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An Experimental Investigation into the Use of Particle Tuned Mass Damper

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Abstract

A particle tuned mass damper (PTMD) system is the combination of a traditional tuned mass damper (TMD) and a particle damper (PD). As we all know, if properly tuned, the TMD can effectively suppress excessive vibrations. However, the very narrow band of suppression frequency, ineffective reduction of non-stationary vibrations and sensitivity problems due to mistuning are the inherent limitations of a conventional TMD. On the other hand, particle damping technology dissipates the vibration energy by collisions and friction between particles or between particles and their container. The advantages of slight change to the primary structure, wide reduction frequency band and insensitivity to the environment changing make the particle damper preferable to the traditional passive control devices. It has been widely researched and applied in machinery and aviation engineering and the damping performance is favorable, but the research in civil engineering is just in the early stage. The novel PTMD can take advantage of them, leading to a potential effective damper device in civil engineering area.

This paper presents a systematic experimental investigation of the effects of particle tuned mass damper attached to a multi degree of freedom (MDOF) system under different dynamic loads (real onsite earthquake excitations and artificial waves). A series of shaking table tests of a five story steel frame with the particle tuned mass damper system are carried out to evaluate the performance, and the influence of some parameters (auxiliary mass ratio, suspending length, gap clearance, mass ratio of particles to the total auxiliary mass, frequency characteristic and amplitude level of input) on the vibration control effects was investigated. It is shown that particle tuned mass damper have good performance in reducing the response of structures under dynamic loads. It can effectively control the fundamental mode of the MDOF primary system; however, the control effect for higher modes is variable. It is also shown that a certain mass ratio of particles leads to a better vibration attenuation effect. Properly designed particle tuned mass damper can effectively reduce the response of lightly damped MDOF primary system with a small weight.

Keywords: Particle tuned mass damper; particle damper; tuned mass damper; passive control

1. Introduction

Structural control plays a very important role in engineering. Since Yao [1] introduced the concept of vibration control to civil engineering area in 1972, the theory and design method have developed significantly. Scholars and engineers have been devoted to developing new type of devices that are more convenient and efficient to control the structural vibration.

The tuned mass damper (TMD) is a traditional passive control device and has favorable effects for wind-induced vibrations, whereas the effects under seismic excitations are less satisfied. In addition, the very narrow bandwidth of suppression frequency limits its wide applications in engineering practice. Therefore, Scholars [2-3] tried to introduce the nonlinear stiffness and nonlinear damping, such as impact damping or particle damping [4], into the TMD to expand its band of suppression frequency and improve its damping performance.

The particle damper (PD) can dissipate the vibration energy effectively by collisions among particles, collisions between particles and the container wall. And it has many advantages in practical situations: slight change to the primary structure; wide reduction frequency band [5]; high ruggedness and reliability; and insensitivity to extreme temperatures. One typical application is a tall building with a particle damper system in Santiago, Chile, and the system performed very well during the 2010 offshore Maule, Chile earthquake [6].

Some experimental studies and numerical simulations have been carried out for the characterization of the particle damper, and the results show that the damping performance of PDs is robust. Lu *et al*. [7] conducted a series of shaking table tests of a three-story steel frame attaching with a particle damper. Papalou *et al*. [8] proposed the use of particle dampers in the form of classical drums, and investigated the influence of some parameters (mass ratio, placement of damper, particle and damper size) on the effectiveness of the particle damper. With regard to numerical simulation, Lu *et al*. [9] evaluated the influence of some system parameters, such as material of particles, mass ratio and excitation frequency, on the vibration control effects of PDs based on the discrete element method.

In this paper, a particle tuned mass damper (PTMD) is proposed by combining the widely used tuned mass damper with the efficient particle damper. In the experiment, the PTMD is applied to the top of an earthquake-excited five-story steel frame. A series of shaking table tests are conducted to investigate the damping performance of the PTMD, and the vibration reduction principals of some influencing parameters are explored.

2. Experimental setup and procedure

The primary structure is a five-story steel frame and Fig. 1 shows the configuration of the model. The total mass of the primary structure is 6000 kg, and the total height is 5.48 m. The frame columns are made of high strength steel plates (Q690) with the width × length × height dimensions of 15 mm×180 mm×1060 mm. The slabs are made of steel plates (Q345) with the plane dimensions of 2 m×2 m, and the thickness is 30 mm. The first three natural frequencies of the primary structure are 1 Hz, 3 Hz and 4 Hz, respectively, and the damping ratio is 0.02.

The particle tuned mass damper is suspended on the top of the primary structure by four steel strands with the same length, as shown in Fig. 1 (b). The container is made up of wooden plates with the thickness of 4 cm. The container has two layers, and for each layer, it is separated by a transverse wooden plate and two vertical wooden plates into 6 small containers with each inner dimensions of 288 mm×283 mm×120 mm. The total mass of the container is 39.345 kg. Learning from the experience of Lu *et al.* [7], 180 steel balls with 51 mm diameter are put into each container uniformly, as shown in Fig. 1 (c). The total auxiliary mass ratio of the damper to the primary system is 2.26%, which corresponded to the practical requirements and considered the optimal design.

Four ground motions (El Centro wave (1940, NS), Wenchuan wave (1995, NS), Japan 311 wave (2011, NS) and Shanghai artificial wave (SHW2, 1996)) are utilized in the shaking table tests. Each type of seismic waves is acted only along one direction and the peak value of the acceleration is increased gradually from 0.05 g to 0.2 g (g is the acceleration due to gravity). Two accelerometers and two displacement sensors are set up in each story to monitor the motion of the test model.

(a) (b) (c)

Fig. 1– Configuration of the test specimen: (a) primary structure; (b) photo of the experimental model; (c) photo of the particle tuned mass damper.

3. System response

The peak value and the root-mean-square (r.m.s) value of displacement and acceleration responses are chosen to evaluate the damping performance of the PTMD. The vibration reduction effect is defined as follow: vibration reduction effect = (response of uncontrolled structure - response of controlled structure) / (response of uncontrolled structure) ×100%.

3.1 Peak and r.m.s responses

Table 1 and 2 list the displacement and acceleration responses at the roof of the test frame under different intensities of seismic waves, respectively, including the peak value and the r.m.s value. The experiments under SHW2 (0.1 g), El Centro wave (0.2 g), Japan 311 wave (0.2 g) and SHW2 (0.2 g) were not conducted since they may cause the collapse of the test frame. It can be clearly noticed that the responses of the test frame attaching with a PTMD are smaller than most of the responses of the uncontrolled structure, which demonstrates a stable and efficient attenuation effects of the PTMD.

Table 1 – Displacement responses at the roof of the test frame

Seismic input		El Centro		Wenchuan		Japan 311		SHW2	
		peak (mm)	r.m.s (mm)	peak (mm)	r.m.s (mm)	peak (mm)	r.m.s (mm)	peak (mm)	r.m.s (mm)
0.05 g	Uncontrolled	44.04	26.08	10.16	22.67	7.00	22.62	91.73	47.62
	Controlled	39.29	23.03	10.18	22.52	5.83	22.45	59.94	25.30
	Reduction effects (%)	10.79	11.69	-0.2	0.66	16.78	0.75	**39.01**	**46.87**
0.1g	Uncontrolled	102.13	37.95	26.00	23.51	13.81	22.94	-	-
	Controlled	79.00	25.29	20.07	23.04	13.51	22.74	-	-
	Reduction effects (%)	22.65	33.36	22.82	2.00	2.20	0.87	-	-
0.2g	Uncontrolled	-	-	-	-	31.92	25.77	-	-
	Controlled	-	-	-	-	25.60	22.99	-	-
	Reduction effects (%)	-	-	-	-	18.56	10.79	-	-

Table 2 – Acceleration responses at the roof of the test frame

Seismic input		El Centro peak (g)	El Centro r.m.s (g)	Wenchuan peak (g)	Wenchuan r.m.s (g)	Japan 311 peak (g)	Japan 311 r.m.s (g)	SHW2 peak (g)	SHW2 r.m.s (g)
0.05 g	Uncontrolled	0.24	0.06	0.21	0.06	0.11	0.03	0.41	0.17
	Controlled	0.23	0.03	0.20	0.05	0.10	0.03	0.27	0.05
	Reduction effects (%)	4.17	50.00	4.76	16.67	9.09	0.00	**34.15**	**70.59**
0.1g	Uncontrolled	0.55	0.13	0.45	0.12	0.28	0.07	-	-
	Controlled	0.47	0.06	0.45	0.11	0.27	0.07	-	-
	Reduction effects (%)	13.92	53.91	0.00	8.00	3.57	0.00	-	-
0.2g	Uncontrolled	-	-	-	-	0.57	0.14	-	-
	Controlled	-	-	-	-	0.54	0.13	-	-
	Reduction effects (%)	-	-	-	-	5.26	7.14	-	-

The reduction effects are favorable, especially under SHW2 and El Centro wave. For displacement responses, the best vibration control effects for the peak value and the r.m.s value are 39.01% and 46.87% (marked in bold), respectively; for acceleration responses, they are 34.15% and 70.59%, respectively.

In addition, it can be found that the levels and types of the seismic inputs exert a significant influence on the reduction effects. As listed in Table 1 and 2, the reduction effects of the displacement and acceleration responses of the PTMD are different under four types of excitations, and the effects both for the maximum and the r.m.s responses are the best under SHW2. This is mainly caused by the frequency characteristic of the input. The acceleration response spectrum of the seismic input and design acceleration response spectrum are plotted in Fig. 2.

It can be noticed that the primary frequency of the SHW2 is approximately 1.1 Hz, which is the closest to the natural frequency of the primary system. In this situation, the primary structure vibrates the most and the particles are activated to collide violently even if the amplitude level is relatively low. In consequence, the PTMD can dissipate the energy significantly under SHW2 input. However, the strongest components of the El Centro wave, Wenchuan wave and Japan 311 wave are concentrated approximately on 2 Hz, 6 Hz and 6 Hz, respectively, which deviate from the natural frequency of the primary structure significantly.

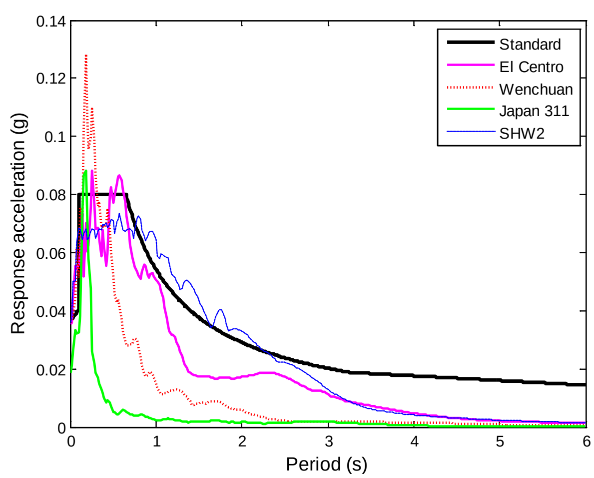


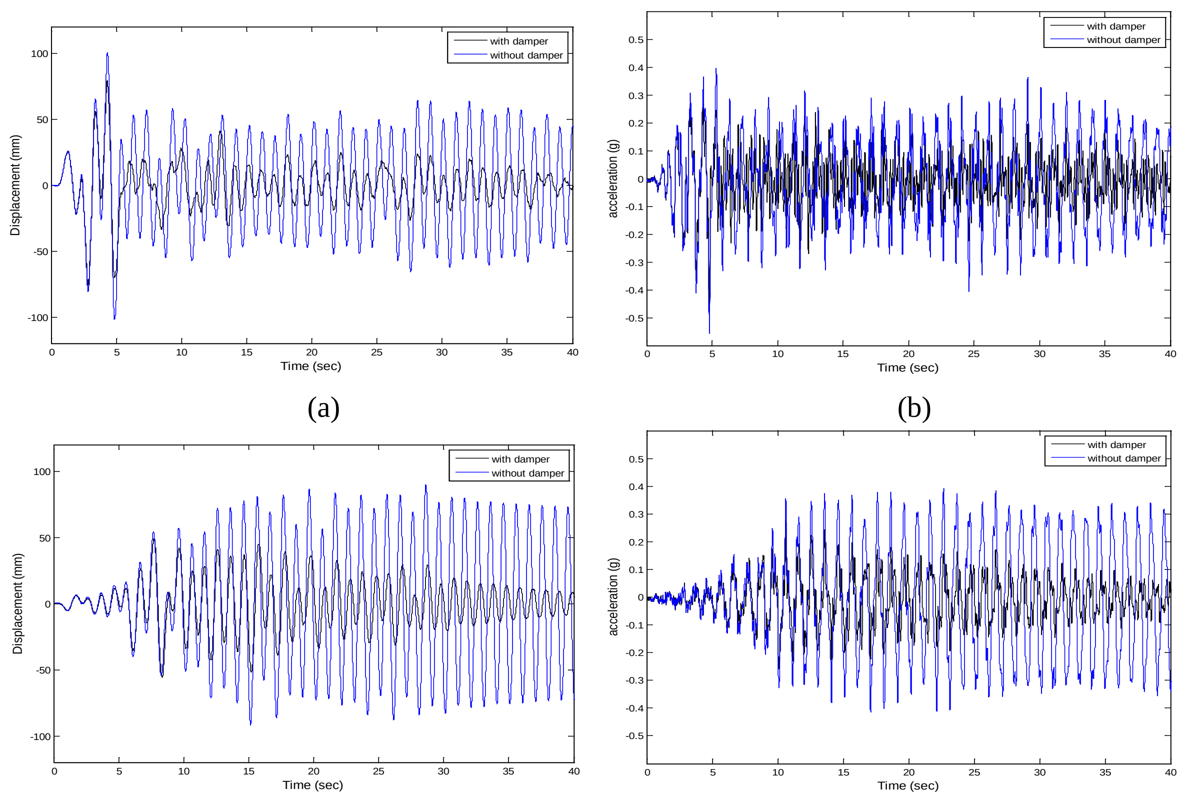
Fig. 2 – The acceleration response spectrum of the input motions and design acceleration response spectrum

With regard to the amplitude level of the input, it can also be observed from Table 1 and Table 2 that, in most cases, the reduction effects are becoming better as the amplitude levels of the input increases. This means that the larger the response of the primary structure, the better reduction effects the PTMD can achieve. For example, under the El Centro wave, when the amplitude levels of the input is relatively low (0.05 g), the reduction effects of the maximum and r.m.s displacement are only approximately 10%–15%, whereas they are 20%–30% under the 0.1 g El Centro wave. This is because that the response of the primary structure is mild and the damper is not shaken sufficiently when the energy of excitation is small. In this condition, the particles move in chaos rather than in the patter of plug flow, which weakens the vibration control effects significantly. However, as the input energy increases, violent collisions occur among particles and between particles and the container, which dissipate the input energy quickly.

3.2 Time history responses

The time histories of the displacement and acceleration responses at the roof of the test frame under El Centro wave (0.1 g) and SHW2 (0.05 g) are shown in Fig. 3. It can be found that the PTMD can not only significantly reduce the peak value of the responses, but also attenuate the responses over a whole time period quickly. This phenomenon also indicates that the PTMD can effectively reduce the r.m.s responses.

Moreover, it can be noticed that the reduction effects are unobvious at the beginning of the vibration. To be specific, under El Centro wave, the time histories of the controlled structure and the uncontrolled structure coincide with each other at around the first 3 seconds, and under SHW2, they coincide with each other at around the first 5 seconds. This is because that the sufficient collisions among particles and collisions between particles and the container take some time. As time goes by, it is sufficient to make the PTMD fully exert its effects, thus the responses of the controlled structure are attenuated quickly, which is similar to the phenomenon of the TMD.



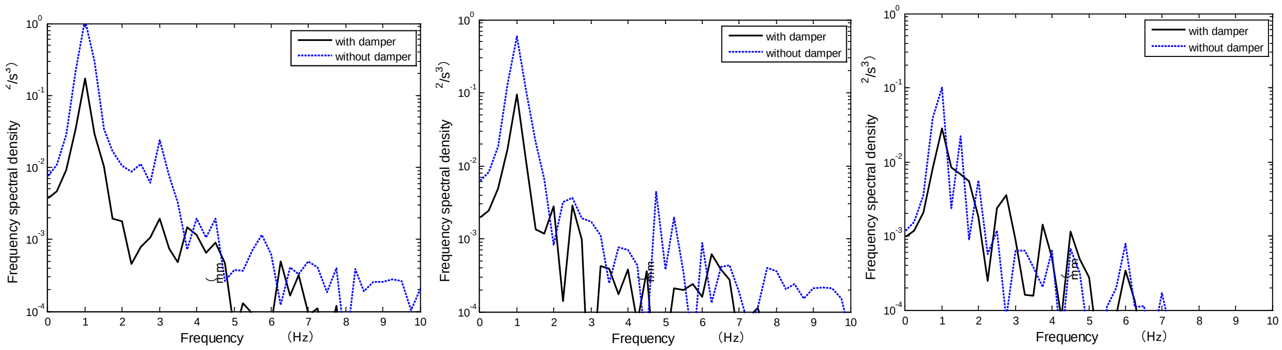
(a) (b)

(c) (d)

Fig. 3 – Response time histories at the roof of the test frame: (a) displacement, El Centro (0.1 g); (b) acceleration, El Centro (0.1 g); (c) displacement, SHW2 (0.05 g); (d) acceleration, SHW2 (0.05 g).

3.3 Frequency responses

Fig. 4 (a)–(c) shows the power spectral density curves of the displacement responses at the 5th floor, the 3rd floor and the 1st floor of the test frame, respectively. It can also be noticed that the reduction effects are better for higher floors than for lower floors. Moreover, the PTMD can significantly attenuate the first mode of vibration due to its installation position, whereas the reduction effects for higher modes are unstable, which coincides with the phenomenon observed by Li [10]. Since the PTMD is suspended on the top of the primary structure, where undergoes the maximum responses of the first mode, the responses can be reduced effectively. However, the maximum responses of the higher vibration modes are not directly controlled by the PTMD, so the reduction effects are less satisfied.



(a) (b) (c)

Fig. 4 – Power spectral density curves of the displacement responses at: (a) the 5th floor; (b) the 3rd floor; (c) the 1st floor.

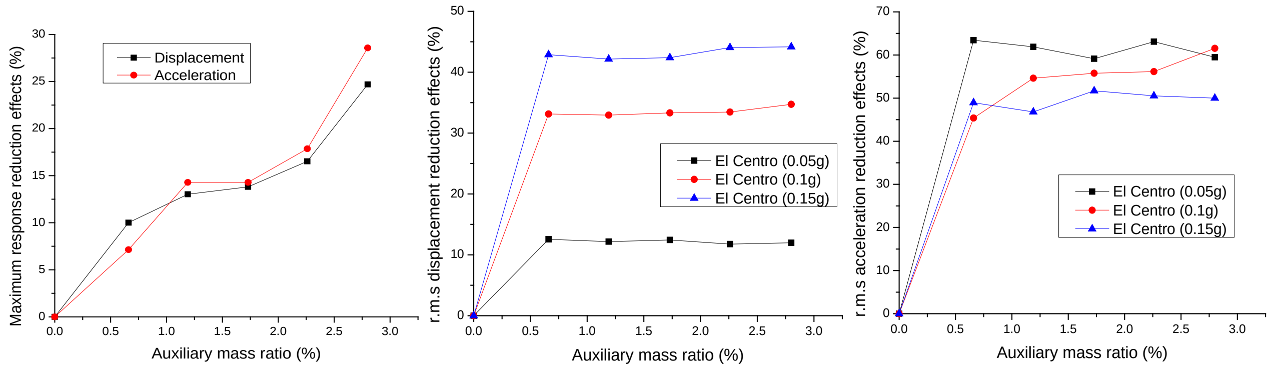
4. Parametric study

To understand the physical working mechanisms of the PTMD and optimize its damping performance, the influence of some system parameters on the vibration control effects of the PTMD is investigated: auxiliary mass ratio, suspending length, gap clearance, mass ratio of particles to the total auxiliary mass.

4.1 Effects of auxiliary mass ratio

The auxiliary mass ratio is a very important parameter to the vibration control effects of the TMD. Similarly, the auxiliary mass ratio affects the energy dissipation of the particle damper significantly. Therefore, the influence of the auxiliary mass ratio on the damping performance of the PTMD is examined by adjusting it as 0.66%, 1.19%, 1.73%, 2.26% and 2.8%. The reduction effects of the maximum displacement and acceleration at the roof of the test frame under El Centro wave (0.1 g) when using different masses of dampers are shown in Fig.5 (a), and the reduction effects of the r.m.s displacement and acceleration under different levels of the seismic input are shown in Fig.5 (b) and (c), respectively.

For the maximum responses, when the auxiliary mass ratio is in the range of 0–2.8%, the larger auxiliary mass ratio can achieve better reduction effects. Since the collision of particles take a large part of the energy dissipation achieved by the PTMD, an increasing mass of particles can result in more energy dissipation in a certain range of auxiliary mass ratio. For the r.m.s responses, when the auxiliary mass ratio is in the range of 0–0.66%, the reduction effects are becoming better as the mass ratios grow; however, when it is in the range of 0.66%–2.8%, the reduction effects are not significantly affected by the mass ratio.



(a) (b) (c)

Fig.5 – The effects of auxiliary mass ratio on the vibration reduction: (a) maximum response; (c) r.m.s displacement; (d) r.m.s acceleration.

4.2 Effects of suspending length

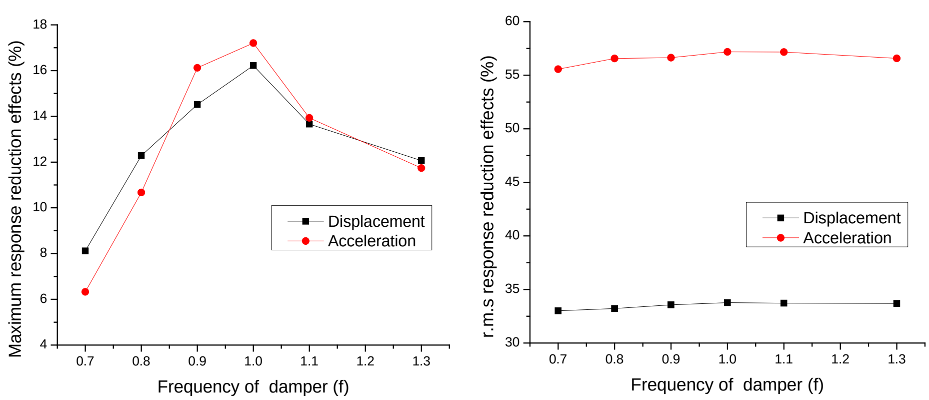
The TMD utilizes the resonance with the primary structure to transfer more energy from the structure to itself and dissipate the energy as much as possible. For the suspended TMD, it is important to make the frequency of the damper close to the natural frequency of the primary structure by adjusting the suspending length to achieve resonance. With regard to the PTMD, it reduces the vibration energy not only by tuning the frequency, but also by the collisions and friction between the particles and the container. Therefore, it is very meaningful to investigate the vibration control effects of the PTMD when the frequency is not tuned.

For simplicity, the PTMD is considered as a single pendulum, and frequency is calculated as shown in Eq. (1):

$$T = 2\pi\sqrt{(L/g)} \tag{1}$$

In the experiment, the frequency of the PTMD is changed as 0.7 f, 0.8 f, 0.9 f, 1.0 f, 1.1 f and 1.3 f (f is the natural frequency of the primary structure) by adjusting the suspending length as 47 cm, 36 cm, 29 cm, 23 cm, 19 cm and 14 cm, respectively. The reduction effects of the maximum responses and the r.m.s responses under different frequency ratios of the PTMD to the primary structure are shown in Fig.6 (a) and (b), respectively.

It can be clearly observed that the vibration control effects of both the maximum displacement and acceleration are the best when the frequency of the PTMD is 1.0 f, and they are approximately 16% and 17%, respectively. As the frequency of the damper deviates from the tuning frequency, the reduction effects gradually decrease. More importantly, the PTMD can still attenuate the system responses even if the frequencies are not tuned. For example, in the 1.3 f case, the reduction effect is about 12%, which indicates the robustness of the PTMD. On the other hand, the reduction effects of both the r.m.s displacement and acceleration are satisfactory, and they are not significantly affected by the suspending length, as shown in Fig.6 (b).



(a) (b)

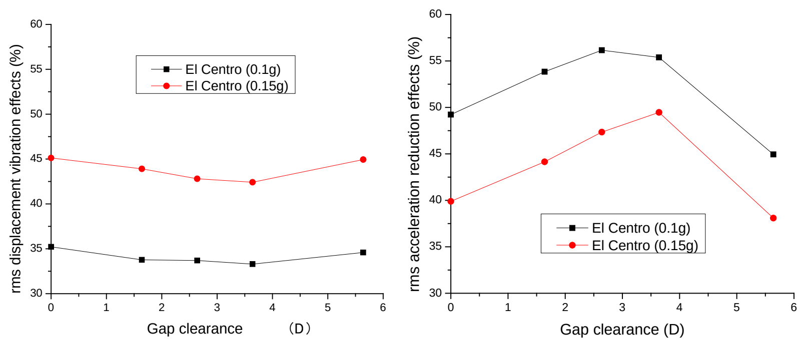
Fig.6 – The effects of suspending length on the vibration reduction: (a) maximum response; (b) r.m.s response.

4.3 Effects of gap clearance

The gap clearance of the particles to the wall of the container is a very important parameter that influences the vibration control effects of the particle dampers. In the experiment, the influence of the gap clearance on the vibration reduction is examined by setting it as 0 D, 1.64 D, 2.64 D, 3.64 D and 5.64 D (D is the diameter of the particle) while keeping the auxiliary mass ratio as the same.

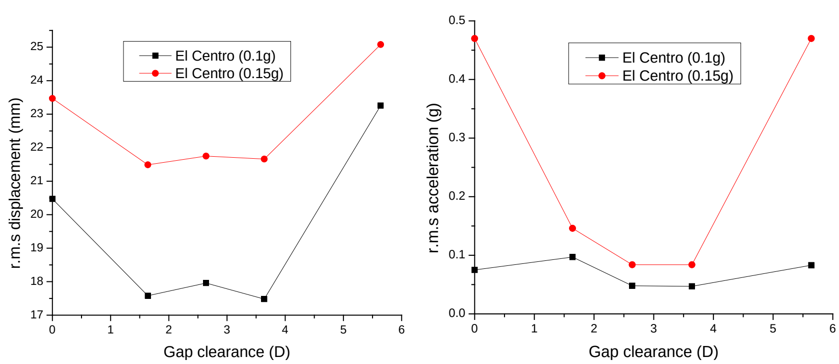
Fig.7 shows the reduction effects of the r.m.s displacement and acceleration responses at the roof of the test frame under different gap clearances. It can be observed that the gap clearance has a slight influence on the reduction effects of the r.m.s displacement of the primary structure, whereas the reduction effects of the r.m.s acceleration increase firstly and then decrease gradually as the gap clearance increases. If the gap clearance is too small, the particles are very likely to move together with the container, which leads to few collisions. However, if the gap clearance is too large, it takes a long time for particles to move from one end of the container to the other, and only limited times of collisions take place, which affects the suppression efficiency. Therefore, the gap clearance should be kept as the optimal value to realize more efficient collisions among particles and between particles and the container.

In addition, the r.m.s displacement and acceleration responses of the PTMD are plotted in Fig.8. It can be found that as the gap clearance increases, the r.m.s responses of both displacement and acceleration firstly decrease and then increase. Moreover, compared Fig.8 (b) with Fig.7 (b), it is easy to find that the reduction effects of the primary structure are more favorable when the responses of the PTMD are relatively small. For example, the reduction effects are satisfied and the responses of the PTMD are relatively mild when the gap clearance is in the range of 1.64 D–3.64 D.



(a) (b)

Fig.7 – The effects of gap clearance on the vibration reduction: (a) r.m.s displacement; (b) r.m.s acceleration.



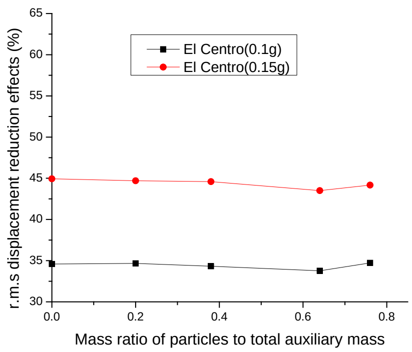
(a) (b)

Fig.8 – The responses of the PTMD under different gap clearance: (a) r.m.s displacement; (b) r.m.s acceleration.

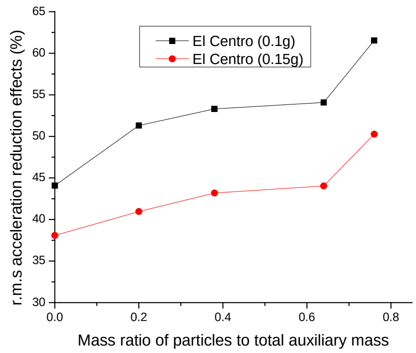
4.4 Effects of mass ratio of particles to the total auxiliary mass

It is known that increasing the auxiliary mass ratio can improve the vibration control effects in a certain range. Furthermore, it is interesting to know the influence of increasing particle mass on the vibration control effects when the total auxiliary mass ratio is kept the same. On one hand, the collisions among particles and the collisions between particles and the container contribute a large part of energy dissipation, so increasing the particle mass can increase the energy dissipation. On the other hand, the damping ratio of the PTMD can be indirectly influenced by changing the particle mass.

In the experiment, the mass ratio of particles to the total auxiliary mass is adjusted as 0, 0.2, 0.38, 0.64 and 0.76 while the total auxiliary mass ratio is remained as 1.73%. Fig.9 shows the reduction effects of the r.m.s displacement and acceleration responses at the roof of the test frame under different particle mass. It is observed that the r.m.s displacements are not influenced significantly, whereas the reduction effects of the r.m.s acceleration become better as the mass ratio of particles to the auxiliary mass ratio increases. Therefore, in the premise of an optimal auxiliary mass ratio, increasing the proportion of the particle mass can improve the vibration control effects to a certain extent.



(a)



(b)

Fig.9 – The effects of mass ratio of particles to the total auxiliary mass on the vibration reduction: (a) r.m.s displacement; (b) r.m.s acceleration

5. Conclusions

A new type of passive control device, the particle tuned mass damper (PTMD), which combines various energy dissipation methods of both tuned mass dampers and particle dampers, is proposed in this paper. A series of shaking table tests of a five-story steel frame attaching with a PTMD are carried out to investigate its damping performance. The influence of some key system parameters is discussed.

The maximum and r.m.s value of both displacement and acceleration responses of the five-story structure are reduced by attaching the PTMD under earthquake excitations. The reduction effects are extremely favorable under Shanghai artificial wave, which indicates that the frequency characteristic has a significant influence on the damping performance of the PTMD. The vibration reduction effects are obvious when the frequency of the seismic input is close to the natural frequency of the primary structure. Besides, the vibration reduction effects get better as the increase of the amplitude level of the earthquake excitations.

For multi-degree-of-freedom structures, the PTMD can suppress the first mode vibration effectively and stably. However, the reduction effects of the high vibration modes are less satisfied. Another obvious advantage of the PTMD is the robustness. In the condition of tuning frequency, the damping effects are remarkable. And the reduction effects are still favorable even in the 30% untuning frequency case.

Increasing the auxiliary mass ratio can improve the damping effects nonlinearly and has a limit. Based on this, the optimal auxiliary mass ratio can be chosen in design of the PTMD. Similarly, the gap clearance of the PTMD also has an optimal range, in which the responses of the PTMD are stable and efficient, leading to an optimized vibration control effects. Moreover, increasing the particle mass can improve the reduction effects provided the total auxiliary mass ratio being constant.

In conclusion, the responses of a MDOF structure can be significantly reduced by attaching a lightweight PTMD on the top of the primary structure, which suggests that the PTMD has a potential wide application in the structural control of civil engineering area.

6. Acknowledgements

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7. References

[1] Yao JTP (1972): Concept of structural control. *Journal of the Structural Division*, *ASCE*, **98**(7): 1567-1574.

[2] Roberson RE (1952): Synthesis of a nonlinear dynamic vibration absorber. *Journal of the Franklin Institute*, **254**(3): 205-220.

[3] Hunt JB (1979): Dynamic vibration absorbers. London: Mechanical Engineering Publications Ltd.

[4] Lu Z, Wang DC, Li PZ (2014): Comparison study of vibration control effects between suspended tuned mass damper and particle damper. *Shock and Vibration*, **33**(2): 233-243.

[5] Panossian HV (1992): Structural damping enhancement via non-obstructive particle damping technique. *Journal of Vibration and Acoustics*, **114**(1): 101-105.

[6] Naeim F, Lew M, Carpenter LD, Yousser NF, Rojas F, Saragoni GR, Adaros MS (2011): Performance of tall buildings in Santiago, Chile during the 27 February 2010 offshore Maule, Chile earthquake. *The Structural Design of Tall and Special Buildings*, **20** (1): 1-16.

[7] Lu Z, Lu XL, Lu WS, Masri SF (2012): Shaking table test of the effects of multi-unit particle dampers attached to an MDOF system under earthquake excitation. *Earthquake Engineering and Structural Dynamics*, **41**(5): 987-1000.

[8] Papalou A, Strepelias E, Roubien D, Bousias S, Triantafillou T (2015): Seismic protection of monuments using particle dampers in multi-drum columns. *Solid Dynamics and Earthquake Engineering*, **77**: 360-368.

[9] Lu Z, Masri SF, Lu XL (2011): Parametric studies of the performance of particle dampers under harmonic excitation. *Structural Control and Health Moni*toring, **18**(1): 79-98.

[10] Li K, Darby AP (2006): Experiments on the effect of an impact damper on a multiple-degree-of-freedom system. *Journal of Vibration and control*, **12**(5): 445-464.