6th International Conference on Advances in Experimental Structural Engineering
11th International Workshop on Advanced Smart Materials and Smart Structures Technology
August 1-2, 2015, University of Illinois, Urbana-Champaign, United States

Outrigger Tuned Viscous Mass Damping System for High-rise Buildings Subject to Earthquake Loadings

Takehiko Asai[1], Kohju Ikago[2], Yoshikazu Araki[3]

1 *JSPS Research Fellow, Disaster Prevention Research Institute, Kyoto University, Japan.*
E-mail: asai.takehiko.68u@st.kyoto-u.ac.jp
2 *Professor, International Research Institute of Disaster Science, Tohoku University, Japan.*
E-mail: ikago@archi.tohoku.ac.jp.
3 *Associate Professor, Dept. of Architecture and Architectural Engineering, Kyoto University, Japan.*
E-mail: araki@archi.kyoto-u.ac.jp.

ABSTRACT
The number of high-rise buildings in urban areas around the world has been increased rapidly. To protect such high-rise buildings from external disturbances, tuned mass dampers (TMDs) have been proposed as an energy dissipation system. The effectiveness of this strategy to wind loadings has been shown, while it is limited against earthquakes due to the limitation of the supplemental mass. Tuned viscous mass dampers (TVMDs) have been developed as an alternative method where an amplified apparent mass is realized by an inertial mass through a ball screw mechanism. However, since they are installed inter-story, they become less effective in high-rise buildings due to insufficient inter-story drifts. To increase the effectiveness of the TVMDs in high-rise buildings, this paper proposes outrigger tuned viscous mass damping systems, in which the TVMDs are installed vertically between the outrigger and perimeter columns of high-rise buildings to achieve large energy dissipation. And the design method for the TVMDs to be tuned to the bending of the building is introduced. Then the validity of the proposed damping system subject to earthquake records are verified through numerical simulation.

KEYWORDS: *Tuned Viscous Mass Damper, High-rise Building, Outrigger Damping System*

1. INTRODUCTION

To date, various structural control strategies for buildings excited by severe earthquakes or strong wind have been proposed by many researchers and engineers [1]. One of the widely-accepted methods is tuned mass dampers (TMDs) [2], which consist of an auxiliary mass located at the top of the building and connected through a passive spring and a damper. Then the auxiliary system is tuned to reduce the amplitude of building motion. In practice, the auxiliary mass is limited up to on the order of 1% of the mass of the total structure. Thus this technology is particularly effective for stationary, narrow band motions, while for broadband excitations such as strong earthquakes, where transient effects are dominant, enough response reduction performance cannot be achieved [1].

To address this issue, tuned viscous mass dampers (TVMDs) have been proposed [3], which is composed of a rotational viscous mass damper part and a supporting spring part. The rotational viscous mass damper is employed to produce an amplified apparent effect of a viscous mass damper by rotating a relatively small mass through a ball screw mechanism. Then this rotational viscous mass damper is connected to a structure through the supporting spring which is tuned to the behavior of the structure so that a large amount of energy dissipation is obtained. While TMD systems are connected to a single story of buildings, the TVMDs are installed between floors. This is because the TVMD generates its output force based on the relative acceleration between the floors. In general, the relative accelerations are not so large compared to the absolute ones, however the ball screw mechanism can produce enough control force by the amplified apparent mass on the order of thousandfold. Therefore the TVMDs can adapt to strong earthquake motions.

The effectiveness of this strategy has been verified in low-rise buildings, such as a SDOF system [3] and a 3DOF system [4]. However, such high performance cannot be expected from the TVMDs in high-rise buildings because the inter-story drifts of a size that is sufficient to dissipate large amounts of input energy are generally not available in high-rise buildings. Thus an effective configuration of the TVMDs in high-rise buildings has been sought [5].

Smith and Salim [6], Charles [7], Smith and Willford [8] have proposed outrigger damper systems as a response amplification method. In this system, vertical viscous dampers are installed between outrigger walls and perimeter columns in a frame-core-tube structure to enhance structural dynamic performance. Willford et al. [9] reported on a real-world implementation in a high-rise building in the Philippines. Also the validity of the outrigger damping systems employing semi-actively controlled MR dampers instead of passive viscous dampers has been investigated in [10, 11].

This paper proposes the outrigger damping system employing the TVMDs for high-rise buildings. The TVMDs are tuned to the bending behavior of the building. Then this paper verifies the efficacy of the proposed structural control system subjected to earthquake loadings through numerical simulations. For comparison, two additional cases, i.e., an uncontrolled building (no supplemental dampers) and a building with a TMD are investigated as well. First, the mechanism of the TVMD is overviewed briefly. Then the equations of motion for the high-rise building models used in this paper are constructed and the dampers used in the models are designed. In numerical simulations, the performances of the different structures are compared and the efficacy of the proposed outrigger TVMDs subject to the 1940 El Centro earthquake recorded at Imperial Valley is shown. Conclusions obtained from this study then follow.

2. TUNED VISCOUS MASS DAMPER

In this section, the mechanism of the TVMD is briefly overviewed. As stated in the preceding section, the TVMD is composed of two parts, i.e., a rotational viscous mass damper and a supporting spring.

A rotational viscous mass damper is illustrated in Fig. 2.1, schematically, which consists of a ball screw mechanism, a rotating mass, and a viscous material. As can been seen, the ball screw mechanism is employed to convert linear motion to rotational behaviour. Then a rotary inertia mass effect is produced by rotating the mass and an amplified apparent mass effect amplified is obtained. Practically, this mechanism can produce an apparent mass effect increased by a few thousand times as the rotational mass. Also, the viscous material provides damping. The rotational viscous mass damper can be modelled as shown in Fig. 2.2 (a), in which m_d and c_d represents the amplified mass and damping coefficient.

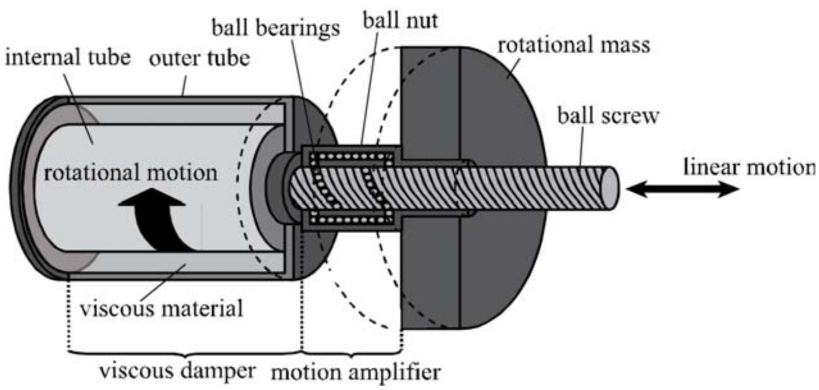

Figure 2.1 Schematic illustration of the rotational viscous mass damper

To connect the rotational viscous mass damper to the structure, a supporting spring is employed. The stiffness of the spring is tuned so that the rotational viscous mass damper absorbs input energy to the structure effectively. The model of the TVMD is given in Fig. 2.2 (b), in which k_d is the stiffness of the supporting spring.

Fig. 2.2 (c) depicts the analysis model for a single-degree-of-freedom structure with the TVMD. m and k are the mass and stiffness of the structure, respectively. As illustrated, the TVMD is installed in parallel with the spring of the structure.

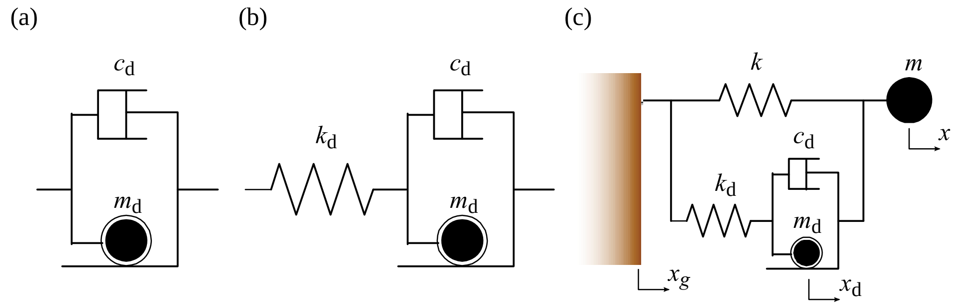

Figure 2.2(a) Rotational viscous mass damper model (b) Tuned viscous mass damper model (c) Analysis model for the tuned viscous mass damper installed in a single-degree-of-freedom structure

Let F_d be the rotational viscous mass damper force. Then the equations of motion of the TVMD can be expressed as

$$m\ddot{x} + kx + F_d = -m\ddot{x}_g \tag{2.1}$$

$$F_d = m_d\ddot{x} + c_d\dot{x} = k_d(x - x_d) \tag{2.2}$$

where x_g is the displacement of the ground and x and x_d is the displacement relative to the ground of the mass and the damper, respectively.

3. PROBLEM FORMULATION

In this section, three equations of motion for three different types of high-rise buildings are developed. Fig. 3.1 illustrates the three high-rise building models considered in this study, schematically, i.e., (a) uncontrolled building (no supplemental damper), (b) building with a TMD, and (c) building with outrigger TVMDs. In these models, every story has one transitional and one rotational degree of freedoms.

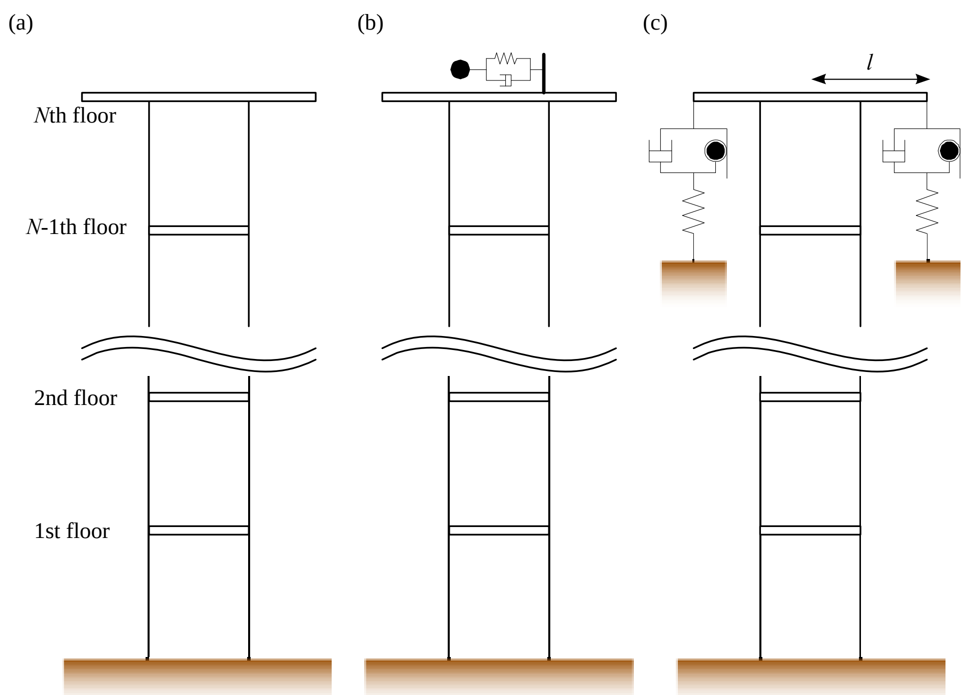

Figure. 3.1 Three building models (a) Uncontrolled (b) With a TMD (c) With TVMDs

As shown in Fig. 3.1 (b), a TMD is placed on the top floor which is connected by a spring and a dashpot. While, in the building with outrigger TVMDs as shown in Fig. 3.1 (c), the TVMDs are concentrated on the highest floor, where the deformation between the outrigger to the ground should be the largest in motion. The building model used in this study is developed in [10, 11].

3.1. Uncontrolled building

The equation of motion of the uncontrolled building shown in Fig. 3.1 (a) can be written as

$$\mathbf{M}_\mathrm{p}\ddot{\mathbf{x}}_\mathrm{p} + \mathbf{C}_\mathrm{p}\dot{\mathbf{x}}_\mathrm{p} + \mathbf{K}_\mathrm{p}\mathbf{x}_\mathrm{p} = -\mathbf{M}_\mathrm{p}\boldsymbol{\Gamma}_\mathrm{p}\ddot{x}_g \tag{3.1}$$

where $\mathbf{M}_\mathrm{p}$, $\mathbf{C}_\mathrm{p}$, and $\mathbf{K}_\mathrm{p}$ are the structural mass, damping, and stiffness of the uncontrolled building, respectively; $\mathbf{x}_\mathrm{p}$ is the structural deformation vector; $\boldsymbol{\Gamma}_\mathrm{p}$ is a vector with entries equal to unity for translational DOFs and zero for others: and $\ddot{x}_g$ is the horizontal ground acceleration. The structural deformation vector $\mathbf{x}_\mathrm{p}$ defined in this study consists of displacements and rotational angles as

$$\mathbf{x}_\mathrm{p} = [x_1 \quad \theta_1 \quad x_2 \quad \theta_2 \quad \cdots \quad x_N \quad \theta_N]^T \tag{3.2}$$

where x_j and θ_j are the displacement and rotational angle relative to the ground of the jth floor, respectively. Thus, the mass matrix $\mathbf{M}_\mathrm{p}$ is defined as

$$\mathbf{M}_\mathrm{p} = \mathrm{diag}[m_1 \quad I_1 \quad m_2 \quad I_2 \quad \cdots \quad m_N \quad I_N] \tag{3.3}$$

where m_j and I_j are the mass and mass moment of inertia of the jth floor, respectively. And the influence vector $\boldsymbol{\Gamma}_\mathrm{p}$ is given by

$$\boldsymbol{\Gamma}_\mathrm{p} = [1 \quad 0 \quad 1 \quad 0 \quad \cdots \quad 1 \quad 0]^T \tag{3.4}$$

3.2. Building with a TMD

Consider the building with a TMD on the top floor as depicted in Fig. 3.1 (b). Let the transformation vector of this model $\mathbf{x}_\mathrm{t}$ be defined as

$$\mathbf{x}_\mathrm{t} = \left[\mathbf{x}_\mathrm{p}{}^T \quad x_\mathrm{td}\right]^T \tag{3.5}$$

where x_td is the relative displacement of the supplemental mass. Then the equation of motion can be written as

$$\mathbf{M}_\mathrm{t}\ddot{\mathbf{x}}_\mathrm{t} + \mathbf{C}_\mathrm{t}\dot{\mathbf{x}}_\mathrm{t} + \mathbf{K}_\mathrm{t}\mathbf{x}_\mathrm{t} = -\mathbf{M}_\mathrm{t}\boldsymbol{\Gamma}_\mathrm{t}\ddot{x}_g \tag{3.6}$$

Given the mass, damping coefficient, and stiffness of the TMD are m_td, c_td, and k_td, the mass matrix, damping coefficient matrix, and stiffness matrix can be expressed as

$$\mathbf{M}_\mathrm{t} = \begin{bmatrix}\mathbf{M}_\mathrm{p} & \mathbf{0}\\ \mathbf{0} & m_\mathrm{td}\end{bmatrix}, \quad \mathbf{C}_\mathrm{t} = \begin{bmatrix}\mathbf{C}_{\mathrm{t},11} & \mathbf{C}_{\mathrm{t},12}\\ \mathbf{C}_{\mathrm{t},21} & c_\mathrm{td}\end{bmatrix}, \quad \mathbf{K}_\mathrm{t} = \begin{bmatrix}\mathbf{K}_{\mathrm{t},11} & \mathbf{K}_{\mathrm{t},12}\\ \mathbf{K}_{\mathrm{t},21} & k_\mathrm{td}\end{bmatrix} \tag{3.7}$$

respectively, where

$$\mathbf{C}_{\mathrm{t},11} = \mathbf{C}_\mathrm{P} + \mathrm{diag}[0 \quad 0 \quad \cdots \quad 0 \quad c_\mathrm{td}] \tag{3.8}$$

$$\mathbf{C}_{\mathrm{t},12} = [0 \quad 0 \quad \cdots \quad 0 \quad -c_\mathrm{td}]^T, \quad \mathbf{C}_{\mathrm{t},21} = \mathbf{C}_{\mathrm{t},12}{}^T \tag{3.9}$$

$$\mathbf{K}_{\mathrm{t},11} = \mathbf{K}_\mathrm{P} + \mathrm{diag}[0 \quad 0 \quad \cdots \quad 0 \quad k_\mathrm{td}] \tag{3.10}$$

$$\mathbf{K}_{\mathrm{t},12} = [0 \quad 0 \quad \cdots \quad 0 \quad -k_\mathrm{td}]^T, \quad \mathbf{K}_{\mathrm{t},21} = \mathbf{K}_{\mathrm{t},12}{}^T \tag{3.11}$$

And the influence vector would be

$$\mathbf{\Gamma}_{\mathrm{t}} = \begin{bmatrix} \mathbf{\Gamma}_{\mathrm{p}}{}^{T} & 1 \end{bmatrix}^{T} \tag{3.12}$$

3.3. Building with outrigger TVMDs

Finally, the equation of motion for the building model with outrigger TVMDs as illustrated in Fig. 3.1 (c) is derived. Let l be the distance from the TVMDs to the center of the core. Then the moment applied to the Nth floor from the TVMDs installed on the Nth floor is

$$M_{\mathrm{od},N} = lk_{\mathrm{od},N}\left(l\theta_N - x_{\mathrm{od},N}\right) \tag{3.13}$$

where $k_{\mathrm{od},N}$ is the stiffness of the supporting spring and $x_{\mathrm{od},N}$ is the relative displacement of the TVMDs installed Nth floor. Let the structural deformation vector be defined as

$$\mathbf{x}_{\mathrm{o}} = \begin{bmatrix} \mathbf{x}_{\mathrm{p}}{}^{T} & x_{\mathrm{od},N} \end{bmatrix}^{T} \tag{3.14}$$

then the equation of motion of this case can be written as

$$\mathbf{M}_{\mathrm{o}}\ddot{\mathbf{x}}_{\mathrm{o}} + \mathbf{C}_{\mathrm{o}}\dot{\mathbf{x}}_{\mathrm{o}} + \mathbf{K}_{\mathrm{t}}\mathbf{x}_{\mathrm{o}} = -\mathbf{M}_{\mathrm{o}}\mathbf{\Gamma}_{\mathrm{o}}\ddot{x}_g \tag{3.15}$$

To correspond with the equation of motion above, $\mathbf{M}_{\mathrm{o}}$, $\mathbf{C}_{\mathrm{o}}$, and $\mathbf{K}_{\mathrm{o}}$ matrices can be developed as

$$\mathbf{M}_{\mathrm{p}} = \begin{bmatrix} \mathbf{M}_{\mathrm{p}} & \mathbf{0} \\ \mathbf{0} & m_{\mathrm{od},N} \end{bmatrix}, \quad \mathbf{C}_{\mathrm{o}} = \begin{bmatrix} \mathbf{C}_{\mathrm{p}} & \mathbf{0} \\ \mathbf{0} & c_{\mathrm{od},N} \end{bmatrix}, \quad \mathbf{K}_{\mathrm{o}} = \begin{bmatrix} \mathbf{K}_{\mathrm{o},11} & \mathbf{K}_{\mathrm{o},12} \\ \mathbf{K}_{\mathrm{o},21} & k_{\mathrm{od},N} \end{bmatrix} \tag{3.16}$$

$$\mathbf{K}_{\mathrm{o},11} = \mathbf{K}_{\mathrm{P}} + \mathrm{diag}\begin{bmatrix} 0 & 0 & \cdots & 0 & l^2 k_{\mathrm{od},N} \end{bmatrix} \tag{3.17}$$

$$\mathbf{K}_{\mathrm{o},12} = \begin{bmatrix} 0 & 0 & \cdots & 0 & -lk_{\mathrm{od},N} \end{bmatrix}^{T}, \quad \mathbf{K}_{\mathrm{o},21} = \mathbf{K}_{\mathrm{o},12}{}^{T} \tag{3.18}$$

where $m_{\mathrm{od},N}$ and $c_{\mathrm{od},N}$ are the apparent mass and damping coefficient of the TVMDs connected to the Nth floor, respectively. The apparent masses of the TVMDs are not influenced by earthquake inputs, so $\mathbf{\Gamma}_{\mathrm{o}}$ is given by

$$\mathbf{\Gamma}_{\mathrm{o}} = \begin{bmatrix} \mathbf{\Gamma}_{\mathrm{p}}{}^{T} & 0 \end{bmatrix}^{T} \tag{3.19}$$

4. DAMPER DESIGN

In this section, the damper design methods used in this paper are described. The dampers are tuned to the 1st mode of the prime building in this study.

4.1 TMD

The values of the stiffness and damping coefficient are determined, based on the method described in [2], as

$$k_{\mathrm{td}} = \left(\beta_{\mathrm{t}}^{\mathrm{opt}}\omega_1\right)^2 m_{\mathrm{td}}, \quad c_{\mathrm{td}} = 2\zeta_{\mathrm{td}}^{\mathrm{opt}}\beta_{\mathrm{t}}^{\mathrm{opt}}\omega_1 m_{\mathrm{td}} \tag{4.1}$$

where ω_1 is the natural frequency of the 1st mode of the prime structure and $\beta_{\mathrm{t}}^{\mathrm{opt}}$ and $\zeta_{\mathrm{od}}^{\mathrm{opt}}$ are given by

$$\beta_{\mathrm{t}}^{\mathrm{opt}} = \frac{1}{1+\mu_{\mathrm{t}}}, \quad \zeta_{\mathrm{td}}^{\mathrm{opt}} = \sqrt{\frac{3\mu_{\mathrm{t}}}{8(1+\mu_{\mathrm{t}})}} \tag{4.2}$$

The mass ratio μ_{t} for the 1st mode is defined as

$$\mu_{\mathrm{t}} = \frac{\overline{M}_{\mathrm{td}}}{\overline{M}_1} = \frac{\boldsymbol{\phi}_1{}^{T}\mathbf{M}_{\mathrm{td}}\boldsymbol{\phi}_1}{\boldsymbol{\phi}_1{}^{T}\mathbf{M}_{\mathrm{p}}\boldsymbol{\phi}_1} \tag{4.3}$$

$$\mathbf{M}_{\rm td} = {\rm diag}[0 \quad 0 \quad \cdots \quad 0 \quad m_{\rm td} \quad 0] \tag{4.4}$$

where $\boldsymbol{\phi}_1$ is the 1st mode shape vector of the prime building.

4.2 Outrigger TVMD

The stiffness of the supporting springs and damping coefficient of the dashpots are decided by the equations developed in [3], which are given as

$$k_{{\rm od},N} = \left(\beta_{\rm o}^{\rm opt}\omega_1\right)^2 m_{{\rm od},N}, \quad c_{{\rm od},N} = 2\zeta_{\rm od}^{\rm opt}\beta_{\rm o}^{\rm opt}\omega_1 m_{{\rm od},N} \tag{4.7}$$

where $\beta_{\rm o}^{\rm opt}$ is the optimum frequency ratio and $\zeta_{\rm od}^{\rm opt}$ is the optimum damping coefficient, which are expressed as

$$\beta_{\rm o}^{\rm opt} = \frac{1-\sqrt{1-4\mu_{\rm o}}}{2\mu_{\rm o}}, \quad \zeta_{\rm od}^{\rm opt} = \frac{\sqrt{3-\left(1-\sqrt{1-4\mu_{\rm o}}\right)}}{4} \tag{4.8}$$

where $\mu_{\rm o}$ is the mass ratio defined as

$$\mu_{\rm o} = \frac{\bar{M}_{\rm od}}{\bar{M}_1} = \frac{\boldsymbol{\phi}_1{}^T\mathbf{M}_{\rm od}\boldsymbol{\phi}_1}{\boldsymbol{\phi}_1{}^T\mathbf{M}_{\rm p}\boldsymbol{\phi}_1} \tag{4.5}$$

$$\mathbf{M}_{\rm od} = {\rm diag}\left[0 \quad 0 \quad \cdots \quad 0 \quad l^2 m_{{\rm od},N}\right] \tag{4.6}$$

5. NUMERICAL SIMULATION

5.1 Building model

The building used in this study is the St. Francis Shangri-La Place in Philippines [9, 10, 11, 12]. This 60-story building has a height of 210 m and has 12 perimeter columns which are 20 m from the building center line. The concrete core is assumed to be 12 m × 12 m with 0.5 m thickness. The total mass of the building is 30,000 tons.

To create the model for evaluation, a vertical cantilever beam model based on the Bernoulli-Euler beam theory is applied. A finite element model is developed so that every story has one translational and one rotational degree of freedoms. Therefore, the total number of degrees-of-freedom should be 120 (60 in translation and 60 in rotation). The first 10 natural frequencies are 0.18, 1.15, 3.14, 6.00, 9.61, 13.84, 18.56, 23.66, 29.06, and 34.66 Hz, respectively. Damping of 2% is assumed in each mode.

5.2 Damper models

The dampers used for the numerical studies are designed using the equations introduced in the preceding section. The supplemental mass for the TMD is determined to be 1% of the total mass of the building. And the sum of the amplified apparent mass for the outrigger TVMD is decided such that the mass ratio becomes 10%. The parameter values for the dampers are summarized in Table 5.1.

Table 5.1 Parameter values for the dampers

TMD		Outrigger TVMD	
$m_{\rm td}$	300 ton	l	10 m
$\mu_{\rm td}$	3.98%	$m_{{\rm od},60}$	175010 ton
$\zeta_{\rm td}$	12.0%	$\mu_{\rm o}$	10.0%
$k_{\rm td}$	374.6 kN/m	$\zeta_{\rm o}$	20.6%
$c_{\rm td}$	83.6 kNsec/m	$k_{{\rm od},60}$	300158 kN/m
		$c_{{\rm od},60}$	94236 kNsec/m

5.3 Results

The transfer functions from input accelerations to 60th floor relative displacements and absolute accelerations are depicted in Fig. 5.1. It can be found that the proposed outrigger TVMD system tuned to the first model lowers the peaks of displacement and acceleration compared to the classical TMD building as expected.

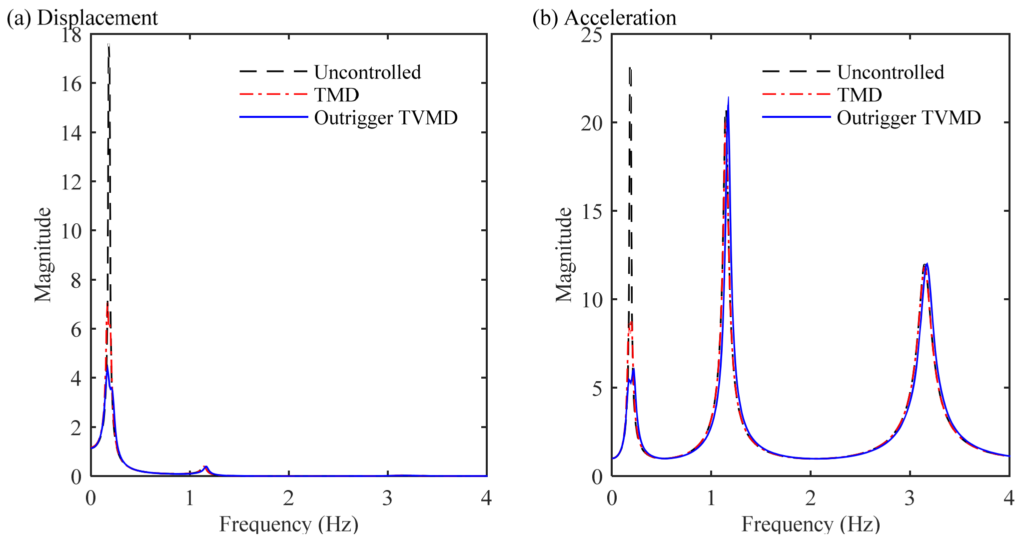

Figure 5.1 Transfer functions from input acceleration to 60th floor (a) Relative displacement (b) Absolute acceleration

Time history responses of 60th floor obtained by numerical simulations are compared in Fig. 5.2. In this study, the El Centro record of the 1940 Imperial Valley Earthquake given in [13] is used as an input acceleration. As can been seen, the proposed TVMD system works well to reduce response displacement. In response acceleration, the differences between three building models are quite small, however, the proposed method shows better performance than other two models.

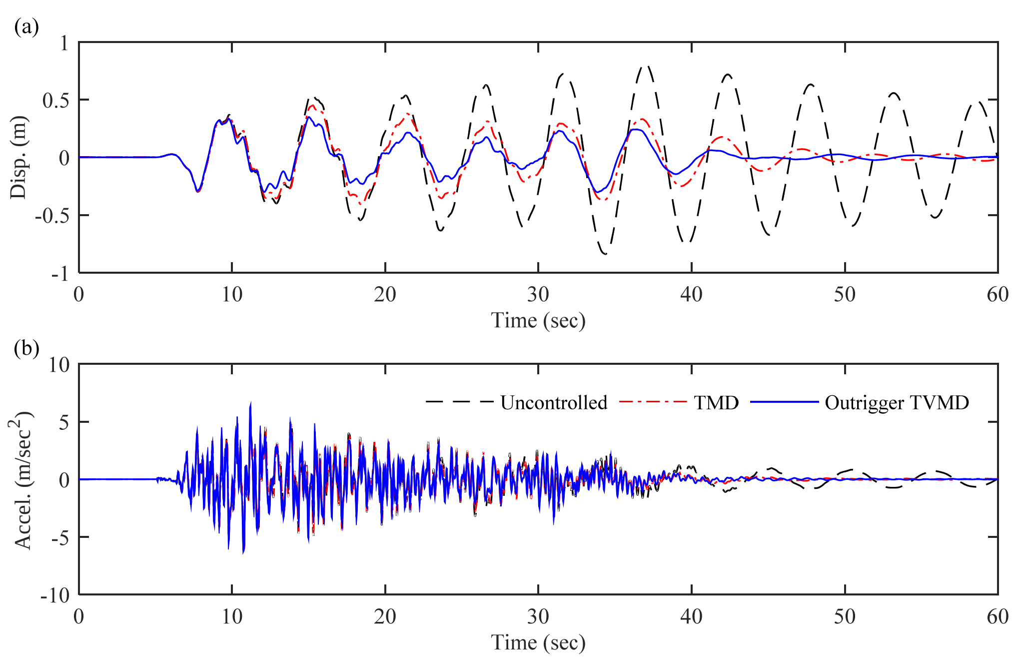

Figure 5.2 Time history responses of 60th floor (a) Relative displacement (b) Absolute acceleration

6. CONCLUSION

This study proposed an effective energy absorption system for high-rise buildings subject to earthquake loadings, which is called outrigger tuned viscous mass damper (TVMD). In this system, rotational viscous mass dampers are installed on an outrigger high-rise building through supporting springs. Then the springs are tuned to the 1st mode of the building using the design formulae proposed in the literature to realize optimum energy absorption capability.

To show the effectiveness of the proposed outrigger TVMD systems, numerical simulations were carried out using the 1940 El Centro earthquake record. The results showed the proposed system worked well to reduce the responses better than the classical TMD system.

ACKNOWLEDGEMENT
This research was supported by JSPS KAKENHI Grant number 26630256, which is gratefully acknowledged. The first author also appreciates Grant-in-Aid for JSPS Fellows.

REFERENCES

1. Housner, G., Bergman, L., Caughey T., Chassiakos A., Claus R., Masri, S., Skelton, R., Soong, T., Spencer, B., and Yao, J. (1997). Structural Control: Past, Present, and Future. *Journal of Engineering Mechanics*. **123:9**, 897-971.
2. Den Hartog, J. (1985). Mechanical Vibrations. Civil, Mechanical and Other Engineering Series, Dover Publications.
3. Ikago, K., Saito, K., and Inoue N. (2012). Seismic Control of Single-Degree-of-Freedom Structure using Tuned Viscous Mass Damper. *Earthquake Engineering & Structural Dynamics*. **41:3**, 453-474.
4. Lazar, I. F., Neild, S., and Wagg, D. (2014). Using an Inerter-Based Device for Structural Vibration Suppression. *Earthquake Engineering & Structural Dynamics*. **43:8**, 1129-1147.
5. Ishii, M., Kazama, H., Miyazaki, K., and Murakami, K. Application of Tuned Viscous Mass Damper to Super-High-Rise Buildings. Proceedings of the Sixth World Conference of Structural Control and Health Monitoring.
6. Smith, B. S., and Salim, I. (1981). Parameter Study of Outrigger-Braced Tall Building Sructures. *Journal of the Structural Division*. **107:10**, 2001–2014.
7. Charles, J. (2006). Application of Damping in High-Rise Buildings. Master's Thesis, M.I.T.
8. Smith, R. J.,and Willford, M. R. (2007). The Damped Outrigger Concept for Tall Buildings. *The Structural Design of Tall and Special Buildings*. **16:4**, 501-517.
9. Willford, M, Smith, R., Scott, D., and Jackson, M. (2008). Viscous Dampers Come of Age. *Structure Magazine* **6**, 15–18.
10. Chang, C. M., Wang, Z., Spencer, B. F, and Chen Z. (2013). Semi-Active Damped Outriggers for Seismic Protection of High-Rise Buildings. *Smart Structures and Systems*. **11:5**, 435-451.
11. Asai, T., Chang, C. M., Phillips B. M., and Spencer, B. F. (2013). Real-Time Hybrid Simulation of a Smart Outrigger Damping System for High-Rise Buildings. *Engineering Structures*. **57**, 177-188.
12. Infanti, S., Robinson, J., and Smith, R. (2008). Viscous Dampers for High-Rise Buildings. *Proceedings of the 14th World Conference on Earthquake Engineering*.
13. Narasimhan, S., Nagarajaiah, S., and Johnson, E. A. (2008). Smart Base-Isolated Benchmark Building Part iv: Phase ii Sample Controllers for Nonlinear Isolation systems. Structural Control and Health Monitoring. **15:5**, 657–672