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Active/robust moment controllers for seismic response control of a large span building on top of ship lift towers

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Abstract

The feasibility of using a vertical ship lift to provide a rapid transfer of ships over a large dam is being actively investigated in China. One of the problems encountered in the feasibility study is how to reduce excessive seismic response of a large span machinery building on the top of huge ship lift towers due to a whipping effect. This paper thus explores the possibility of using active/robust piezoelectric moment controllers to prevent the machinery building without/with parameter uncertainty from the whipping effect. The use of moment controllers meets the special space requirement for the machinery building. Basic equations for piezoelectric moment controllers interacting with the building are first derived. The active control of seismic response of the building–ship lift tower system with moment controllers is then presented. The robust moment controllers for the building–ship lift tower system with structural uncertainty are finally addressed. By taking an actual large ship lift structure to be built in China as example, the effectiveness of the proposed moment controllers and the behavior of the controlled ship lift structure are examined. The results show that the active moment controllers can effectively prevent the whipping effect and reduce the seismic response of the building. In the presence of structural uncertainty, the robust moment controllers give superior performance to the active moment controllers but require larger control power.

1. Introduction

The feasibility of using a vertical ship lift to provide a rapid transfer of ships over a large dam is being actively investigated in China [1]. One of the problems encountered in the feasibility study is the design of ship lift structure. For a large dam with a large water level drop between the two

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sides of the dam, a ship lift structure possesses many unique features. In particular, the seismic resistant design of ship lift structure becomes a challenging task if the dam is located in a seismic zone.

Depicted in Fig. 1 is a bird's-eye view of a large dam with a one-stage vertical ship lift structure being constructed in China [1]. Figs. 2a and b show schematic elevation and plan views, respectively, of the one-stage vertical ship lift structure. It consists of four huge reinforced concrete towers with a thick reinforced concrete top platform. A single story steel–concrete machinery building is built on the platform. If ships are lifted between the towers using the lifting equipment installed directly on the top platform, the span of the machinery building must be large enough to accommodate the large lift equipment and the high cranes for maintenance (see Fig. 2a). Thus, no bracing systems can be used to increase the lateral stiffness of the building except for the two end walls of the building. The building roof is often made of a space truss system having high stiffness in the horizontal plane but lightweight and pin supported on the columns of the building. Since the ship lift towers are designed to carry very heavy loads, their lateral stiffness is much larger than that of the machinery building. The weight of the ship lift towers including the top platform is also much greater than that of the machinery building. As a result of seismic inputs, the machinery building may suffer from a whipping effect due to the sudden change of lateral stiffness and mass at the top platform. The seismic response of the building may be much greater than that of the building directly constructed on the ground.

Moreover, huge ship lift structures are rarely built and less commonly experienced by designers. The estimation of structural parameters in the design may involve some uncertainties. After construction, the building materials may deteriorate with time because of a harsh environment around the building. The structural properties of the building attributed from non-structural components, such as the two end filler walls of the machinery building, may also vary with time during earthquake. Therefore, an effective and robust response control of the large span

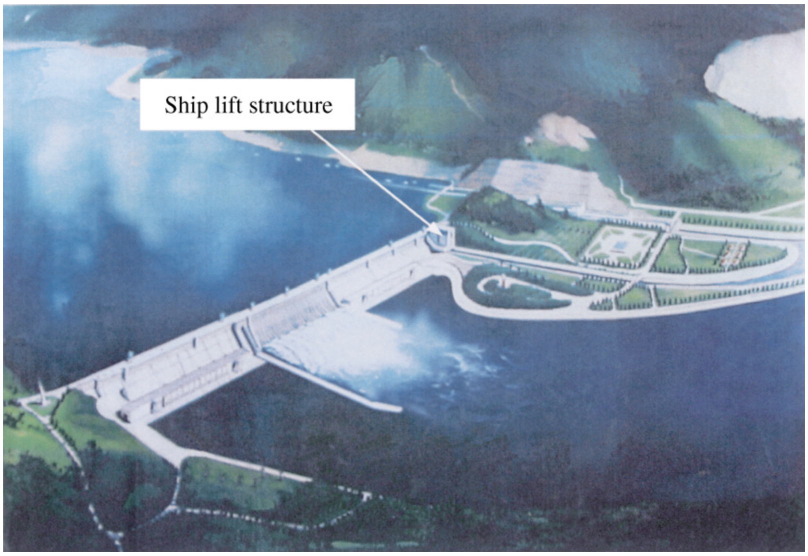

Fig. 1. Bird's-eye view of a large dam with a ship lift structure [1].

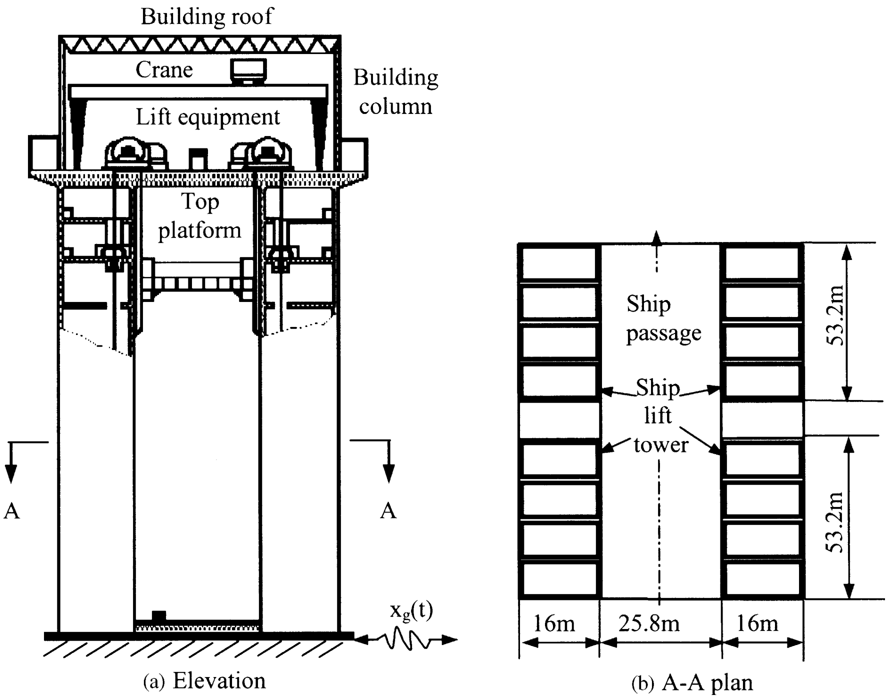

Fig. 2. Elevation and plan views of ship lift structure: (a) elevation; (b) $A-A$ plan.

machinery building subject to earthquake excitation becomes imperative towards a safety design of ship lift structure.

In this connection, this paper explores the possibility of using active/robust piezoelectric moment controllers to prevent the whipping effect and to reduce seismic response of the machinery building without/with parameter uncertainties. A piezoelectric moment controller comprises mainly a pair of pre-stressed piezoelectric actuators which provide a control moment to the building column through a lever system and a horizontal rigid arm rigidly connected to the building column (see Figs. 4 and 5). The use of a lever system can reduce the axial deformation of the piezoelectric actuator, caused by the rotation of rigid arm, to a great extent to ensure that piezoelectric actuators function properly. Under a horizontal earthquake excitation, the building roof will have a large horizontal displacement relative to the top platform, and the building column will be excessively bent accordingly. By actively controlling the moment controller according to the feedback of building response, the moment controller will then generate a moment against the column bending. Such an arrangement does not violate the requirement of a large span for the machinery building on the top of ship lift towers. A similar concept was studied by Kamada et al. [2] for the active control of seismic-excited frame structures using piezoelectric moment controllers. However, the piezoelectric moment controllers and control strategies they used for frame structures may not be suitable for the huge ship lift structure concerned in this study. They also did not address the effects of parameter uncertainty and the applicability of robust control.

In this paper, the basic equations for piezoelectric moment controllers interacting with the building are first derived and the active control of seismic response of the building–ship lift tower system is addressed. The robust control of the seismic response of the coupled system with structural parameter uncertainty is then presented. Finally, taking an actual large ship lift structure to be built in China as an example, the effectiveness of the proposed moment controllers and control algorithms is examined.

2. Moment controllers

As a first stage study, only the horizontal earthquake excitation perpendicular to the direction of ship passage is considered, for the ship lift structure has much higher stiffness in the direction of ship passage (Fig. 2b). It is also assumed that the ship is not in mid lift and thus the beating between ship pendulum motion and ship lift tower motion is not considered. The ship lift structure can be seen as a symmetric structure as shown in Fig. 3. Both the top platform and the building roof are modelled as horizontal rigid plates. The ship lift towers are modelled as lumped-mass systems. The towers are fixed at the ground and are rigidly connected to the top platform. The building columns are also rigidly connected to the top platform but pin connected to the building roof. The building columns are assumed to be massless. The moment controller is installed near the bottom of each building column (Fig. 4).

Under the horizontal earthquake excitation, the excessive displacement of the building roof relative to the top platform may cause the large bending moment in the column. The piezoelectric moment controller should therefore generate a control moment of proper magnitude and direction to reduce the relative displacement of the building roof and the bending moment in the building column. In fact, the control moment M_d can be seen to produce a horizontal control force u to the building roof to reduce its relative displacement (see Fig. 5). The control moment

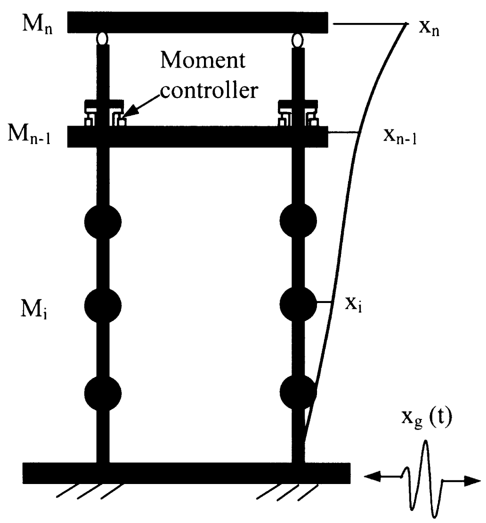

Fig. 3. Mechanical model of ship lift structure.

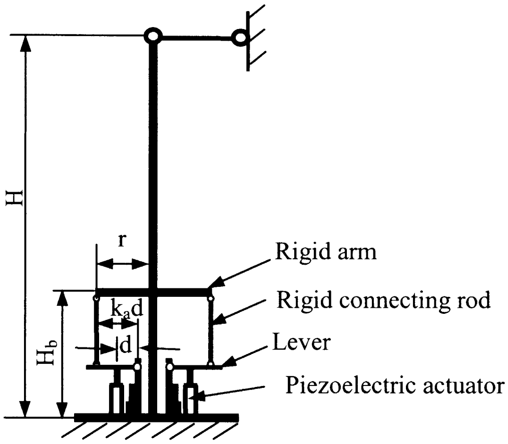

Fig. 4. Principle of moment controller.

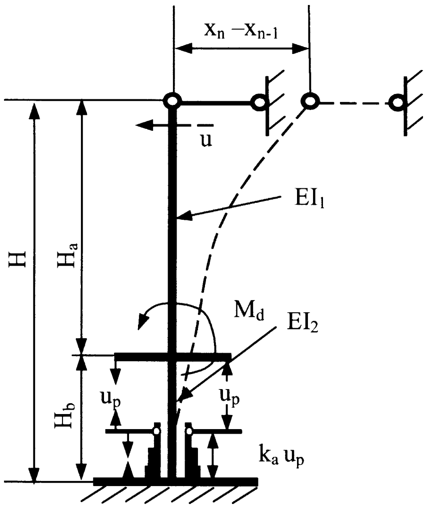

Fig. 5. Mechanical model of moment controller interacting with building.

M_d is in turn provided by a pair of control forces, u_p, which act on the rigid arm and originate from the two (or $2n_k$) piezoelectric actuators in a moment controller through the lever system. The relationship between the horizontal control force at the end of the building column and the control force acting on the rigid arm can be found as

$$u = \frac{H^2 - H_a^2}{EI_2\,\delta} r u_p, \tag{1}$$

in which

$$\delta = \alpha^3 \frac{H^3}{3EI_1} + (1 - \alpha^3)\frac{H^3}{3EI_2}, \quad \alpha = \frac{H_a}{H}, \tag{2}$$

where EI_1 and EI_2 represent the flexural rigidity of the column above and below the rigid arm, respectively; H is the height of the building column, H_a is the distance between the top of the column and the rigid arm of the moment controller, u_p is the control force acting on the rigid arm, r is the distance between the column axis and the control force u_p, and n_k is the number of piezoelectric actuators on one side of a column.

Piezoelectric material, a functional material which is widely used as both sensor and actuator in mechanical engineering and aeronautical engineering, is now attracting more and more attention in the field of vibration control of civil engineering structures [3]. Upon applying an electric charge or voltage to the piezoelectric material, it induces mechanical stress or strain, producing the so-called converse piezoelectric effect. This phenomenon is conceptually used in this study to generate a control moment against the deformation of building through a lever system and a rigid arm fixed on the building column (see Fig. 4). The control force induced by a piezoelectric actuator depends on the restraint of the axial deformation of piezoelectric material produced by the applied voltage, but the achievable axial deformation of the materials is very limited. Therefore, a lever system is designed to reduce the required axial deformation of the piezoelectric actuator due to the rotation of the rigid arm caused by the horizontal movement of the building. A voltage V_0 also has to be pre-applied to each piezoelectric actuator to generate a pre-compressive force of such magnitude that two actuators work always in compression. The piezoelectric actuator may be made of multiple layers to achieve the required control force and to allow certain amount of axial deformation. Taking all these factors into consideration, one may have the following relationship among the control force acting on the rigid arm, the applied voltage, and the vertical displacement of the rigid arm at the position of the rigid connecting rod due to the arm rotation:

$$u_p = -\left(\frac{d_{33}}{t} V \mp \frac{w}{b_a k_a}\right)\frac{E_p A_p n_k}{k_a}, \tag{3}$$

where d_{33} is one of the piezoelectric material constant in the normal mode, t is the thickness of each piezoelectric layer, V is the applied voltage increment with reference to V_0, b_a is the total thickness of a piezoelectric actuator, w is the vertical displacement of the rigid arm at the position of rigid connecting rod due to the arm rotation, k_a is the force amplification coefficient of the lever system, E_p is the equivalent Young's modulus of the piezoelectric material of multiple layers, A_p is the force-bearing area of one piezoelectric actuator, and the negative sign in the bracket is used for the actuator with a positive voltage increment while the positive sign is used for the actuator with a negative voltage increment.

The vertical displacement caused by the rotation of the rigid arm at the rigid connecting rod can be determined by

$$w = (\theta_b - \theta_M)r, \tag{4}$$

where θ_b is the angle of rotation of the rigid arm due to the displacement of the building roof relative to the top platform, and θ_M is the angle of rotation of the rigid arm due to the control moment M_d:

$$\theta_b = \frac{H^2 - H_a^2}{2EI_2\,\delta}(x_n - x_{n-1}), \tag{5}$$

$$\theta_M = \frac{H_b r}{EI_2}\left(2 - \frac{H_b(H+H_a)^2}{2EI_2\,\delta}\right)u_p, \tag{6}$$

where $(x_n - x_{n-1})$ represents the relative displacement (story drift) of the building roof, and H_b is the distance between the rigid arm and the top platform, which is equal to $H - H_a$. Eqs. (1), (3)–(6) constitute the basic equations for piezoelectric moment controllers used in the large span machinery building on the top of ship lift towers.

3. Active control of building

3.1. Equation of motion

The equation of motion of the controlled large span machinery building including the ship lift towers can be obtained as

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{1\}\ddot{x}_g(t) - [S]\{u_p\}, \tag{7}$$

where $\{x\}$, $\{\dot{x}\}$ and $\{\ddot{x}\}$ are the relative displacement vector, relative velocity vector and relative acceleration vector of n components with respect to the ground, respectively; $[M]$, $[C]$ and $[K]$ are the nxn mass matrix, damping matrix, and stiffness matrix of the ship lift structure, respectively; $\ddot{x}_g(t)$ is the ground acceleration, $\{u_p\}$ is the vector of control forces acting on the rigid arms and originated from the piezoelectric actuators, and $[S]$ is the matrix denoting the locations of the control forces at the rigid arms.

Assume that the machinery building has m columns and m moment controllers. $[S]$ is an nxm matrix and $\{u_p\}$ is a vector of m components:

$$[S] = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ -S_1 & -S_2 & \cdots & -S_{m-1} & -S_m \\ S_1 & S_2 & \cdots & S_{m-1} & S_m \end{bmatrix}, \tag{8}$$

in which

$$S_j = \frac{H_j^2 - H_{aj}^2}{EI_{2j}\,\delta_j} r_j \quad (j = 1, 2, \ldots, m). \tag{9}$$

Eq. (7) can be reformulated into a first order $2n$-dimensional equation in the state space.

$$\{\dot{z}\} = [A]\{z\} + [B]\{u_p\} + \{D\}\ddot{x}_g(t), \tag{10}$$

where

$$[A] = \begin{bmatrix} [0] & [I] \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix}, \quad [B] = \begin{bmatrix} [0] \\ -[M]^{-1}[S] \end{bmatrix}, \{D\} = \begin{bmatrix} \{0\} \\ -\{1\} \end{bmatrix} \{z\} = \begin{bmatrix} \{x\} \\ \{\dot{x}\} \end{bmatrix}. \tag{11}$$

3.2. Active control strategy

The performance index used in the linear quadratic regulator (LQR) algorithm is defined as [4]

$$J = \int_0^{t_f} \frac{1}{2}(\{z\}^{\mathrm{T}}[Q]\{z\} + \{u_p\}^{\mathrm{T}}[R]\{u_p\})\mathrm{d}t, \tag{12}$$

where $[Q]$ is the weighting matrix of displacement and velocity responses of the structure, it is an $2n \times 2n$ positive semi-definite matrix, $[R]$ is the weighting matrix for control force, it is $m \times m$ positive-definite matrix in this study, and t_f is a duration defined to be longer than that of the earthquake.

By using this performance index, one may adjust the two weighting matrices to have a trade-off between the response reduction and the control force and power required. For a close-loop control configuration, minimizing the performance index expressed by Eq. (12) subject to the constraint of Eq. (10) results in the following optimal control force vector:

$$\{u_p\} = -[R]^{-1}[B]^{\mathrm{T}}[P]\{z\}, \tag{13}$$

where $[P]$ is the solution of the following Riccati equation:

$$[P][A] + [A]^{\mathrm{T}}[P] - [P][B][R]^{-1}[B]^{\mathrm{T}}[P] + [Q] = [0]. \tag{14}$$

By numerically solving Eqs. (10) and (13), the seismic response of actively controlled ship lift structure and the control force or applied voltage from the actuators can be computed.

4. Robust control of building

Since the huge ship lift structures are not only rarely built and less commonly experienced by designers but also surrounded by a very harsh environment, the precise estimates or measurements of structural properties may be difficult and the degradation of building materials as a function of time may not be determined with confidence. Furthermore, during earthquake the structural properties due to non-structural components, such as the two end filler walls, may also vary with time. If this is the case, the robust control strategy may have to be sought to maintain control performance.

4.1. Equation of motion

For the large span machinery building on the top of ship lift towers, the most uncertain but important structural parameter is the lateral stiffness of the building due to the non-structural components in the two end filler walls. Accordingly, this study considers the uncertainty in the lateral stiffness of the building only. The equations of motion of the controlled ship lift structure with the uncertainty of lateral stiffness of the building can be written as

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + ([K] + [\Delta K])\{x\} = -[M]\{1\}\ddot{x}_g(t) - [S]\{u_p\}, \tag{15}$$

where

$$[\Delta K] = \begin{bmatrix} & & & & 0 \\ & & & & \vdots \\ & & [0] & & 0 \\ & & & & -C_k(t)k_n \\ 0, & \cdots, & 0 & -C_k(t)k_n & C_k(t)k_n \end{bmatrix}, \tag{16}$$

in which k_n is the total lateral stiffness of the machinery building, and $C_k(t)k_n$ represents the time-varying uncertainty of lateral stiffness of the machinery building. Eq. (15) can be written in the state-space form as follows:

$$\{\dot{z}\} = ([A] + [\Delta A])\{z\} + ([B] + [\Delta B])\{u_p\} + \{D\}\ddot{x}_g(t), \tag{17}$$

in which

$$[\Delta A] = \begin{bmatrix} [0] & [0] \\ -[M]^{-1}[\Delta K] & [0] \end{bmatrix}, \quad [\Delta B] = [0]. \tag{18}$$

The matrices $[\Delta A]$ and $[\Delta B]$ are called uncertain matrices. The inclusion of the zero matrix $[\Delta B]$ in Eqs. (17) and (18) is to facilitate the use of the existing robust linear quadratic optimal control law, as discussed in the following section.

4.2. Robust linear quadratic optimal control law

The main objective of a robust control is to design a control law to guarantee the stable and effective operation of active controllers for all possible variations of uncertain parameters of the structure. In the field of automatic control, Chen [5] developed a non-linear controller for stabilizing uncertain dynamic systems based on Lyapunov's direct method. Tsay et al. [6] and Ni and Wu [7] applied the conventional linear quadratic optimal state feedback design method to find the robust linear quadratic optimal control law for linear systems with uncertain parameters which satisfy some matching conditions. They also utilized the Lyapunov stability criterion to prove that the robust linear quadratic optimal control law can quadratically stabilize the uncertain system, even if the uncertainties are time varying. In the frequency domain, the H_∞ control law was developed to design a stabilizing controller in such a way that the infinity norm of the transfer function is minimized [8]. The H_∞ control law has been used by Schmitendorf et al. [9] for large structures subjected to earthquake.

The robust linear quadratic optimal control law suggested in Refs. [6,7] is simple yet effective. The uncertain parameter of the machinery building concerned in this study satisfies the matching conditions specified in the law. Thus, the robust linear quadratic optimal control law is used in this study. The performance index in the robust linear quadratic optimal control law is defined as

$$J = \int_0^{t_f} \tfrac{1}{2}(\{z\}^{\mathrm{T}}[\bar{Q}]\{z\} + \{u_p\}^{\mathrm{T}}[\bar{R}]\{u_p\})\,\mathrm{d}t. \tag{19}$$

The robust linear quadratic optimal control law states that if the uncertain matrices in Eq. (17) satisfy the following matching conditions:

$$[\Delta A] = [B][D(t)], \quad [\Delta B] = [B][E(t)], \tag{20}$$

$$2[I] + E(t) + [E(t)]^{\mathrm{T}} > \bar{\delta}[I], \quad \bar{\delta} \succ 0, \tag{21}$$

then, the feedback control

$$\{u_p\} = [F]\{z\}, \quad [F] = -\gamma[B]^{\mathrm{T}}[P], \tag{22}$$

makes the sructural system described by Eq. (17) quadratically stable. The coefficient γ meets the condition

$$\gamma > \frac{1}{\bar{\delta}}, \tag{23}$$

$[P]$ is the positive-definite solution of the Riccati equation.

$$[A]^{\mathrm{T}}[P] + [P][A] - [P][B][R]^{-1}[B]^{\mathrm{T}}[P] + [Q] = [0]. \tag{24}$$

The weighting matrices in the performance index specified by Eq. (19) are

$$[\bar{R}] = \frac{[I]}{\gamma\delta - 1}, \quad [\bar{Q}] \geq [D(t)]^{\mathrm{T}}[D(t)] + \varepsilon[I], \tag{25}$$

in which ε is an arbitrarily small positive number.

4.3. Applicability of robust control law

Now let us examine the applicability of the robust linear quadratic optimal control law for the machinery building on the top of ship lift towers. Because of the uncertain matrix $[\Delta B] = [0]$ in this problem, it follows that $[E(t)] = [0]$ according to the matching condition specified by Eq. (20). Then, the matching condition stipulated by Eq. (21) can be met if $\bar{\delta} < 2.0$. Furthermore, the stiffness uncertainty function $C_k(t)$ in Eq. (16) is assumed to take the form

$$C_k(t) = C_k\alpha(t), \quad |\alpha(t)| \leqslant 1.0, \tag{26}$$

where $\alpha(t)$ is the time-varying function describing the variation of the uncertain lateral stiffness of the building with time, and the value C_k is the maximum value of uncertain lateral stiffness of the building. The satisfaction of the first matching condition $[\Delta A] = [B][D(t)]$ then yields the matrix $[D(t)]$:

$$[D(t)] = [D]\alpha(t), \tag{27}$$

in which

$$[D] = \begin{bmatrix} 0, \ldots, 0, d_{n-1}, d_n, 0, \ldots, 0 \\ \cdots \\ 0, \ldots, 0, d_{n-1}, d_n, 0, \ldots, 0 \end{bmatrix}_{m\times 2n}, \tag{28}$$

$$d_{n-1} = -\frac{C_k k_n}{\sum_{j=1}^{m} S_j}, \quad d_n = \frac{C_k k_n}{\sum_{j=1}^{m} S_j}, \tag{29}$$

in which m is the total number of the controlled columns; and S_j is calculated using Eq. (9). By numerically solving Eqs. (17) and (22), the seismic response of actively controlled structure with parameter uncertainty and the corresponding control force or applied voltage from the actuators can be computed. Furthermore, it is interesting to know what will occur if one still uses the active control algorithm discussed in Section 3 "active control of building" to control the building with parameter uncertainty. To do this, Eq. (17) for the controlled ship lift structure with the uncertainty of lateral stiffness of the building is computed in conjunction with the control gain defined by Eq. (13).

5. Numerical example—without uncertainty

A large ship lift structure to be built in China is simplified in this study and taken as an example to see if the active piezoelectric moment controllers proposed in this study can effectively reduce the seismic response of the machinery building. The large ship lift structure consists of four identical reinforced concrete tube towers. Each of the towers has a height of 134.5 m, a width of 53.2 m, and a depth of 16.0 m, cast at the top reinforced concrete platform. The single story machinery building on the top platform has a span of 57.8 m and a total of 24 columns. Each column has a cross-section of $1.0\,\text{m} \times 2.0\,\text{m}$ and a height of 30 m. The building roof is a steel space truss structure. As a first stage study, only the horizontal earthquake excitation perpendicular to the direction of ship passage is considered, for the ship lift structure has much higher stiffness in the direction of ship passage (see Figs. 2 and 3). The N–S 1940 El Centro ground excitation scaled to have a peak acceleration of $1.0\,\text{m/s}^2$ is used as input ground acceleration. Both the top platform and the building roof are modelled as horizontal rigid plates. The ship lift towers are modelled as five lumped-mass systems. The towers are fixed at the rigid foundation and rigidly connected to the top platform. The building columns are also rigidly connected to the top platform but pin connected to the building roof. The building columns are assumed to be massless. The structural parameters are listed in Table 1. The first and second structural damping ratios of the ship lift tower with the top platform are assumed to be 0.05 whereas those of the machinery building are assumed to be 0.02, from which the Rayleigh damping matrix is constructed for the ship lift structure. For each column, the five piezoelectric actuators are installed on one side of the column. The rigid arm is located at a 5 m height (H_b) above the top platform and the moment arm (r) of the vertical connecting rod is 2.0 m. The flexural rigidity of each column is $2.0 \times 10^7\,\text{kN}\,\text{m}^2$ (EI_1) above the rigid arm and $1.6 \times 10^7\,\text{kN}\,\text{m}^2$ (EI_2) below the rigid arm. The reason why different column flexural rigidities are selected will be explained later.

5.1. Control performance of piezoelectric moment controllers

To assess the effectiveness of active piezoelectric moment controllers for reducing the seismic response of the machinery building on the top of ship lift towers, the seismic responses of the ship

Table 1
Parameters in the mechanical model of ship lift structure

Story	1	2	3	4	5	6
Mass (t)	2.964×10^4	2.964×10^4	2.964×10^4	2.964×10^4	3.885×10^4	6.003×10^3
Stiffness (kN/m)	3.525×10^6	3.525×10^6	3.525×10^6	3.525×10^6	3.525×10^6	2.668×10^4

lift structure with and without piezoelectric moment controllers are computed and compared with each other. Fig. 6 shows the variations of the maximum horizontal displacement response with structural height for two cases. The parameters of piezoelectric moment controllers used in the computation are listed in Table 2. Looking at the displacement response distribution of the original structure without control, one may see that due to the sudden change of mass and stiffness at the top platform (at the fifth mass), the machinery building has a very large lateral displacement, resulting in the so-called whipping effect. With the installation of the active piezoelectric moment controllers, the maximum lateral displacement response of the building is reduced by 65%, and the whipping effect is completely abated. The other fact is that the installation of active piezoelectric moment controllers only slightly increases the maximum horizontal displacement response of the ship lift towers at the second and third level, but the active piezoelectric moment controllers reduce the maximum displacement response of the top platform.

Fig. 7 depicts the bending moment distribution along the building column for two cases. It is seen that for the original building without control, the bending moment varies linearly. The maximum bending moment occurs at the bottom of the column of 13 240 kN m. With the installation of piezoelectric moment controllers, the maximum bending moment still occurs at the bottom of the column but of 5845 kN m, leading to a 56% reduction. The bending moments at the section just below and just above the rigid arm are even smaller.

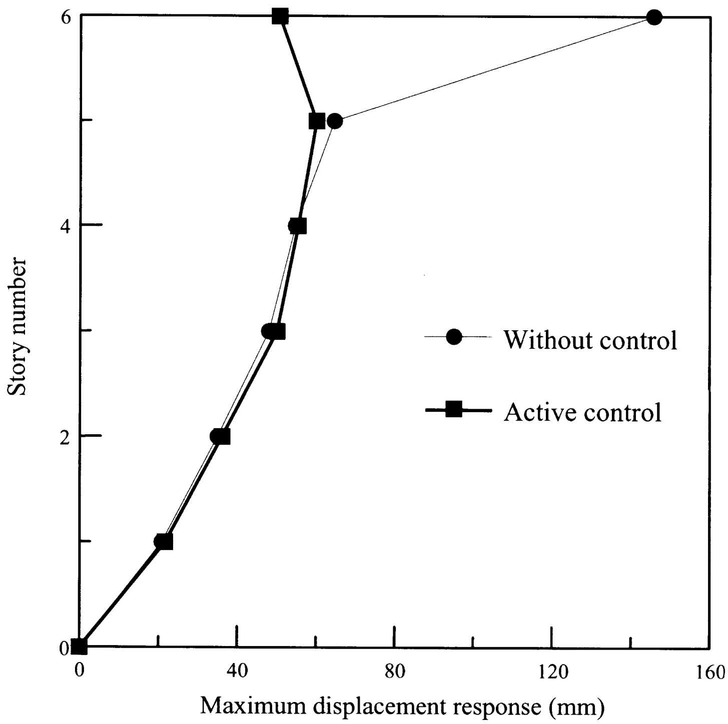

Fig. 6. Variations of maximum story displacement response with structure height.

Table 2
Basic parameters of moment controller used in the example

d_{33} (c/N)	E_p (N/m^2)	A_p (m^2)	b_a (m)	t (m)	k_a	n_k
500×10^{-12}	8.1×10^{10}	0.05	2.0	0.0001	10	5

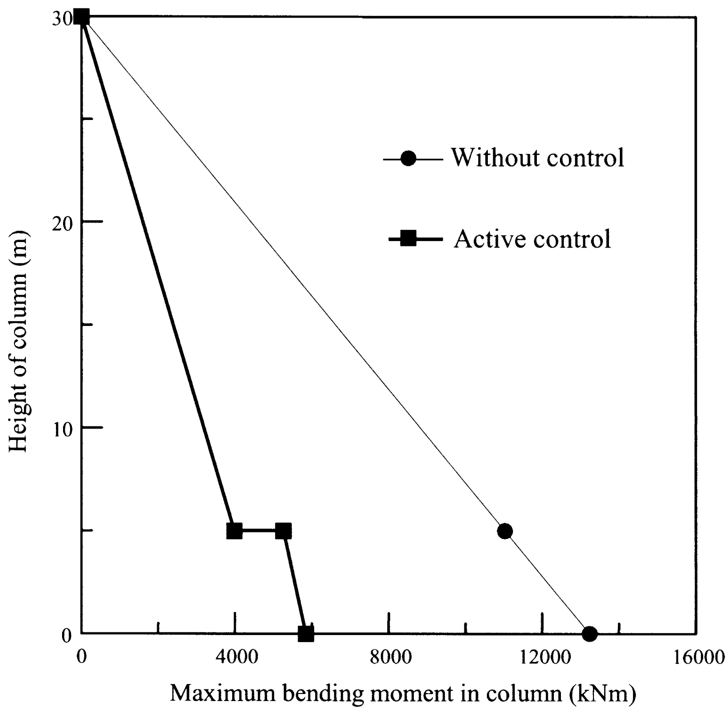

Fig. 7. Variations of maximum bending moment with column height.

5.2. Effects of structural parameters

The effects of two parameters on the performance of piezoelectric moment controllers are discussed in this section: one is the stiffness ratio S_1 of the controlled column above the rigid arm to the controlled column below the rigid arm ($S_1 = EI_2/EI_1$); and the other is the position of the rigid arm H_b. While one parameter is changed in the computation, the other parameters are kept the same as the basic parameters listed in Tables 1 and 2.

Fig. 8 shows variations of the maximum bending moments at the three key sections of a controlled column with the stiffness ratio S_1. The three key sections refer to the section just above the rigid arm (M_{cl}), the section just below the rigid arm (M_{cr}), and the section at the bottom of the column (M_b). It is seen from Fig. 8 that the bending moments of the column at the three key sections all increase with the increase of the stiffness ratio. It is seen that if unit stiffness ratio is

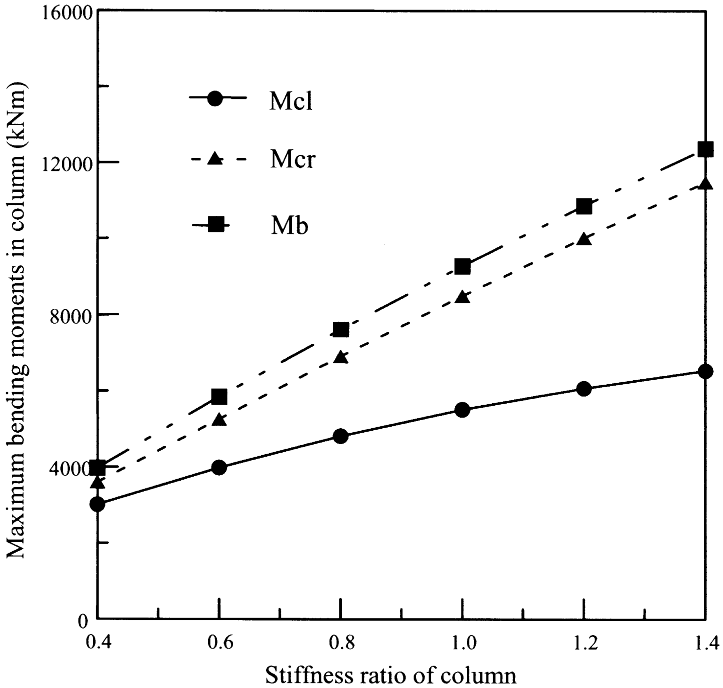

Fig. 8. Variations of three key maximum bending moments in column with stiffness ratio S_1.

selected for the column, the piezoelectric control performance is not so satisfactory compared with a stiffness ratio of 0.6. This is because the stiffer the bottom part of the column is, the less the control force from the piezoelectric moment controller. However, the stiffness of the bottom part of column cannot be too small since it is still subjected to certain amount of the bending moments M_{cr} or M_b and the vertical load. Thus, the iterative or trade-off process is required to select a proper stiffness ratio of the controlled column, in which some factors for practical implementation should be taken into consideration as well.

Depicted in Fig. 9 are the variations of column bending moments at the three key sections with the controller position H_b. The reduction rates of the maximum bending moments M_b and M_{cr} are very high for H_b in the range from 1 to 3 m. Afterwards, the further reduction of the column bending moments becomes less and less. The height H_b, however, does not significantly affect the maximum bending moment M_{cl}. In consideration that the space required for the lever system of a moment controller, the height H_b of 5 m is selected in this study.

6. Numerical example—with uncertainty

To assess the performance of the piezoelectric moment controllers with robust control algorithm on the reduction of seismic response of the machinery building with parameter uncertainty, three cases are considered. The first one is to use the robust control described in Section 4 to control the building with parameter uncertainty; the second one is to use the active

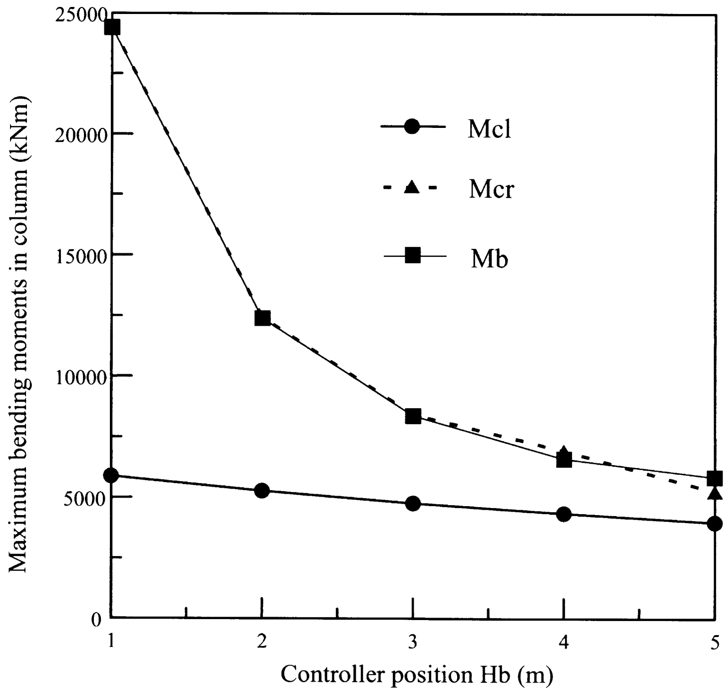

Fig. 9. Variations of three key maximum bending moments in column with controller position H_b.

control described in Section 3 to control the building with parameter uncertainty; and the third one is the building with parameter uncertainty but without control. Since huge ship lift structures are rarely built and accordingly there is no enough information publicly available to the writers, the time-varying coefficient function of uncertain lateral stiffness of the machinery building is thus selected as follows:

$$C_k(t) = C_k\alpha(t) = 0.8\alpha(t), \quad |\alpha(t)| = |0.8 + 0.2\sin\omega t|, \tag{30}$$

in which C_k is taken as 0.8 and ω is selected as 2.832 rad/s. The selection of a large time-varying uncertainty in the lateral stiffness of the building is to examine the effectiveness of the robust control in the worst case. Because the uncertainty in the lateral stiffness is much larger than that in the control force, the uncertain matrix $[\Delta B]$ is thus taken as zero in this study. The other parameters are ε of 0.1, $\bar{\delta}$ of 1.6, and γ of 6.875.

Fig. 10 shows variations of the maximum horizontal displacement response with structural height for three cases. The parameters of piezoelectric moment controllers used in the computation are the same as those listed in Table 2. It is clear that due to the sudden change of mass and stiffness at the top platform, the machinery building with parameter uncertainty but without control has a very large lateral displacement, yielding the so-called whipping effect. With the installation of the piezoelectric moment controllers with robust control algorithm, the maximum lateral displacement response of the building is reduced by 80%, and the whipping effect is completely abated. When the piezoelectric moment controllers with active control algorithm are used for the building with parameter uncertainty, the maximum lateral

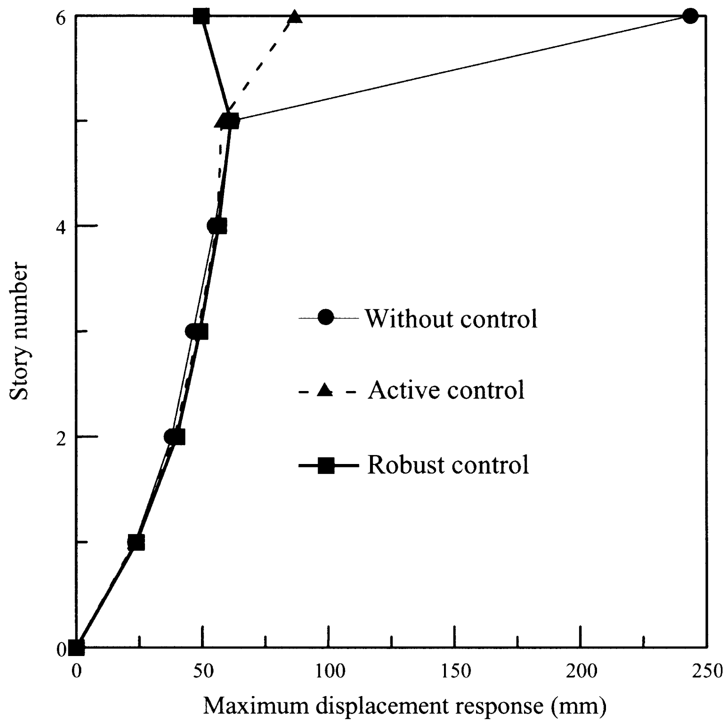

Fig. 10. Maximum displacement response of structure with uncertainty.

displacement response of the building is significantly reduced by 64% compared with the uncontrolled case, but the whipping effect is not completely eliminated. The maximum displacement response is 1.7 times that of the building with robust control.

Fig. 11 depicts the bending moment distributions along the building column for the three cases. For the original building without control yet with parameter uncertainty, the bending moment varies linearly. The maximum bending moment occurs at the bottom of the column of 16 788 kN m. With the installation of robust piezoelectric moment controllers, the maximum bending moment occurs at the section just below the rigid arm of 6975 kN m, leading to a 59% reduction. For the active control of the building with uncertainty, the maximum bending moment at the bottom of the column is 8591 kN m, which is 51% of the maximum bending moment of the building without control but 1.23 times of the maximum bending moment of the building with robust control.

It is clear that for the building with structural parameter uncertainty, the robust control is superior to the active control. However, the control force or the applied voltage required by the robust control is larger than that by the active control. Fig. 12 shows the time-histories of applied voltage to one of the piezoelectric actuators for the cases of robust control and active control. Table 3 also gives the maximum control forces and the maximum applied voltages required for the deterministic building with active control, the uncertain building with active control, and the uncertain building with robust control. Clearly, the uncertain building with robust control needs

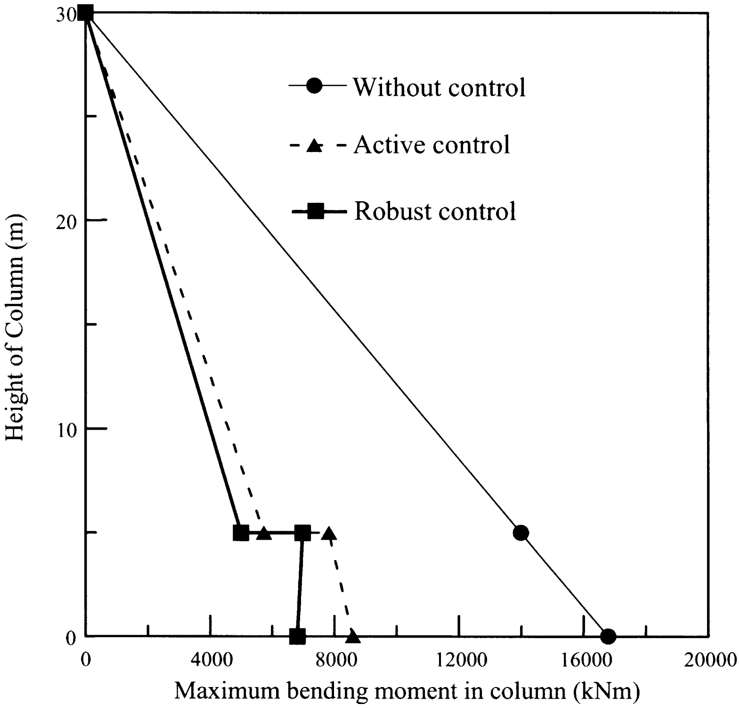

Fig. 11. Maximum bending moments in building column of structure with uncertainty.

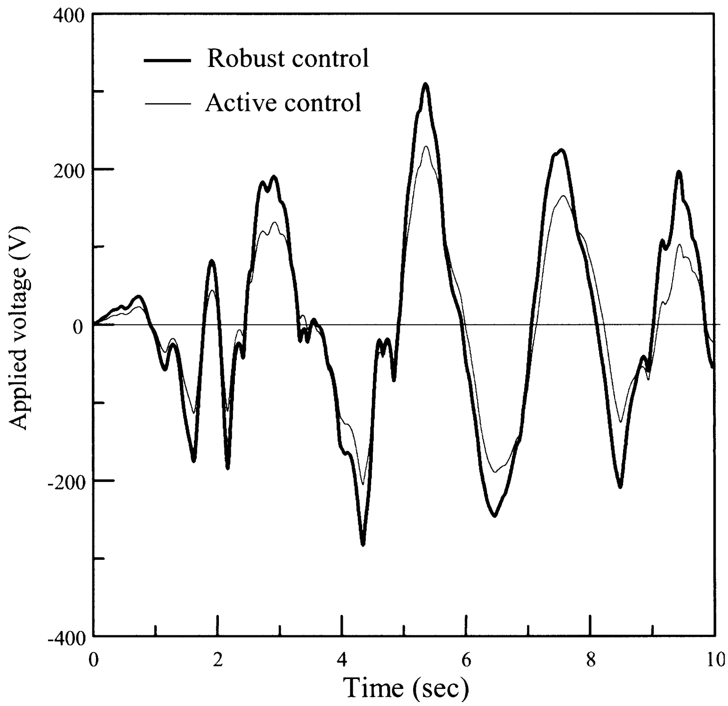

Fig. 12. Time-histories of applied voltage from one piezoelectric actuator.

Table 3
Control forces and applied voltages from one of piezoelectric actuator

	Building without uncertainty			Building with uncertainty		
	Maximum control force (kN)	Maximum applied voltage (V)		Maximum control force (kN)	Maximum applied voltage (V)	
		Left actuator	Right actuator		Left actuator	Right actuator
Active control	305	141/−168	141/−132	424	229/−205	190/−179
Robust control				561	309/−282	244/−208

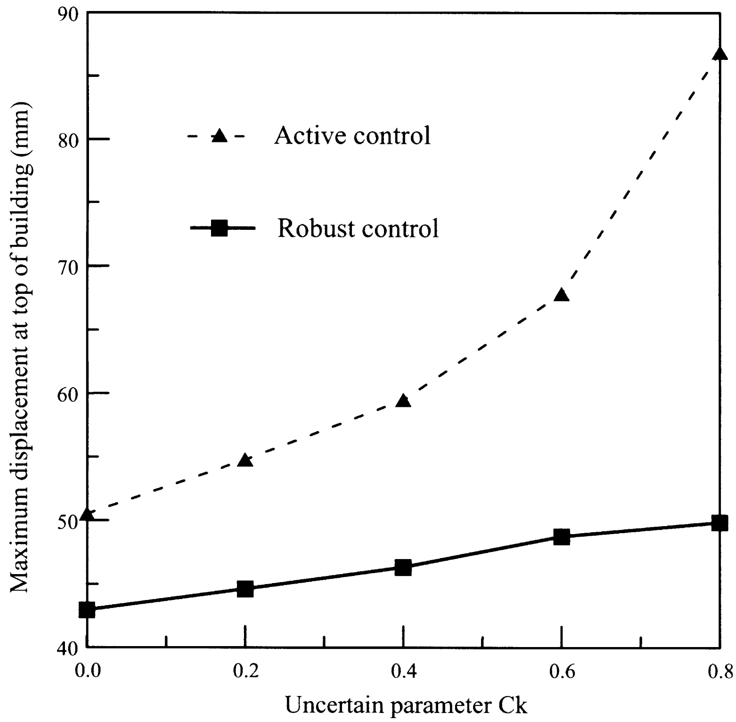

Fig. 13. Variations of maximum displacement at top of building with uncertain parameter C_k.

the largest control force or applied voltage while the deterministic building with active control requires the smallest control power.

Displayed in Fig. 13 are the variations of maximum displacement response at the top of the building with uncertain parameter C_k for the robust control and active control. It is seen that as the uncertainty of the building becomes smaller, the maximum displacement response of the building also becomes small, and the performance of active control approaches that of robust control.

7. Conclusions

The possibility of using active/robust piezoelectric moment controllers to reduce seismic response of the machinery building on the top of ship lift towers without/with parameter uncertainty has been explored in this study. The use of moment controllers met the special space requirement for the machinery building. Basic equations for active/robust piezoelectric moment controllers interacting with the building without/with uncertain parameters have been derived. The effectiveness of the proposed moment controllers and the behavior of the controlled ship lift structure have been examined through a case study. The results showed that the active/robust piezoelectric moment controllers could effectively prevent the whipping effect and significantly reduce the seismic response of the building while not affecting the seismic response of huge ship lift towers. In the presence of structural uncertainty, the robust moment controllers gave superior performance to the active moment controllers but required larger control power. The optimal parameters, such as the position of moment controller and the stiffness ratios of building column, were also identified through parametric studies.

The assumption made in this study that the ship is not in mid lift during an earthquake and therefore the beating between ship pendulum motion and ship lift tower motion does not occur may deserve further investigation.

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References

[1] The Water Conservancy Committee of Yangtze River, Research on Permanent Navigation Structures of Three-Gorge Dam, Hubei Science and Technology Periodical Press, Hubei, China, 1997 (in Chinese).
[2] T. Kamada, T. Fujita, T. Hatayama, T. Arikabe, N. Murai, S. Aizawa, K. Tohyama, Active vibration control of frame structures with smart structures using piezoelectric actuators-vibration control of bending moments of columns, Smart Materials and Structures 6 (1997) 448–456.
[3] T.T. Soong, Active Structural Control: Theory and Practice, Longman, London, 1990.
[4] J.N. Yang, A. Akbarpour, P. Ghaemmaghami, New optimal control algorithms for structural control, Journal of Engineering Mechanics, American Society of Civil Engineering 113 (9) (1987) 1369–1386.
[5] Y.H. Chen, Design of robust controllers for uncertain dynamical system, IEEE Transactions on Automatic Control 33 (1988) 487–491.

[6] S.C. Tsay, I.K. Fong, T.S. Kuo, Robust linear quadratic optimal control for systems with linear uncertainties, International Journal of Control 53 (1) (1991) 81–96.
[7] M.L. Ni, H.X. Wu, Design of robust controllers for linear uncertain system, Acta Automatica Sinica 18 (5) (1992) 585–589 (in Chinese).
[8] G.W. Housner, L.A. Bergman, T.K. Caughey, A.G. Chassiakos, R.O. Claus, S.F. Masri, R.E. Skelton, T.T. Soong, B.F. Spencer, J.T.P. Yao, Structural control: past, present and future, Journal of Engineering Mechanics, American Society of Civil Engineering 123 (9) (1997) 897–971.
[9] W.E. Schmitendorf, Faryar Jabbari, J.N. Yang, Robust control techniques for buildings under earthquake excitation, Earthquake Engineering and Structural Dynamics 23 (1994) 539–552.