Seismic Response Control of a Building and Elevator Rope with Active Mass Damper

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Elevator rope-ways is a serious problem for a high-rise building under seismic excitation. Vibration control of the rope-ways using active mass damper (AMD) is investigated, which is usually designed simply for control of building response. The linear quadratic regulator (LQR) is employed as the AMD control system. Numerical simulations are conducted and the responses are analyzed in both frequency and time domains. The relative displacement between the building and the rope is evaluated as well as the story drift and the absolute acceleration of the building. It is observed that the control method considering the rope-ways can effectively decrease response of the rope after seismic excitations.

1. INTRODUCTION

An elevator system has become an indispensable means of transportation in a high-rise building. However, the longer elevator rope is, the more easily it sways under earthquake excitation. Recently, in the 2004 Niigata-ken Chuetsu earthquake, elevator rope of Roppongi Hills Mori Tower swayed widely and entwined the equipment in the elevator shaft, which lead to the failure of the whole elevator system. Because it took considerable time until its restoration, numbers of people remained confined in the cage\(^1\). In the 2005 Chiba-ken Hokuseibu earthquake, 64,000 elevators stopped and 78 confinement accidents occurred\(^2\).

To prevent elevators from damage and to secure passenger’s safety, control systems are commonly used\(^3\) that stop a cage at the nearest floor when earthquake motion is detected. However, the sway of the rope can grow larger even after stopping the cage. Obviously, it is very dangerous if the system recovers to run while the rope is swaying intensely. Therefore, we must take into account the rope-way to consider safe recovery of the system. There has been considerable research on vibration of elevator rope as that of variable length cable\(^4\), \(^5\). Yamamoto et al.\(^4\) investigated the free and forced vibrations of a string with time-variable length theoretically. Zhu and Xu\(^5\) analyzed the free lateral vibration of a moving elevator rope with variable length. In recent research, Kimura et al.\(^6\) presented an exact solution to the forced vibration of elevator rope with time-varying length, and Otsuki et al.\(^7\), \(^8\) presented control of the sway of elevator rope using input device with gaps and demonstrated its effectiveness. Additionally, Mitsui and Kohiyama\(^9\) clarified the correlation between vibration of elevator rope and characteristics of a building, such as stiffness and damping.

Currently, there are various vibration control devices that protect a high-rise building from an earthquake and wind; a “mass damper” is one of them. It controls the building motion using reaction force which balances inertia force of an added mass. A mass damper that actively controls the building motion is called an “active mass damper” (AMD). The AMD controls motion of a building, such as story drift and absolute acceleration of a floor response, and it is not usually designed to control the sway of the elevator.
rope. There is as yet no study that controls a coupled structure of a building and elevator rope.

The objective of this paper is to examine the effectiveness of vibration control of both a building and elevator rope using AMD. First, we model a system consisting of a building, elevator rope and AMD, and examine the vibration characteristics. Second, we define three reference functions: the story drift of the building, absolute acceleration of the building, and the relative displacement between the building and the rope, and compare the effects of the controls based on frequency response analysis. Finally, we clarify the effectiveness and the problem of control of the rope sway using AMD based on time-history response analysis.

2. ANALYTICAL MODEL

A typical composition of a building and an elevator is illustrated in Fig. 1. The main rope, the governor rope, and the travelling cable could sway under earthquake excitation, but in this study, we assume that the elevator is composed of the traction sheave, the cage and the main rope on the cage side for simplicity. Fig. 2 shows an analytical model in this study. It consists of a building structure, an elevator system and AMD on the top of the building. This study assumes that the building response is linear elastic because AMD usually controls building vibration caused by moderate earthquake or wind.

2.1 Formulation of Model

First, we formulate an elevator rope by the finite element method (FEM). Generally, the main ropes consist of about 5 to 10 ropes, but we formulate only one of them for simplicity. We discuss only the vibration in the horizontal direction, and disregard the vibration in the vertical direction. The motion equation of the rope divided into N elements is as follows:

\[
M_r \ddot{x}_r + C_r \dot{x}_r + K_r x_r = -M_r \{ \ddot{z} \}
\]

\[
M_r = \begin{bmatrix}
 2\alpha & \alpha & 0 \\
 4\alpha & 2\alpha & \alpha \\
 0 & 2\alpha & 2\alpha \\
\end{bmatrix}
\quad \quad
K_r = \begin{bmatrix}
 2\gamma & \gamma & 0 \\
 \gamma & 2\gamma & \gamma \\
 0 & \gamma & 2\gamma \\
\end{bmatrix}
\quad \quad
C_r = \begin{bmatrix}
 2\gamma & \gamma & 0 \\
 \gamma & 2\gamma & \gamma \\
 0 & \gamma & 2\gamma \\
\end{bmatrix}
\quad \quad
x_r = \begin{bmatrix}
x_{r_1} \\
x_{r_2} \\
\vdots \\
x_{r_N} \\
\end{bmatrix}
\]

where \( \alpha = \frac{\rho AL}{6N} \), \( \beta = \frac{TN}{L} \), \( \gamma = \frac{CL}{6N} \).
In the above equation, the matrices \( \mathbf{M} \), \( \mathbf{C} \), and \( \mathbf{K} \) represent the mass, damping, and stiffness of the rope, respectively. The vector \( \mathbf{x} \) denotes the relative displacements of the rope, and \( z \) is the ground motion. The scalars \( \rho A \), \( L \) and \( T \) are the linear density, the length and the tension of the rope. The scalar \( C \) is the damping coefficient of the rope per unit length defined by

\[
C = \frac{2\pi \zeta \nu}{L} \sqrt{\rho AT}
\]  

in which the scalar \( \zeta \) is the damping ratio of the rope\(^{10}.\)

Next, we formulate the analytical model of the whole system. We assume that the traction sheave of the elevator is on the top floor of the building and the cage stays on \( i \)th mass of the building, i.e. \( (i+1) \)th floor of the building. Both the traction sheave and the cage are attached to the building via a spring and a damper. Hereafter we call this model as a building-elevator model. The motion equation of the building-elevator model is as follows:

\[
\mathbf{M}\ddot{\mathbf{x}} + \mathbf{Cx} + \mathbf{Kx} = -\mathbf{M}\{t\} + \mathbf{f}\alpha
\]

where

\[
\mathbf{M} = \begin{bmatrix}
    m_1 & & & & \\
    & m_2 & & & \\
    & & m_3 & & \\
    & & & \ldots & \\
    & & & & m_n
\end{bmatrix},
\mathbf{C} = \begin{bmatrix}
    c_1 & -c_2 & & & \\
    -c_2 & c_3 & -c_4 & & \\
    & -c_4 & \ddots & \ddots & \\
    & & \ddots & c_{n-2} & -c_{n-1} \\
    & & & -c_{n-1} & c_n
\end{bmatrix},
\mathbf{K} = \begin{bmatrix}
    k_1 + k_2 & -k_2 & & & \\
    -k_2 & k_1 + k_3 & -k_3 & & \\
    & \ddots & \ddots & \ddots & \\
    & & \ddots & k_{n-1} + k_n & -k_n \\
    & & & -k_n & k_{n-1} + k_n
\end{bmatrix}
\]

The matrices \( \mathbf{M} \), \( \mathbf{C} \) and \( \mathbf{K} \) represent the mass, damping and stiffness matrices of the model, respectively. The vector \( \mathbf{x} \) denotes the relative displacements of the model. The scalar \( n \) is the number of mass of the building. We assume that the model is a 60-story building with a height of 240 m, and number of mass of the building \( n \) is 60. The building story height \( \Delta h \) is 4 m. The scalars \( m_1, m_2, \ldots, m_n, k_1, k_2, \ldots, k_n \), and \( c_1, c_2, \ldots, c_n \) are the mass, damping and stiffness coefficients of the building; the scalars \( m_a, m_m \) and \( m_c \) are the mass of AMD, the traction sheave and the cage, respectively. The scalars \( k_a, k_m \) and \( k_c \) represent the stiffness coefficients between AMD and the building, between the traction sheave and the building, and between the cage and the building, respectively. Similarly, the scalars \( c_a, c_m \) and \( c_c \) represent damping coefficients. The scalar \( \alpha \) is the controlling force of which location is identified by the vector \( \mathbf{f} \). The parameters used in this study are shown in Table 1.

The first natural period of the building \( \sqrt{T} \) is given to be 5.8 s, and the first modal damping ratio \( \zeta = 1\% \). The stiffness of the building, \( k_1, k_2, \ldots, k_n \), are determined using \( A_i \) distribution, which
is designated by the Building Standards Law of Japan. The damping matrix is given to be proportional to stiffness matrix except elements of the rope. The cage stays at the level of the first mass of the building on the assumption that the rope becomes the longest. The difference between responses of a finite element model and a real-existing system decrease when the size of the elements becomes small enough. Kimura et al. suggest the number of finite elements of rope, \( N \) should be 20 or more for a 180-meter-high building, and thus we assume that \( N \) is 60 for the 240-meter-high.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_1, m_2, \ldots, m_n )</td>
<td>Mass of a building</td>
<td>7.5( \times 10^3 ) kg</td>
</tr>
<tr>
<td>( m_a )</td>
<td>Mass of AMD</td>
<td>1.8( \times 10^3 ) kg</td>
</tr>
<tr>
<td>( m_s )</td>
<td>Mass of a traction sheave</td>
<td>1.9( \times 10^3 ) kg</td>
</tr>
<tr>
<td>( m_c )</td>
<td>Mass of a cage</td>
<td>7.5( \times 10^3 ) kg</td>
</tr>
<tr>
<td>( k_a )</td>
<td>Stiffness coefficient between AMD and a building</td>
<td>0 N/m</td>
</tr>
<tr>
<td>( k_m )</td>
<td>Stiffness coefficient between a traction sheave and a building</td>
<td>3.0( \times 10^6 ) N/m</td>
</tr>
<tr>
<td>( k_c )</td>
<td>Stiffness coefficient between a cage and a building</td>
<td>2.7( \times 10^4 ) N/m</td>
</tr>
<tr>
<td>( c_a )</td>
<td>Damping coefficient between AMD and a building</td>
<td>0 Ns/m</td>
</tr>
<tr>
<td>( c_m )</td>
<td>Damping coefficient between a traction sheave and a building</td>
<td>4.7( \times 10^3 ) Ns/m</td>
</tr>
<tr>
<td>( c_c )</td>
<td>Damping coefficient between a cage and a building</td>
<td>9.0( \times 10^3 ) Ns/m</td>
</tr>
<tr>
<td>( \rho A )</td>
<td>Linear density of the rope</td>
<td>1.7 kg/m</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>Damping ratio of the rope</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

2.2 Modal Analysis

We analyze the vibration characteristics of the building-elevator model regarding the natural frequency and the modal shapes. Tables 2, 3 and 4 present the natural frequencies of a building-elevator model, an independent building model and an independent rope model, respectively. The modal shapes of a building-elevator model, a building model and a rope model are shown in Figs. 3, 4 and 5. Comparing Tables 2, 3 and 4, we find that the natural frequencies of a building model (Table 3) and a rope model (Table 4) appear in Table 2. For example, the first natural frequency of a building-elevator model corresponds to the first natural frequency of a building model. The second natural frequency of a building-elevator model equals the first natural frequency of a rope model. Besides, Figs. 3, 4 and 5 indicate that the modal shapes of a building-elevator model fall into two main categories: those which contain the sway of both the building and the rope (Type A) and those which contain the sway of only the rope (Type B). Two patterns of modal shapes of a building-elevator model are illustrated in Fig. 6. The usual vibration control using AMD, which considers only the building, might decrease the rope-sway of Type A. However, it might not be able to decrease the rope-sway of Type B.

Fig. 7 shows frequency response of relative displacement between the building and the rope at 1/2 of the height of the building. This figure indicates that the response increases mainly at the two kinds of vibration modes mentioned above. The modes which contain the sway of only the rope exert a great influence on the rope-sway. Thus it is important to control the rope-sway of these modes.
Table 2 Natural Frequency of a Building-Elevator Model

<table>
<thead>
<tr>
<th>Mode</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>9th</th>
<th>10th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Frequency (Hz)</td>
<td>0.17</td>
<td>0.21</td>
<td>0.42</td>
<td>0.45</td>
<td>0.63</td>
<td>0.73</td>
<td>0.84</td>
<td>0.95</td>
<td>1.01</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Fig. 3 Modal Shapes of a Building-Elevator Model

Table 3 Natural Frequency of a Building Model

<table>
<thead>
<tr>
<th>Mode</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Frequency (Hz)</td>
<td>0.17</td>
<td>0.45</td>
<td>0.73</td>
<td>1.01</td>
<td>1.29</td>
</tr>
</tbody>
</table>

Fig. 4 Modal Shapes of a Building Model

Table 4 Natural Frequency of an Elevator Model

<table>
<thead>
<tr>
<th>Mode</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Frequency (Hz)</td>
<td>0.21</td>
<td>0.42</td>
<td>0.63</td>
<td>0.84</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Fig. 5 Modal Shapes of an Elevator Model

a) Type A Both a Building and a Rope

b) Type B Only a Rope Sways

Fig. 6 Two Patterns of Modal Shapes of a Building-Elevator Model

3. DESIGN OF CONTROL TARGET

In this section, we design the active control force realized by AMD. We adopt the linear quadratic regulator (LQR), which is often employed as the AMD control system. In the LQR, the control target is controlled by the state space equation as follows:
\[
\dot{y} = Ay + Bu + C\ddot{z}
\]  
(4)

where \( y = [x \ x^T] \), \( A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \), \( B = \begin{bmatrix} 0 \\ M^{-1}f \end{bmatrix} \), \( G = \begin{bmatrix} 0 \\ -1 \end{bmatrix} \).

The feedback control force \( u \) is given by minimizing the cost function:

\[
J = \int_0^t \left[ y^T Q y + 2 y^T S u + R u^2 \right] dt
\]  
(5)

Where both \( Q \) and \( S \) are the weighting matrices for the control target, and \( R \) is the weighting scalar for the control force. The smaller \( R/\|Q\| \) and \( R/\|S\| \) are, the larger the control force is. The control force \( u \) is defined by

\[
u = -Fy
\]  
(6)

where \( F \) is given by

\[
F = R^{-1} \left( S^T + B^T P \right)
\]  
(7)

\( P \) is the solution of the Riccati equation:

\[
P(A - BR^{-1}S^T) + (A - BR^{-1}S^T)^T P - PBR^{-1}B^T P + Q - SR^{-1}S^T = 0
\]  
(8)

By varying \( Q \) and \( S \), we define what the control targets are. In conventional vibration control using AMD, the story drift and the absolute acceleration of the building is considered, but the elevator rope-sway is not. In this study, we compare three control strategies: reduction of the story drift of the building, the absolute acceleration of the building, and the relative displacement between the building and the rope (hereinafter called the “rope-sway”). We define these three controls as Story Drift Control, Abs. Acc. Control and Rope Control, respectively. Table 5 shows the weighting matrices of the three control strategies. In Table 5, where \( L, D, e, \) and \( T \) are as follows:

\[
L = \frac{1}{\Delta h} \begin{bmatrix} 1 & 0 & \cdots & \cdots & 0 & 0 & \cdots & 0 \\ -1 & 1 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\ \vdots & \ddots & -1 & 1 & 0 & \cdots & \cdots & \cdots \\ 0 & \cdots & 0 & -1 & 1 & 0 & \cdots & 0 \end{bmatrix}, \quad D = NM^{-1}[K \ \ C], \quad e = NM^{-1}f, \quad T = \begin{bmatrix} t_1 \\ \vdots \\ t_n \end{bmatrix}
\]

where

\[
N = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\ \vdots & \ddots & 0 & \ddots & \ddots & \ddots & \ddots \\ 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \end{bmatrix}
\]

<table>
<thead>
<tr>
<th>Weighting Matrix</th>
<th>Story Drift Control</th>
<th>Abs. Acc. Control</th>
<th>Rope Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>L^T L</td>
<td>( \begin{bmatrix} t_1 \ \vdots \ t_n \end{bmatrix} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D^T D</td>
<td>( -D^T e )</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>T^T T</td>
<td>( e^T e + R_v )</td>
<td>( R_v )</td>
<td></td>
</tr>
</tbody>
</table>
and the vector \( t_i \) is defined to meet the condition that \( t_i y \) is the relative displacement between the \( i \)th node of the rope and the building.

4. NUMERICAL CALCULATION

4.1 Frequency Domain Analysis
First, we compare the effect of the three control strategies defined in the previous chapter based on frequency domain analysis. Figs. 8, 9 and 10 show the frequency response of the “rope-sway” at 3/4 of the height of the building, the frequency response of the “rope-sway” at 1/2 of the height of the building, and the frequency response of the “rope-sway” at 1/4 of the height of the building, respectively. Figure sub-numbers (a), (b) and (c) represent the frequency response using Story Drift Control, the frequency response using Abs. Acc. Control, and the frequency response using Rope Control, respectively. The control force is gradually enlarged by varying \( R_v \) from \( 10^{-1} \) to \( 10^{-25} \) with factor \( 10^{-1} \). Thin solid line denotes the response in no control case. The case of \( R_v \) equals \( 10^{-25} \) is represented by thick solid line.

Fig. 8 Frequency Response of the “Rope-Sway” at 3/4 of the Height of the Building

Fig. 9 Frequency Response of the “Rope-Sway” at 1/2 of the Height of the Building

Fig. 10 Frequency Response of the “Rope-Sway” at 1/4 of the Height of the Building
Comparing Figs. 8, 9 and 10, the response of the modes which contain the sway of both the building and the rope can be suppressed by all the controls, but the response of the modes which contain the sway of only the rope can be suppressed by only Rope Control. Additionally, there is a trend that the response in high frequency range would increase using Rope Control.

Fig. 11 shows the comparison of the building control effects at the top of the building using Rope Control, and Fig. 12 the comparison of the building control effects at 1/2 of the height of the building. Figure sub-number (a) and (b) represent the frequency response of the story drift of the building and the frequency response of the absolute acceleration of the building, respectively. We find that there are wide frequency ranges in which the building response increases in using Rope Control. Especially, the response of the top floor tends to increase significantly in high frequency range.

4.2 Time Domain Analysis
Second, we investigate the effect of the three controls in time domain. Six input ground motions are shown in Table 6: El Centro 1940 NS (Imperial Valley earthquake), Taft 1952 NS (Kern Country earthquake), Hachinohe 1968 NS (Tokachi-oki earthquake), JMA Kobe 1995 NS (Hyoogo-ken Nanbu earthquake), K-NET Tomakomai 2003 NS (Tokachi-oki earthquake) and K-NET Shinjuku 2004 EW (Niigata-ken Chuetsu earthquake). The power spectrum densities of the seismic ground motions are shown in Fig. 13. The El Centro, the Taft and the Kobe waves have a relatively short predominant period, and the Hachinohe, the Tomakomai, and the Shinjuku waves have a longer predominant period. In order to examine the attenuation characteristics of the free vibration, zero data are added to the seismic records of the El Centro, the Taft, the Hachinohe and the Shinjuku for 30 seconds. The weighting parameter $R$, is varied from $10^{-3}$ to $10^{-25}$ with factor $10^{3}$ in the same way as the previous section.

As mentioned above, the smaller $R/||Q||$ and $R/||S||$ are, the larger the control force is. However, the force generated by a real actuator of AMD has a limitation. So the upper and lower limits are set on the control force $\hat{u}(t)$ by defining the following condition of constraint:
Table 6 Input Ground Motions

<table>
<thead>
<tr>
<th>Record</th>
<th>Earthquake</th>
<th>Duration (s)</th>
<th>Max. Acc. (cm/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Centro 1940 NS</td>
<td>Imperial Valley</td>
<td>53.8*</td>
<td>342</td>
</tr>
<tr>
<td>Taft 1952 NS</td>
<td>Kern Country</td>
<td>54.4*</td>
<td>153</td>
</tr>
<tr>
<td>Hachinohe 1968 NS</td>
<td>Tokachi-oki</td>
<td>51.0*</td>
<td>230</td>
</tr>
<tr>
<td>JMA Kobe 1995 NS</td>
<td>Hyogo-ken Nanbu</td>
<td>200</td>
<td>579</td>
</tr>
<tr>
<td>K-NET Tomakomai 2003NS</td>
<td>Tokachi-oki</td>
<td>290</td>
<td>70.1</td>
</tr>
<tr>
<td>K-NET Shinjuku 2004 EW</td>
<td>Niigata-ken Chuetsu</td>
<td>150*</td>
<td>15.3</td>
</tr>
</tbody>
</table>

*In the dynamic analysis, zero data are added to the record for 30

![Graphs](image)

Fig. 13 Power Spectrum Density of Input Ground Motions

![Bar graphs](image)

Fig. 14 Response Reduction Ratio of Three Controls on the Maximum “Rope-Sway”

![Bar graphs](image)

Fig. 15 Response Reduction Ratio of Three Controls on the Maximum RMS of the “Rope-Sway” over the Height of the Building
Fig. 16 Time Histories of the “Rope-Sway” at the 1/2 Height of the Building When Optimal $R_\nu$ is Selected to the Maximum “Rope-Sway”

Fig. 17 Time Histories of the “Rope-Sway” at the 1/2 Height of the Building When Optimal $R_\nu$ is Selected to the Maximum RMS of the “Rope-Sway”
\[ \hat{u}(t) = \begin{cases} -u_{\text{max}} & (u(t) \leq -u_{\text{max}}) \\ u_{\text{max}} & (u_{\text{max}} \leq u(t)) \\ u(t) & \text{(others)} \end{cases} \] (9)

In this paper, \( u_{\text{max}} \) equals 1000 kN.

In the result of the linear dynamical analysis, the interstory drift angle of the building does not exceed 1/200 rad except the case of the Kobe wave. In the case of the Kobe wave, it exceeds 1/200 rad in the range of 34 to 39 seconds of time-history, and the evaluated “rope-sway” is not exact. Nonlinear analysis is required to obtain more accurate result.

When \( R_v \) is selected to decrease the “rope-sway” most in the three controls, we examine how much the “rope-sway” each control can decrease. Figs. 14 and 15 show the maximum “rope-sway” for the three controls and the maximum RMS of the “rope-sway” over the height of the building for the three controls, respectively. Figs. 14 and 15 are normalized by the maximum “rope-sway” for no control and the maximum RMS of the “rope-sway” for no control, respectively. In other words, the figures show the response reduction ratio compared with the response without AMD.

Figs. 14 and 15 demonstrate that all the three controls are able to decrease the maximum “rope-sway” and the maximum RMS of the “rope-sway”, respectively. Thus, Story drift Control and Abs. Acc. Control can decrease the rope response as well as Rope Control. The reason is that both Story Drift Control and Abs. Acc. Control can suppress the modal shapes that contain the sway of both the building and the rope in Fig. 6. In Fig. 14, when the Hachinohe, the Kobe and the Tomakomai waves are input, Story Drift Control and Abs. Acc. Control achieve almost the same effect of the vibration control as Rope Control. When the rope is excited by the sway of the building, the maximum rope response can be reduced by controlling the building response. On the other hand, in Fig. 15, Rope Control is the best and successfully reduces “rope-sway” for all cases. This is because Rope Control suppresses the rope-sway in short time after seismic excitations.

Figs. 16 and 17 present the time histories of the “rope-sway” at 1/2 of the height of the building. Fig. 16 depicts the time histories when \( R_v \) is selected to decrease the maximum relative displacement most. Fig. 17 shows the time histories when \( R_v \) is selected to decrease the maximum RMS of relative displacement most. As well as the result obtained from Figs. 14 and 15, the three controls have a good effect to the rope-sway and it is not necessarily the case that Rope Control is the best control strategy to the control of the maximum rope response. However, Story Drift Control and Abs. Acc. Control cannot decrease the “rope-sway” rapidly after seismic excitations. The reason is that the two controls cannot suppress the modes which contain the sway of only the rope. On the other hand, Rope Control can decrease the “rope-sway” after seismic excitations because it can suppress all modes which contain the rope-sway. It is very important to reduce the “rope-sway” as much as possible in short time for the early recovery of the elevator system.

5. CONCLUSIONS

A numerical investigation was conducted to study the vibration control of an elevator rope using active mass damper (AMD) set on a building. A building with an elevator system controlled by AMD was modeled. The linear quadratic regulator (LQR) was employed as the AMD control system. Three control strategies were defined as the cost functions: the story drift of the building, the absolute acceleration of the building and the relative displacement between the building and the rope. The important conclusions obtained from the results in the frequency and time domains are summarized below.

- The vibration modes of the building-elevator model fall into two main categories: those which contain the sway of both the building and the rope and those which contain the sway of only the rope.
- In the frequency domain analysis, it is observed that the response of the modes which contain the
sways of both the building and the rope can be suppressed using Story Drift Control and Abs. Acc. Control. On the other hand, the response of the modes which contain the sway of only the rope cannot be suppressed while Rope Control can suppress.

- In the time domain analysis, Rope Control is effective in decreasing rope-sway after seismic excitations, compared with conventional Story Drift Control and Abs. Acc. Control.

In future study, we will see how the changes in cage position and building height affect the vibration control performance.

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