Applicability of Force-Restricted Tuned Viscous Mass Dampers to High-Rise Buildings Subjected to Long-Period Ground Motions

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SUMMARY:
In this paper, we verify the applicability of force-restricted tuned viscous mass dampers (FRTVMD) to high-rise buildings as a precautionary measure against vibrations induced by long-period ground motions. The tuned viscous mass damper (TVMD) achieves effective displacement control for high-rise buildings subjected to long-period ground motions, with a small damping coefficient because the secondary vibration system enlarges the deformation and velocity in viscous materials such that large energy dissipation is created. Although energy dissipation in viscous materials deteriorates when a force restriction is applied to the TVMD, the seismic control performance remains effective even if the restricted force is relatively large because the frictional damping generated by the force restriction mechanism compensates for the loss of the energy dissipation. Analytical and experimental studies show that the force restriction mechanism achieves effective displacement control with a small damper reaction force.

Keywords: Tuned viscous mass damper, Rotational inertia, Long-period ground motion

1. INTRODUCTION

Recently, unexpected large displacements have been observed when long-period structures such as high-rise or base-isolated buildings are subjected to long-period ground motions. This phenomenon has also been observed in urban areas that are located on Japan's thick sedimentary basins (Architectural Institute of Japan 2007a) that have components that resonate with long periods. Although the peak ground acceleration (PGA), observed at the base of a high-rise building located about 770 km away from the epicenter of the Tohoku earthquake (Eastern Japan, March 11, 2011) was very small (PGA = 0.34 m/s/s. Building Research Institute 2011a), several people were locked in the elevator for a long time, and many interior and exterior materials were displaced or cracked because of the long-period ground motion.

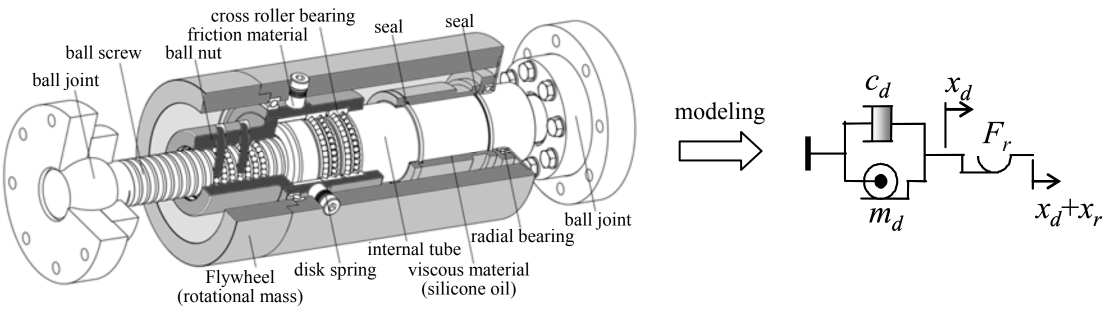


Figure 1.1. Viscous mass damper using rotational inertia with damper force restriction mechanism

A seismic control device that can reduce the component resonance responses is considered as a remedy for long-period ground motion problems. However, a conventional tuned mass damper (TMD) (Den Hartog 1985), is found to be insufficient for seismic control of high-rise buildings (Kaynia *et al.*

1981) because of the difficulties in obtaining a sufficient secondary mass and long stroke, although it is known to be effective against wind-induced vibrations (McNamara 1979).
The tuned viscous mass damper (TVMD) (Saito, Kurita, and Inoue 2007b, Saito *et al.* 2008, Ikago *et al.* 2010a, Kida *et al.* 2010b, Kida *et al.* 2011b, and Sugimura *et al.* 2011c) consists of a viscous mass damper with a cylindrical flywheel (Kida *et al.* 2011b) and a supporting member (Fig. 1.1.), whose natural period is tuned to that of the primary system. Although the basic concept and damping effect of a TVMD is similar to that of a conventional TMD, unlike a conventional TMD, it can impart a large apparent mass effect that is several thousand times larger than that of the actual mass via the amplifying mechanism using a ball screw.
Whereas a conventional TMD is activated by an absolute acceleration, TVMD is activated by the relative acceleration between the neighboring floors, which is smaller compared to the absolute acceleration. However, the ball screw mechanism amplifies the low relative acceleration and apparent mass effect, resulting in a large inertial force.
Large mass effects and unexpectedly large excitations might cause excessive stresses in the supporting member, damper body itself, and/or the primary structure. To avoid this, the authors have previously developed a mechanism to restrict the maximum damping force of TVMD using a rotary sliding mechanism (Kida *et al.* 2011b). The device is collectively called a force-restricted TVMD (FRTVMD).
This paper aims to verify the applicability and effectiveness of FRTVMD as a precautionary measure for high-rise buildings subjected to long-period ground motions.

2. SEISMIC CONTROL SYSTEM USING TUNED VISCOUS MASS DAMPERS

2.1. Outline of force-restricted tuned viscous mass damper

As shown in Fig. 2.1., TVMD comprises of a supporting member and a viscous mass damper (Fig. 1.1.) connected in series. In Fig. 2.2., the actual displacements in the rotational direction are expressed as the virtual axial displacements. While the outer cylinder (cylindrical flywheel) is firmly connected to the ball screw, the secondary system has a natural circular frequency ω that is derived from the equivalent translational mass m_d and supporting member stiffness k_b. Once the damping force reaches the limit F_r, traction between the outer cylinder and the ball screw is broken. Although a virtual residual displacement x_r shown in the analytical model (Fig. 2.1.) might remain even if the damper is unloaded, both ends of the damper return to their original positions because the residual displacement in the rotary sliding mechanism occurs in the rotational direction.

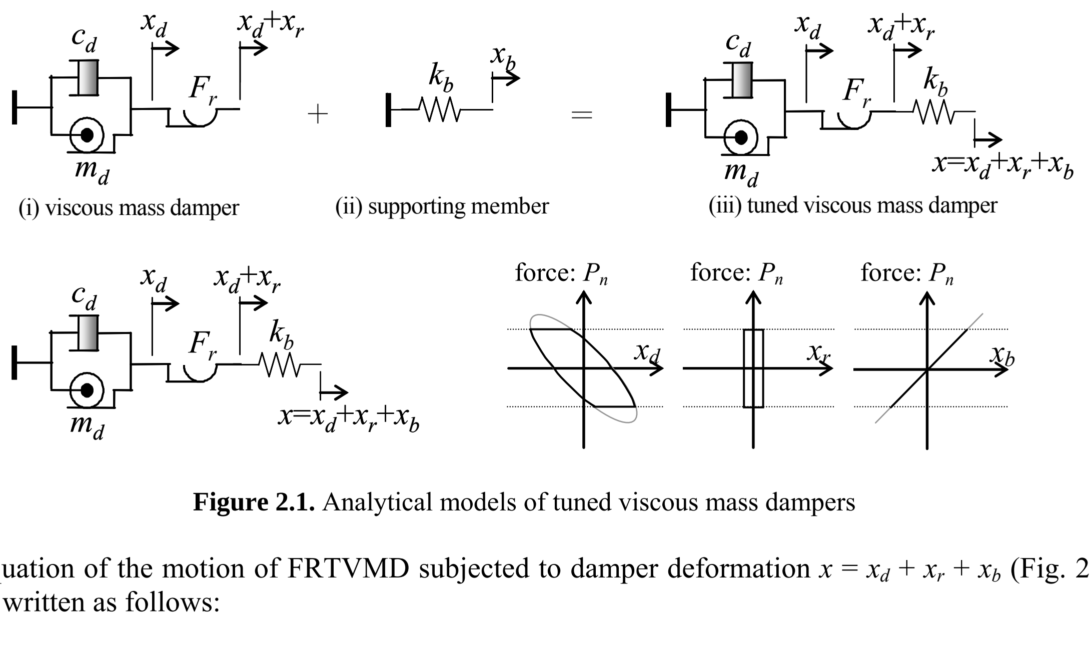


Figure 2.1. Analytical models of tuned viscous mass dampers

The equation of the motion of FRTVMD subjected to damper deformation $x = x_d + x_r + x_b$ (Fig. 2.1.) can be written as follows:

without rotary slip

$$x_r = 0\ ,\quad x = x_d + x_b\ ,\quad |c_d \cdot \dot{x}_d + m_d \cdot \ddot{x}_d| < |F_r|$$

$$P_n = c_d \cdot \dot{x}_d + m_d \cdot \ddot{x}_d = k_b(x - x_d) \tag{2.1a}$$

with rotary slip

$$x = x_d + x_r + x_b\ ,\quad c_d \cdot \dot{x}_d + m_d \cdot \ddot{x}_d = F_r$$

$$P_n = F_r = k_b(x - x_d - x_r) \tag{2.1b}$$

where,

$$\begin{cases} P_n : \text{damping force of FRTVMD} \\ F_r : \text{equivalent maximum axial force derived from the maximum rotary friction} \\ c_d : \text{modeling shear resistance due to viscous material in the axial direction} \end{cases}$$

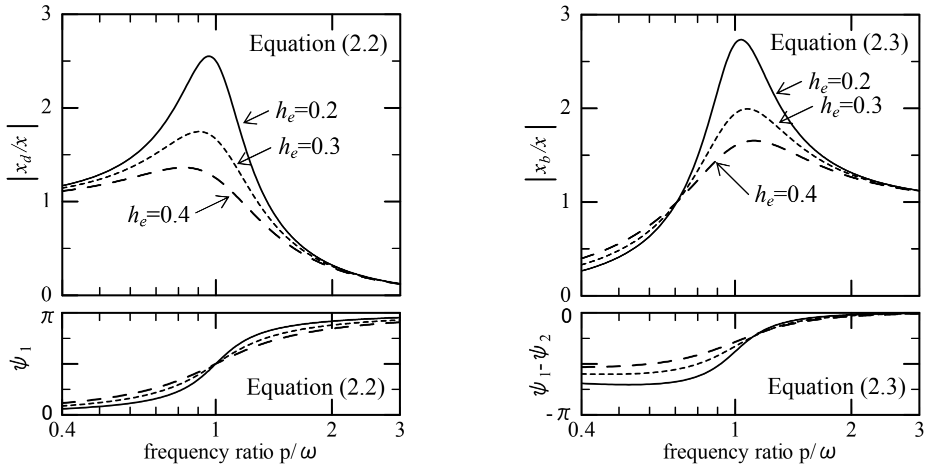
Eqs. (2.2) and (2.3) express the displacement amplification factors of the displacements of the mass damper and supporting member.

$$\frac{x_d}{x} = \frac{1}{\sqrt{\left\{1-(p/\omega)^2\right\}^2 + \left\{2h_e(p/\omega)\right\}^2}} \times e^{-i\psi_1} \tag{2.2}$$

$$\frac{x_b}{x} = \sqrt{\frac{(p/\omega)^4 + \left\{2h_e(p/\omega)\right\}^2}{\left\{1-(p/\omega)^2\right\}^2 + \left\{2h_e(p/\omega)\right\}^2}} \times e^{-i(\psi_1-\psi_2)} \tag{2.3}$$

where the secondary damping ratio and natural circular frequency are $h_e = c_d/2(m_d\omega)$ and $\omega^2 = k_b/m_d$, respectively, and $\psi_1 = \tan^{-1}\left[2h_e(p/\omega)/\left\{1-(p/\omega)^2\right\}\right]$, $\psi_2 = \tan^{-1}\left[2h_e(p/\omega)/\left\{-(p/\omega)^2\right\}\right]$, and p is the excitation frequency.

Fig. 2.2. shows the displacement amplification factor, and the phase angle with respect to the excitation frequency ratio.



(i) viscous mass damper: x_d (ii) supporting member: x_b

Figure 2.2. Displacement response amplification factor and phase

Eqs. (2.2) and (2.3) and the results shown in Fig. 2.2. illustrate that the viscous mass damper displacement x_d and supporting member displacement x_b have opposite phases, such that the viscous mass damper displacement x yields the enlarged displacements x_d and x_b. As the the secondary damping ratio h_e increases, the lower and the higher the frequencies of the peak amplification factors of the viscous mass damper and the supporting member increase, respectively.

2.2. Design method of tuned viscous mass damper

To design the TVMD seismic control system, it is necessary to determine the three design variables: the equivalent translational mass of the cylindrical flywheel, the viscous damping coefficient, and the supporting member stiffness. The primary structure mode to be controlled must also be chosen. Then, the appropriate limit force for TVMD is determined. The optimum set of design parameters is determined based on the fixed-point method shown in Table 2.1. (Saito, Kurita, and Inoue 2007b, Saito *et al.* 2008, and Sugimura *et al.* 2011c).

Table 2.1. Design method of TVMD parameters based on the fixed-point method.

Step1	Specify the primary mode to be controlled by each damper. Determine the equivalent translational mass ${}_i m_{dk}$ derived from the ith TVMD rotary inertia of the kth-story.
Step2	Solve the uncontrolled primary system eigenvalue problem. Calculate the generalized primary and secondary masses ${}_i\overline{M}_d$ and ${}_i\overline{M}$, respectively. $${}_i\overline{M} = \sum_{k=1}^{n} \left\{ m_{sk} \cdot \left({}_i\beta \cdot {}_i u_{sk}\right)^2 \right\},\quad {}_i\overline{M}_d = {}_i m_{d1} \cdot \left({}_i\beta \cdot {}_i u_{s1}\right)^2 + \sum_{k=2}^{n} \left[{}_i m_{dk} \cdot \left\{ {}_i\beta \cdot \left({}_i u_{sk} - {}_i u_{s(k-1)}\right) \right\}^2 \right]$$ where ${}_i u_{sk}$ and ${}_i\beta$ are the kth component of the ith eigenvector and the ith participation factor, respectively.
Step3	Derive the mass ratio ${}_i\mu$. $${}_i\mu = {}_i\overline{M}_d / {}_i\overline{M}$$
Step4	Obtain the optimum frequency ratio ${}_i\gamma_{opt}$ and the optimum-damping ratio ${}_i h_{opt}$. (The following equations minimize the peak displacement amplification factor.) $${}_i\gamma_{opt} = \frac{1-\sqrt{1-4{}_i\mu}}{2{}_i\mu},\quad {}_i h_{opt} = \frac{\sqrt{3\left(1-\sqrt{1-4{}_i\mu}\right)}}{4}$$
Step5	Determine the supporting member stiffness ${}_i k_{bk}$ and the viscous damping coefficient ${}_i c_{dk}$ of the kth-story. $${}_i k_{bk} = {}_i m_{dk} \cdot \left({}_i\gamma_{opt} \cdot {}_i\omega_s\right)^2,\quad {}_i c_{dk} = 2 \cdot {}_i h_{opt} \cdot {}_i m_{dk} \cdot {}_i\gamma_{opt} \cdot {}_i\omega_s$$ where ${}_i\omega_s$ is the ith natural circular frequency of the primary structure.

Thus, given the equivalent translational masses for TVMDs, we can readily obtain the mass ratios, supporting member stiffness, and viscous damping coefficients.

3. EARTHQUAKE RESPONSE ANALYSIS

3.1. Analytical model

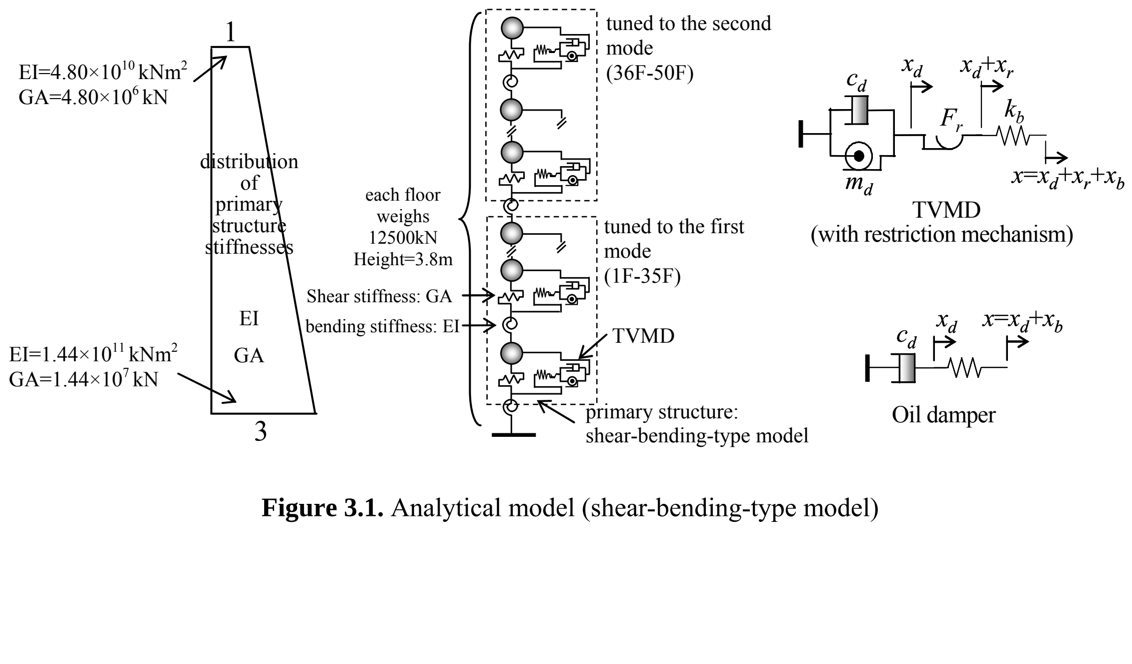


Figure 3.1. Analytical model (shear-bending-type model)

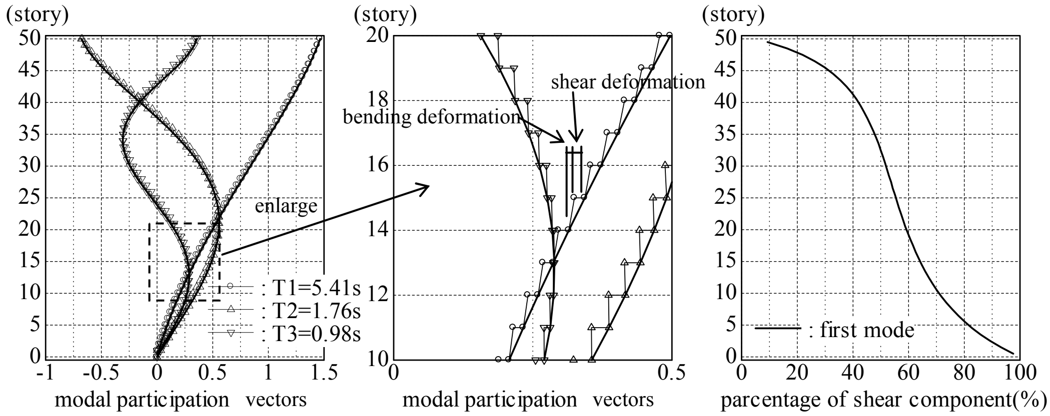


Figure 3.2. Eigenvalue problem results (uncontrolled primary structure)

We employ a fifty story high-rise steel structure for an analytical study. The height of each story is 3.8 m. Each floor weighs 7.6 kN per m^2 and the typical floor area is 1650 m^2. Thus, each floor weighs 12500 kN. The bending and shear stiffness are distributed such that the stiffness at the top is one third of the ones at the bottom. The first fundamental period of the uncontrolled primary structure is 5.41 s. We assume that the inherent damping of the primary structure is stiffness proportional with 1% critical damping.

The analytical model is a shear-bending type model taking into account the shear deformation and bending deformation of the whole structure caused by the bending deformation of the beams, columns, and the axial deformation of the columns. Fig. 3.1. depicts the analytical model and Fig. 3.2. shows the eigenvalue problem results of the uncontrolled primary structure. The ratio of the shear deformation to the total deformation of the first mode in each story becomes smaller as the number of floors increase. The ratios are 60% and 40% on the 20th and 40th floors, respectively. Because TVMD is not activated by the bending deformation but by the shear deformation of the primary structure, dampers tuned to the first mode are allocated to the lower stories.

3.2. Input ground motions

As the ground motion, we use the Tokyo Meteorological Agency ground motion (NS component) during the hypothetical simulation of the Kanto earthquake (Sato, Dan 2001), which has a long duration and contains components that resonate with the first fundamental 5.41 s period of the primary structure. We also use the historical earthquake record Taft 1952 EW whose peak ground velocity (PGV) is normalized to 0.5 m/s. Their accelerograms and response spectra (h = 5%) are shown in Fig. 3.3. T_1, T_2, and T_3 in this figure indicate the first, second, and third fundamental period of the primary structure, respectively.

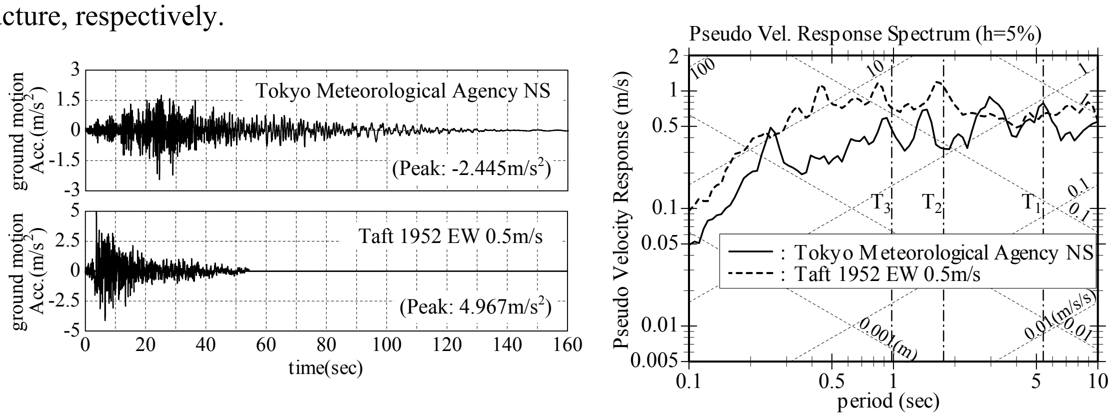


Figure 3.3. Accelerograms and response spectra of input ground motions

3.3. Comparison of Seismic Control Performance

We compare the seismic control performances of TVMD and FRTVMD with that of an oil damper.

The FRTVMDs and oil dampers are designed such that the maximum response inter-story drift angles yielded by the two systems are almost the same for each story. More specifically, the design criterion for the maximum response inter-story drift angle of the structure subjected to the Tokyo Meteorological Agency NS ground motion is set to 1/100. The specifications of the TVMDs and oil dampers sought to satisfy this criterion are shown in Tables 3.1. and 3.2. Each seismic control system has five dampers in each story. Table 3.1. shows the properties of the five oil dampers incorporated into each story. The oil dampers are equipped with relief valves, which are activated when the damping forces reach 800 kN in each damper. The damping ratio provided by the oil dampers is 1.6% of the critical damping while the relief valve is inactive. TVMDs tuned to the first and second modes are incorporated into the 1st to 35th story and 36th to 50th story, respectively.
As shown in Table 3.2., a maximal manufacturable cylindrical flywheel that yields an equivalent translational mass of 5000 metric tons, is attached to each damper to obtain a maximum mass effect in the first mode control. The restriction force for each damper is set to half of the maximum force of the oil damper.

Table 3.1. Parameters of Oil damper (each floor)

Qty.	Damping coefficient		Relief Vel. and force		Max. force	Support. member Stiff.
	C1: kNs/mm	C2: kNs/mm	mm/s	kN	kN	kN/mm
1-50F 5	125 (25 × 5)	8.45 (1.69 × 5)	32	4000 (800 × 5)	5000 (1000 × 5)	1000 (200 × 5)

Table 3.2. Parameters of TVMD (each floor)

Target mode	Qty.	Equivalence mass ton	Damping Coeff. kNs/mm	Support. member Stiff. kN/mm	Restriction force kN
First mode	1-35F 5	25000 (5000 × 5) $\mu = 0.0064$	2.869 (0.574 × 5) Oil damper: 1/44	34.167 (6.833 × 5) Oil damper: 1/29	2250 (450 × 5)
Second mode	36-50F 5	7500 (1500 × 5) $\mu = 0.0146$	4.057 (0.811 × 5) Oil damper: 1/31	98.683 (19.737 × 5) Oil damper: 1/10	2250 (450 × 5)

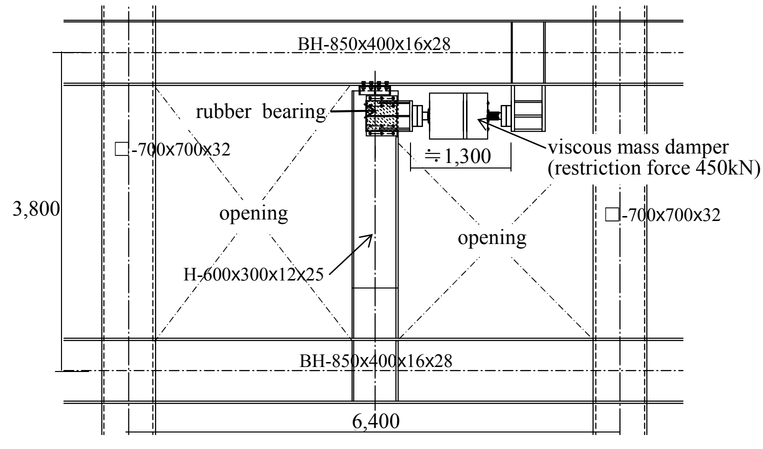


Figure 3.4. Schematic of the frame installed with TVMD

As a result, the viscous damping coefficient and supporting member stiffness of TVMD are less than 1/10 of those of the oil damper. As the supporting member stiffness required in the TVMD system is small, the volume of the supporting member required can be reduced, which results in cost reduction. Fig. 3.4. shows how a TVMD is installed in a building frame. The dimensions and specifications of the damper are as follows:

1. The length and diameter of the cylindrical flywheel are 750 mm and 600 mm, respectively.
2. The diameter of the internal cylinder is 450 mm.
3. The lead length of the ball screw is 20 mm.
4. The actual mass and the equivalent translational mass of the cylindrical flywheel are 0.720 tons and 5054 tons, respectively. Thus, the apparent mass amplification factor is 6940.

3.4. Analytical results

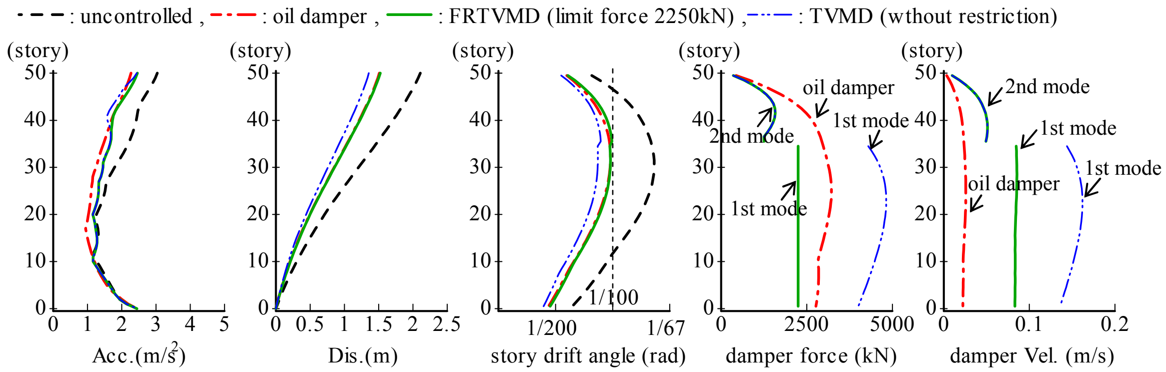


Figure 3.5. Maximum responses (input ground motion: Tokyo Meteorological Agency NS)

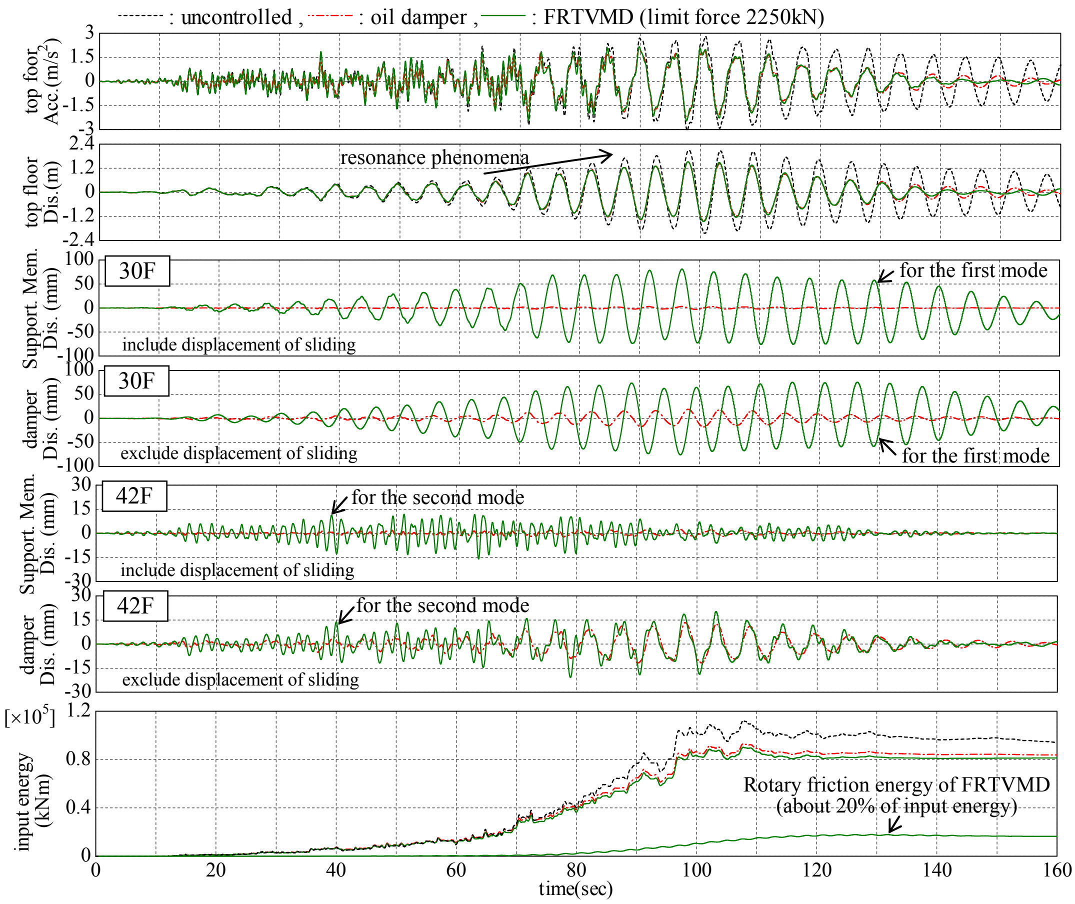


Figure 3.6. Time history responses (input ground motion: Tokyo Meteorological Agency NS)

Figs. 3.5. and 3.6., respectively, show the maximum responses and time histories of the analytical model subjected to the Tokyo Meteorological Agency ground motion (NS component), which contains predominantly long-period components. As shown in Table 3.1., a large damping coefficient is required for an oil damper to generate sufficient damping force because the response velocity is low. This is due to the large response displacement caused by the low predominant response frequency.

Figs. 3.5. and 3.6. exhibit displacement reduction effects of TVMD and FRTVMD that are equivalent to those of the oil dampers, despite the smaller damping coefficients, supporting the member stiffness and damping forces. This is because the secondary vibration system amplifies the viscous mass damper deformation in TVMD and FRTVMD, consequently, large energy dissipation is achieved.

Although the energy dissipation in FRTVMD deteriorates because of the damping force restriction, the seismic response reduction effect is sustained because friction damping in the rotary friction mechanism compensates for the loss of energy dissipation.
Fig. 3.7. depicts the maximum responses yielded by Taft 1952 EW whose PGV is normalized to 0.5 m/s, which shows that oil dampers generate damping forces that are approximately twice as large as those of the FRTVMDs even though the response displacements are almost the same. This is because the Taft 1952 EW ground motion is considered to contain many short-period components that yield a substantial damping force in the oil dampers.

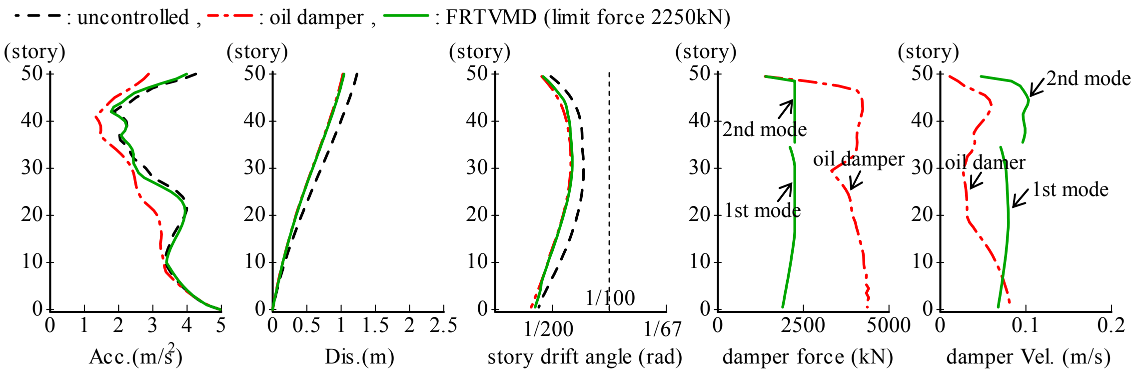


Figure 3.7. Maximum responses (input ground motion: Taft 1952 EW [PGV = 0.5 m/s])

Thus, it can be said that the FRTVMD has an advantage in seismic response reduction compared with a conventional oil damper but a smaller damping force.

4. CONCLUSIONS

In this paper, we confirmed the applicability of a force-restricted tuned viscous mass damper as a precautionary measure against long-period ground motion in high-rise buildings. We obtained the following results:

1) The TVMD system is a seismic control system that can impart additional damping to a specified mode. In an analytical example, TVMDs tuned to the first mode and the second mode are allocated in the lower part and upper part of the structure, respectively, which clarifies the effectiveness of a multi-modal control to reduce predominant modes.
2) FRTVMD works as a TVMD while the damping force is unrestricted. Even after the force restriction is activated, FRTVMD gives an effective seismic response reduction when compared with TVMD. Note that the frictional damping in the force restriction mechanism compensates for the loss of the viscous damping energy.
3) An analytical study using two types of ground motions (Tokyo Meteorological Agency NS as a long-period ground motion, and the Taft 1952 EW as a short-period ground motion) showed the advantage of a FRTVMD over a conventional oil damper. The result of long-period ground motion required a large damping coefficient to generate a large damping force, which resulted in an excessively large damping force for the TAFT 1952 EW. On the other hand, FRTVMD showed effective seismic control performance for both types of ground motions using the secondary vibration system in combination with the force restriction mechanism to amplify the viscous mass damper motion.

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