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DEVELOPMENT OF TUNED MASS DAMPER FOR BUILDINGS WITH DIFFERENT NATURAL PERIODS IN TWO DIRECTIONS

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Abstract

Recently, there have been increasing applications of tuned mass dampers (TMD) to existing high-rise buildings for seismic upgrading against large earthquakes. These devices have the advantages of requiring few construction points, and their influence on users and change to the building's appearance are minimized.

However, there is a problem that the seismic control performance declines when they are applied to buildings with different natural periods in the two horizontal directions. This is because conventional TMD uses wires or rubber bearings that have isotropic restoring characteristics in the horizontal directions as restoring force elements. These TMDs have the same vibration period in two directions and cannot be perfectly tuned to different two periods.

In order to solve this problem, some methods have been studied. One is to tune the TMD to the middle period in two directions. Although this method does not require device improvements, the control performance is lower than that of a perfectly tuned TMD because there remains deviations of tuning in both direction. Another method is to install two TMDs: one tuned for X direction and one tuned for Y direction. With this method, one of the two TMDs performs effectively, but the other doesn't. The other method is to add devices such as inertial mass dampers which adjust the resonance frequency. These devises enable the resonance frequency in two directions to be determined independently, but the control efficiency becomes lower as well.

As a solution to these problems, authors developed a new simple TMD mechanism that can be tuned in both directions of buildings. The developed TMD consists of two springs connected in series and a damper placed in parallel with only one of the springs. The damper in this system plays the role of determining the resonance frequency as well as providing damping, therefore enables the TMD to be tuned to different periods by setting its damping coefficient in each direction independently.

In this paper, the principle of tuning mechanism is described using a complex stiffness model, a simple method for determining the parameters of the system is shown, and control performance superiority to conventional TMD is demonstrated by resonance curves and seismic response analyses. In addition, to confirm that the developed TMD works smoothly and shows intended dynamic performance, shaking table tests on the 1/10 scaled specimen are conducted. The result of resonance vibration tests and seismic response tests and an accurate trace using a simple analytical model are mentioned.

Keywords: Tuned mass damper, Different natural period in two direction, Seismic retrofit, Long-period earthquake

1. Introduction

In recent years, many large tuned mass dampers (TMD) have been applied to high-rise buildings for the purpose of improving seismic performance. Actually, we have developed these types of TMD and applied them to several high-rise buildings since 2013 [1, 2]. As elements which support the weight of the TMD, structural wires or rubber bearings with sufficient vertical support capacity are often used. Since these elements have isotropic restoring characteristics in horizontal directions, it is difficult to set the natural frequency of the TMD to different values in horizontal directions. Therefore, this type of TMD installed to a building which has different natural periods in the two horizontal directions will have an inevitable tuning deviation, not be able to demonstrate full capability of its own mass and perform less effectively.

There are several possible solutions to this problem. The first solution is to install a TMD with a sufficiently large weight. This is because the larger the TMD's mass is, the less sensitive to the tuning deviation. However, unnecessarily large TMD is uneconomic. The second is to set the TMD's natural period to the middle of the natural periods in both directions of the building. Although this method can minimize the tuning deviation, it cannot cancel the detuning radically and there remains declines of seismic performance. The third is to divide the TMD into two, and tune one of them for X direction and the other for Y direction. This method can provide optimum tuning in both directions, however the optimally tuned mass is halved. The last method is adjusting the resonance frequency of the TMD by installing inertial mass only in one direction [3]. Although this method can cancel the tuning deviation, it is known that the effective mass becomes less as compared with a TMD optimized without inertial mass.

In this paper, we propose a TMD system that can be optimally tuned respectively for horizontal two directions (Proposed TMD). First, the conventional TMD settings for buildings with different natural periods in two directions are investigated in the point of damping performance. Next, the mechanism of the Proposed TMD is introduced. Its system is presented using a complex stiffness model and a simple method for determining the system parameters is proposed. Then, dynamic analyses against earthquake ground motion are carried out, and the outperformance of the Proposed TMD is confirmed. Finally, shaking table tests of a scaled specimen are carried out, and we confirm the validity and feasibility and shows that simulation analyses can trace the results accurately.

2. Performance of Conventional TMD

In this chapter we discuss the control performance of TMDs with conventional tuning methods. Fig. 1 shows the applied structure model. To focus on the basic principle, the main structure is assumed to be a SDOF model without damping. A TMD with mass m is installed on the top of it.

First, we set some parameters of the model. The ratio of the TMD's mass m to the main structure's mass M_X, M_Y is an important parameter that determines the TMD's control performance. The mass ratio μ_X and μ_Y are defined in the following.

$$\mu_X = \frac{m}{M_X}, \mu_Y = \frac{m}{M_Y} \tag{1}$$

The ratio of main structure's natural periods in X and Y direction η is defined and assumed as follows:

$$\eta = \frac{T_Y}{T_X} = \frac{\Omega_X}{\Omega_Y} > 1 \tag{2}$$

where T_X is the natural period of the main structure in X direction and T_Y is that in Y direction. Similarly, Ω_X and Ω_Y are the circular frequency in X and Y direction.

Fig. 2(a) shows the Single TMD model. According to the fixed points theory [4], optimum frequency ω_{opt} and damping ratio h_{opt} of the Single TMD and the peak value of the amplitude ratio at resonance are given by the following equations, where $\ddot{x}$ and $\ddot{y}$ indicate the relative acceleration of main structure, $\ddot{x}_0$ and $\ddot{y}_0$ indicate the ground acceleration.

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$$\omega_{optX} = \frac{1}{1+\mu_X}\Omega_X, \quad h_{optX} = \sqrt{\frac{3\mu_X}{8(1+\mu_X)}} \tag{3}$$

$$\omega_{optY} = \frac{1}{1+\mu_Y}\Omega_Y, \quad h_{optY} = \sqrt{\frac{3\mu_Y}{8(1+\mu_Y)}} \tag{4}$$

$$\left|\frac{\ddot{x}+\ddot{x}_0}{\ddot{x}_0}\right|_{\max} = \sqrt{\frac{2+\mu_X}{\mu_X}}, \quad \left|\frac{\ddot{y}+\ddot{y}_0}{\ddot{y}_0}\right|_{\max} = \sqrt{\frac{2+\mu_Y}{\mu_Y}} \tag{5}$$

A TMD that satisfy both Eq. (3) and Eq. (4) is desirable, but in general, a Single TMD cannot satisfy both of them simultaneously because its horizontal stiffness is common in two directions. If a Single TMD is designed based on Eq. (3), it is less effective in Y direction although optimized for X direction. Similarly, if it is designed based on Eq. (4), it is less effective in X direction although optimized for Y direction. On the other hand, if it is tuned to the middle frequency between Ω_X and Ω_Y, the decline of performance can be alleviated in both directions, however the damping performance becomes less than that of optimum tuning in both direction.

As another solution, Dual TMD model is shown in Fig. 2(b). By tuning one of the TMD for X direction and the other for Y direction, optimum tuning is achieved in both directions. But, one of them is not tuned optimally, therefore the performance is inferior to that of optimum tuning in both direction.

Fig. 2(c) shows a TMD model with inertial mass. This is a method of tuning a Single TMD for X direction, that is the direction with shorter natural period, and then introducing an inertial mass in the Y direction. Due to the negative stiffness effect of inertial mass, the period in Y direction can be controlled to the longer value. Based on the fixed points theory, the optimum values of the inertial mass m_d and optimum damping ratio h_{opt} of the Y direction are given by the following equations [5].

$$m_{d\,opt} = \frac{\eta^2-1}{1+\mu_Y}m, \quad h_{optY} = \sqrt{\frac{3\mu_Y}{8(1+\mu_Y)}} \tag{6}$$

Eq. (6) indicates that larger inertial mass is necessary along with the increase of η. The value of the amplitude ratio in Y direction at resonance is expressed by the following.

$$\left|\frac{\ddot{y}+\ddot{y}_0}{\ddot{y}_0}\right|_{\max} = \sqrt{\frac{2+\mu_Y/\eta^2}{\mu_Y/\eta^2}} \tag{7}$$

Because Eq. (7) is obtained by replacing μ_Y in Eq. (5) for μ_Y/η^2, it can be interpreted as decrease of mass ratio by adjusting period with inertial mass.

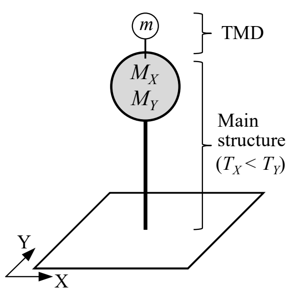
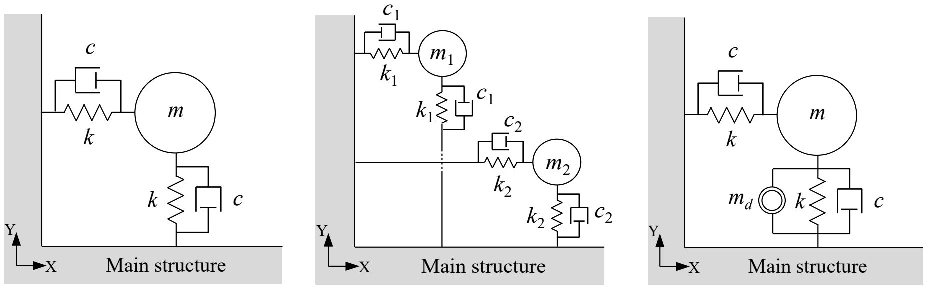


Fig. 1 – Applied structure



(a) Single TMD (b) Dual TMD (c) TMD with inertial mass

Fig. 2 – Mechanical model of conventional TMD

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Resonance curves of the above types of TMD under the condition of $\mu_X = \mu_Y = 0.05$ and $\eta = 1.5$ are shown in Fig. 3. Every type of TMD has larger peak value than derived from Eq. (5) in either direction.

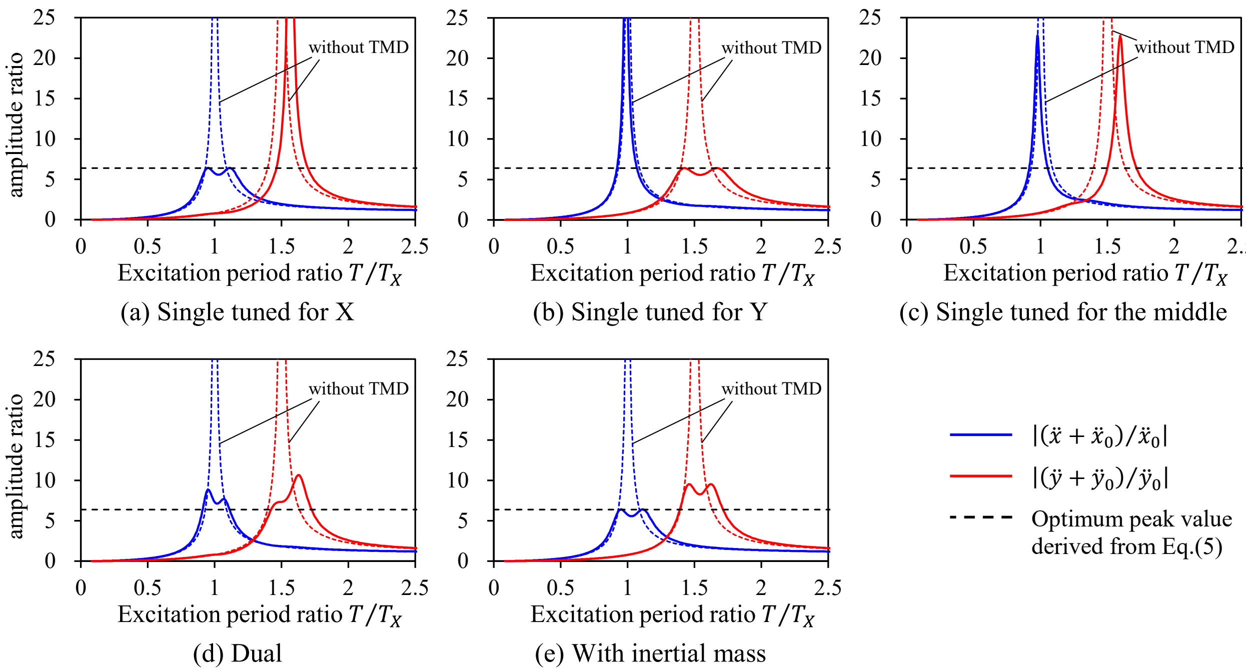

Fig. 3 – Resonance curve of conventional TMD ($\mu_X = \mu_Y = 0.05$, $\eta = 1.5$)

Table 1 – Setting parameters of each TMD

Type of TMD	Single tuned for X	Single tuned for Y	Single tuned for the middle	Dual	With inertial mass
μ_X	0.050	0.050	0.050	0.025, 0.025	0.050
μ_Y	0.050	0.050	0.050	0.025, 0.025	0.050
m_d	-	-	-	-	$m_{d\ opt}$
Frequency	ω_{optX}	ω_{optY}	$(\omega_{optX} + \omega_{optY})/2$	$\omega_{optX}{}^{*1}$, $\omega_{optY}{}^{*1}$	ω_{optX}
Damping ratio	h_{optX}	h_{optY}	$(h_{optX} + h_{optY})/2$	$h_{optX}{}^{*1}$, $h_{optY}{}^{*1}$	h_{optX}

*1 Calculated using individual mass ratio: 0.025

3. Proposition of TMD for Buildings with Different Natural Periods in Two Directions

In this chapter, we propose a TMD for buildings with different natural periods in two directions, utilizing the mechanism of semi-active TMD adaptable to a structure's period fluctuation [6]. First, we explain the principle of its tuning mechanism using a complex stiffness model and describe the design method. Next, the superiority of the Proposed TMD is shown using resonance curves. Finally, dynamic analyses against earthquake ground motions are carried out, and the control performance of the Proposed TMD is confirmed.

3.1 Mechanism of Proposed TMD

Fig. 4 provides a typical composition of the Proposed TMD. Rubber bearings are piled up to make two layers and oil dampers in parallel with rubber bearings are installed to one of the layer. In terms of using rubber bearings, Proposed TMDs also have the isotropic restoring characteristics. However, by setting the damping coefficient of the oil dampers in X and Y direction to different values, the resonance frequency of this TMD can be controlled independently in two directions. In this system, oil dampers play two important roles of adding damping and adjusting the resonance frequency.

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The mechanical model of a building with a Proposed TMD is shown in Fig. 5. In this TMD, the stiffness ratio of the two springs is an important parameter that determines the adaptable period range, so we define it as λ expressed by the following equation.

$$\lambda = \frac{k'}{k} \tag{8}$$

Similarly, the damping coefficient ratio of the two directions is defined as γ by the following.

$$\gamma = \frac{c_Y}{c_X} \tag{9}$$

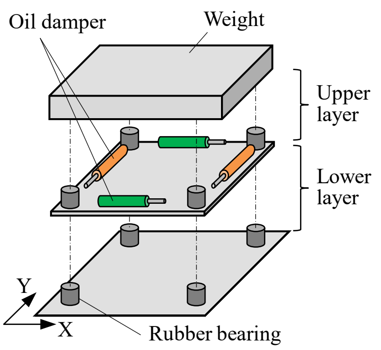
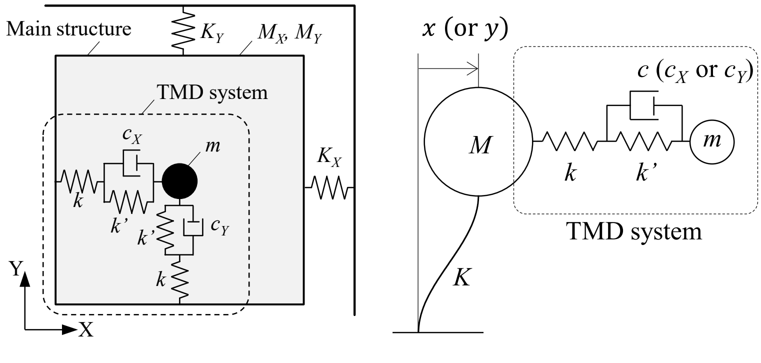


Fig. 4 – Composition of Proposed TMD



(a) Plan (b) Elevation

Fig. 5 – Mechanical model of Proposed TMD

3.2 Principle of Tuning Mechanism

To comprehend the tuning mechanism, we focus on the TMD system shown in Fig. 5, and the relation between the damping coefficient of the dashpot and the resonance frequency and damping ratio of the TMD system is investigated.

Considering the harmonic external force $F = F_0 e^{ipt}$, the complex stiffness of the TMD system's supporting part k^*, which is composed of k, k' and c is expressed by:

$$k^* = \frac{\lambda k^2 + kcpi}{(1+\lambda)k + cpi} \tag{10}$$

The equivalent stiffness, resonance frequency and equivalent damping ratio under resonance vibration are given as $k_e = \mathrm{Re}[k^*]$, $\omega_e = \sqrt{k_e/m}$ and $h_e = \mathrm{Im}[k^*]/2k_e$ respectively. By substituting k^* in Eq. (10) into these formulas, the resonance frequency and equivalent damping ratio are expressed by:

$$\frac{\omega_e}{\omega} = \sqrt{\frac{{g_0}^2 - (1+\lambda)^2 + \sqrt{{g_0}^4 - 2{g_0}^2(1-\lambda^2) + (1+\lambda)^4}}{2{g_0}^2}} \tag{11}$$

$$h_e = \frac{g_e}{2{g_e}^2 + 2\lambda(1+\lambda)} \tag{12}$$

where ω, g_0 and g_e are parameters as follows.

$$\omega = \sqrt{\frac{k}{m}} \tag{13}$$

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$$g_0 = \frac{c\omega}{k} = \frac{c}{\sqrt{mk}} \tag{14}$$

$$g_e = \frac{\omega_e}{\omega} g_0 \tag{15}$$

Fig. 6 shows the relation between resonance frequency ω_e and non-dimensional damping coefficient g_0 obtained from Eq. (11). Fig. 7 shows the relation between the equivalent damping ratio h_e and g_0 obtained from Eq. (12). The resonance frequency of the TMD system in each direction can be determined by changing the damping coefficient of the dashpot. Then, we have to pay attention to the equivalent damping ratio of the TMD system which also changes accordingly. If the parameters λ and γ are set to the proper value, the optimum condition shown in Fig. 8 can be acquired. Under this condition in which both Eq. (3) and Eq. (4) are satisfied simultaneously, optimum tuning is achievable in both directions.

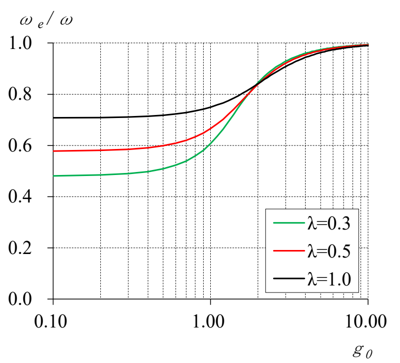

Fig. 6 – Resonance frequency of Proposed TMD

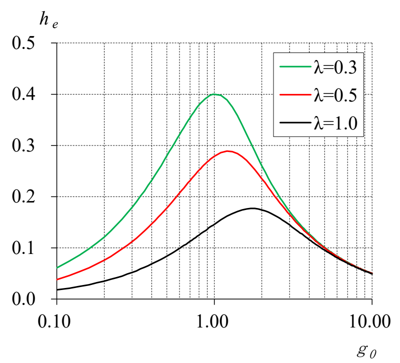

Fig. 7 – Equivalent damping ratio of Proposed TMD

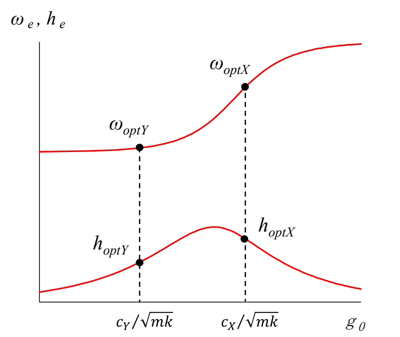

Fig. 8 – Optimum tuning for both direction

3.3 Design method of Proposed TMD

To determine the parameters of Proposed TMD, we assume $\mu_X = \mu_Y = \mu$ in the first. The equivalent mass of the building depends on the direction, but the difference is not so large generally. Therefore, this assumption is not unreasonable. Next, by substituting Eq. (11) and Eq. (12) into the optimum tuning formulas Eq. (3) and Eq. (4), we can calculate four design parameters k, c_X, λ and γ. The relationship between λ and η is shown in Fig. 9 and the relationship between γ and η is shown in Fig. 10. k and c_X can be calculated by substituting λ and γ obtained from these figures into following equations [7].

$$k = \frac{{g_X}^2 + (1+\lambda)^2}{{g_X}^2 + \lambda(1+\lambda)} \cdot m{\omega_{optX}}^2 \tag{16}$$

$$c_X = \sqrt{\frac{{g_X}^2 + (1+\lambda)^2}{{g_X}^2 + \lambda(1+\lambda)} \cdot mk} \tag{17}$$

where g_X is a parameter

$$g_X = \frac{1 + \sqrt{1 - 16\lambda(1+\lambda){h_{optX}}^2}}{4h_{optX}} \tag{18}$$

In this way, all the parameters of Proposed TMD can be determined uniquely when parameters of the main structure (M, Ω_X and Ω_Y) and the mass of TMD (m) are given.

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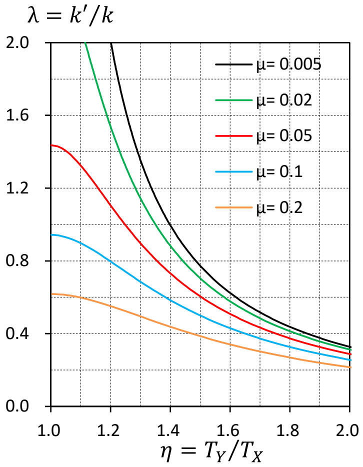

Fig. 9 – Optimum λ

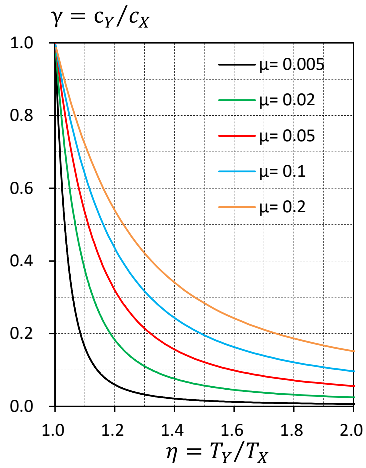

Fig. 10 – Optimum γ

3.4 Resonance curve of Proposed TMD

The resonance curve of Proposed TMD is shown in Fig. 11. The main structure has no damping and the Proposed TMD is designed with the above method under the condition $\mu = 0.05$ and $\eta = 1.5$, that is the same condition as Fig. 3. The parameters λ and γ are determined from Fig. 9 and Fig. 10 as $\lambda = 0.605$ and $\gamma = 0.122$. Fig. 11 also shows the peak value of an optimally tuned Single TMD having the same mass ratio. It indicates that the proposed TMD has the same damping performance as the Single TMD independently tuned for each direction and that the Proposed TMD outperforms conventional TMDs in Fig. 3 even though its restoring characteristics is also isotropic.

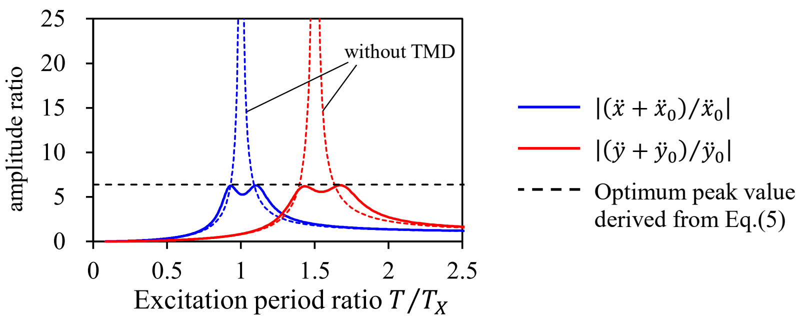

Fig. 11 – Resonance curve of Proposed TMD (μ=0.05 , η=1.5)

4. Seismic Response Analyses of High-rise Building

In this chapter, we examine the control performance of the Proposed TMD through seismic response analyses. Fig. 12 shows the characteristics of the applied structure. A 30-story lumped mass model shown in Fig. 12(a) is employed. The mass of every floor is the same, and the stiffness of every story is linear. The distribution of stiffness is shown in Fig. 12(b). The natural periods of the first mode are 3.0 sec in X direction and 4.5 sec in Y direction ($\eta = 1.5$). The damping ratio of the main structure is set to 2% for the first mode.A TMD is installed on the top of the main structure as illustrated in Fig. 12(a). We examine three type of TMDs listed in Table 2 and compare their control performance. The weight of every TMD is set to the same value and their mass ratio to the main structure's equivalent mass is 5%. Fig. 13(a) shows the acceleration time history of the input ground motion used for the analyses, which is a artificial ground motion. Fig. 13(b) shows its velocity response spectrum.

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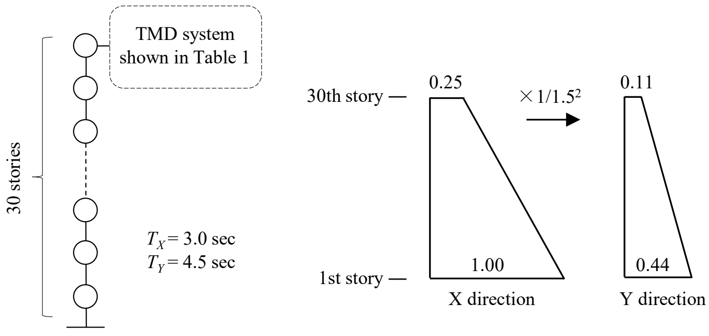
Fig. 14(a) shows the maximum displacement of the main structure. It indicates that Single TMDs are less effective in the detuned direction, and what is worse, the Single TMD tuned for X direction makes the top displacement in Y direction larger than that without TMD. On the other hand, the Proposed TMD reduces the response to the same level as the optimized Single TMD in both direction and its superiority to conventional TMDs is verified. The maximum stroke of TMD is focused on in Fig. 14(b). The total stroke of Proposed TMD is approximately equal to the stroke of the optimized Single TMD. Because the oil dampers of Proposed TMD are installed in only one of the layer, the stroke of the oil damper is smaller than the TMD's total stroke. It is advantageous in terms of mechanism design and construction in which the length of the oil damper is often a matter.

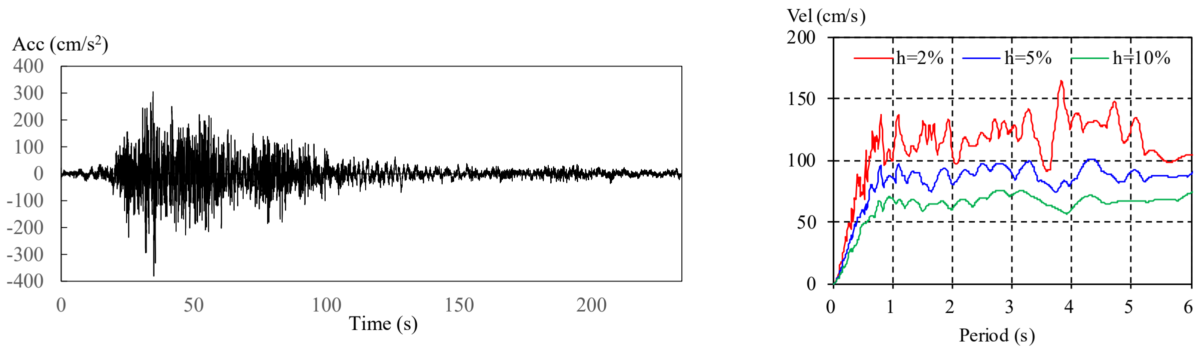


(a) Analitical model (b) Stiffness distribution

Fig. 12 – Characteristics of applied structure

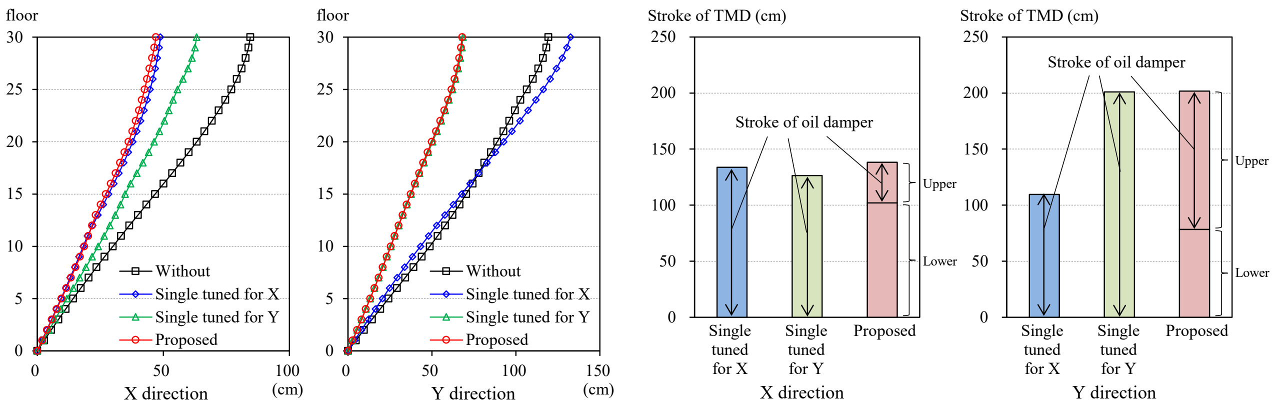
Table 2 – Setting parameters of each TMD

Type of TMD	Without	Single tuned for X	Single tuned for Y	Proposed
Mass ratio μ	Nothing	5%	5%	5%
TMD's period (sec)	-	3.150	4.725	3.150 (X) 4.725 (Y)
Damping ratio	-	13.4%	13.4%	13.4%



(a) Acceleration time history (b) Velocity response spectrum

Fig. 13 – Input ground motion



(a) Maximum displacement (b) Maximum TMD stroke

Fig. 14 – Results of seismic response analysis

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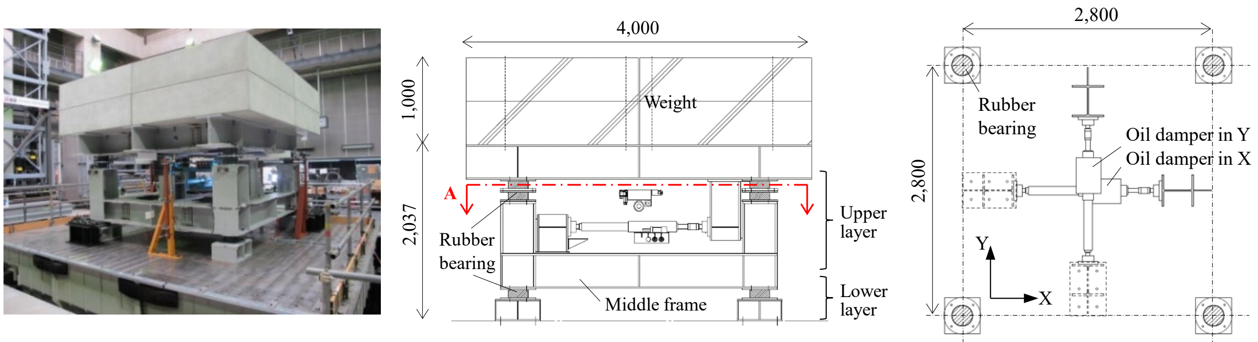
5. Shaking Table Test

In this chapter, we report the shaking table test conducted on a scaled specimen of Proposed TMD. First, the basic characteristics of the TMD without oil dampers is checked. After that, oil dampers with different damping coefficients are installed in each direction, and the resonance frequency and the equivalent damping ratio in each direction are confirmed through a sinusoidal excitation. Finally, a simultaneous excitation in two horizontal direction with a seismic response wave is performed, and the validity of the analytical model is confirmed by a simulation analysis.

5.1 Scaled specimen of Proposed TMD

The specimen is assumed to be a TMD installed on a 30-story building with $T_X = 2.7$ sec and $T_Y = 4.2$ sec ($\eta = 1.56$) and its mass ratio to the building's equivalent mass is assumed to be 5%. Considering the limitations of the excitational capacity of the shaking table and the deformational capacity of the rubber bearings, the weight of the TMD is reduced to about 1/10, and the time scale is shortened to 1/2. The apparence and the specification of the specimen is shown in Fig. 15(a) and Table 3. The weight is made of precast concrete, and connected to the steel frame with PC steel bars. Although the middle frame also has some mass, it is relatively enough lighter than the weight (approxmately 1/10).

Optimum values of λ and γ under this condition $\mu = 0.05$ and $\eta = 1.56$ can be determined as $\lambda = 0.5$ and $\gamma = 0.11$ from Fig. 9 and Fig. 10. To set the stiffness ratio λ to 0.5, two rubber bearings which have the same specification as those used in the lower layer are piled up in the upper layer as shown in Fig. 15(b). The damping coefficient of the oil dampers in Y direction is set to smaller value than those in X direction so as to sartisfy $\gamma = 0.11$.



(a) Apparence (b) Elevation (c) A-section

Fig. 15 – Specimen of Proposed TMD

Table 3 – Specification of the specimen

	Measurement data in product inspection
Weight	407.9 kN (including steel frame)
Middle frame	40.0 kN
Rubber bearing	Diameter : 225 mm Total thickness of rubber layers : 56 mm Horizontal stiffness : 490.6 kN/m (Upper layer) 981.2 kN/m (Lower layer) (under 10°C, 2.5 N/mm^2)
Oil damper	Stroke : ±120(mm) Stiffness : 60000(kN/m) Damping coefficient : 6.0 kNs/cm (X), 0.8 kNs/cm (Y)

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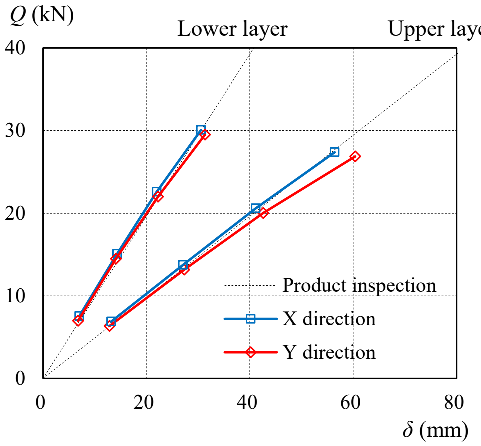
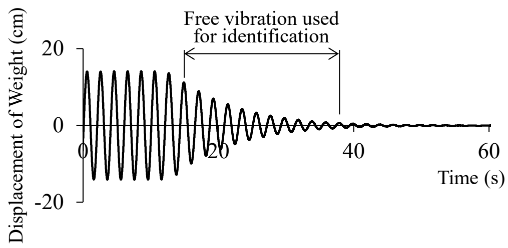
5.2 Basic characteristics of specimen

In order to examine the horizontal stiffness and damping of the rubber bearings, tilt table tests and free vibration tests were performed without installing oil dampers. The results of tilt table tests are shown in Fig. 16(a). Although there is a slight difference between the X direction and the Y direction, it can be seen that the stiffness of the TMD roughly shows a good correspondence with the value calcurated from product inspection result (under the same vertical load and 100% shear strain of the rubber). The vibration periods identified from the free vibration tests were about 2.1 sec in both directions, and the damping ratio was identified to be about 4% as shown in Fig. 16(b).



(a) Tilt table test



Identified	X	Y
T (s)	2.10	2.11
h	0.04	0.04

(b) Free vibration test

Fig. 16 – Basic characteristics of specimen without oildampers

5.3 Resonance vibration test

For the purpose of exmining the effect of oil dampers on the resonance frequency and equivalent damping ratio in each direction of the specimen, the oil dampers were installed and resonance vibration tests with sinusoidal input were performed. The amplitude of input acceleration was constant ($27\mathrm{cm/s^2}$), and the maximum resonance acceleration of the weight in the steady state was measured at each frequency. Fig. 17 shows the resonance curves obtaind from the tests. It indicates that the specimen has different resonance frequencys in two directions and it is approximately 0.75 Hz (1.3 sec) in X direction and 0.50 Hz (2.0 sec) in Y direction. The equivalent damping ratios guessed from the peak vlues are approximately 16% in both directions, and does not deviate so much from the optimum value (h_{opt} = 13.4%) under μ = 0.05. We can confirmed that this TMD has dynamic characteristics neccesary for the building with different natural periods in two directions.

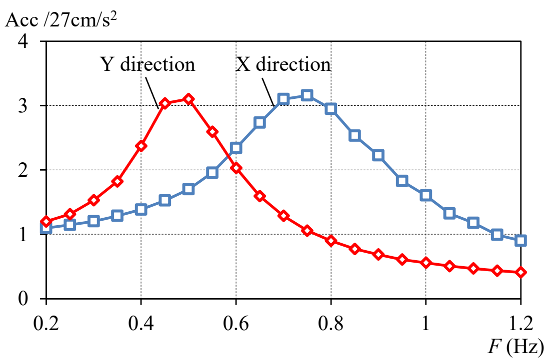


Fig. 17 – Resonance curve of specimen

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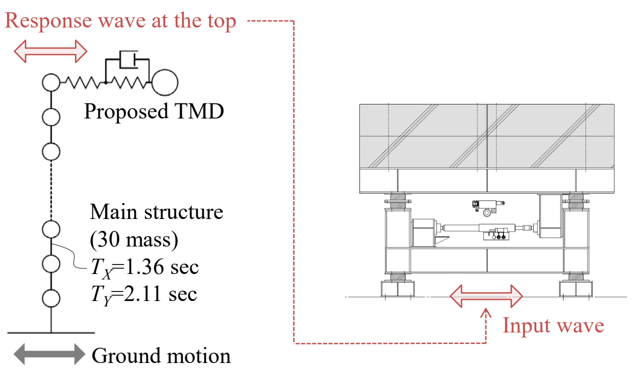
5.4 Seismic response test

Finally, a simultaneous excitation in two horizontal direction with a seismic response wave is performed. The input wave is assumed to be the acceleration at the top of a building and made by a seismic response analysis demonstrated in Fig. 18. Considering the scale of mass and time of the specimen, the mass and stiffness of the applied structure (originally $T_X = 2.7$ sec and $T_Y = 4.2$ sec) are adjusted so that the mass ratio μ will keep 5% and the natural periods will be halved. The ground motion used for the analysis is the same as shown in Fig. 13, but its time scale is shortened to 1/2 for the same reason.

We also conducted a simulation analysis of the experiment. Fig. 19 shows the analytical model. The values shown in Table 3 are used for the specifications of each element. The rubber bearing is modeled as a linear spring, and 4% (for the specimen's vibratation period without oil dampers) internal viscous damping is provided. The oil damper is modeled as linear Maxwell model, and a rigid-plastic spring (maximum load: 1.0 kN) simulating friction is arranged in parallel. In addition, the mass of the middle frame is considered. The input for the simulation is the acceleration time history in each direction measured on the shaking table, and X and Y directions are independently analized.

Comparisons between the experiment and the simulation results are shown in Fig. 20. Fig. 20(a) shows the time histories of the lower layer's total shear force which means the controlling force to the building from TMD. Fig. 20(b) shows the displacement orbit of the weight. In both directions, the simulation corresponds well with the experiment. It is confirmed that the dynamic behavior of Proposed TMD can be accurately traced by the simple analytical model.



Seismic response analysis　　Experiment

Fig. 18 – How to make input for specimen

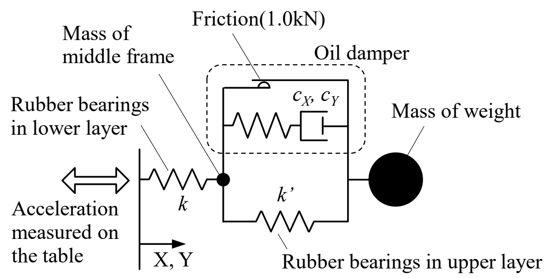
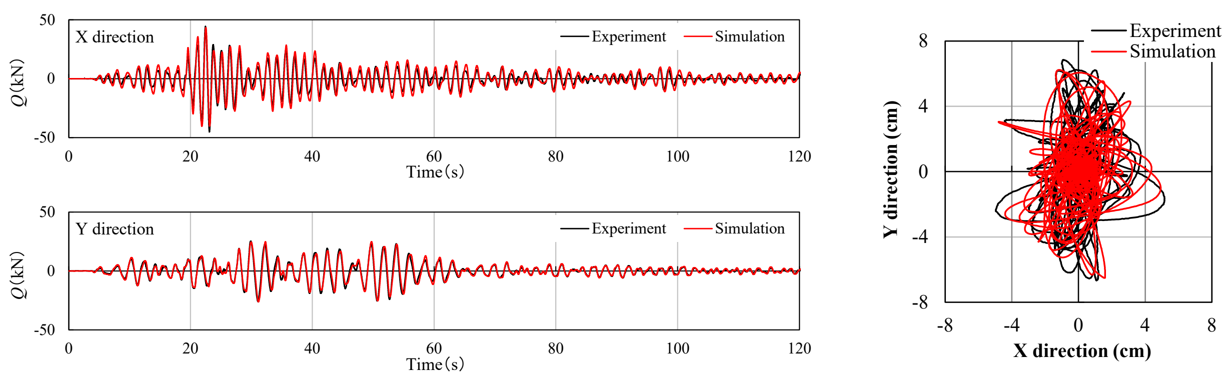


Fig. 19 – Simulation model of specimen



(a) Time history of lower layer's total shear force　　(b) Displacement orbit of weight

Fig. 20 – Comparison between experiment and simulation results

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6. Conclusions

This paper proposed a newly developed TMD system applicable to buildings with different natural periods in two horizontal directions. The Proposed TMD can simultaneously satisfy the optimum tuning conditions in both directions in spite of using isotropic restoring elements. The tuning principle and design method of the Proposed TMD are presented based on a complex stiffness model. Its control performance was compared to that of other types of TMD by resonance curve and seismic response analysis, and its superior performance was demonstrated. Finally, we built a scaled specimen of the Proposed TMD and performed a shaking table tests. The expected dynamic characteristics of the specimen and the validity and accuracy of the analytical model are confirmed.

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