Seismic Response Control of High-rise Buildings by Using TMD with Lever and Pendulum Mechanism

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Abstract
In this study, we propose a system to reduce the displacement of the tuned mass damper (TMD) with lever and pendulum mechanism that was placed in the roof for seismic response control of high-rise buildings. This is a displacement magnifying mechanism attaching the weight and lever in the horizontal direction in the space between the roof and TMD. In particular, in this paper, the optimal tuning method of the dynamic mass (D.M.) is examined, and by applying this control system to the single degree of freedom (SDOF) building and the multi-degree of freedom (MDOF) buildings as shown in Figs.1 and 2 subjected long-period earthquake motions for response control, its effectiveness is examined.

Keywords: Response Control, TMD, Lever and Pendulum, Long-period Earthquake Motion

1. Introduction

After the 1995 Kobe Earthquake has occurred, higher seismic performance is increasingly required in the building. To satisfy the seismic target performance, research and development for the seismic improvement are actively performed at present. Particular, according to the development of seismic technology for supporting the dynamic design, construction of high-performance building, the technology of seismic response control has attracted attention from the social background of the safety of building, et al. The technology of seismic response control is to control the responses of high-rise buildings and towers caused by an earthquake or strong wind by using the various mechanisms and devices. For example, the method of installing on the additional mass with damping elements on the building top is relatively used as compact apparatus for easy maintenance. The lever device in this paper is expected to utilize as a vibration control device of the high-rise building. This device is used by adjusting the amount of additional mass and the ratio of the distances between its fulcrum and its power point, and between its fulcrum and its action point, namely a kind of tuned mass damper (TMD).

Also, in the Niigata Chubetsu Earthquake in 2004, long-period ground motion occurred in central area of Tokyo around a distance of about 200km from the epicenter and then accidents of elevators in the high-rise buildings occurred. In the 2011 off the Pacific Coast of Tohoku Earthquake, the elevators and so on of high-rise building in Osaka Prefecture away about 770km from the epicenter were damaged. Furthermore, the sloshing phenomenon for the oil tank occurred due to long-period ground motion in the Niigata East Port, the damage, such as oil leakage came out. In addition, it is pointed out that by the Tokai earthquake, East-Nankai earthquake, et al., long-period earthquake motion will occurs and then the great damages have occurred[1]. From this background, in order to apply the lever device to the existing building, the evaluation of earthquake resistance due to long-period ground motion have been studied. The authors et al. have proposed the hybrid TMD using a lever and pendulum mechanism (LP-TMD) for controlling the seismic response of MDOF structures, its optimum tuning conditions. Recently, using the base isolated buildings with the dynamic mass (D.M.) based on the idea of LP-TMD and the long-period earthquake motions, its effectiveness of response reduction was examined analytically[2],[3].

In this paper, using the high-rise buildings with the LP-TMD; that is D.M., and the long-period earthquake motions, its optimum conditions are shown and its effect of response reduction is examined analytically and finally the mechanical structure of D.M. is shown.
In this study, as an example of high-rise building, the models of one story building and ten story building are used as shown in Fig. 1 and Fig. 2. \(m, c, k\) in Fig.1 are mass, damping coefficient and stiffness of building, respectively. \(x\) and \(y\) are the absolute displacements of \(m\) and the earthquake ground displacement, respectively. \(m_i, c_i\) and \(k_i\) are mass, damping coefficient and stiffness of \(i\)-th story, respectively. In this study, the fundamental(first) natural period is taken as \(T_1=4.0s\) by tuning for high-rise building or base isolated building. The rigidity distribution of this model is shown in Table 1.

First, the equation of motion of this system is given by

\[
M\ddot{x} + C\dot{x} + Kx = -M\ddot{y}
\]

(1)

Mass, damping coefficient and stiffness matrices \(M, C, K\) of building model in Fig.2 are give by

\[
M = \begin{bmatrix}
m_0 & 0 & 0 & 0 & 0 \\
0 & \ddots & 0 & 0 & 0 \\
0 & 0 & m_2 & 0 & 0 \\
0 & 0 & 0 & m_1 & 0 \\
0 & 0 & 0 & 0 & m_0 \\
\end{bmatrix}
\]

(2)
Assuming a stiffness proportional damping, the damping coefficient $c_i$ of $i$-th story is obtained as

$$c_i = \frac{2\xi_0}{\omega_0} k_i$$

Where, $\omega_0$ and $\xi_0$ are modal circular frequency and modal damping ratio of first mode of building, respectively.

Substitute Eq.(5) into Eq.(3), the damping matrix is rewritten as

$$C = \begin{bmatrix}
  k_n & -k_n & 0 & 0 & 0 \\
  -k_n & \ddots & \ddots & 0 & 0 \\
  0 & \ddots & k_1 + k_2 & -k_1 & 0 \\
  0 & 0 & -k_1 & k_0 + k_1 & -k_0 \\
  0 & 0 & 0 & -k_0 & k_0
\end{bmatrix}$$

3. Concept of dynamic mass mechanism

The concept of dynamic mass(D.M.) is simply described as follows.
(1) The lever device with the tip mass in the space between two slabs separated through the elastic body is mounted as shown in Fig.3. In this figure, blue balls denote the ball bearings.
(2) A two-dimensional relative horizontal displacement $x$ between the lower and upper slabs becomes the rotational motion of tip mass of lever around fulcrum installed at lower slab.
Therefore, at the point of action of lever, the displacement response $Bx$ increases by lever ratio $B$ (that is the ratio of distance between the point of action and fulcrum, distance between the power point and fulcrum). Using Two-dimensional relative horizontal acceleration $x$ and tip mass $m$, the inertia force $m_{p}Bx$ occurs.

(4) Multiplying this inertial force by the distance from the tip of the lever to the fulcrum, the resulting bending moment around the fulcrum is obtained as. When this $m_{p}Bx$ is divided by the distance of the fulcrum and the power point, the couple acting at the power point and fulcrum is obtained. The upper force is used as the response control force of upper slab and lower force acts the lower slab.

4. Models of high-rise building with D.M. and its optimum tuning condition

![Single degree of freedom base isolation model with lever.](image)

![Equivalent shear-spring model of structure with lever.](image)

In this study, as an example of high-rise building with TMD and a lever device (D.M.), one story building and ten story building are used as shown in Fig. 4 and Fig. 5. $m_0$, $c_a$, $k_0$ in Fig. 1 are mass, damping coefficient and stiffness of TMD, respectively. $x_a$ are the relative displacement of $m_a$ from the earthquake ground displacement. In this study, the fundamental (first) natural period is taken as $T_0=4s$ by tuning for high-rise building or base isolated building.

First, the optimum tuned conditions of the analytical model with a lever device (D.M.) in Fig. 1 are obtained by the fixed point method. The equation of motion of this system with $c=0$ is given by

\[
\begin{aligned}
-m_p B(1+B)\dddot{x} + (m_a + m_p B^2)\dddot{x}_a + c_a (\dddot{x}_a - \dddot{x}) + k_a (x_a - x) &= 0 \\
(m + m_p (1 + B)^2)\dddot{x} - m_p B(1 + B)\dddot{x}_a + k x + c_a (\dddot{x} - \dddot{x}_a) + k_a (x - x_a) &= f
\end{aligned}
\]

(7)

The natural circular frequencies of main building and TMD, damping ratio of main building and its mass ratio are defined as

\[
\omega_0 = \sqrt{\frac{k}{m}}, \quad \omega_a = \sqrt{\frac{k_a}{m_a}}, \quad \zeta_a = \frac{c_a}{2\sqrt{m_a k_a}}, \quad \mu_1 = \frac{m_a}{m}, \quad \mu_2 = \frac{m_p}{m_a}
\]

(8)

Assuming that the seismic force $f = F_0 e^{i\omega t}$ is sinusoidal wave, the amplitude ratios of $X/X_a$, $x/x_a$ are obtained as.

\[
\begin{bmatrix}
1 - \nu^2(1 + \mu_1 \mu_2 (1 + B)^2) + \mu_1 \gamma^2 + 2\mu_1 \zeta_a \gamma \\
\mu_1 \nu^2 B(1 + B) - \gamma^2 - 2\zeta_a \gamma
\end{bmatrix}
\begin{bmatrix}
X/X_a \\
x/x_a
\end{bmatrix} = 
\begin{bmatrix}
1 \\
0
\end{bmatrix}
\]

(9)

where

\[
\nu = \frac{\omega}{\omega_0}, \quad \gamma = \frac{\omega_0}{\omega}, \quad x_{st} = \frac{F}{k_c}
\]

By the fixed point theory, the optimum ratio of natural circular frequencies and optimum damping ratio are given by

\[
\gamma^2 = \frac{AD - C^2 \mu_1 \mu_2}{A + D \mu_1 - 2C \mu_1 \mu_2}
\]
\[ \zeta_a = \frac{-H - 2D(\gamma^2 - D\nu^2)}{4\gamma^2(1 - G)\{3(1 - G) - 4\}} \]  
\[ \eta = \frac{-D - E\nu}{1 + F\nu^2} \]  
\[ \gamma = A + \mu_1 c + \mu_2 (1 + B) \]  
\[ C = B(1 + B) \]  
\[ D = 1 + \mu_2 B^2 \]  
\[ E = AD - \mu_2 C^2 \]  
\[ F = -D - A\gamma^2 - D\mu_1 \gamma^2 + 2\mu_1 \mu_2 \gamma^2 \]  
\[ G = 1 - A\nu^2 - D\mu_1 \nu^2 + 2C\mu_1 \mu_2 \nu^2 \]  

Where,

\( A = 1 + \mu_1 \mu_2 (1 + B)^2 \)

5. Earthquake motions for numerical simulation

5.1 Introduction of earthquake motions

In this study, in order to investigate the effectiveness of D.M., as the standard earthquake motion, The 1940 Imperial Valley Earthquake (El Centro EW), The 1952 Kern County Earthquake (Taft NS), The 1978 Miyagiken-oki Earthquake (Tohoku Earthquake EW), The 1968 Tokachi-oki Earthquake, The 1995 Hyogo-ken Nanbu Earthquake (JR Kobe EW) and Kanto Earthquake (Great Kanto)[4] are used. And, as the long-period earthquake motion, the artificial earthquake of Building Center of Japan (BCJ-L2)[5], Nagoya Sannomaru EW[6], The 2003 Tokachi-oki Earthquake (Tomakomai EW), Tokai Urayasu, Tonankai Yokohama [7] and The 2011 off the Pacific Coast of Tohoku

Table 2: Earthquake motions for simulation.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Max. acceleration [gal]</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Centro EW</td>
<td>292.34</td>
</tr>
<tr>
<td>Taft NS</td>
<td>514.49</td>
</tr>
<tr>
<td>Tohoku EW</td>
<td>362.79</td>
</tr>
<tr>
<td>Hachinohe EW</td>
<td>261.85</td>
</tr>
<tr>
<td>JMAKobe EW</td>
<td>447.14</td>
</tr>
<tr>
<td>Great Kanto</td>
<td>630.42</td>
</tr>
<tr>
<td>BCJ-L2</td>
<td>320.97</td>
</tr>
<tr>
<td>Nagoya Sannomaru EW</td>
<td>189.31</td>
</tr>
<tr>
<td>Tomakomai EW</td>
<td>272.96</td>
</tr>
<tr>
<td>Tokai Urayasu</td>
<td>129.07</td>
</tr>
<tr>
<td>Tonankai Yokohama</td>
<td>290.79</td>
</tr>
<tr>
<td>Osaka NS</td>
<td>121.58</td>
</tr>
</tbody>
</table>
Earthquake (Osaka NS) are used. The peak accelerations of these motions are normalized as taking their peak velocity $v_{max}=50 \text{ cm/s}$ as shown in Table 2.

5.2 Response spectra of earthquake motions

The acceleration, velocity and displacement response spectra obtained by these motions are shown in Figs.7, 8 and 9, respectively. From the acceleration response spectrum in Fig.7, it is shown that the standard earthquake motions such as El Centro EW, Tohoku EW, Great Kanto et al. have the short period component of 1 second or less. From Figs.8 and 9, it is somewhat constant in the all periods, and is contained within a relatively small value. In the seismic isolation structure, by making the fundamental natural period of the structure longer, it is possible to suppress an increase in its response. It can be said, however, if the damping and the stiffness of the structure are too large, there is a risk that causes an increase in acceleration response. As shown in Fig.4, in the case of long-period earthquake motions such as Nagoya Sannomaru EW, Tonankai Yokohama and Osaka NS, the acceleration response spectrum is smaller than that of the standard earthquake motions. However, from Figs.4 and 5, the displacement response spectrum and velocity response spectrum are dominated by long-period area of more than 3 seconds. If these base-isolated structures of natural period of 4 seconds or longer period are subjected to the long-period earthquake motions, the concerns about the possibility that an increase in the displacement response occurs are high.
6. Simulation results
6.1 Case of SDOF system

Using the Tohoku EW, Tonankai Yokohama motions and optimum damping ratio, lever ratio $B=7$, the acceleration responses of main mass and mass of tuned mass damper TMD are shown in Figs.10 and 11, respectively. Focusing on the maximum acceleration of the TMD, that of main mass in the Tohoku EW motion has doubled, and the same results are obtained in the Tonankai Yokohama motion. Since a variety of results were just released by an earthquake for this result, it is considered that the characteristics of each earthquake have affected. Next, focusing on the displacement of TMD, their maximum values are reduced to about 1/10 than those without D.M. (LP-TMD) in any seismic motions for the effect of D.M. (LP-TMD) However, for the case of the standard earthquake motions and cases of long-period earthquake motions, the maximum acceleration responses are decreased from about 1/10 to 1/2 of those without D.M.(LP-TMD), respectively. Also with respect to the maximum displacement of the main system, its reduction is up to 7/10 from 1/10, respectively. It is clear that no change almost in the maximum acceleration response with the increase of mass ratio for TMD occurs. Therefore, it is believed that the couple of negative occurred as an additional mass acts as a damping force to the TMD, it had a positive working couple becomes exciting force to the main mass.

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Fig.11 Acceleration response of a mass damper.

Fig.12 Displacement response of main mass.
6.2 Case of MDOF system

For the MDOF model of high-rise building, using the all above earthquake motions, optimum damping ratio, and lever ratio $B=3$, $\zeta=0.02$, $\mu=0.01$, the maximum acceleration responses and maximum displacement response of each story main mass and mass of tuned mass damper (TMD) are shown in Figs. 14 and 15, respectively. From these figures, it can be seen that the maximum displacements of the TMD become lower markedly. In particular, in the case of Tonankai Yokohama motion which is a long-period ground motion, the maximum displacement of TMD is down to less than half. From these results, it can be seen that for the long-period ground motion, lever device is effective in reducing the maximum displacement of the TMD. However, the maximum acceleration of each layer has a similar changes and when the lever device is installed, the value of the maximum acceleration increases more than twice. The effect of parameters, such as analysis and other conditions of the TMD on the maximum response must be considered.
Fig. 14 Acceleration response of main mass.

- (c) With D.M. (Standard earthquake motion).
- (d) With D.M. (Long-period earthquake motion).

Fig. 15 Displacement response of main mass.

- (a) With TMD (Standard earthquake motion).
- (b) With TMD (Long-period earthquake motion).
- (c) With D.M. (Standard earthquake motion).
- (d) With D.M. (Long-period earthquake motion).
7. Conclusions

In this study, in order to reduce the seismic response of high-rise building, the numerical simulations are carried out using the mechanical model of lever device (D.M.). The main results are summarized as follows:

1) Using the lever device for SDOF system subjected to the long-period ground motion, by the leverage, the maximum values of the displacement response and acceleration response of SDOF system have been slightly increased as compared to the tuned mass damper (TMD). It is clear that the acceleration response of the mass damper reduces and its displacement responses become smaller than those of TMD.

2) In the MDOF system, the maximum acceleration and the maximum displacement of each story using D.M. (LP-TMD) are compared with those using TMD. It is shown that the maximum displacement using D.M. (LP-TMD) becomes small slightly. However, for case of the standard earthquake motions, effectiveness of D.M. (LP-TMD) is not shown. Future, we intend to consider this problem and the problem of seismic response control of high-rise building using D.M. (LP-TMD) with damping element as shown in Fig. 16.

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Fig. 16 High-rise building with TMD installed by D.M. with damper.
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