16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 265

Registration Code: S-J1461812805

SHAKING TABLE TEST AND NUMERICAL ANALYSIS OF TALL BUILDINGS USING A NEW EDDY-CURRENT TUNED MASS DAMPER

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Abstract

Vibration control devices such as tuned mass dampers (TMDs), tuned liquid dampers (TLD) and other supplemental damping devices have been used to improve the vibration performance of tall buildings and proved quite economical and efficient. Due to Faraday's Law of Induction and Lenz's Law, a new application is created incorporating eddy current damping which consists of the permanent magnet and metal conductor into a large-scale, pendulum-based TMD in tall buildings to mitigate the structural vibration under wind or seismic scenarios. A shaking table test of a five-story steel frame with eddy-current TMD was performed and the results are presented to evaluate the earthquake-induced vibration control performance. The results indicate that the earthquake-induced acceleration and displacement response of the steel frame can be effectively reduced by the TMD. A 1000 ton eddy-current TMD was installed on the top of Shanghai Center Tower (SHC), a 632m-height building in China. Numerical analysis of the SHC structural model with the TMD was conducted and the results indicate that for SHC the eddy-current TMD was able to reduce wind-induced structural acceleration by 45%-60% and earthquake-induced structural displacement by 5%-15%.

Keywords: eddy-current TMD; shaking table test; vibration control

1. Introduction

A large number of tall buildings have been constructed during the last few decades. The design of the lateral load resisting systems in high-rise buildings are typically controlled by wind and seismic loads. With the continuous development of structural design, human comfort to wind- and earthquake-induced vibration has become one of the most important evaluation criteria. In the process of the development of high-rise building design, two main methods have been used to control the structural vibration. The first one is to enhance the structure's lateral stiffness. Using this method, a tall building will be designed with components with larger size and more construction material. The disadvantage of this method is that the structure will have to withstand larger seismic force. As a consequence, this method is inefficient. The other approach is to embed vibration control devices, which can be divided into three categories: namely, passive control, active control and hybrid control devices. The passive control strategy has been proved economical and efficient by utilizing TMDs, TLDs and other damping devices. TMD strategy is especially widely applied due to its simplicity and no-external-power requirements.

The control effect of TMD is sensitive to the mass ratio (TMD/superstructure), the frequency ratio, and the damping ratio of TMD. In many cases, the damping of TMD is provided by various damping devices such as conventional fluid viscous dampers and rubbers. However, some drawbacks may exist in viscous dampers and rubbers. They are limited service life, undesired flexibility in connections and support system, and property sensitivity to heat generated during service for instance. To overcome these limitations, a new eddy-current damping system was proposed and applied to real TMD in tall buildings. The focus of this paper is on the mechanism of eddy-current TMD, the shaking table test and numerical analysis of tall buildings with this new TMD.

2. Eddy-current TMD

Eddy currents are circular electric currents induced within conductors by a changing magnetic field, due to Faraday's law of induction [1]. The eddy currents flow in closed loops within the conductor in planes perpendicular to the magnetic field. They can be induced by relative motion between a magnet and a nearby conductor or within a stationary conductor in a time-varying magnetic field. According to Lenz's Law [2], an eddy current creates a magnetic field that opposes the magnetic field that created it. Thus, eddy currents generated by moving a permanent magnet near a conductor will generate forces that oppose relative motion between the magnet and conductor. This effect can be employed in eddy current brakes which are used to stop rotating power tools quickly when they are turned off [3]. They can also be used in vibration control, in which the drag force acts as the damping force. In previous research, the eddy-current TMD had small size and was used to control the vibration of structural components such as the beam [4-6]. In this article, a new application of eddy-current system was created for large scale pendulum TMD to control the vibration of super high buildings.

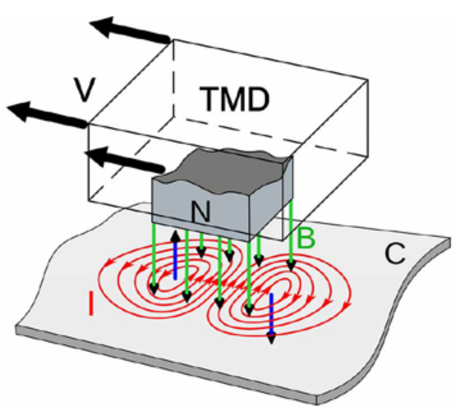

Fig. 1 – Eddy currents induced by relative motion between a magnet and a conductor

As shown in Fig.1, a magnet (*N*) is attached to the bottom of a TMD's mass block. With the mass and magnet moving left in this figure with a velocity (*V*), eddy current (*I, shown in red*) are induced in a conductive metal plate (*C*) installed under the magnet on the structural floor. The magnetic field (*B, shown in green*) is directed down through the plate. From Lenz's law, the increasing field at the leading edge of the magnet (*left side*) induces a counterclockwise current which creates its own magnet field (*left blue arrow*) directed up, which opposes the magnet's field, producing a retarding force. Similarly, at the trailing edge of the magnet (*right side*), a clockwise current and downward counter field is created (*right blue arrow*) and also producing a retarding force. Therefore, due to this new eddy current system, the movement of the TMD mass is retarded and the energy is dissipated.

Shanghai Research Institute of Materials (SRIM) has carried out a series of studies to identify the properties of the eddy-current TMD without main structure in laboratory, including magnet and metal material tests, small-scale TMD model test and moderate-scale TMD model test. It was proved that the eddy-current TMD has good damping performance and can be attempted in structures to control the vibration. It was also confirmed that the damping ratio of the eddy-current TMD can be adjusted by changing the gap between the magnet and the copper plate. To evaluate the earthquake-induced vibration control performance of the TMD in structures, a shaking table test of a five-story steel frame with eddy-current TMD was performed and the results are presented in this paper.

Fig. 2 – Shaking table test model with eddy-current TMD and the sensor arrangement

3. Description of shaking table model test

The shaking table tests had been completed in June 2015. A five-story steel frame test model (Fig.2) was built for the shaking table test. Tests of the steel frame model without/with the eddy-current TMD were performed to evaluate the TMD performance.

3.1 Design of the model

The story height is 1.06 meters, and the plane dimension is 2 × 2 meters. Q690 steel was used for the columns with the section dimension of 15 × 180 × 1060 millimeters. Q345 steel was used for the floor slab. Total mass of the test model was 6 tons. The first fifth natural periods of the frame along the weak axis were 1.0002s, 0.3466s, 0.2197, 0.1710s, and 0.1496s. Several key parameters of the test model is listed in Table 1.

Table 1 – Parameters of shaking table test model

Natural period of vibration	1.000s
Structural generalized mass (1st mode)	3120.8kg
Total mass	6000.0kg
Total height	5.490m
Plan dimension	2.0m×2.0m

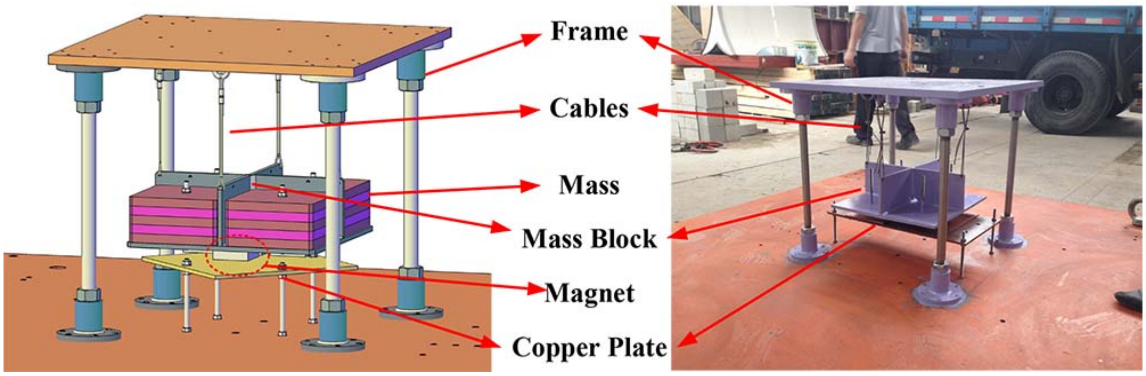

Fig. 3 – Shaking table test model with eddy-current TMD

3.2 Design of the eddy-current TMD

The eddy-current TMD model in this test was constructed by SRIM. The TMD was made up with a supporting frame, four cables, a mass block, some mass bodies and the eddy-current system, as is shown in Fig. 3. The eddy-current system consisted of a magnet attached to the bottom of the mass block and a copper plate supported below the magnet. This design can ensure that the mass of the TMD can be changed by gaining or reducing the number of mass bodies, and that the TMD damping ratio can be adjusted by changing the gap between the magnet and the copper plate. Furthermore, when the copper plate was removed, the influence of the magnet would be quite insignificant that the TMD could be close to traditional TMD without the eddy-current system. To control the first mode vibration of the main structure, the cable length was adjusted as 0.248m to make the TMD natural frequency 1Hz, the same as the natural frequency of the structure in weak axis. TMD with different parameters performed in the tests were listed in Table 2.

Table 2 – Parameters of eddy-current TMDs in tests

Sequence	TMD mass (kg)	Mass ratio (TMD/Frame Model)	Gap between magnet and copper plate（mm）	TMD damping ratio
1	120	4%	30	9.2%
2	60	2%	30	9.2%
3	35	1%	30	9.2%
4	35	1%	20	11.5%
5	35	1%	15	13.5%
6	35	1%	Conventional TMD	5.7%

3.3 Test loading schedule

The El Centro wave, Wenchuan wave, 3.11 Great East Japan earthquake wave (Japan311) and one of Shanghai artificial waves (AWX0.9-2) were adopted as excitations. Fig. 4 and Fig. 5 show the normalized acceleration time-history and corresponding power spectrum. The peak acceleration value was from 0.05g to 0.15g according the performance of the model in preparing experiment. Before and after applying these excitations in each acceleration level, the white noise (WN) with a peak acceleration value of 0.06g was applied to the model test to study the corresponding changes in the dynamic characteristics of the system.

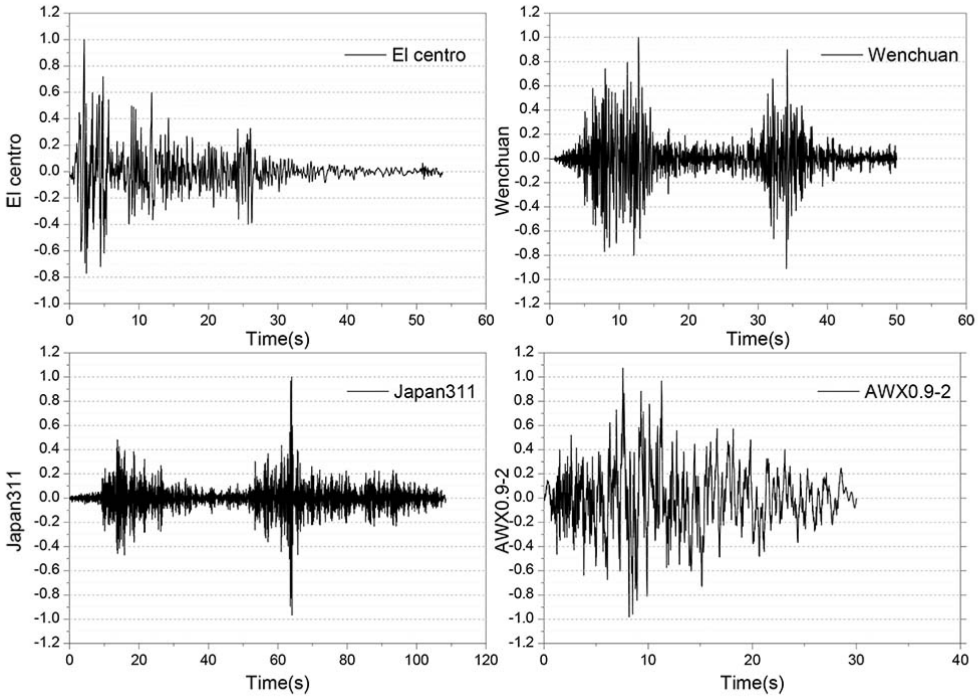

Fig. 4 – Normalized acceleration time-history of excitations

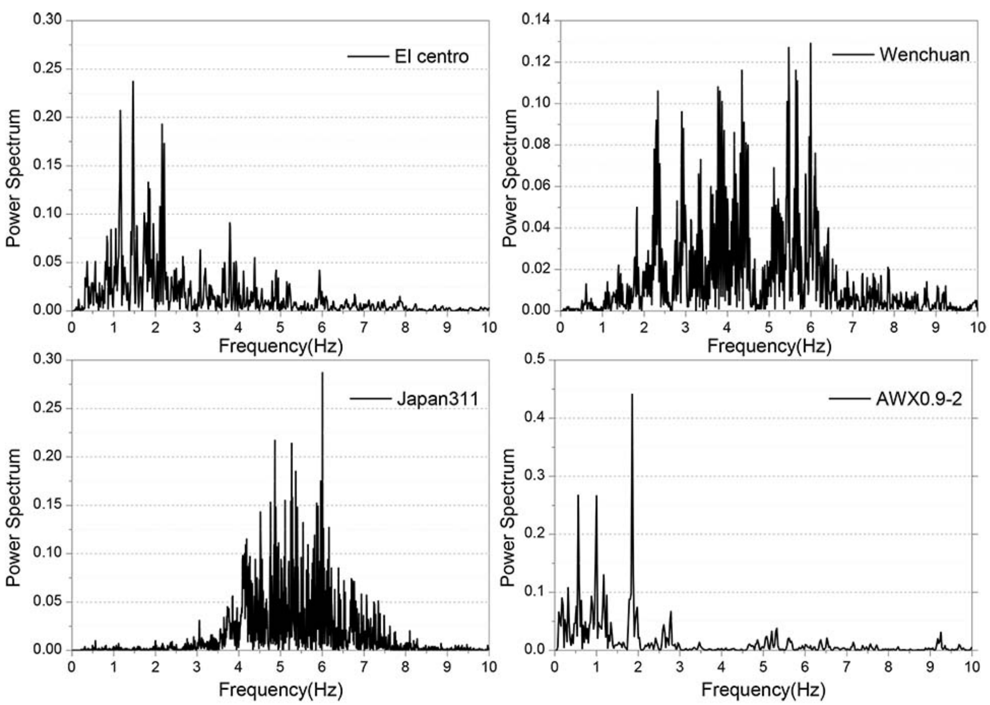

Fig. 5 – Corresponding power spectrum of excitations

4. Tests phenomena

As is shown in Fig. 6, different excitations have different kinds of power spectrum. In terms of the frequency, the energy of El Centro wave and Shanghai artificial wave are concentrated in the range from 0.5Hz to 2Hz, which is close to the natural frequency of the model. The energy of Wenchuan wave and 311Japan wave are concentrated in the range from 2.5Hz to 6Hz, which is far from the model frequency.

Compared the test phenomena between these tests (with different TMDs and without TMD), several results can be achieved as follows. (1) In El Centro and Shanghai sequences, the first mode was dominated in structural vibration, which is obviously controlled by the TMD. In Wenchuan and 311Japan sequences, the first mode was minor and the higher modes were dominated. Among the structural vibration, first mode part was effectively controlled while the higher mode parts were unobviously controlled. (2) In all sequences, the displacement response of the fifth floor reached the maximum value immediately following the earthquake wave peak. After the peak, the displacement response entered a state of decay. The response of the model without TMD decayed quite slowly due to the tiny structural damping ratio. The response of the model with TMD decayed rapidly, which indicated that the TMD played a good control effect. (3) TMD started to swing with no delay when the structure vibrated. TMD vibration amplitude was minor throughout most of the procedure. When wave peak arrived, TMD swung violently to decrease the severe structural vibration and then returned to the minor-amplitude state in a short time.

5. Comparisons of the dynamic responses

The dynamic responses of the tests were compared in the following, including the frequency response function (FRF) of the top floor acceleration under WN excitation, the acceleration and displacement response of the top floor, the stain response of column, and the swing response of the TMD.

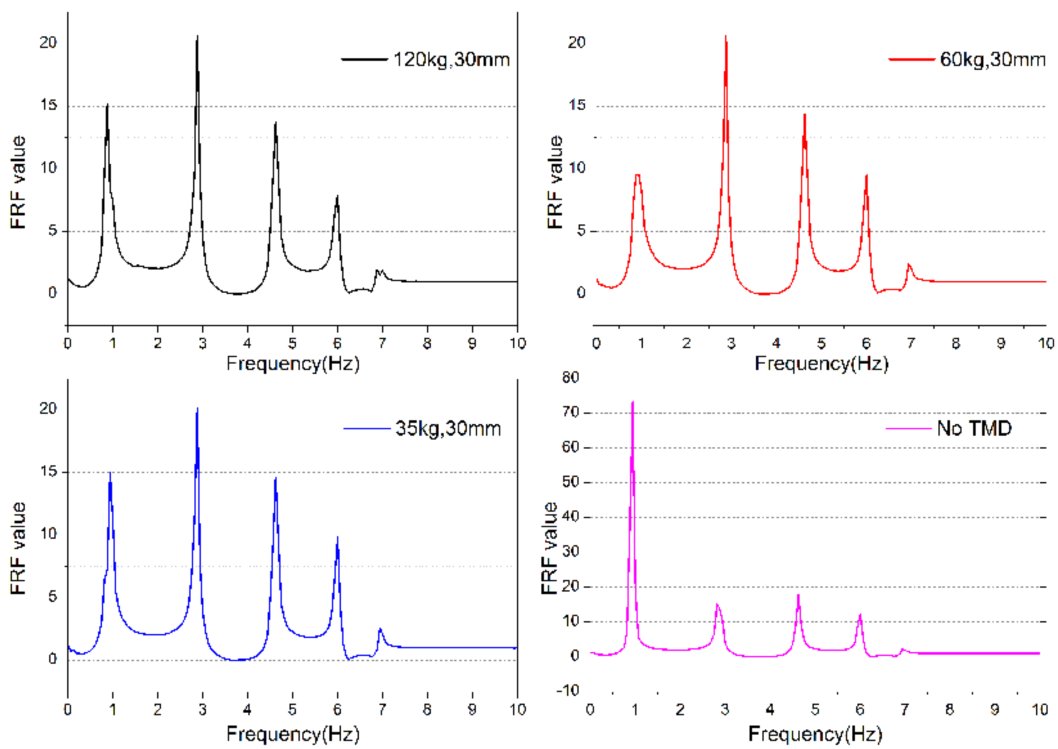

Fig. 6 – FRF value of the acceleration response of the top floor

5.1 Comparisons of the structural fundamental frequency

Fig. 6 shows the FRF value of the acceleration response of the 5th floor of frame with eddy-current TMDs and the frame without TMD under the WN excitation. Fig. 6 tells that the structural fundamental frequency was not obviously changed by the eddy current TMDs. The first mode frequency was still 1Hz, same as before. Meanwhile, a conclusion that the structural first mode vibration was significantly controlled by the TMD could be drawn by comparing the first three figures with the fourth one.

5.2 Comparisons of the acceleration response

Table 3 shows the RMS values of the acceleration response of the top floor under some typical sequences. Results in Table 3 indicated that the control effect was affected by the excitation type. The structural fundamental frequency is 1Hz. When the excitation was El Centro wave or Shanghai wave, which contained large power around the frequency of 1Hz, the first mode was dominated in structural vibration and the displacement of the top floor was larger than that of other floors. As a consequence, the TMD achieved a good control performance, and the reduction ratio reached to 60%-75%. When the excitation was Wenchuan wave or Japan311 wave, which contained little power around the frequency of 1Hz, the first mode was minor and the displacement of the top floor was not significantly larger than that of other floors. Therefore, the TMD achieved limited control performance. Even so, the reduction ratio reached to 15%-30% all the same.

To show the control effect of the eddy-current TMD clearly, the time-history acceleration responses of the top floor under El Centro wave with the peak of 0.1g were drawn in Fig. 7. The comparisons of the acceleration of the structure with and without TMD indicated that the structural vibration was immediately decreased after the earthquake peak by the TMD. The vibration of the frame without TMD decayed much more slowly.

Table 3 – RMS values of acceleration response of the top floor (unit: g; TMD mass:35kg; PGA:0.05g)

Excitation	El Centro	Wenchuan	Japan311	AWX0.9-2
No-TMD	0.057	0.045	0.026	0.174
Eddy-current TMD (Damping ratio: 9.2%)	0.021	0.033	0.017	0.044
Reduction ratio	63.10%	27.73%	34.82%	74.89%
Eddy-current TMD (Damping ratio: 11.5%)	0.022	0.033	0.017	0.046
Reduction ratio	61.99%	27.74%	35.32%	73.60%
Eddy-current TMD (Damping ratio: 13.5%	0.022	0.032	0.017	0.049
Reduction ratio	62.10%	29.46%	36.12%	72.03%
Conventional TMD (Damping ratio: 5.7%)	0.022	0.038	0.017	0.049
Reduction ratio	62.22%	15.24%	35.57%	71.57%

5.3 Comparisons of the displacement response

Table 4 shows the RMS values of the displacement response of the top floor under some typical sequences. The TMD controlled the top floor displacement with a good performance, and the reduction ratio reached to 70%-75% under El Centro or Shanghai wave. The reduction ratio reached to 40% under Japan311 wave and to 10%-20% under Wenchuan wave. Fig. 8 shows the time-history displacement responses of the top floor under El Centro wave with the peak of 0.1g.

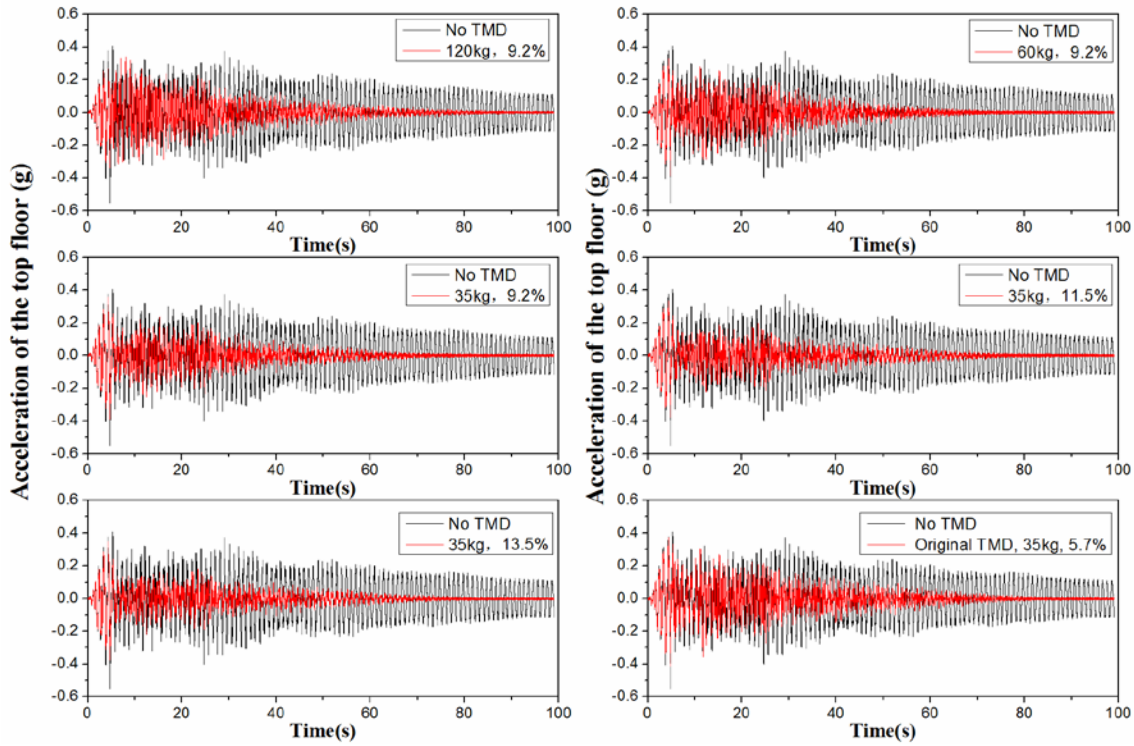

Fig. 7 – Time-history acceleration response of the top floor (El Centro, 0.1g)

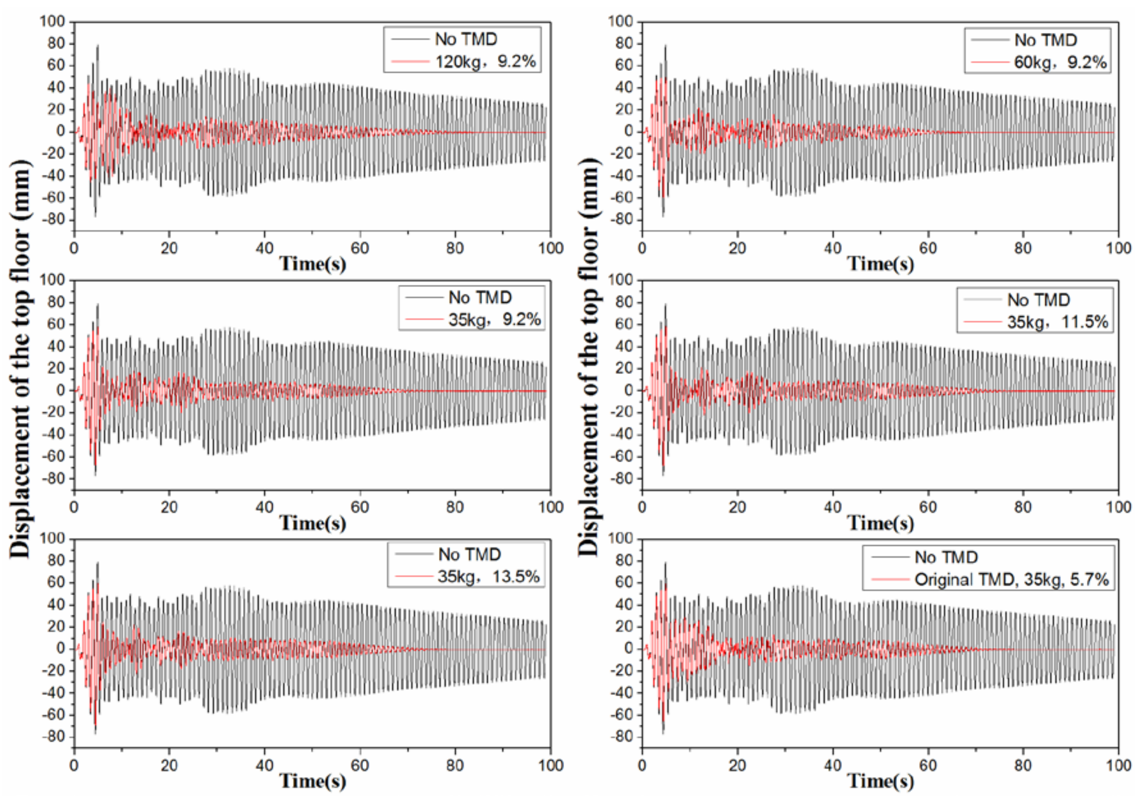

Fig. 8 – Time-history displacement response of the top floor (El Centro, 0.1g)

Table 4 – RMS values of displacement response of the top floor (unit: mm; TMD mass:35kg; PGA:0.05g)

Excitation	El Centro	Wenchuan	Japan311	AWX0.9-2
No-TMD	13.02	1.77	1.23	41.39
Eddy-current TMD (Damping ratio: 9.2%)	3.82	1.41	0.74	9.36
Reduction ratio	70.67%	20.45%	40.18%	77.38%
Eddy-current TMD (Damping ratio: 11.5%)	4.04	1.45	0.74	10.04
Reduction ratio	68.97%	17.91%	39.81%	75.75%
Eddy-current TMD (Damping ratio: 13.5%	4.07	1.46	0.74	11.05
Reduction ratio	68.74%	17.69%	39.91%	73.30%
Conventionall TMD (Damping ratio: 5.7%)	3.98	1.55	0.75	9.60
Reduction ratio	69.41%	12.58%	39.38%	76.80%

5.4 Comparisons of the inter story drift

Fig.9 shows the inter story drift of the frame model under El Centro wave with the peak value of 0.1g. Some conclusions can been drawn as follows. (1) The inter story drift was effectively controlled by the TMD. (2) If other conditions are the same, the control effect became better with the increase of the TMD mass. (3) On condition that others are same, the control effect varied little by the TMD damping ratio. There was little difference of the control effect between eddy-current TMD and original TMD with the same mass.

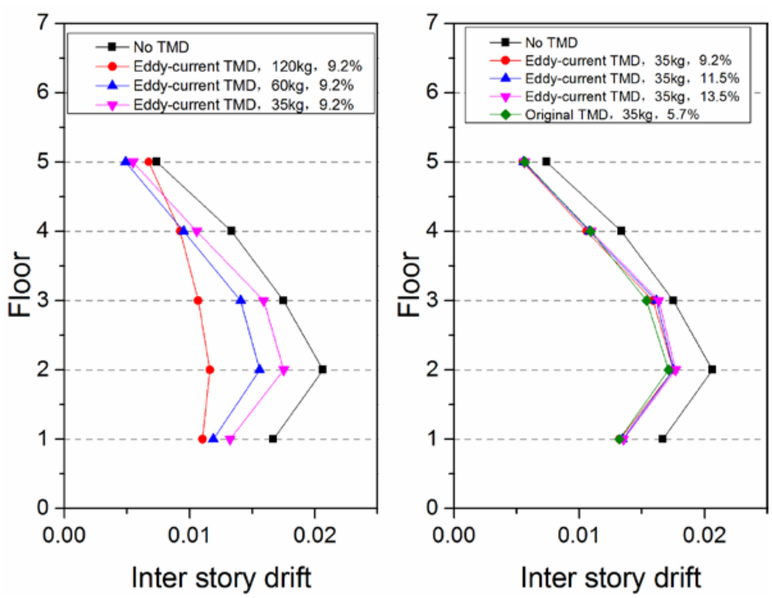

Fig. 9 – Inter story drift of the frame model (El Centro, 0.1g)

5.5 Comparisons of TMD amplitude

From the previous results in this article, both the eddy-current TMD and original TMD performed well to control the structural vibration and their performance were close. In real projects, the TMD amplitude are generally expected not too large in order to avoid the impact between TMD and main structure. Fig.10 shows the amplitude of the eddy-current TMD and the original TMD with the same mass of 35kg under El Centro wave with the peak of 0.1g. It can be seen that, after the El Centro wave peak, the amplitude of eddy-current TMD decayed faster and remained at a lower level than that of the original TMD. In other words, the eddy-current system improved the TMD energy dissipation ability.

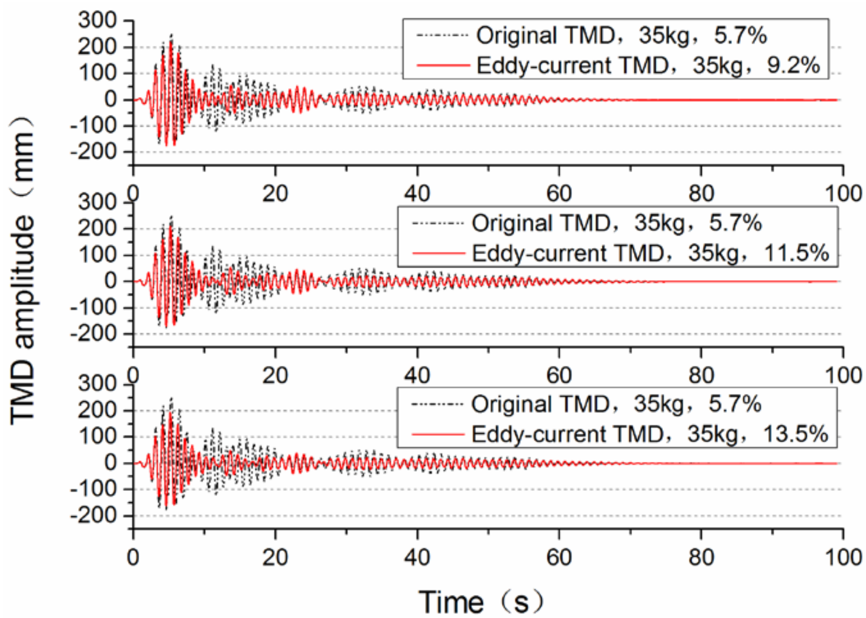

Fig. 10 – Comparisons of TMD amplitude (El Centro, 0.1g)

6. Engineering application of eddy-current TMD

Eddy-current TMD had been proved to have good structural vibration control performance and energy dissipation ability in experimental studies. A real 1000-ton eddy-current TMD (Fig. 11) was installed on the 125th floor of Shanghai Center Tower (SHC), which is a super high-rise landmark building in Shanghai, China, with the height of 632m. The SHC was completed and will be open to public in late 2016. The fundamental frequency of the real TMD is 0.111Hz, close to the first mode frequency of SHC. Before installation the control performance of the TMD was evaluated through numerical simulation. Analysis of the overall SHC structure with the full-scale eddy-current TMD installed was conducted under wind and earthquake excitations using software program SAP2000.

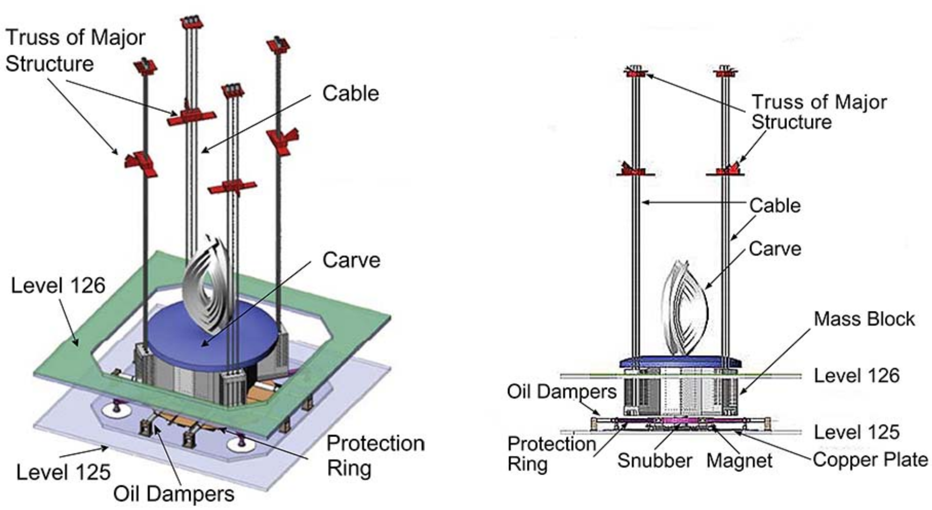

Fig. 11 –The diagram of the 1000-ton eddy-current TMD in SHC

Due to space limitation of the article, few key analytical results of the structural vibration control performance are shown in Table 5 and Table 6. Table 5 shows the RMS values of the acceleration response of the 125th floor under wind excitation. The value decreases approximately 48% under the wind sequence having a 1-year return period, while decrease approximately 56%-67% under the sequences having 10-, 50- and 100-year return periods. Table 6 shows the seismic analytical results. It indicated that the eddy-current TMD has modest effect on seismic vibration control. The base shear is reduced less than 2%, while the maximum story drift decreases less than 9.1%. In addition, the roof displacement decreases about 15% under the frequently occurring and design-basis earthquakes, and decreases only 4.9% under a rarer earthquake.

Table 5 – RMS value of acceleration responses of SHC in wind analyses in SAP2000 (unit: m/s2)

Return period	**Floor**	**Wind direction A=80°**			**Wind direction A=270°**		
		Without TMD	**With TMD**	**Reduction ratio**	**Without TMD**	**With TMD**	**Reduction ratio**
1 Year	Top	0.058	0.031	46.9%	0.052	0.027	47.7%
	TMD Floor	0.054	0.029	47.3%	0.049	0.025	48.2%
10 Years	Top	0.228	0.082	64.2%	0.256	0.099	61.2%
	TMD Floor	0.215	0.076	64.4%	0.241	0.092	61.9%
50 Years	Top	0.342	0.143	58.1%	0.547	0.182	66.8%
	TMD Floor	0.322	0.133	58.7%	0.516	0.170	67.0%
100 Years	Top	0.348	0.156	55.3%	0.566	0.200	64.7%
	TMD Floor	0.327	0.143	56.1%	0.534	0.187	64.9%

Table 6 – Seismic analytical results of the SHC with 1000-ton eddy-current TMD in SAP2000

Average values		**Frequent earthquake**	**Design-basis earthquake**	**Rare earthquake**
Base shear	Without TMD (kN)	82,170	167,070	527,860
	With TMD (kN)	80,580	165,160	525,930
	Reduction ratio	2%	1.1%	0.4%
Story drift	Without TMD	0.0011	0.0022	0.0078
	With TMD	0.001	0.0020	0.0072
	Reduction ratio	9.1%	9.1%	7.6%
Roof displacement	Without TMD (m)	0.416	0.82	2.65
	With TMD (m)	0.353	0.71	2.52
	Reduction ratio	15%	13.4%	4.9%

7. Conclusions

Shaking table test and numerical analysis of tall buildings using a new eddy-current tuned mass damper have been conducted. From the studies, the following conclusions were obtained.

(1) Eddy-current TMD assembled on the top of a shaking table test frame model had achieved a significant vibration control effect. Due to complexity of earthquake in the frequency spectrum and energy distribution, the control performance were affected by the excitation type.

(2) Both of the new type TMD and conventional TMD has similar effect on structural vibration control. Compared with conventional TMD, the eddy-current TMD has advantages in energy dissipation and amplitude control. The eddy-current system can avoid the impact between TMD mass and main structure.

(3) According to numerical simulation results, the new eddy-current TMD installed in SHC can reduce the wind-induced vibration significantly. The results also predicted that the TMD has relatively insignificant beneficial effects and no adverse effects under seismic situation.

All results show that the new eddy-current TMD perform well both in experimental and analysis studies, and can be used to control the first mode vibration of high-rise buildings.

8. Acknowledgements

The financial support of National Natural Science Foundation of China (NSFC) through the grant 91315301-4 and the grant 51478361, Science and Technology Commission of Shanghai Municipality (STCSM, Grant No. 13231201600) and the Programme of Introducing Talents of Discipline to Universities (the 111 Project) are gratefully acknowledged. Shanghai Tower Construction and Development Co., Ltd is gratefully acknowledged for providing the opportunities of analysis and consultation. The findings, observations and conclusions in this paper are those of the authors and do not necessarily represent those of the sponsors.

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