchers have developed new passive control devices to overcome the shortcomings of conventional TMD systems.

In recent years, much attention has been paid to the research and development of a new kind of passive control device named a particle damper, which has a very similar configuration and ap-plication method to the tuned mass damper; however, the damping mechanisms are different. Hence, systematic comparative studies on these dampers are very important for future applications. In this paper, three cases including single-degree-of-freedom structure, 5-story linear-elastic steel frame and 20-story nonlinear benchmark building, are used as primary structures to compare the structural performance with optimal tuned mass damper and optimal particle damper. The optimal parameters of the particle damper are designed by a differential evolution algorithm and the optimal parameters of the tuned mass damper are designed by the classical Den Hartog theory, providing the same additional mass.

The numerical simulation shows that the properly designed particle damper certainly has better vibration control effect than that of the optimal tuned mass damper, not only for elastic performance indexes, but also for nonlinear performance indexes, such as the number and maximum rotation of plastic hinges, and energy dissipation of components. Moreover, the more obvious advantages are that, compared with the optimal tuned mass damper system, the optimal particle damper can significantly reduce the relative displacement between primary structure and the damper itself, as well as its better robustness.

Keywords: Tuned mass damper; Particle damper; Optimization; Passive control; Vibration control

1. Introduction

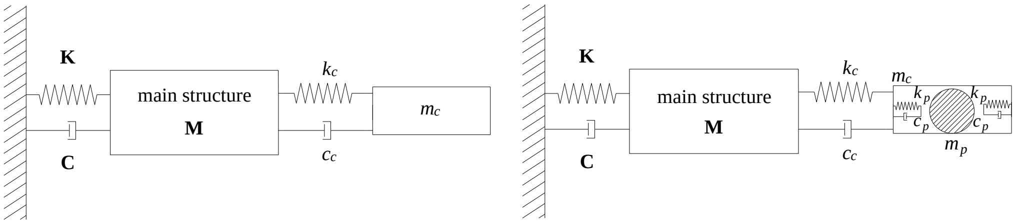
As a traditional passive control device, tuned mass damper (TMD) has been widely ap-plied in practical engineering structures, such as Shanghai Center Tower, Taipei 101 building and Milad Tower. Many experiments were conducted to evaluate the performance of structures with a TMD system under wind loads, and numerous engineering practices and experimental tests have proven that the TMD system has favorable vibration control effects under wind loads when it is properly tuned.

However, TMDs have some inherent limitations such as narrow effective frequency range, poor durability and deterioration over time. Hence some researchers have developed new passive control devices to overcome the shortcomings of conventional TMD systems, such a novel pounding TMD [1], a robust eddy current TMD [2] and a particle damper (PD) system [3].

Although there is much related research on experimental and numerical study of the TMD and PD separately, due to their very similar configurations and application methods, the comparative studies on their damping mechanisms are very important. However, such comparative studies are limited [4]. Moreover, the investigated performance parameters only include some elastic indexes, not involved with nonlinear performance indexes. On the other hand, the major earthquake will always cause structural members to exceed their elastic limits. Therefore, the further systematically comparative study on structures with a TMD and a PD is very important for the decision making when the two high efficiency damping technologies are applied to practical engineering applications.

2. Optimization methods

The simplified diagram of the primary structure with the TMD system and PD system are shown in Fig. 1. In this paper, the optimal parameters of particle damper (PD) are determined by differential evolution (DE) algorithm [5], including rigid collision coefficient between particle mass and the container λ, the mass ratio of the container μ_1, mass ratio of the particle μ_2, the damping ratio of the container ξ_1, the damping ratio of the particle ξ_2, gap clearance between the particle and the container d, while the optimal parameters of tuned mass damper (TMD) including frequency ratio and damping ratio are determined by the classical optimization Den Hartog formulas [6], where the mass ratio of optimal TMD keeps consistent with that of optimal PD system. These two optimal objectives are essentially equivalent in terms of structural displacement response. In addition, specific governing equations and optimization method of PD systems can be found in reference [5].



(a) (b)

Fig. 1 – Illustration of an example figure: (a) TMD system; (b) PD system

3. Case studies

3.1 Single degree of freedom structure

The comparative TMD and PD system are attached to a SDOF structure respectively, and the corresponding vibration control effects are obtained under harmonic excitation. The parameters of primary structure are: k=1, m=1 and ζ=0.01; The additional mass for TMD and PD remains the same. Table 1 shows the optimal parameters of TMD and PD systems.

Table 1 – The optimal parameter of tuned mass damper of particle damper

TMD_{opt}	μ		f		ξ	
value	0.0500		0.9404		0.1353	
PD_{opt}	λ	ξ_1	ξ_2	μ_1	μ_2	d
value	88.7906	0.0261	0.1094	0.045	0.005	0.0016

The maximum dynamic magnification factor (DMF), defined by the ratio of structural steady-state displacement under harmonic excitation and unit static load, is introduced as an index to compare the vibration control effect of PDopt with TMDopt when attached to the SDOF structure. Fig. 2 shows the max DMF of the primary structure under uncontrolled case, with optimal TMD case and with optimal PD case. It can be seen that the PDopt has a larger vibration control effect than TMDopt when the frequency ratio ranges from 0.9 to 1.1, while for other frequency ratios, their control effects are similar. Particularly, under the resonance condition, the maximum DMF are 50, 5.41 and 3.01 for the three cases, which further indicates the superiority of a properly designed PD over the optimal designed TMD in terms of reducing steady-state response under harmonic excitation.

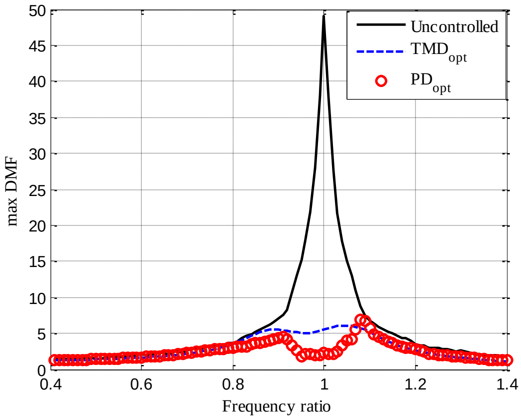


Fig. 2 – Maximum DMF of primary structure for three cases

3.2 Five-story linear-elastic steel frame

The five-story linear-elastic steel frame is obtained from a shaking table test conducted by Lu et al. [7]. The optimal parameters of TMD system and PD system attached to the top of five-story linear-elastic steel frame are shown in Table 2. The results show that RMS vibration control effect of displacement response for TMD case is 65.53%, while it is 66.80% for PD case, indicating that the optimal designed TMD and PD can achieve comparable vibration control effects for MDOF structure under El Centro wave.

Table 2 – The optimal parameter of tuned mass damper of particle damper

TMD_{opt}	μ		f		ξ	
value	0.035		0.9577		0.1136	
PD_{opt}	λ	ξ_1	ξ_2	μ_1	μ_2	d
value	11.4875	0.0935	0.1208	0.030	0.005	0.7590

On the other hand, the relative displacement between primary structure and the damper is also an essential factor for structural design, which relates closely to usable area. The smaller relative movement occupies smaller rooms, hence is preferable in the design. Fig. 3 shows the relative displacement between primary structure and the damper under El-Centro wave. It can be seen that the PDopt system can significantly reduce the peak relative displacement by 24.5% compared with TMDopt.

Fig. 4 shows the vibration control effects of RMS and peak displacement at the top of the structure. It can be seen that the vibration control effect of TMDopt system is more sensitive to frequency ratio compared with PDopt system. When the frequency ratio of primary structure deviates from the resonance case, the vibration control effect of TMDopt decreases much faster than PDopt system.

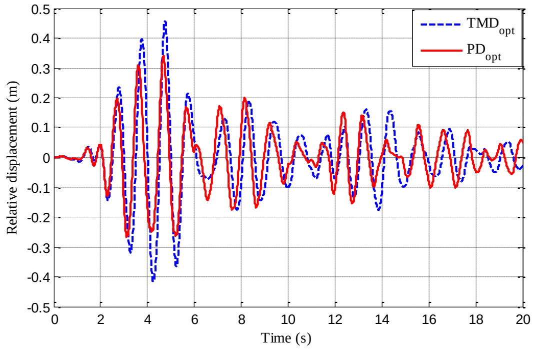
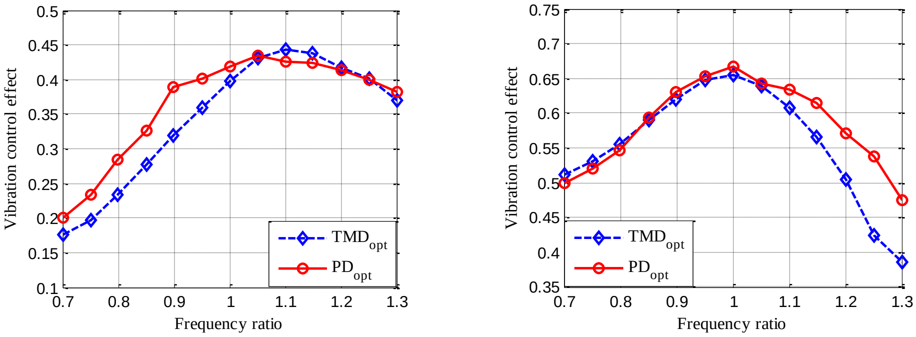


Fig. 3 – Relative displacement between primary structure and damper under El Centro wave



(a) (b)

Fig. 4 – Vibration control effect of displacement at the top of primary structure with variable frequency ratios under El Centro wave: (a) peak; (b) root mean square

3.3 Twenty-story nonlinear benchmark building

The 20-story nonlinear steel moment-resisting frame structure is used for numerical simulations, which accounts for nonlinear behavior by material non-linearity (moment-curvature bi-linear hysteresis model for structure member bending, which is a cross section-based restoring force model). More details of the nonlinear benchmark structure can be found in reference [8]. The vibration control performance analysis of the nonlinear benchmark building is carried out using MATLAB (SIMULINK). The optimal parameters of TMD and PD systems are shown in Table 3. Further, the TMDopt and PDopt systems are attached to the top of the 20-story nonlinear benchmark building, respectively.

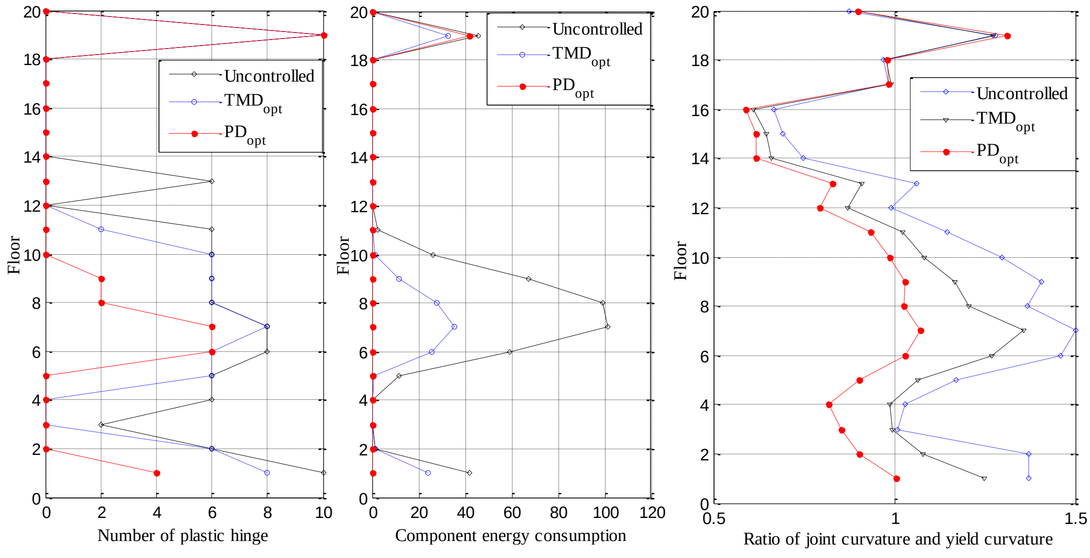
The RMS displacement at the top floor is reduced by 19.6% with the TMDopt system, and by 23.5% with the PDopt, the improvement rate of PDopt compared with TMDopt system can reach 20%; the peak displacement at the top floor is reduced by 12.8% with the TMDopt system, and by 19.6% with the PDopt, the improvement rate of PDopt compared with TMDopt system can reach 53%, which further validates the superiority of the PDopt system (the improvement rate is defined as follows: the improvement rate = (vibration control effect of PD - vibration control effect of TMD) / vibration control effect of TMD × 100%).

Table 3 – The optimal parameter of tuned mass damper of particle damper

TMDopt	μ		f		ξ	
value	0.0355		0.9571		0.1144	
PDopt	λ	ξ_1	ξ_2	μ_1	μ_2	d
value	11.3624	0.0603	0.1971	0.0058	0.0297	0.0433

Plastic hinge and energy dissipation are important indexes to evaluate structural nonlinear behavior, shown in Fig. 5(a) - (b). It can be seen that the PDopt can significantly decrease the number of plastic hinges from 86 to 30 of the primary structure, but for TMDopt system, the number of plastic hinges is only reduced from 86 to 64. The component energy consumption of the primary structure with PDopt system is fewer than that with TMDopt system, thus the damage and inelastic response of the primary structure can be reduced. Fig. 5(c) shows the maximum ratio of joint curvature and yield curvature for three cases under El Centro wave. It can be seen that the PDopt system can significantly reduce the deepness that joints are in nonlinear range compared with the TMDopt system.

Fig. 6 shows the relative displacement between primary structure and damper. It can be seen that the peak relative displacement of PDopt system is reduced by 18.0% compared with the TMDopt system, which further validates the superiority of the PDopt system in aspect of increasing the building space.



(a) (b) (c)

Fig. 5 – Nonlinear indexes: (a) number of plastic hinge; (b) component energy consumption; (c) maximum ratio of joint curvature and yield curvature

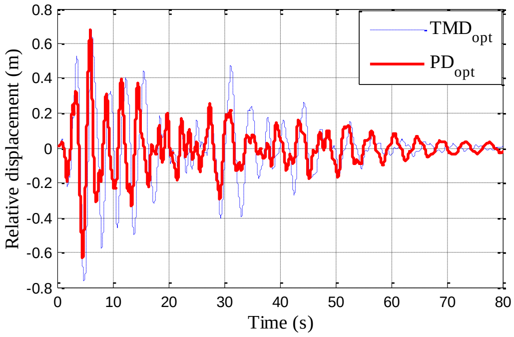


Fig. 6 – Relative displacement between primary structure and damper under El Centro wave

4. Conclusions

The numerical simulation shows that the properly designed PD has certain better vibration control effect than that of the optimal TMD, not only for elastic performance indexes, but also for nonlinear performance indexes, such as the number and maximum rotation of plastic hinges, and energy dissipation of components. Besides, the more obvious advantages are that, compared with optimal TMD system, the optimal PD can significantly reduce the relative displacement between primary structure and the damper itself, as well as it has better robustness.

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