# Vibration Reduction of a Building–Elevator System Considering the Intensity of Earthquake Excitation

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**SUMMARY:**
To maximize the control effects under the limited capacity of a control force, a control method based on variable gain feedback control for a coupled model of a building and an elevator is proposed. In this method, a controller selects a proper control objective and prevents the saturation of the control force considering the intensity of the ground motion and the associated building response level. For preventing saturation, the maximum required control force is estimated on the basis of the square root of sum of squares (SRSS) method using the input ground acceleration. The effectiveness of the proposed method is verified by a time-history analysis. The analysis is performed using the long-period ground motion record of the 2011 off the Pacific coast of Tohoku Earthquake, 100 simulated waves with the peak ground velocity of about 25 cm/s$^2$ and 300 waves obtained by scaling the simulated waves.

*Keywords: Vibration control, Seismic response, Variable gain, Multi-control objectives, Saturated control*

## 1. INTRODUCTION

It is significant to maintain elevator functions from the perspective of fire fighting, rescue operation, evacuation activities of elderly or disabled people, and dwelling of people living in upper floors. Seismic damage of elevators has been reported in recent earthquakes such as the 2011 off the Pacific coast of Tohoku Earthquake. Elevator ropes swayed for a few minutes because of resonance vibration associated with long-period ground motion at high-rise buildings situated far from the epicentre, and they got entangled with prominent objects in the elevator shaft. To date, active control devices for building structures have been designed and installed. Kohiyama and Baba (2010) have proposed a method where a control device for a building is used for maintaining the functioning of an elevator. For the control, it is important to maximize the control effects under the constrained capacity of the control force. Control force saturation causes not only control performance degradation but also instability. It is also desirable to use sufficient control force for suppressing the swaying of the rope that continues even after the building vibration becomes relatively small.

In this paper, a control method based on variable gain feedback for a coupled system of a building and an elevator is proposed to help choose the proper control objective (a building or an elevator rope) that prevents saturation of the control force considering the intensity of the ground motion and level of the building response.

## 2. ANALYSIS MODEL

The analysis model shown in Fig. 2.1 is a coupled model consisting of an elevator and a high-rise building in which a vibration control device, e.g. an active mass damper or a connected control device, is installed on the top layer. In this model, vibration in the horizontal shear direction only is considered as the vertical and rotational vibrations are low in intensity in this type of system. The building and the elevator rope are modelled as a mass-shear spring model with $N_f$ layers and $N_r$ finite elements, respectively (Otsuki et al., 2005). In this study, the elevator cage is assumed to remain at the $j$-th layer of the building, and the main rope by which the cage is suspended is considered although there are many long ropes and cables in an elevator shaft. Considering the boundary conditions that the top edge of the rope is connected to the traction sheave and the elevator cage is connected to the $j$-th layer of the building, the motion equation of the analysis model is given by

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}\mathbf{x}(t)=-\mathbf{M}\{1\}\ddot{x}_{\mathrm{g}}(t)+\mathbf{f}u(t) \tag{2.1}$$

$$\mathbf{x}=\{x_{\mathrm{b}1}\quad x_{\mathrm{b}2}\quad\cdots\quad x_{\mathrm{b}j}\quad\cdots\quad x_{\mathrm{b}N_{\mathrm{f}}}\quad x_{\mathrm{r}1}\quad x_{\mathrm{r}2}\quad\cdots\quad x_{\mathrm{r}N_{\mathrm{r}}}\quad x_{\mathrm{r}(N_{\mathrm{r}}+1)}\}^{T} \tag{2.2}$$

$$\mathbf{f}=\{f_1\quad\cdots\quad f_k\quad\cdots\quad f_N\}^{T},\ f_k=\begin{cases}0 & k\neq N_f\\ 1 & k=N_f\end{cases} \tag{2.3}$$

where **M**, **C**, **K**, **x**, $x_{\mathrm{g}}$ and **f** represent the mass, damping, stiffness matrices, the displacement vector of the layers relative to the building foundation, the absolute displacement of the building foundation and the distribution vector of the control force $u$, respectively. The physical parameters are shown in Table 2.1. The building parameters are defined on the basis of an actual building and the elevator parameters are taken from previous studies (Otsuki et al., 2005; Otsuki et al., 2006). The stiffness of the $n$-th layer $k_{\mathrm{b}n}$ is determined using the $A_i$ distribution prescribed by the Building Standard Law of Japan and it is assumed to be linear elastic; the intensity of ground motion is assumed to be sufficiently small so that the building is not structurally damaged. The damping coefficient of the $n$-th layer $c_{\mathrm{b}n}$, which is proportional to stiffness, is given by Eqn. 2.4 using the fundamental period $T_{\mathrm{b}1}$ and the damping factor $\zeta_{\mathrm{b}}$.

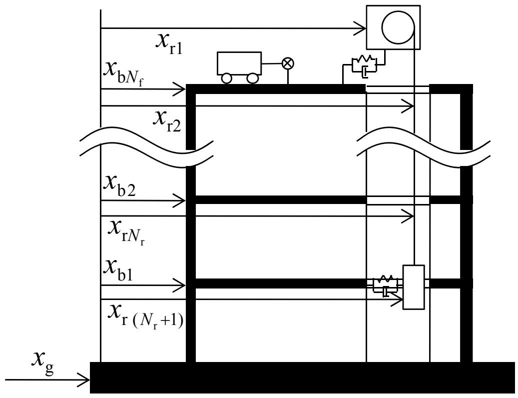



**Figure 2.1.** Analysis model

**Table 2.1.** Physical parameters

| Parameter | Symbol | Value |
|---|---|---|
| Layer height (twice of the story height) | – | 8.0 m |
| Number of layers (half of the number of stories) | $N_{\mathrm{f}}$ | 30 |
| Fundamental period of the building | $T_{\mathrm{b}1}$ | 5.8 s |
| Damping factor of the building | $\zeta_{\mathrm{b}}$ | 0.01 |
| Mass of the $n$-th layer of the building | – | $2.0 \times 10^6$ kg |
| Mass of the traction sheave | – | $1.9 \times 10^4$ kg |
| Stiffness between the traction sheave and the top layer of the building | – | $3.0 \times 10^6$ kg/s$^2$ |
| Damping coefficient between the traction sheave and the top layer of the building | – | $4.7 \times 10^4$ kg/s |
| Mass of the elevator cage | – | $7.5 \times 10^3$ kg |
| Line density of the elevator rope | – | 1.7 kg/m |
| Stiffness between the elevator cage and the building | – | $2.7 \times 10^5$ kg/s$^2$ |
| Damping coefficient between the elevator cage and the building | – | $9.0 \times 10^3$ kg/s |
| Damping ratio of the elevator rope | – | 0.008 |
| Division number of the elevator rope | $N_{\mathrm{r}}$ | 29 |
| Position of the elevator cage (layer number) | $j$ | 1 |
| Distance between the $N_{\mathrm{f}}$-th layer and the traction sheave | – | 0 m |

$$c_{bn} = (\zeta_b T_{b1} / \pi) k_{bn} \qquad (n = 1, 2, \ldots, N_f) \tag{2.4}$$

Since the purpose of this study is to verify the effectiveness of the control method, the elevator cage is assumed to remain at the lowest layer of the building in order for the rope to sway widely (Kohiyama and Kita, 2011). However, there are multiple elevators in an actual high-rise building, and there are many types of elevators, positions of an elevator cage, and so on. In a future study, we will extend the control method to consider these cases. For the elevator rope model, Kimura et al. (2008) showed that by dividing the elevator rope model into more than 20 elements, the response error rate becomes less than about 10%, thus the division number $N_r = 29$ is adopted.

## 3. FREQUENCY-SHAPED LINEAR QUADRATIC GAUSSIAN (LQG) CONTROL

The control method is constructed on the basis of the evaluation function of the linear quadratic regulator (LQR) control. For the basic LQR controls, the controlled output equation of the absolute acceleration of the building $\mathbf{y}_a$, the controlled output equation of the interstory drift of the building $\mathbf{y}_s$, and the controlled output equation of the distance between the building and the elevator rope $\mathbf{y}_r$ are given using the state vector $\mathbf{x}_{ss} = \{\mathbf{x}^T \quad \dot{\mathbf{x}}^T\}^T$ :

$$\mathbf{y}_a(t) = \mathbf{C}_a \mathbf{x}_{ss}(t) + \mathbf{d}_a u(t) \tag{3.1}$$

$$\mathbf{y}_s(t) = \mathbf{C}_s \mathbf{x}_{ss}(t) \tag{3.2}$$

$$\mathbf{y}_r(t) = \mathbf{C}_r \mathbf{x}_{ss}(t) \tag{3.3}$$

Regarding the evaluation function of the LQR control, the trade-off between responses and control force has to be considered. In addition, the difference in order between the responses of the control objectives influences the control performance. In this study, the control objectives are dimensionless (Miura and Kohiyama, 2012) using the following performance objectives:

$$\mathbf{C}'_a = \mathbf{C}_a / \{N(1.3\,\mathrm{m/s^2})\} \tag{3.4}$$

$$\mathbf{d}'_a = \mathbf{d}_a / \{N(1.3\,\mathrm{m/s^2})\} \tag{3.5}$$

$$\mathbf{C}'_s = \mathbf{C}_s / \{N(5 \times 10^{-3}\,\mathrm{rad})\} \tag{3.6}$$

$$\mathbf{C}'_r = \mathbf{C}_r / \{(N_r + 1)(0.3\,\mathrm{m})\} \tag{3.7}$$

- The interstory drift angle of the building is 1/200 rad, and this angle is to be suppressed below 1/200 rad so that the structural deformation is in the elastic region.
- The absolute acceleration of the building is 1.3 m/s$^2$, and this value is based on the evacuation capability. The relation between the evacuation capability and absolute acceleration is based on the limit curve of evacuation under a sinusoidal wave (Takahashi et al., 2007), and the absolute acceleration is 1.3 m/s$^2$ at the fundamental period ($T_{b1}$ = 5.8 s), where the building response tends to dominate.
- The distance between the building and the elevator rope is 0.3 m. This distance value is the threshold for an elevator rope possibly tangled by prominent objects in an elevator shaft (Kohiyama and Kita, 2011), however this value may differ according to the type of elevator.

It is shown that the interstory control in the low-frequency range and the absolute acceleration control for a building in the high-frequency range effectively suppress the vibrations in a high-rise building. Furthermore, the distance control in the low-frequency range and absolute acceleration control for a building in the high-frequency range is preferred for the vibration suppression of elevator rope (Kohiyama and Baba, 2010). Thus, using the frequency-shaped LQG method (Gupta, 1980), where the control objectives are multiplied by weighting functions in the frequency domain, the evaluation function for the vibration suppression of the building $J_b$ and that for the vibration suppression of the elevator rope $J_r$ are constructed (Kohiyama and Baba, 2010). For the weighting functions, a high-pass filter $\overline{Q}_{\mathrm{H}}$ and a low-pass filter $\overline{Q}_{\mathrm{L}}$ are used.

$$\overline{Q}_{\mathrm{H}}(s) = \{s^2 / (s^2 + 2\zeta_{\mathrm{H}}\omega_{\mathrm{H}} s + \omega_{\mathrm{H}}^2)\}^2 \tag{3.8}$$

$$\overline{Q}_{\mathrm{L}}(s) = \{\omega_{\mathrm{L}}^2 / (s^2 + 2\zeta_{\mathrm{L}}\omega_{\mathrm{L}} s + \omega_{\mathrm{L}}^2)\}^2 \tag{3.9}$$

where $\zeta_{\mathrm{H}} = \zeta_{\mathrm{L}} = 0.6$, $\omega_{\mathrm{H}}/2\pi = \omega_{\mathrm{L}}/2\pi = 1.5$ Hz.

## 4. EVALUATION FUNCTION FOR VARIABLE GAIN CONTROL

To resolve the saturation of the control force, the variable gain control method (Nagashima et al., 1996) is applied, which switches the control laws. Considering the limit of the control force $u_{\mathrm{lim}}$, the control input $u_{\mathrm{inp}}$ is given by the following relation:

$$u_{\mathrm{inp}}(t) = \begin{cases} u(t) & |u(t)| \le u_{\mathrm{lim}} \\ u_{\mathrm{lim}}\mathrm{sign}(u(t)) & |u(t)| > u_{\mathrm{lim}} \end{cases} \tag{4.1}$$

To use the control device effectively, it is important to use a control force of proper intensity for proper control objectives. Kohiyama and Baba (2010) proposed the variable gain feedback control that suppresses the response of the elevator rope rather than the building when the building vibration is sufficiently small. They demonstrated the effectiveness of this switching method in control of a building–elevator system. Thus, in this study, a variable gain feedback control using two variables is proposed, and feedback gains are adjusted considering the control objectives and control force. As the stability of the gains used in the variable gain feedback control has been checked, the method can suppress the spillover unsteadiness in the higher modes (Nagashima et al., 1996).

The evaluation function $J$ is a linear combination of the two cost functions of the building and elevator rope, $J_{\mathrm{b}}$ and $J_{\mathrm{r}}$, in which the weighting function $g_{\mathrm{b}}(\alpha)$ is used, and the control force is regulated by the weighting function $R(\beta)$:

$$\begin{aligned} J &= g_{\mathrm{b}}(\alpha)J_{\mathrm{b}}(\beta) + (1 - g_{\mathrm{b}}(\alpha))J_{\mathrm{r}}(\beta) \\ &= g_{\mathrm{b}}(\alpha)E[\mathbf{z}_{\mathrm{b}}^T(t)\mathbf{z}_{\mathrm{b}}(t) + R(\beta)u^2(t)] + (1 - g_{\mathrm{b}}(\alpha))E[\mathbf{z}_{\mathrm{r}}^T(t)\mathbf{z}_{\mathrm{r}}(t) + R(\beta)u^2(t)] \end{aligned} \tag{4.2}$$

where $\mathbf{z}_{\mathrm{b}}$ and $\mathbf{z}_{\mathrm{r}}$ represent the controlled output vectors extended for the frequency filters, and indices b and r represent the values for the building and elevator rope controls, respectively. This LQG control aims at reducing the average response in the height direction, as the elevator rope also vibrates in higher modes. The weighting functions in the evaluation function $J$ are formulated as follows (Nagashima et al., 1996; Kohiyama and Baba, 2010). First, the weighting functions $g_{\mathrm{b}}(\alpha)$ and $R(\beta)$ are set:

$$g_{\mathrm{b}}(\alpha) = a_{\mathrm{b}} \exp(\alpha / b_{\mathrm{b}}) \tag{4.3}$$

$$R(\beta) = a_R \exp(\beta / b_R) \tag{4.4}$$

Second, the maximum and minimum values of the function $g_{\mathrm{b}}(\alpha)$, $g_{\mathrm{bH}}$ and $g_{\mathrm{bL}}$, are given by Eqns. 4.5 and 4.6 using the minimum and maximum values of $\alpha$, $\alpha_{\mathrm{min}}$ and $\alpha_{\mathrm{max}}$, respectively. Similarly, the maximum and minimum values of the function $R(\beta)$, $R_{\mathrm{H}}$ and $R_{\mathrm{L}}$, are given by Eqns. 4.7 and 4.8 using the minimum and maximum values of $\beta$, $\beta_{\mathrm{min}}$ and $\beta_{\mathrm{max}}$, respectively.

$$g_{\mathrm{bH}} = g_{\mathrm{b}}(\alpha_{\mathrm{min}}) = a_{\mathrm{b}} \exp(\alpha_{\mathrm{min}} / b_{\mathrm{b}}) \tag{4.5}$$

$$g_{\mathrm{bL}} = g_{\mathrm{b}}(\alpha_{\mathrm{max}}) = a_{\mathrm{b}} \exp(\alpha_{\mathrm{max}} / b_{\mathrm{b}}) \tag{4.6}$$

$$R_{\mathrm{H}} = R(\beta_{\mathrm{min}}) = a_R \exp(\beta_{\mathrm{min}} / b_R) \tag{4.7}$$

$$R_{\mathrm{L}} = R(\beta_{\max}) = a_R \exp(\beta_{\max}/b_R) \tag{4.8}$$

Finally, the coefficients $a_{\mathrm{b}}$, $b_{\mathrm{b}}$, $a_R$ and $b_R$ calculated by Eqns. 4.6–4.8 give

$$g_{\mathrm{b}}(\alpha) = g_{\mathrm{bL}} \left(g_{\mathrm{bH}}/g_{\mathrm{bL}}\right)^{\frac{\alpha_{\max}}{\alpha_{\max}-\alpha_{\min}}} \exp\{-\alpha/(\alpha_{\max}-\alpha_{\min})\ln(g_{\mathrm{bH}}/g_{\mathrm{bL}})\} \tag{4.9}$$

$$R(\beta) = R_{\mathrm{L}} \left(R_{\mathrm{H}}/R_{\mathrm{L}}\right)^{\frac{\beta_{\max}}{\beta_{\max}-\beta_{\min}}} \exp\{-\beta/(\beta_{\max}-\beta_{\min})\ln(R_{\mathrm{H}}/R_{\mathrm{L}})\} \tag{4.10}$$

The parameter values are listed in Table 4.1. Using the weighting functions $g_{\mathrm{b}}(\alpha)$ and $R(\beta)$, the feedback gain $\mathbf{G}_{\mathrm{f}}$ is given as a discrete value $\mathbf{G}_{\mathrm{f}ij}$ for discrete ($\alpha_i$, $\beta_j$). In this study, the gain is linearly interpolated. As the standard setting of a P wave sensor is 0.025, 0.05 or 0.1 m/s$^2$ (Japan Building Equipment and Elevator Center Foundation and Japan Elevator Association, 2009), the update of the feedback gain starts when the observed acceleration at the foundation exceeds 0.05 m/s$^2$.

**Table 4.1.** Parameter values for variable gain

| Symbol | Value | Symbol | Value |
|---|---|---|---|
| $g_{\mathrm{bL}}$ | $1.0 \times 10^{-2}$ | $R_{\mathrm{L}}$ | $1.0 \times 10^{-20}$ |
| $g_{\mathrm{bH}}$ | 1.0 | $R_{\mathrm{H}}$ | $1.0 \times 10^{-6}$ |
| $\alpha$ | 0.00, 0.01, …,1.00 | $\beta$ | 0.00, 0.01, …,1.00 |

## 5. UPDATING METHOD OF PARAMETERS FOR GAINS

We assume that $\alpha$ and $\beta$ are independent of each other.

### 5.1. Updating method of $\boldsymbol{\beta}$

The control force $u(t)$ that minimizes the evaluation function $J$ is given by Eqn. 5.1. To estimate the maximum required control force, first, the feedback gain $\mathbf{G}_{\mathrm{f}}$ is separated into the displacement gain $\mathbf{G}_{\mathrm{fd}}$ and the velocity gain $\mathbf{G}_{\mathrm{fv}}$, then the control force is rewritten as the linear combination of the displacement and velocity terms as follows:

$$u(t) = -\mathbf{G}_{\mathrm{f}}\mathbf{x}_{\mathrm{ss}}(t) = -\mathbf{G}_{\mathrm{fd}}\mathbf{x}(t) - \mathbf{G}_{\mathrm{fv}}\dot{\mathbf{x}}(t) \tag{5.1}$$

However, when the displacement takes extremal values, the velocity is equal to zero; in contrast, when the velocity takes extremal values, the displacement is nearly equal to zero. Thus, the maximum required control force can be estimated omitting either the displacement or the velocity term from the calculation. When comparing the maximum absolute value of all gain components, the displacement gain components are more than 10 s$^{-1}$ times as large as those of the velocity gain. Considering a simple harmonic motion at the $k$-th mode, the relation between the modal displacement amplitude $|x_k|$ and the modal velocity amplitude $|\dot{x}_k|$ is given by Eqn. 5.2 using the $k$-th natural period $T_k$.

$$|\dot{x}_k| = 2\pi|x_k|/T_k \qquad (k = 1, 2, ...) \tag{5.2}$$

By substituting the natural periods shown in Table 5.1 for $T_k$, it can be deduced that the ratio of the velocity response to the displacement is not more than 10 s$^{-1}$ at the first to 14th modes. Thus, the maximum required control force is estimated using the influential displacement response.

**Table 5.1.** Natural periods

| Mode | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [s] | 5.8 | 4.7 | 2.3 | 2.2 | 1.6 | 1.4 | 1.2 | 1.0 | 1.0 | 0.93 | 0.78 | 0.77 | 0.65 | 0.65 | 0.57 |

In this study, the maximum required control force is estimated on the basis of modal analysis. There are several kinds of modal analysis; the square root of sum of squares (SRSS) method (Der Kiureghian,

1981) is effective in estimating the maximum response of a system in which the modes are separated from each other. In contrast, in a system where the phase difference and correlation among modes are important, a method that can consider modal correlation, e.g. the complete quadratic combination (CQC) method (Der Kiureghian, 1980), is more effective. Furthermore, a method which can be applied to a non-proportional damping system, e.g. the complex complete quadratic combination (CCQC) method (Zhou et al., 2004), is proposed. Although it is better to use the method for the non-proportional damping system for accurate estimation, the method requires computation time and is not appropriate for real-time control. The computation time of the CCQC method is about 10 times longer than that of the SRSS method. Comparing the estimation based on the CQC method with that based on the SRSS method, the difference is smaller than 10% of the range of $\beta$. This is because the maximum absolute value of the gain components is of the displacement gain, which is multiplied by the displacement near the top layer of the building to obtain the control force, and the displacement is not considerably excited by higher modes. Thus, in this study, the maximum required control force is estimated on the basis of the SRSS method.

First, using the mass matrix $\mathbf{M}$ and the stiffness matrix $\mathbf{K}$, the $k$-th natural circular frequency $\omega_k$ and the $k$-th eigenvector $\boldsymbol{\varphi}_k$ are computed. Then, ignoring the effects of the non-proportional damping for simplicity, the $k$-th modal damping factor $\zeta_k$ and the $k$-th modal participation factor $\gamma_k$ are calculated. The estimated maximum response using the SRSS method is given by

$$\left|x_j\right|_{\max} \approx \sqrt{\sum_{k=1}^{s} (\gamma_k \varphi_{kj} S_{\mathrm{D}}(\zeta_k, \omega_k))^2} \tag{5.3}$$

where $S_{\mathrm{D}}$, $s$, and $\varphi_{kj}$ are the displacement response spectrum, the number of considered modes, and the $j$-th component of $\boldsymbol{\varphi}_k$, respectively. On the basis of Eqn. 5.3, the maximum required control force $u_{\mathrm{exp}}$ is estimated as follows:

$$u_{\mathrm{exp}} \approx \sqrt{\sum_{k=1}^{s} \left\{ \sum_{j=1}^{N_{\mathrm{f}}+N_{\mathrm{r}}+1} g_{\mathrm{fd}j} \gamma_k \varphi_{kj} S_{\mathrm{D}}(\zeta_k, \omega_k) \right\}^2} \tag{5.4}$$

where $g_{\mathrm{fd}j}$ is the $j$-th component of $\mathbf{G}_{\mathrm{fd}}$. In this method, the displacement response spectrum $S_{\mathrm{D}}$ is computed using ground acceleration data for past $\Delta t_{\mathrm{rec}}$. The evaluation duration of the ground acceleration, $\Delta t_{\mathrm{rec}}$, is given so that $\Delta t_{\mathrm{rec}} \geq T_{\mathrm{b1}}$ in order to evaluate the first mode vibration, which tends to dominate. Actually, as the vibration characteristics of the system ($\omega_k$ and $\zeta_k$) change according to the control force, $S_{\mathrm{D}}$ should be calculated for the following equivalent uncontrolled system:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + (\mathbf{C} + \mathbf{f}\mathbf{G}_{\mathrm{fv}})\dot{\mathbf{x}}(t) + (\mathbf{K} + \mathbf{f}\mathbf{G}_{\mathrm{fd}})\mathbf{x}(t) = -\mathbf{M}\{1\}\ddot{x}_{\mathrm{g}}(t) \tag{5.5}$$

However, it requires considerable time to reliably calculate $\omega_k(t)$ and $\zeta_k(t)$ of the equivalent system for past $\Delta t_{\mathrm{rec}}$. Thus, in this study, it is assumed that $\omega_k(t)$ and $\zeta_k(t)$ are those of the uncontrolled system. In addition, introducing the safety factor $\rho_{\mathrm{u}}$, $\beta$ is updated for the estimated maximum required control force $u_{\mathrm{exp}}$ in order to satisfy Eqn. 5.6.

$$u_{\mathrm{exp}} \leq u_{\mathrm{lim}} \rho_{\mathrm{u}} \tag{5.6}$$

However, when the ground acceleration for past $\Delta t_{\mathrm{rec}}$ is small, its displacement response spectrum $S_{\mathrm{D}}$ is small even if the seismic response is influenced by past input. In this case, the estimation of the maximum required control force might be underestimated. Thus, in the case that the displacement response spectrum $S_{\mathrm{D}}(\zeta_{\mathrm{b}}, T \mid T \leq T_{\mathrm{b1}})$ is smaller than the threshold value $S_{\mathrm{Dlim}}$, the following method (Nagashima et al., 1996) is applied. However, in this study, the parameters are updated using not predictive responses but data for past $\Delta t_{\mathrm{est}}$; $\Delta t_{\mathrm{est}} = T_{\mathrm{b1}}/2$ is given to evaluate the vibration antinode. Based on $u_{\mathrm{exp}}$ for the past $\Delta t_{\mathrm{est}}$, the margin $\eta_\beta(t)$ of the control force to $u_{\mathrm{lim}}$ is given by Eqn. 5.7. Then, $\beta$

is updated by Eqn. 5.8 using the updating weight $\Delta\beta$.

$$\eta_\beta(t) = 1 - \max_{t-\Delta t_{\mathrm{est}} \le \tau \le t} (|u(\tau)|/u_{\mathrm{lim}}) \tag{5.7}$$

$$\beta_{i+1} = \beta_i + \Delta\beta\eta_\beta(t) \tag{5.8}$$

### 5.2. Updating method of *α*

The method proposed by Kohiyama and Baba (2010) is applied to update the parameter $\alpha$. However, in this study, the parameters are updated using not predictive responses but data for the past $\Delta t_{\mathrm{est}}$ (= $T_{\mathrm{b1}}/2$). The margin $\eta_\alpha(t)$ of the interstory drift to the threshold $x_{\mathrm{thr}}$ is computed by Eqn. 5.9. Then, $\alpha$ is updated by Eqn. 5.10 using the updating weight $\Delta\alpha$.

$$\eta_\alpha(t) = 1 - \max_{t-\Delta t_{\mathrm{est}} \le \tau \le t} \{\max_k(|x_k(\tau) - x_{k-1}(\tau)|/x_{\mathrm{thr}})\} \tag{5.9}$$

$$\alpha_{i+1} = \alpha_i + \Delta\alpha\eta_\alpha(t) \tag{5.10}$$

### 5.3. Parameters and algorithm

The parameters $\Delta\alpha$ and $\Delta\beta$ govern the rapid response of the variable gain control, and they are determined using previous studies (Kohiyama and Baba, 2010: Nagashima et al., 1996) as reference; consequently, the value change of $\alpha$ and $\beta$ in an updating interval is not large compared with the ranges of $\alpha$ and $\beta$. The initial value of $\alpha$ is set to 0 in order to control the building vibration first. The initial value of $\beta$ is chosen to be 0.46, as $\beta$ changes around 0.46 when controlling the vibration under the excitation of ‘Level 1’ wave, which is based on the design acceleration response spectrum defined in the Notification No. 1461 of the Japanese Ministry of Construction in 2000. The values of the parameters are listed in Table 5.2.

**Table 5.2.** Parameter values for updating $\alpha$ and $\beta$

| Parameter | Symbol | Value |
|---|---|---|
| Time step of analysis | $\Delta t$ | 0.005 s |
| Threshold value for switching control objectives | $x_{\mathrm{thr}}$ | $h \times 10^{-3}$m |
| Capacity of control force | $u_{\mathrm{lim}}$ | 500 kN |
| The initial value of $\alpha$ | $\alpha_{\mathrm{ini}}$ | 0.000 |
| The initial value of $\beta$ | $\beta_{\mathrm{ini}}$ | 0.460 |
| Updating weight of $\alpha$ | $\Delta\alpha$ | 0.002 |
| Updating weight of $\beta$ | $\Delta\beta$ | 0.001 |
| Updating interval | – | 0.1 s |
| Evaluating time of responses and control force | $\Delta t_{\mathrm{est}}$ | $T_{\mathrm{b1}}/2$ |
| Evaluating time of ground acceleration | $\Delta t_{\mathrm{rec}}$ | $T_{\mathrm{b1}}$ |
| Threshold value for switching method | $S_{\mathrm{Dlim}}$ | 0.1 m |
| Number of considered modes | $s$ | 15 |
| Safety factor for control force | $\rho_{\mathrm{u}}$ | 0.9 |

## 6. RESULTS

The effectiveness of the proposed method is verified based on time-history analysis, comparing with the case that $\beta$ is fixed at the initial value $\beta_{\mathrm{ini}}$. The analysis is performed using a long-period ground motion record, 100 simulated ‘Level 1’ waves and 300 of the scaled waves, which are ‘Level 1’ waves scaled by 0.5, 1.5 and 2.0. The long-period ground motion is the NS component of the main shock record of the 2011 off the Pacific coast of Tohoku Earthquake observed at the ground surface at OSKH02 observation station, which is provided through the KiK-net database by the National Research Institute for Earth Science and Disaster Prevention. This record is chosen as elevator damage was reported near the station. The 100 simulated waves are evaluated as waves at an outcrop of engineering bedrock, and their phases are randomly assigned. The distribution of the central frequency, in which the power spectral density takes the maximum value, and the maximum acceleration of the ground motion are shown in Fig. 6.1. In addition, the intensity of these ground motions is so small that the interstory drift is less than 1/200 rad even in the uncontrolled cases. Thus, the building stiffness is assumed to be linear elastic. The dynamic analysis is carried out for a time twice as much as the duration of the input motion.

For the simulated waves, the reduction rate of the maximum response value, $r_{\max}$, and that of the root-mean-square (RMS) value, $r_{\text{RMS}}$, defined respectively by Eqns. 6.1 and 6.2 are listed in Table 6.1. In this case, since the elevator rope does not vibrate widely after the response of the building is suppressed, the difference between the two controlled cases is small.

$$r_{\max} = \frac{1}{400}\sum_{w=1}^{400}\frac{\text{The average of controlled maximum response in height direction}}{\text{The average of uncontrolled maximum response in height direction}} \tag{6.1}$$

$$r_{\text{RMS}} = \frac{1}{400}\sum_{w=1}^{400}\frac{\text{The average of controlled RMS value in height direction}}{\text{The average of uncontrolled RMS value in height direction}} \tag{6.2}$$

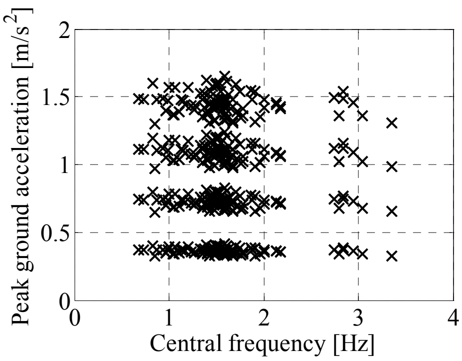



**Figure 6.1.** Four hundred simulated waves

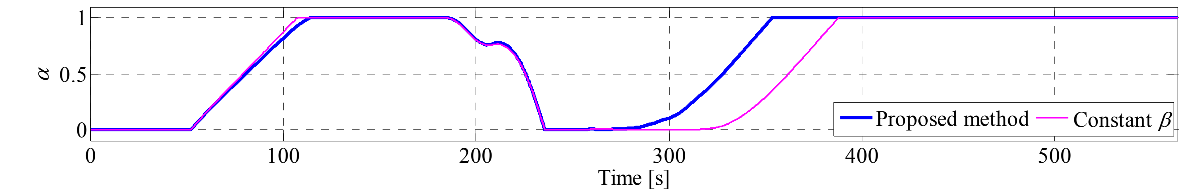
**Table 6.1.** Response reduction rate under the excitation of simulated waves
(a) Maximum value

| | | Absolute acceleration | | Interstory drift | | Rope sway | |
|---|---|---|---|---|---|---|---|
| Control method | | Proposed method | Constant $\beta$ | Proposed method | Constant $\beta$ | Proposed method | Constant $\beta$ |
| Scaling factor | 0.5 | 80.75% | 81.44% | 64.69% | 66.24% | 43.31% | 45.01% |
| | 1.0 | 85.91% | 86.05% | 77.95% | 78.11% | 64.84% | 65.81% |
| | 1.5 | 92.05% | 92.79% | 93.12% | 93.75% | 90.68% | 92.35% |
| | 2.0 | 94.53% | 94.54% | 96.02% | 96.13% | 94.98% | 95.55% |

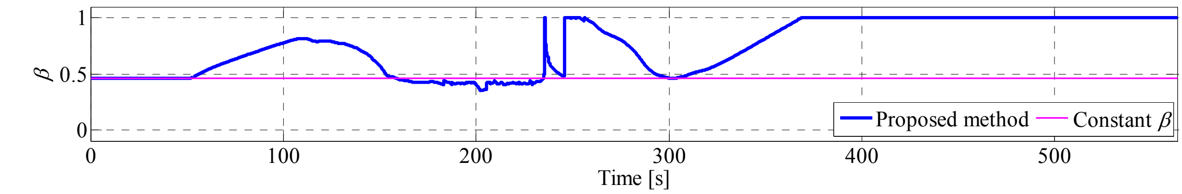
(b) RMS value

| | | Absolute acceleration | | Interstory drift | | Rope sway | |
|---|---|---|---|---|---|---|---|
| Control method | | Proposed method | Constant $\beta$ | Proposed method | Constant $\beta$ | Proposed method | Constant $\beta$ |
| Scaling factor | 0.5 | 87.01% | 87.05% | 43.41% | 44.19% | 29.67% | 30.90% |
| | 1.0 | 89.98% | 90.40% | 60.02% | 61.01% | 50.25% | 51.93% |
| | 1.5 | 94.93% | 96.35% | 86.16% | 89.50% | 83.79% | 87.26% |
| | 2.0 | 96.39% | 97.27% | 91.85% | 94.07% | 91.62% | 93.74% |

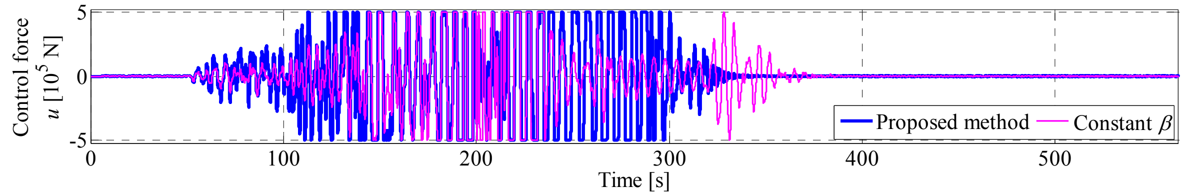
The results in the case that the input acceleration is the long-period ground motion record are shown in Fig. 6.2. The proposed method can decrease the building and elevator responses sooner than the method in which $\beta$ is constant. Especially, the control device works effectively after 280 s when the building response becomes small. Although the weight $R(\beta)$ is set for the estimated maximum required control force to be within 90% of $u_{\text{lim}}$ with parameter $\rho_u$, the control force saturates. The reason may be that input energy of the ground motion before the evaluation duration $\Delta t_{rec}$ cannot be evaluated and the estimated maximum control force is smaller. With respect to the weight $g_b(\alpha)$, as the suppression of the building response is faster when using the proposed method (Fig. 6.2 e)), the control objective switches to the elevator rope control earlier (Fig. 6.2 a)).



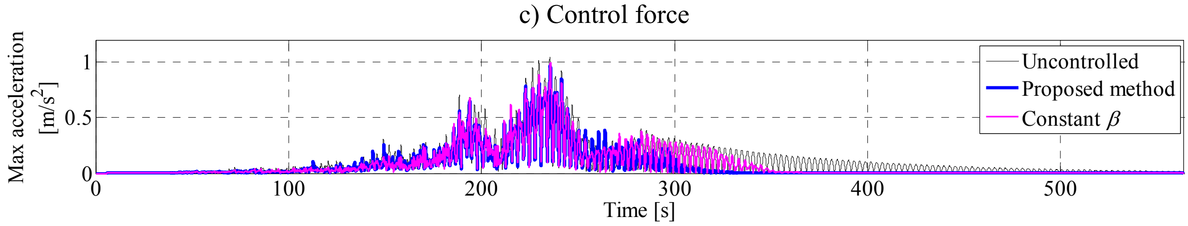

a) Parameter for switching control objectives, $\alpha$



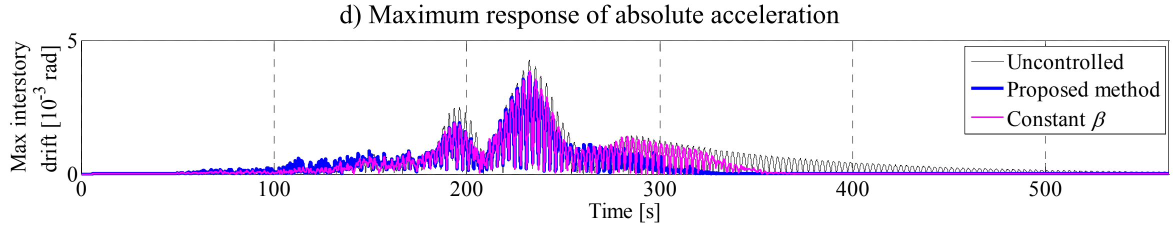

b) Parameter for adjusting control force, $\beta$



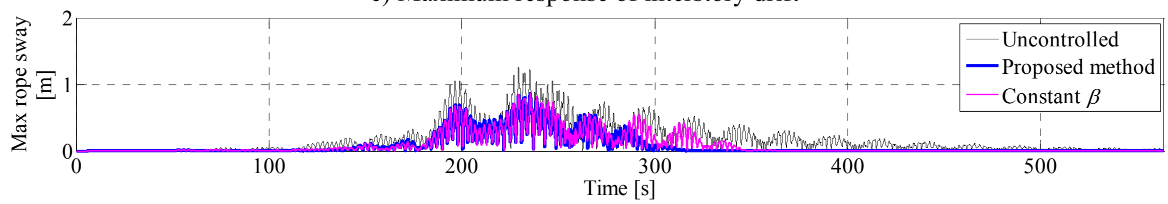

c) Control force




d) Maximum response of absolute acceleration




e) Maximum response of interstory drift




f) Maximum response of distance between building and elevator rope

**Figure 6.2.** Time-history responses (KiK-net record of the 2011 off the Pacific coast of Tohoku Earthquake)

## 7. CONCLUSIONS

For suppressing the response of a high-rise building–elevator coupled system, an algorithm based on variable gain feedback to update the feedback gains is proposed in order to use the control force effectively. The controller examines the margin rates of the building response to its threshold and of the control force to the maximum required control force; the control force is estimated on the basis of the SRSS method using the ground acceleration. The result of the dynamic response analysis using a long-period ground motion record verified that the responses of both the building and elevator rope could be effectively decreased by choosing the proper control objective and preventing the saturation of the control force considering the ground motion intensity and level of building responses.

In future studies, we will extend the method to other elevator models, non-linear control and robust control considering the time lag of the control force and modelling error.

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