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Advanced control for a super high rise building

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ABSTRACT: Vibration control of a Super High Rise Building (SHRB)(more than 300m, 100 story, for example) is investigated. It has extremely low frequency, lightly damped structural modes. Reductions of acceleration, displacement between stories, a force to control and the stroke of a damper are the objectives in the control of a seismic response to assure the amenities of the building. To deal with these problems, we use a mass damper for a passive and active control. As control laws to implement the controls, Linear Quadratic (LQ) optimal control method, and H^∞ control method are examined. It is shown that the proposed control system can effectively reduce the absolute displacement response to winds and earthquake.

1. Introduction

A Super High Rise Building (SHRB) will tend to be flexible to avoid destruction due to earthquake. As result,it has extremely low-frequency, lightly damped structural modes. Since SHRB is regarded as a distributed parameter system, we have to make a model that preserves the structural properties of the original distributed parameter system to analyze the responses of the building. To design the control laws, we approximate it by a linear multi-mass-model. Two of the most important control problems for SHRB are 1) Reduction of a seismic response, and 2) Vibration control of the response for the winds to assure the amenities of the building. To deal with these problems, we use a mass damper for a passive and active control. The mass damper absorbs a small disturbance with high frequency. Advanced control techniques such as the optimal control theories by an H^∞ norm and the LQ control method are used to synthesize the control system. The synthesis is performed mainly in a frequency domain. It is shown that the proposed control system can effectively reduce the absolute displacement response to winds and earthquake.

2. Modeling of a super high rise building

We deal with a 100 stories building of $380m$ height and $175,000tonf$ in total weight that has symmetrical square plane. With prototype plane shown in **Fig.1**, this building is the tube structure and the center core type, and consists of beam-column steel frame with reinforced concrete shear walls. We need to consider not only the bending effect but also the shearing effect in the lateral deflection of the SHRB.

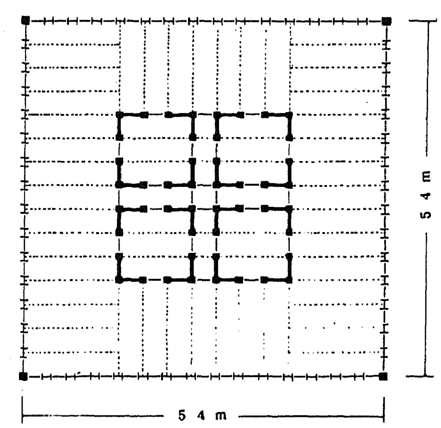

Fig.1 Ground plan of SHRB

Since SHRB is regarded as a distributed parameter system, we have to make a model that preserves the structural properties of the original distributed parameter system to analyze the responses of the building and to design the control laws. Thus, we approximate it by a five-degree-of-freedom system. As to the structure damping effect, we assume Rayleigh type owing to first and second modes. Then, the equation of this model is represented by

$$M\ddot{x} + C\dot{x} + Kx = -M\ddot{f} + Lu \qquad (1)$$

where f represents a seismic force and u represents control inputs from dampers.
Fig.2 shows a 5-mass (five-degree-of-freedom) model with a mass-damper at the top floor.

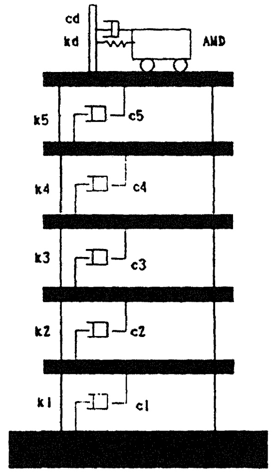

Fig.2 5-mass model with mass-damper

The frequency response of this model is shown in **Fig.3**. The natural frequencies of this system are $0.13Hz$, $0.53Hz$, $1.04Hz$, $1.39Hz$, $1.63Hz$, and the first mode period is about 7.75 second.

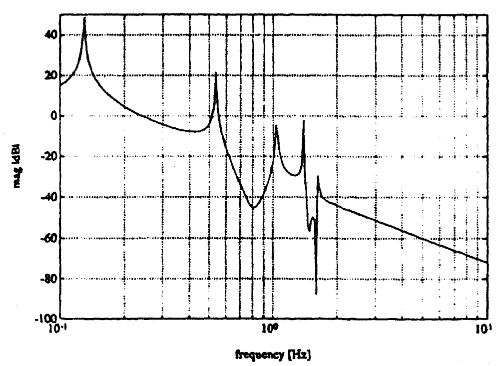

Fig.3 Frequency response of the model

3. Control of SHRB

The objectives of control of SHRB are to reduce an acceleration, the displacement between stories, a force to control and the stroke of a mass damper against the winds and an earthquake to assure the amenities of the building. To deal with these problems, we use a mass damper for a passive and active control. As control laws to implement the controls, LQ control method, and H^∞ control method are examined.

3.1 System equation

The motion equation of the system shown in **Fig.2** is given as follows:

$$\dot{X} = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} X + \begin{bmatrix} 0 \\ -M^{-1}L \end{bmatrix} u - \begin{bmatrix} 0 \\ -1 \\ \vdots \\ -1 \end{bmatrix} \ddot{f}$$

$$y = [0\ 1\ \underbrace{0 \cdots 0}_{10\text{times}}]X \qquad (2)$$

where X denotes 12×1 state vector, such as $X := [x\ \dot{x}]^T$ and y denotes scalor output.

3.2 Controllability

In the case of one mass damper attached to the top of the building, 5-mass model has the following singular values of controllability gram matrix:

9.4	8.1e-05
6.0	5.9e-05
0.53	3.7e-06
0.35	2.4e-06
9.6e-04	2.5e-07
2.1e-04	8.8e-09

This indicates that the system is controllable from the theoretical point of view, but actually only four modes are easy to move, the rest of the modes are hardly to be moved by finite control energy. An additional damper set at the intermediate story changes the controllability indices as follows:

37.3	1.9e-03
24.4	3.7e-04
4.72	1.4e-04
1.27	2.9e-05
.680	8.2e-06
.356	1.3e-06
.021	1.8e-07

This shows improvement of controllability by the additional damper. But the higher modes have small gain, as known from **Fig.3**, we can neglect the higher modes.

3.3 Active mass damper (AMD) control

For the system shown in **Fig.2** , we design the following several control laws : i) Pole assignment ii) Optimal regulator iii) Direct velocity feedback and compare the effects.

i) Pole assignment method

We examine two kinds of method; the usual method and a turn over method that transforms poles located in right hand side of a vertical line to symmetric positions in the left hand side of the vertical line. The result of the usual pole assignment method that changes only four eigen values and keeps other poles at the same positions is shown in **Fig.4**. **Fig.5** shows the result of the turn over method that takes a line $s = -0.3$ as the vertical symmetric axis.

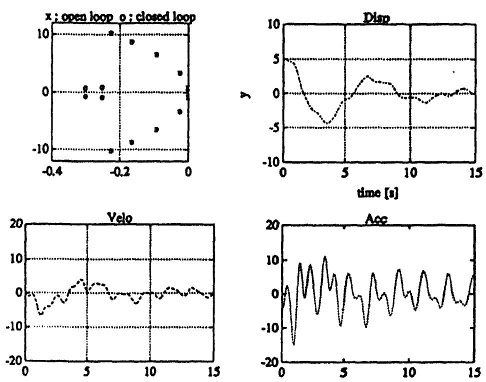

Fig.4 Pole assignment method

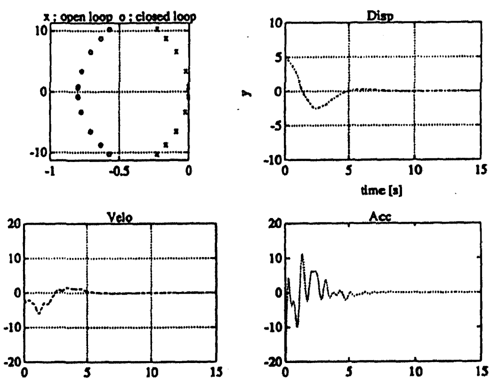

Fig.5 Turn over method

The usual pole assignment method can not give good result as the turn over method. Furthermore the usual method requires many trials on poles positions to get good result. The turn over method simplfies this procedure.

ii) Optimal regulator method

We examined two performance indices:

$$J_1 = \int_0^\infty \left[X^T Q X + u^T R u \right] dt$$

$$J_2 = \int_0^\infty \left[\alpha X_2^2 + \beta \ddot{x}_2^2 + u^T R u \right] dt$$

where X_i or x_i means the ith element of vector X or x. The performance index J_1 is well known usual one, J_2 evaluates the mixed effects of the acceleration and the displacement of the top mass.

In the case of J_1, a simular effect as the turn over method for large waiting Q. The result of an optimal regulator is shown in **Fig.6** for $R = 1$ and

$$Q = diag[1\ 1000\ \underbrace{1 \cdots 1}_{5\text{times}}\ 1000\ \underbrace{1 \cdots 1}_{4\text{times}}]$$

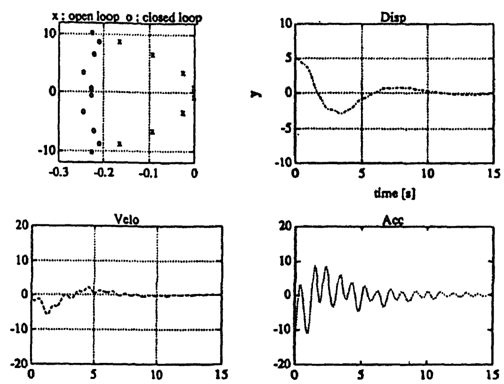

Fig.6 Optimal regulator method with J_1

Although the allocated closed loop poles have the same configulation to that of the turn over method and the both time responses are all alike, the time response of an optimal regulator is more oscillatory.

In the case of J_2, as the weighting on the acceleration increases, the poles of AMD becomes very oscillatory. But it does not affect on the modes higher than second. The result for $\alpha = 10000$, $\beta = 100$ is shown in **Fig.7**

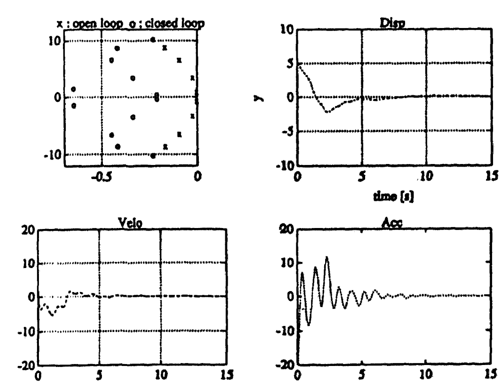

Fig.7 Response of the system controlled by regulator with J_2 ($\alpha = 10000$, $\beta = 100$)

This result has a very similar response to that of the turn over method. To see the effect of α, β to the poles of AMD, the movements of the first mode eigenvalue and the poles of AMD for the changers of α, β is shown in **Fig.8**.

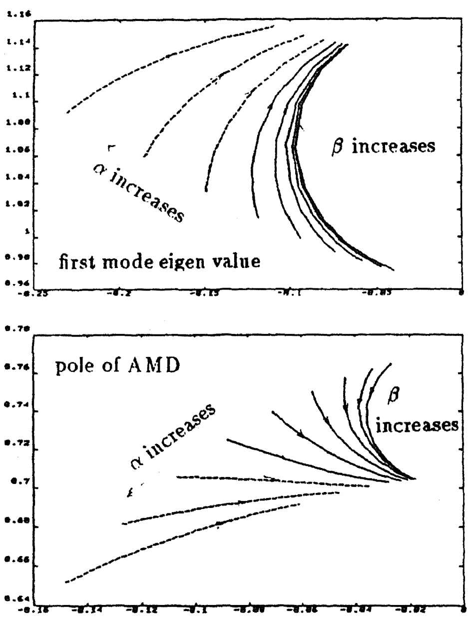

Fig.8 Change of first mode pole for α and β

As α increases, the position of the first mode eigen value and pole of AMD move to the left. As β increases, the positions of both poles move to the right but to the opposite direction.

In the case of DVFB, there is little effect in spite of increase feedback gains.

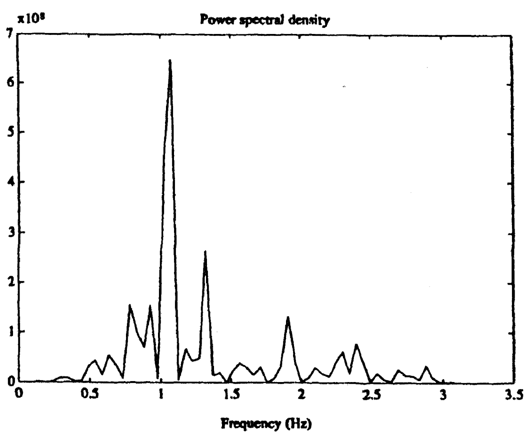

Fig.9 Power spectral of the Miyagikenoki earthquake

4. Earthquake response

As an earthquake model, we use seismic data measured at Tohoku University the Miyagikenoki earthquake that occurred at Miyagi Prefecture Japan in 1978. **Fig.9** shows the power spectral density of the earthquake.

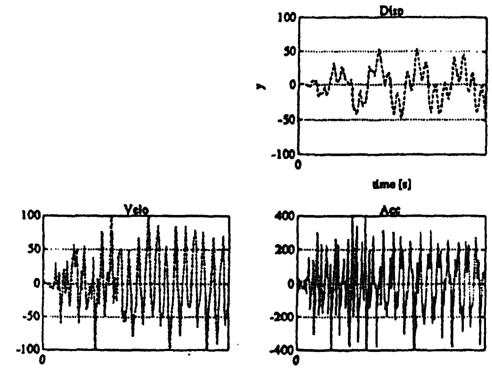

Fig.10 Seismic response of the system without contol

Fig.11 shows the seismic response of the system controlled by a usual regulator with $R = 1$ and

$$Q = diag[1 \underbrace{10000\cdots}_{5\text{times}}, 1 \underbrace{10000\cdots}_{5\text{times}}].$$

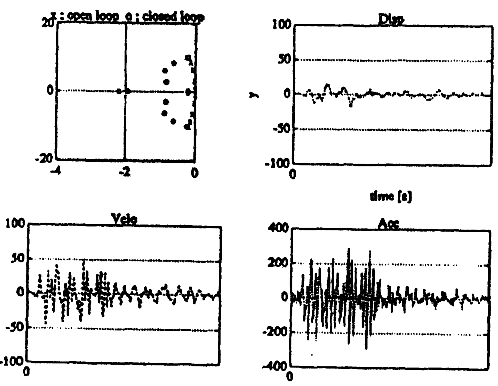

Fig.11 Seismic response of the system controlled by a regulator

5. Robust control system

In designing the control laws, we use a reduced order model for SHRB. The omitted parts and uncertainties of parameters may cause deterioration of the performance of the controller. It is important for the control system to be not sensitive to the model error and parameter error.

Here we consider H^{∞} control taking account of the characteristic of earthquake wave.

The control system used for low sensitivity problem is shown in **Fig.12**, where G is the transfer function of SHRB plus the active damper, K is the transfer function of the controller to be designed, W is a weighting function that is determined taking account of the response of SHRB for the input disturbance (earthquake) characteristic, u is a control input y is an system output used for feedback control and z is a control variable d is the input disturbance.
Problem is to determine a controller K so as to satisfy

$$|SW|_\infty < \gamma$$

where S is a sensitivity function defined by

$$S = \frac{1}{1+KG} \tag{3}$$

and $|\quad|_\infty$ represents H^∞ norm.

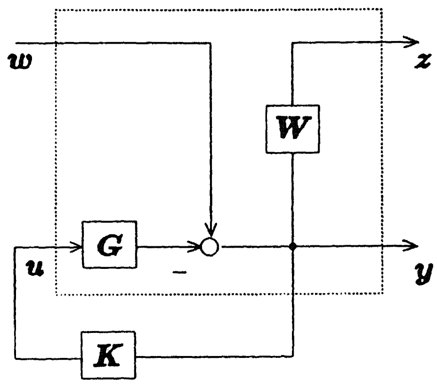

Fig.12 H^∞ control system

As weighting function, we use the following a second order band-pass- filter:

$$W(s) = \frac{b/q}{s^2 + (b/q)s + b^2} \tag{4}$$

The total system that is augmented by the band-pass-filter is described by the following equation:

$$\begin{aligned} \dot{X}_a &= A_a X_a + B_{a1} w + B_{a2} u \\ Z_a &= C_{a1} X_a + D_{a12} u \\ Y_a &= C_{a2} X_a + D_{a21} w \end{aligned}$$

and we assume the controller is represented by the following equation:

$$\begin{aligned} \dot{x}_c &= A_c x + B_c Y_a \\ y_c &= C_c x_c \\ u_c &= y_c \end{aligned}$$

Then we have the following closed loop system equations :

$$\begin{bmatrix} \dot{X}_a \\ \dot{x}_c \end{bmatrix} = \begin{bmatrix} A_a & B_{a2}C_c \\ B_c C_{a2} & A_c \end{bmatrix} \begin{bmatrix} X_a \\ x_c \end{bmatrix} + \begin{bmatrix} B_{a1} \\ B_c D_{a21} \end{bmatrix} w$$

For this system we use the Matlab robust control tool to get the solution. To suppress the oscillation at near $1Hz$, where the frequency response (power spectrum) of SHRB for the earthquake has the biggest peak as shown in **Fig.13**.

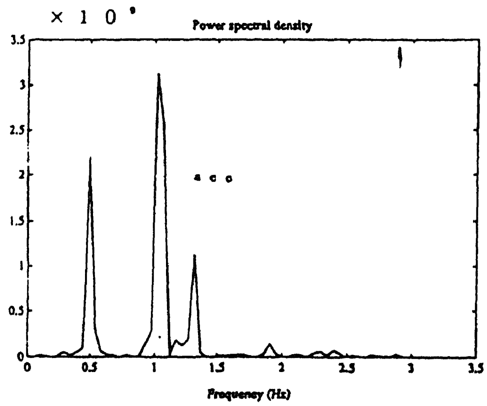

Fig.13 Power spectrum of the dispracement and velocity of the top mass

We use weighting function shown in **Fig.14**.

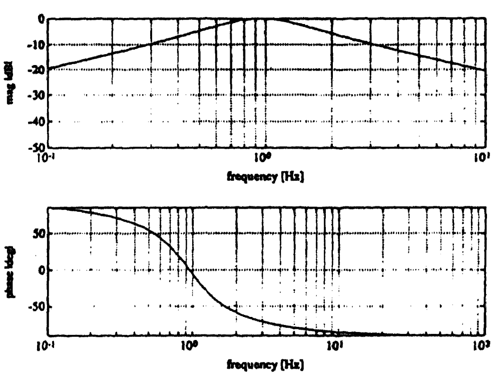

Fig.14 Frequency response of weighting function

The resulting frequency response of closed loop systems is shown **Fig.15**, and the time response of the closed loop system is shown in **Fig.16**.

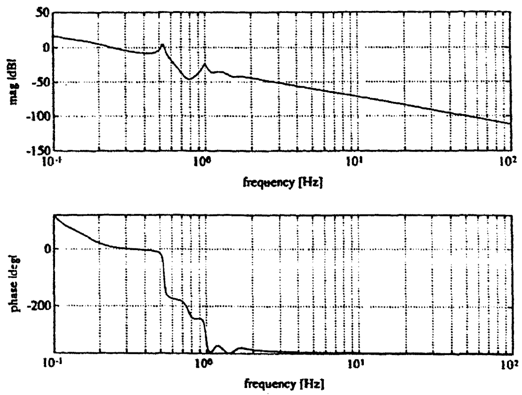

Fig.15 Frequency response of the closed loop H^{∞} system

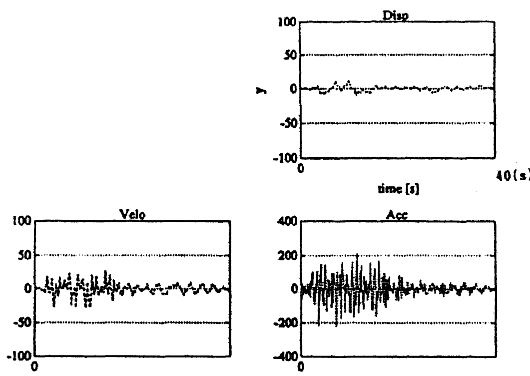

Fig.16 Time responce of the closed loop H^{∞} system

To compare this result to that of the system controlled by a regulator, we consider a case that the mass of the active mass damper is relatively small and show the result in **Fig.17**.

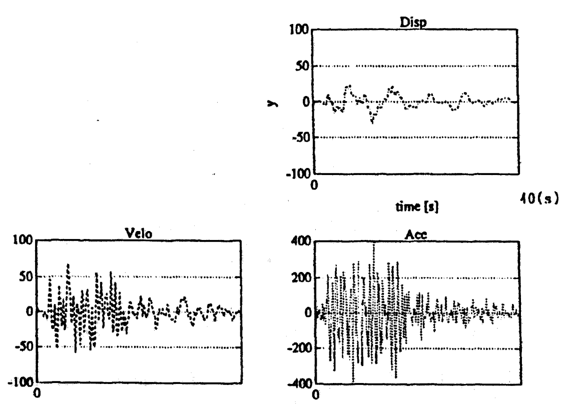

Fig.17 Time response of the closed loop system controlled by a regulator

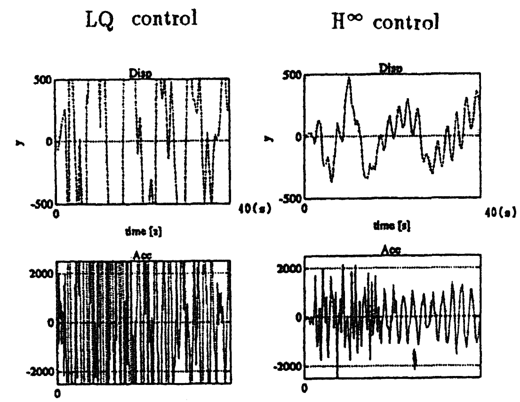

Fig.18 Time response of the active mass damper

In the H^{∞} control system, the damper works well and the oscillation of the building can be reduced. While, in the regulator system, the damper moves rapidly and vigorously as shown in **Fig.18** and this shows practical use of the damper is impossible.

7. Conclusion

Vibration control of a Super High Rise Building is investigated. It is shown that

1)Additional dampers will improve the controllability.
2)The turn over method gives the same or better result as LQ method, and it simplifies the design procedure.
3)H^{∞} control system, can effectively reduce the absolute displacement response to an earthquake. In the case when the mass of the active mass damper is relatively small, H^{∞} control system shows more practical use than the LQ control system.

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