

# EFFICACY OF TUNED VISCOUS MASS DAMPER SEISMIC CONTROL SYSTEM INCORPORATED INTO A HIGH-CEILINGED STOREY

Saito, K<sup>1</sup>, Ikago, K<sup>2</sup>, Ikenaga, M<sup>3</sup> & Inoue, N<sup>4</sup>

<sup>1</sup>NTT Facilities Research Institute Inc., 4-27-3, Higashi-Ueno, Taito Ward, Tokyo 110-0015, Japan

<sup>2</sup>IRIDeS, Tohoku Univ., 468-1, Aramaki, Aoba Ward, Sendai, Miyagi 980-0845, Japan

<sup>3</sup>Kansai Univ., 3-3-35, Yamate-cho, Suita, Osaka 564-8680, Japan

<sup>4</sup>Tohoku Univ., 468-1, Aramaki, Aoba Ward, Sendai, Miyagi 980-0845, Japan

ikago@irides.tohoku.ac.jp

**ABSTRACT.** In Japan, the application of energy-dissipating devices in high-rise buildings has increased significantly since the 1990s. Many recently constructed high-rise buildings containing energy dissipaters enclose large spaces with high ceilings, such as concert halls and theaters, where there is concern that the efficacy of the energy dissipaters incorporated into such high-ceiling frames might be compromised because of long and thereby flexible supporting members. A viable way to somewhat exploit the flexibility of a damper-supporting member in a high-ceilinged frame is to employ a tuned viscous mass damper (TVMD), which consists of an apparent mass produced by rotary inertia and a viscous element, as well as a flexible spring, resulting in an energy-dissipating system similar to a conventional tuned mass damper (TMD). When the supplemental vibration system consisting of the apparent mass and the flexible supporting spring is properly tuned to the primary structure, the deformation of the viscous element is amplified, whereas the deformation of the supporting member results in decreased deformation of the damping element and thus to decreased energy dissipation in conventional devices. An analytical example illustrates the efficacy of a TVMD incorporated into a high-ceilinged frame.

**KEYWORDS:** Rotary inertial damper, Inerter, Tuned mass damper, Fixed-point method, H-infinity control.

## 1 INTRODUCTION

An inerter [1] or a dynamic mass [2] is an apparent mass element that produces inertial resistance forces proportional to the relative acceleration between two nodes. Currently, a rotary inertial damper, designated the inertial rotary damping tube (*i*RDT, Fig. 1), which combines a ball screw and a cylindrical flywheel, is one of the most viable implementations of an inerter [3]. In a rotary inertial damper, a viscous element is arranged in parallel to an inerter-like apparent mass element, such that the device generates viscous resistance forces as well as inertial forces. A tuned mass damper-like response control system, designated a tuned viscous mass damper (TVMD), can be constructed by connecting a rotary inertial damper in series with a flexible supporting spring [4, 5].

In Japan, many recently constructed high-rise buildings have energy-dissipating devices that enclose large spaces with high ceilings, such as concert halls and theaters. It seems difficult to ensure the efficacy of conventional energy-dissipating devices incorporated into such high-ceilinged storeys owing to

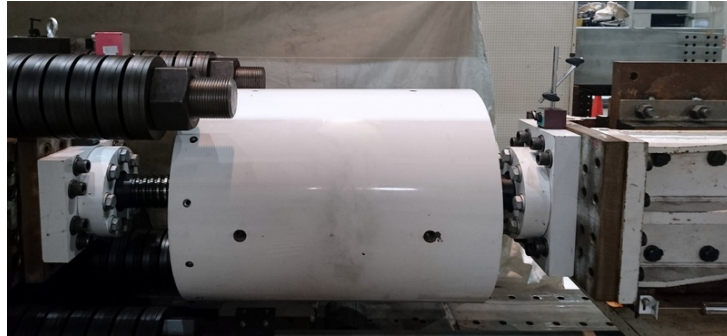


Figure 1: The inertial rotary damping tube (*iRDT*).

the long and therefore flexible supporting members, resulting in decreased deformation in the energy dissipaters, whereas a TVMD exploits the flexibility of the supporting member to construct a supplemental vibration system consisting of the apparent mass and the supporting spring, which are tuned to the primary system, ensuring increased deformation in its energy-dissipating element.

In this study, an analytical example illustrates the benefits of a tuned viscous mass damper seismic control system incorporated into a high-ceilinged storey in a high-rise building.

## 2 THE TUNED VISCOUS MASS DAMPER

The TVMD is an energy-dissipating device similar to a conventional tuned mass damper (TMD), which uses an inerter-like apparent mass as the mass element. Similar to the optimum design of a TMD, that of the TVMD is sought such that the maximum values of the response amplification factors are minimized in the response control system.

### 2.1 The inerter

Smith [1] defined a two-node apparent mass element as the inerter, which in Japan is referred to as a dynamic mass [2]. Unlike a physical mass, the inerter generates an inertial resistance force proportional to the relative acceleration between its two nodes (Fig. 2).

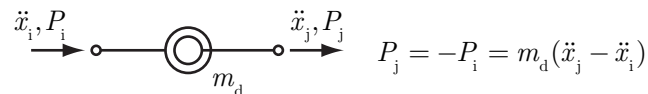


Figure 2: Numerical model of inerter.

There are many ways to implement the concept of the inerter as a physical device [3, 7, 8, 9, 10, 11, 12, 13]. The advantages of these inerter-like devices include an amplified apparent mass and new response control strategies that they bring about through the analogy between electrical and mechanical systems [6].

## 2.2 $\mathcal{H}_\infty$ optimal design of TVMD-controlled system

Ormondroyd and Den Hartog [14, 15] presented the concept of a TMD and its  $\mathcal{H}_\infty$  optimal design method using fixed points on the resonance curves. Saito *et al.* [4] and Ikago, Saito, and Inoue [5] derived closed-form  $\mathcal{H}_\infty$  optimal designs of single-degree-of-freedom (SDOF) structures containing a TVMD according to the same method.

Here, as shown in Fig. 3, we consider an SDOF structure having mass  $m$  and stiffness  $k$ , which is incorporated with a TVMD whose apparent mass, supporting spring stiffness, and damping coefficient are  $m_d$ ,  $k_b$ , and  $c_d$ , respectively.

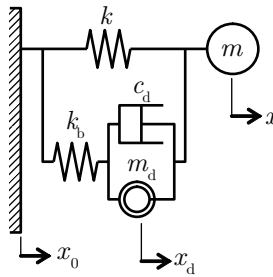


Figure 3: SDOF structure containing TVMD.

In Fig. 3,  $x$ ,  $x_0$ , and  $x_d$  are the displacement of the primary mass relative to the ground, the ground displacement, and the deformation of the viscous element, respectively. The deformation of the damper supporting spring is  $x - x_d$ .

Figure 4 depicts the amplification factor,  $|X(\omega)/X_0(\omega)|$ , where  $\omega$  is the excitation angular frequency and  $X(\omega)$  and  $X_0(\omega)$  are the Fourier transformations of  $x(t)$  and  $x_0(t)$ , respectively.  $\gamma$  is the ratio of the excitation angular frequency,  $\omega$ , to the natural angular frequency of the undamped primary system,  $\omega_0 (= \sqrt{k/m})$ .

There are fixed points on the amplification factor curves, regardless of the damping coefficient,  $c_d$ . In a manner similar to that proposed by Ormondroyd and Den Hartog, the optimal design that minimizes the maximum value of the amplification factor, *i.e.*, the  $\mathcal{H}_\infty$  norm of the amplification factor, can be found under the following conditions: the supporting spring stiffness is determined such that the ordinates of the fixed points are the same, and the damping coefficient,  $c_d$ , is determined such that the curve reaches a maximum value at the fixed points (Fig. 4).

It is well known that the  $i$ -th peak value of the amplification factor can be approximated by  $1/(2h_i)$ , where  $h_i$  is the damping ratio of the  $i$ -th mode. The SDOF structure incorporated with a TVMD makes a two-degrees-of-freedom system. The optimal condition that the two peak values are equal requires that the damping ratios of the first and second modes are equal as well. Thus, an alternative optimal design problem for the TVMD-controlled SDOF structure for a given supplemental apparent mass,  $m_d$ , can be formulated as follows:

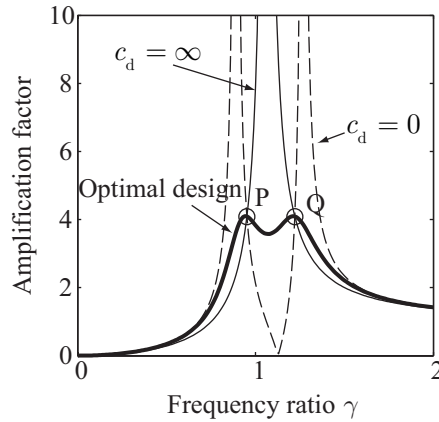


Figure 4: Amplification factor of SDOF structure containing TVMD.

---

**$[\mathcal{H}_\infty$  Optimal design problem for TVMD controlled system]**

find  $k_b, c_d$   
to maximize  $\min\{h_i; i = 1, 2\}$

---

### 3 ANALYTICAL EXAMPLE

#### 3.1 Structural model and input ground motions

To examine the efficacy of a TVMD incorporated into a high-ceilinged frame in a high-rise building, a benchmark structure provided by the Japan Society for Seismic Isolation (JSSI) [16] is employed. Figure 5 shows the analytical models for the bare frame model, the oil damper model (Maxwell model), and the TVMD model. Table 1 lists the masses, stiffnesses, and storey heights of the bare frame.

Table 2 lists the input ground motions employed in the analytical example. The peak ground velocities (PGVs) of ground motions 1–3, which are commonly used as the design input ground motions in practice in Japan, are scaled such that they are 0.5 m/s. As for the Tohoku University record of the 2011 Great East Japan Earthquake, the original record is used.

#### 3.2 Design of energy-dissipating devices

Table 3 lists the specifications of the energy-dissipating devices in the oil damper and TVMD models. The following explains how these specifications are determined.

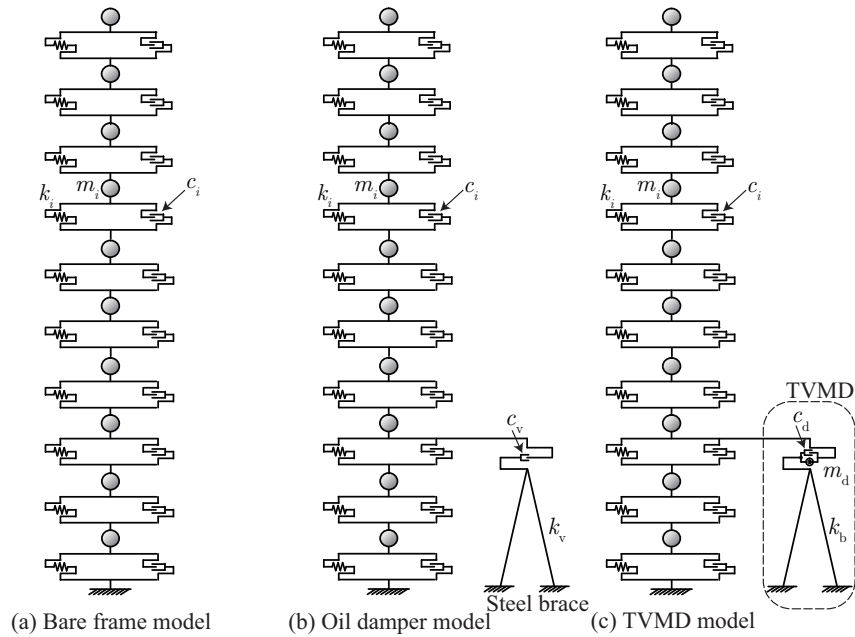


Figure 5: Analytical models for the (a) bare frame, (b) oil damper (Maxwell model), and (c) TVMD models.

Table 1: Characteristics of the analytical models

Storey	Primary structure		
	Mass $m_i$ [t]	Stiffness $k_i$ [kN/m]	Height[m]
10	875.4	158550	4
9	649.5	180110	4
8	656.2	220250	4
7	660.2	244790	4
6	667.2	291890	4
5	670.1	306160	4
4	675.7	328260	4
3	680.0	383020	4
2	681.6	383550	4
1	699.9	279960	6

### 3.2.1 Tuned viscous mass damper

As discussed in Section 2.2, an optimally designed TVMD having a supplemental mass  $m_d$  can be found subject to the equality of the damping ratios of the first and second modes. The supplemental mass

Table 2: Recorded ground motions

Number	Earthquake	Station	Component	PGV (m/s)
1	Imperial Valley, USA, 1940	El Centro	NS	0.50
2	Kern County, USA, 1952	Taft	EW	0.50
3	Tokachi-oki, Japan, 1968	Hachinohe Harbor	NS	0.50
4	Great East Japan, 2011	Tohoku University	NS	0.45

Table 3: Specifications of energy-dissipating devices

	Oil damper			TVMD	
	$m_d$	-		$m_d$	4000
Supporting spring (kN/m)	$k_v$	$0.96 \times 10^5$	$1.44 \times 10^5$	$k_b$	$0.96 \times 10^5$
Damping coefficient (kN·s/m)	$c_v$	$1.50 \times 10^4$		$c_d$	$1.50 \times 10^4$
Damping ratio	$h_1$	0.080	0.091	$h_1, h_2$	0.266

$m_d$  is sought such that the maximum response inter-storey drift angle is less than 1/100.

We found that 4000 t of supplemental mass is required for the TVMD to meet the criterion. Figures 6(a) and (b) show the contours of the damping ratios of the first and second modes, respectively. The ratios  $\beta$  and  $h_d$  are the frequency ratio and damping ratio, respectively, which are defined as follows:

$$\beta = \sqrt{k_b/m_d}/\omega_0, \quad h_d = c_d/2\sqrt{m_d k_b} \quad (1)$$

Alternatively,

$$k_b = (\beta\omega_0)^2 m_d, \quad c_d = 2h_d\beta\omega_0 m_d \quad (2)$$

where  $\omega_0$  is the fundamental circular frequency of the bare frame.

The contours of the smaller damping ratio among the two modes are depicted in Fig. 6(c), which show that the optimum frequency ratio and damping ratio for the TVMD are  $\beta=1.57$  and  $h_d=0.38$ , respectively.

### 3.2.2 Oil damper

As can be seen from Figs. 3 and 5, removing the apparent mass element from a TVMD whose spring stiffness and damping coefficient are  $k_b = 0.96 \times 10^5$  kN/m and  $c_d = 1.50 \times 10^4$  kN·s/m, respectively, results in a Maxwell model. A Maxwell model having the same spring stiffness and damping coefficient as the TVMD is employed in the oil damper model. Because the Maxwell model fails to meet the response drift angle criterion as discussed below, another Maxwell model having the same damping

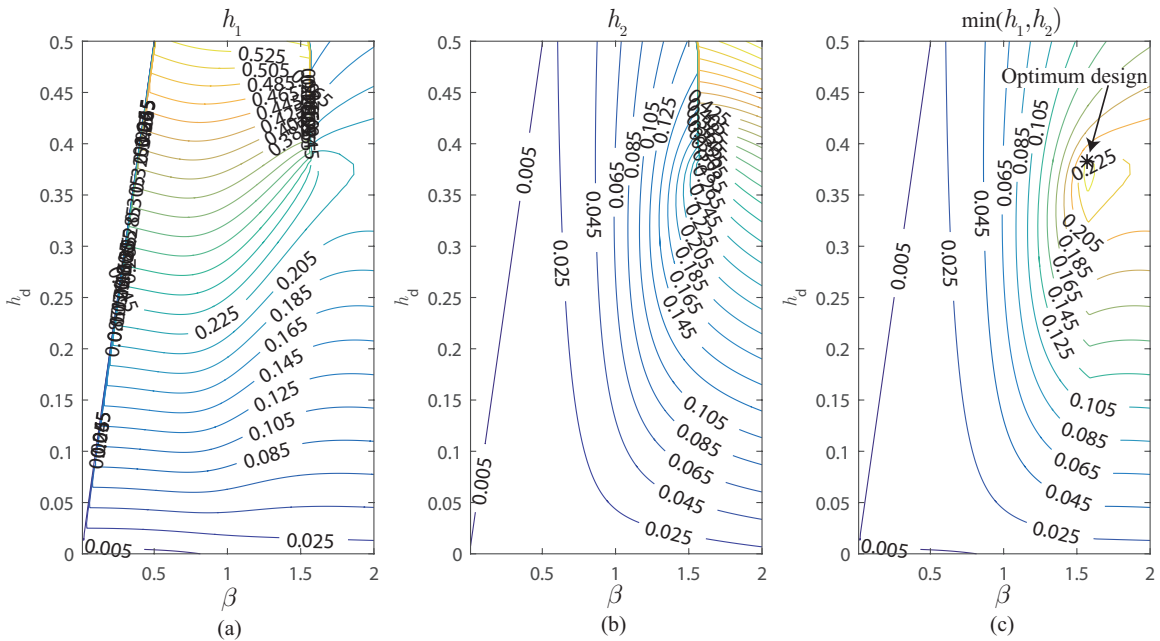


Figure 6: Contours of damping ratios.

coefficient and a stiffer spring is considered as well. As for the stiffer spring, a large steel section, Box-600x600x40x40, is chosen (Fig. 7 ); for this case, the spring stiffness is  $k_v = 1.44 \times 10^5$  kN/m.

**4 ANALYTICAL RESULTS**

Figures 8–11 depict the maximum responses of the four differently damped models. Tables 4–6 list the maximum responses at each storey among the four input ground motions. As shown in Table 4, the TVMD base shear force is reduced by 35% as compared to that of the bare frame. Although the base shear coefficient of the TVMD model is 16–22% higher than those of the Maxwell models, the shear force coefficient at the top of the TVMD model is lower than those of the Maxwell models by 9–12%. As shown in Table 5, the Maxwell model with the stiffer spring ( $k_v = 1.44 \times 10^5$ ) and the TVMD model meet the criterion of the inter-storey drift angle (1/100), whereas the bare frame and the Maxwell model with a flexible spring violate the criterion. TVMD is thus proven to be effective in reducing the accelerations given in Table 6; TVMD achieved the lowest floor response acceleration at each floor except the eighth storey among the four differently damped models.

**5 CONCLUSION**

This paper examined the efficacy of a TVMD incorporated into a high-ceilinged storey, where it is difficult to ensure the stiffness of the damper-supporting member. In an analytical example, the optimum

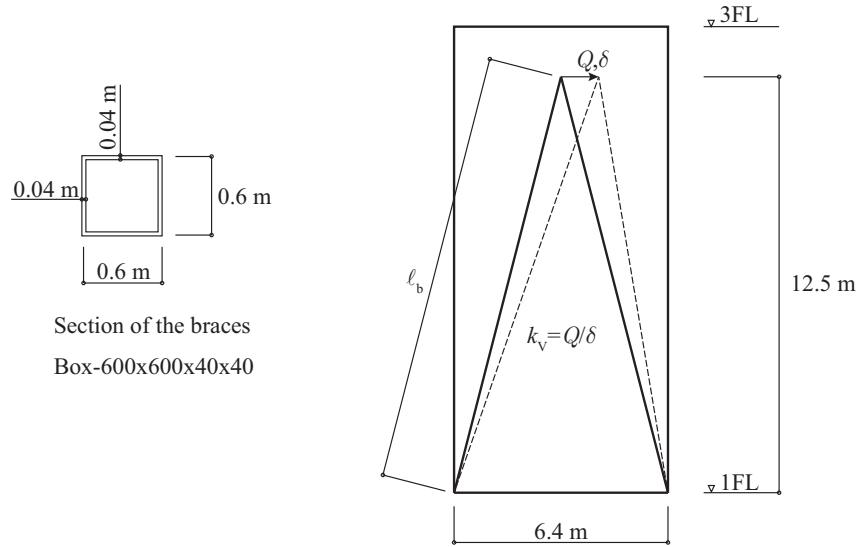


Figure 7: Horizontal stiffness of the brace.

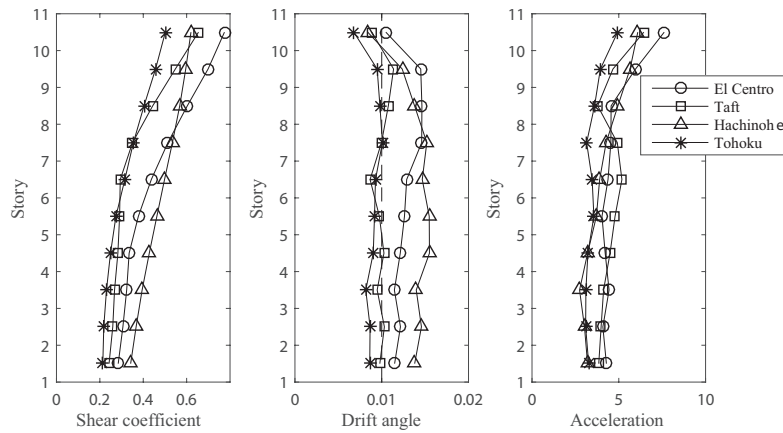


Figure 8: Maximum responses of bare frame.

design of a TVMD for a 10-storey benchmark structure subject to the criterion regarding the inter-storey drift angle was sought. A Maxwell model, which was obtained by removing the supplemental mass from the TVMD model, was employed as a control case. Because the Maxwell model with a flexible spring failed to meet the criterion, another Maxwell model with a stiffer spring was considered as well in order



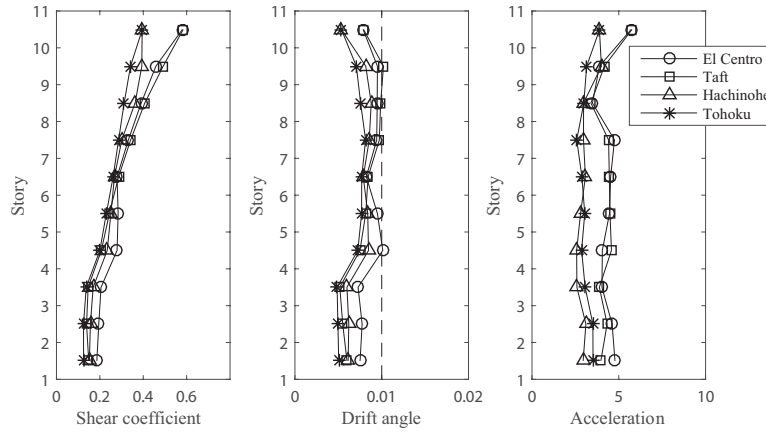


Figure 9: Maximum responses of Maxwell model having flexible brace.

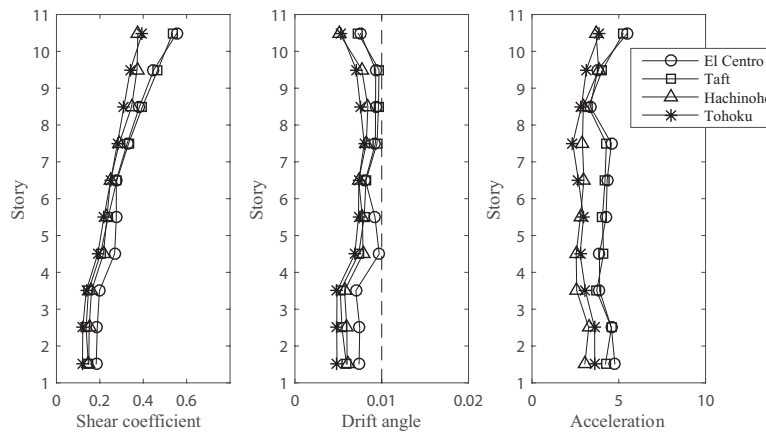


Figure 10: Maximum responses of Maxwell model having stiff brace.

to meet the criterion. It is worth noting that ensuring the effect of the Maxwell model demanded a larger quantity of steel, resulting in higher costs.

An analytical example demonstrated that the TVMD performed the best among the four differently damped models: an uncontrolled bare frame, Maxwell models having flexible and stiff springs, and the TVMD model. Another benefit of the TVMD is that it can reduce the quantity of steel used to support the damper by exploiting its flexibility.

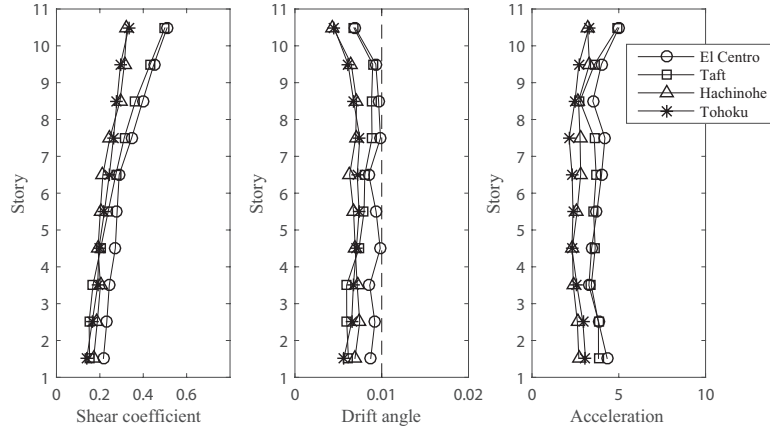


Figure 11: Maximum responses of TVMD model.

Table 4: Maximum response shear force coefficients

Storey	Bare frame	Oil damper (Maxwell model)		TVMD
		$k_v = 0.96 \times 10^5 \text{ kN/m}$	$k_v = 1.44 \times 10^5 \text{ kN/m}$	
10	0.77	0.58	0.56	0.51
9	0.70	0.49	0.47	0.45
8	0.60	0.41	0.40	0.40
7	0.53	0.34	0.33	0.35
6	0.50	0.29	0.28	0.29
5	0.46	0.28	0.28	0.28
4	0.43	0.28	0.27	0.27
3	0.39	0.21	0.20	0.24
2	0.37	0.20	0.19	0.23
1	0.34	0.19	0.18	0.22

## ACKNOWLEDGEMENTS

This work was supported by a research grant provided by the Maeda Engineering Foundation.

## REFERENCES

- [1] Smith, M. C. Synthesis of mechanical networks: The inerter, *IEEE Transactions on Automatic Control*, 2002; **47**(10): 1648-1662.

Table 5: Maximum inter-storey drift angles

Storey	Bare frame	Oil damper (Maxwell model)		TVMD
		$k_v = 0.96 \times 10^5$ kN/m	$k_v = 1.44 \times 10^5$ kN/m	
10	0.0105	0.0079	0.0075	0.0069
9	0.0145	0.0102	0.0097	0.0093
8	0.0146	0.0099	0.0096	0.0096
7	0.0152	0.0097	0.0095	0.0099
6	0.0147	0.0084	0.0082	0.0085
5	0.0155	0.0095	0.0092	0.0093
4	0.0155	0.0101	0.0097	0.0098
3	0.0140	0.0073	0.0070	0.0086
2	0.0146	0.0077	0.0075	0.0092
1	0.0138	0.0075	0.0074	0.0087

Table 6: Maximum floor response accelerations

Storey	Bare frame	Oil damper (Maxwell model)		TVMD
		$k_v = 0.96 \times 10^5$ kN/m	$k_v = 1.44 \times 10^5$ kN/m	
10	7.62	5.76	5.51	5.02
9	5.97	4.17	4.06	4.00
8	4.95	3.48	3.36	3.50
7	4.91	4.75	4.57	4.20
6	5.18	4.53	4.33	4.01
5	4.78	4.49	4.27	3.74
4	4.50	4.58	4.12	3.64
3	4.44	4.03	3.90	3.41
2	4.08	4.62	4.57	3.84
1	4.29	4.78	4.78	4.34

- [2] Furuhashi, T. & Ishimaru, S. Mode control seismic design with dynamic mass, *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China, 2008.
- [3] Ikago, K. & Inoue, N. Seismic control of buildings using apparent mass dampers with rotational amplifying mechanisms: a review of the state of the art, *Proceedings of the 13th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures*, 2013; Sendai, Japan: Paper #900564.
- [4] Saito, K., Sugimura, Y., Nakaminami, S., Kida, H. & Inoue, N. Vibration tests of 1-story response

- control system using inertial mass and optimized soft spring and viscous element, *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China, 2008.
- [5] Ikago, K., Saito, K. & Inoue, N. Seismic control of single-degree-of-freedom structure using tuned viscous mass damper. *Earthquake Engineering and Structural Dynamics*, 2012; **41**(3): 453-474.
- [6] Firestone, F.A. A new analogy between mechanical and electrical systems, *Journal of Acoustical Society of America*, 1993; **4**(3): 249-267.
- [7] Kawamata, S. Liquid type mass damper with elongated discharge tube, *United States Patent*, No. 4,872,649, 1989.
- [8] Sone, A., Yamamoto, S., Masuda, A. Sliding mode control for building using tuned mass damper with pendulum and lever mechanism during strong earthquake, *Proceedings of the 2nd World Conference on Structural Control*, Kyoto, Japan, 1998; 531-540.
- [9] Arakaki, T., Kuroda, H., Arima, F., Inoue, Y., Baba, K. Development of seismic devices applied to ball screw: Part 1 Basic performance test of RD-series (in Japanese), *AIJ Journal of Technology and Design*, 1999; (8): 239-244.
- [10] Arakaki, T., Kuroda, H., Arima, F., Inoue, Y., Baba, K. Development of seismic devices applied to ball screw: Part 2 Performance test and evaluation of RD-series (in Japanese), *AIJ Journal of Technology and Design*, 1999; (9): 265-270.
- [11] Okumura, A. Vibration blocking mechanism, *Waseda University Technology Series*, 2000; No. LTO2000-02. (in Japanese)
- [12] Wang, F.C., Hong, M.F., Lin, T.C. Designing and testing a hydraulic inerter, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 2010; **225**: 66-72.
- [13] Watanabe, Y., Ikago, K., Inoue, N., Kida, H., Nakaminami, S., Tanaka, H., Sugimura, Y., Saito K. Full-scale dynamic tests and analytical verification of a force-restricted tuned viscous mass damper, *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon Portugal, 2012; Paper ID 1206.
- [14] Ormondroyd J, Den Hartog J.P. The theory of dynamic vibration absorber, *Journal of Applied Mechanics ASME*, 1928; **50**(7): 9.
- [15] Den Hartog J.P. Mechanical vibrations. (4th ed.). Dover: New York, 1985.
- [16] The Japan Society for Seismic Isolation “Manual for design and fabrication for passive vibration control of structures”, 2nd ed. (in Japanese), 2005.