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ACTIVE VIBRATION CONTROL SYSTEM INSTALLED IN A HIGH-RISE BUILDING

T. SUZUKI, M. KAGEYAMA, A. NOBATA, O. YOSHIDA and S. INABA

Obayashi Corporation, Technical Research Institute,
4-640, Shimokiyoto, Kiyose-shi, Tokyo 204, JAPAN

ABSTRACT

Computer operated active vibration control system which is capable of controlling a multiple number of vibration modes at the same time was installed in an actual high-rise building for the first time in the world, in order to provide high quality wind and seismic vibration resistant living environments.

This report describes an outline of this system and vibration control effects verified by the tests carried before actual operation of the system and the earthquake response observation. From the tests results and earthquake obserbations, large damping effects can be obtained in four target vibration modes and the effectiveness of the system for actual high-rise building was verified.

KEYWORDS

Vibration control; active mass damper; high-rise building; multi-mode control; robustness; spillover.

INTRODUCTION

In recent years, there have appeared an increasing number of structures in which vibration can easily be felt due to increases in height, and demand for vibration control devices from the standpoints of living comfort and functionality has been relatively strong. In response to such demand, passive control methods for controlling only the first vibration mode such as the tuned mass system and tuned liquid system which are installed on the roofs are generally used. However, since the humans easily feel vibration with relatively short periods, so it is at times necessary to control higher-order vibration modes like the second, third, and similar modes.

For the past several years, the authors have been engaged in the development of active control systems capable of controlling a multiple number of vibration modes of tall structures, and have repeatedly studied control methods with high vibration control efficiency and superior robustness, as well as various factors such as the securing of soundness and safety of systems as a whole, from both theoretical and experimental standpoints. In this paper, an outline of the active vibration control system that has been applied to an actual building and vibration control effects are reported.

OUTLINE OF THE STRUCTURE

The structure is an steel-reinforced, pure frame building which is scheduled to be completed in summer of 1994 in Tokyo, and its lower section is to be used for offices, while its upper section is for residence. Because the structure is steel-framed and its upper section is for residence, vibration due to strong winds needs to be reduced to a minimum level. In order to efficiently control lateral vibrations because the plane shape is flat, in particular, it was decided to use an active vibration control system. The main specifications of the building are listed in Table 1. View of the entire structure is shown in Fig.1. The controlled vibration modes are the translational 1st to 3rd modes in the transverse direction and the 1st torsional vibration mode.

Table 1. Outline of Building

Stories : Above Ground 33 stories	Height : 134.4 m		Total Weight : 52,000 ton
Design Frequency :			
(Transverse Direc.)	1st Mode 0.290 Hz	2nd Mode 0.780 Hz	3rd Mode 1.22 Hz
(Torsion)	1st Mode 0.355 Hz		

Fig.1. View of the entire of the building

OUTLINE OF THE VIBRATION CONTROL SYSTEM

The composition of the vibration control system is illustrated in Fig.2. This system is composed of sensors for detecting disturbances and state variables of the building, active dynamic absorbers to be installed on the roof, and a CPU(control unit and monitoring unit) which controls the system as a whole. Information from the CPU is indicated in the central control room.

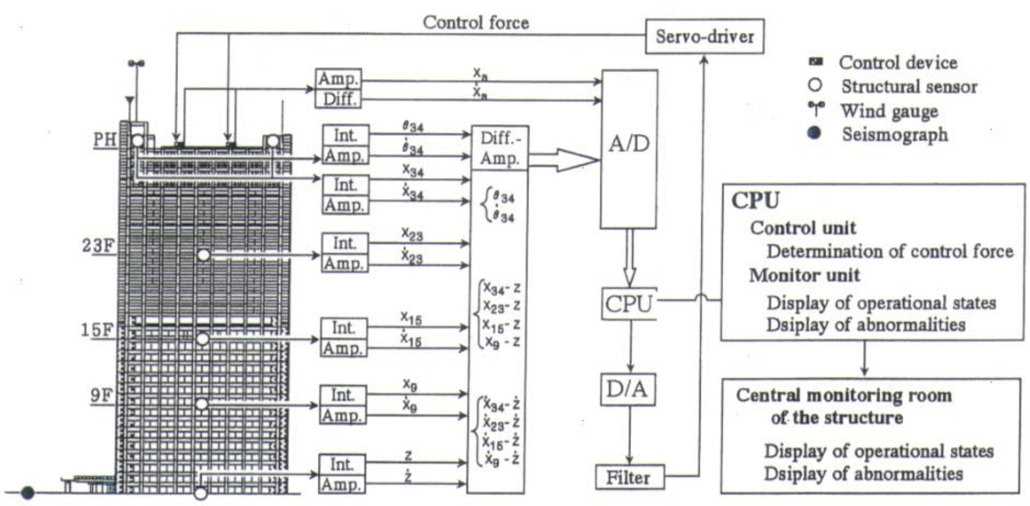

Fig.2. Composition of the vibration control system

Active Dynamic Absorbers

A pair of active dynamic absorbers as indicated in Fig.3 and Fig.4 are installed in the transverse direction on the roof as shown in Fig.5. Each dynamic absorber is an active type which drives an added mass, supported by a linear bearing, by means of an AC servo motor via a ball screw. The absorbers are compact, each measuring only some 5m, 2m, and 1.5m in depth, width, and height, respectively. These devices were installed on vibration-eliminating rubber mats inside pits that were built with reinforced concrete on the roof. Table 2 lists the specifications of each device.

As for the overruns of the added mass, a three-stage checking procedure as described below is used so as to secure the safety of the device as well as to prevent any adverse effect on the building.

(1) Software displacement limit: By the use of a control software program to be described later, the added mass is stopped.
(2) Hardware displacement limit: A mechanical limit switch is used to shut of the motor current and stop the added mass.
(3) Hydraulic shock absorber: The motion energy of the added mass is absorbed to stop the mass physically.

It should be noted here that the overrun detection positions are set in the order of (1) (2) (3) in terms of displacement levels.

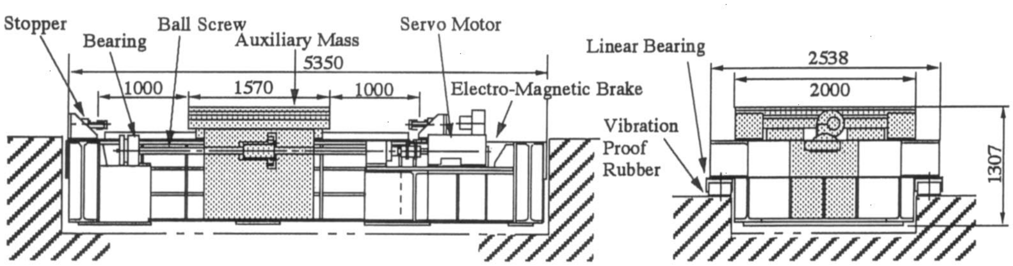

Fig.3. Active vibration absorber

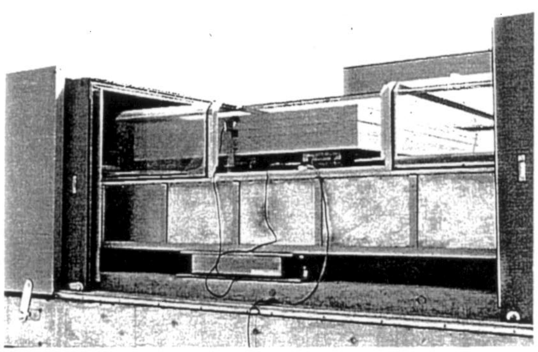

Fig.4. Dynamic vibration absorber

Fig.5. Scene of device installation

Table 2. Specifications of dynamic vibration absorber

Control Type : Active Mass Damper	Control Direction : Transverse	Number of Device : 2
Specification of a Device Added Mass Weight : 15 ton AC Servo Motor : 55 kW	Max. Disp. : 100 cm	Max. Control Force : 8.7 ton

Installation of Sensors

The sensors for observing the state variables of the building necessary for determining control gains were decided to be absolute velocity gauges and were installed on the roof, at the 23th, 16th, and 9th floors, and in the foundation, as indicated in Fig.2. Moreover, the added masses of the dynamic absorbers have a built-in action transformer. In addition, a wind velocity gauges and an earthquake gauges were installed on the roof and in the foundation, respectively, in order to detect disturbances.

Control Unit

As indicated in Fig.2, all of the relative velocity and displacement signals obtained from the absolute velocity sensors installed on the roof, at the 23th, 15th, and 9th floors, and in the foundation, the relative displacement and velocity signals from differential transformers attached to the dynamic absorbers, and the torsional angle and angle velocities of the roof floor were sent to the CPU through A/D convertors with a sampling interval of 10ms, and control variables are computed there.

A block diagram of the control system for control gain determination is shown in Fig.6. The dynamic model of the building has the translational vibration and torsional vibration uncoupled and is based on the modeling of up to 5th vibration mode in the translational vibration and of only the first vibration mode in the torsional vibration. From this dynamic model, the translational and torsional control variables are computed inside the CPU and passed through band pass filters. These band pass filters play both the role of a low pass filter for the control of the spillover instability of higher-order vibration modes not subjected to vibration control and the role of a high pass filter for preventing any drift of the added masses of the dynamic absorbers due to long-period-disturbances. In addition, digital filters are used for these filters so as to be able to easily change the cut-off frequencies. Signals from these filters are sent to the servo driver through an analog low-pass filter after D/A conversion, and then used to drive the motors and thereby to activate the added masses.

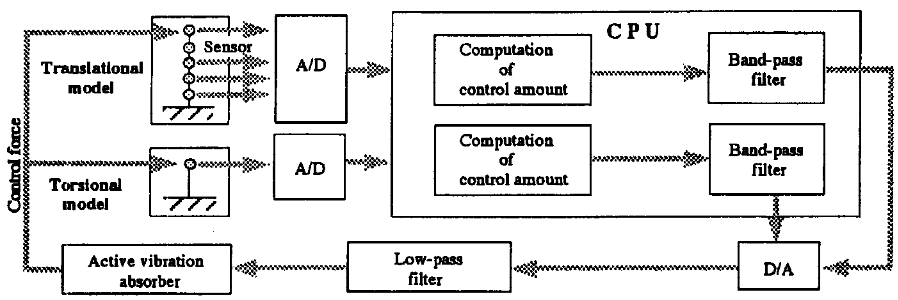

Fig.6. Block diagram of the vibration control system

Control Rule

By regarding the input voltages into the velocity control drivers of the AC servo-motors as control variables, the control system as a whole of Fig.6 is formulated. These input voltages are determined after a criterion function is established, the Ricatti equation is solved, and the optimal feedback gain is obtained, and then after the sub-optimal feedback gain is obtained by the application of the minimum norm method.

Features of the control system

Several features of control software for this system may be summarized as follows:
(1) By introducing the concept of a variable gain and varying the control force in accordance to the scale of the vibration of the building, effective control is possible.
(2) Control object are many vibration modes even including the torsional mode.
(3) Robust control design has been achieved by the insertion of filters in order to deal with spill over caused by the control of limited state variables.
(4) An independent route for monitoring the relations among the control force, the building response, and disturbances, namely a malfunction-detecting system, is established.
(5) In the event of an excessive input exceeding the capacity of the device or an emergency such a power failure, the safety of the system is secured.

Identification of Building Dynamic Characteristics

In order to obtain translational and torsional dynamic characteristics of the building, sinusoidal excitation experiments using the dynamic absorbers as vibrators were carried out. Frequency response characteristics and vibration modes of transverse direction are shown in Fig.7 and 8,respectively, as circular marks. Natural frequencies and damping coefficients of transverse and torsional directions obtained by the experiments are shown in Table 3 and 4 ,respectively. The rigid lines in Fig.7 and 8 are the calculated results of the dynamic model for translation.

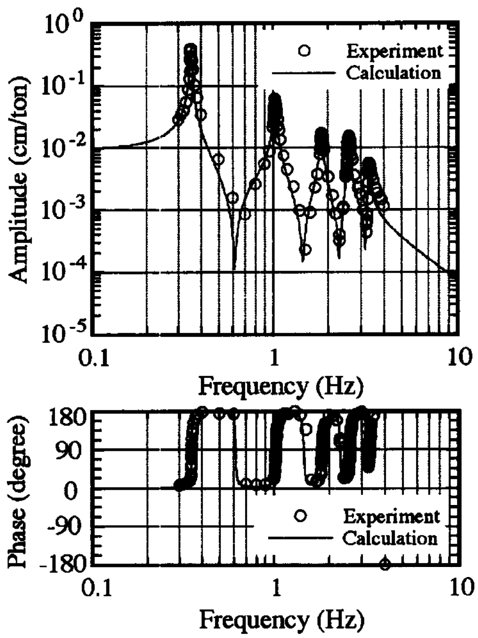

Fig.7. Frequency response characterristics on the roof

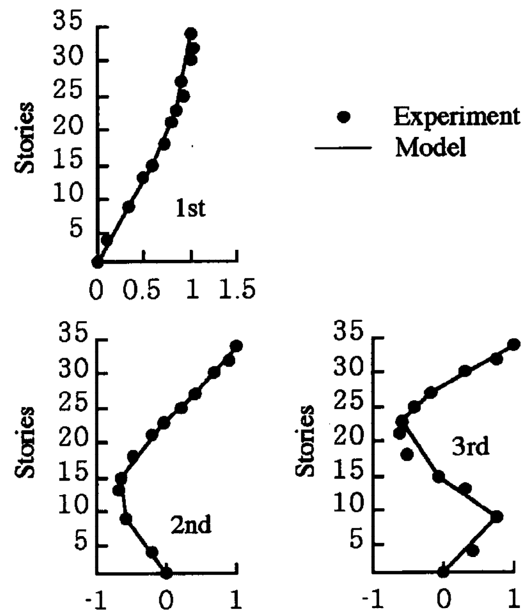

Fig.8. Vibration modes of translational direction

Table 3. Modal characteristics of translation

	1st	2nd	3rd	4th	5th
Natural frequency [Hz]	0.35	1.03	1.83	2.59	3.34
Damping [%]	0.85	1.20	1.48	0.94	0.90

Table 4. Modal characteristics of torsion

	1st	2nd	3rd
Natural frequency [Hz]	0.35	1.03	1.83
Damping [%]	0.85	1.20	1.48

Design of Filters

The band pass filter for translational model as shown in Fig.6 is decided as follows. Concerning the low pass filter, the cut-off frequency is taken to be 2.0Hz, between 3rd and 4th mode frequencies, to eliminate the spilover instability caused by higher order vibration modes. The cut-off frequency of the high pass filter for preventing any drift of added mass is set up at 0.2Hz considering both closeness to the first mode frequency 0.35Hz and easy grade of the filter phase change adjacent to the 0.35Hz.
As for the filter for torsional model, the cut-off frequency of the low pass filter is 0.6Hz between 1st and 2nd mode frequencies and that of the high pass filter is 0.2Hz.
Analog low pass filter just prior to the servo motor is installed to remove noise of the input for the actuator. The cut-off frequency of the filter is 10Hz.

Identification of Dynamic Characteristics of Control System

Dynamic characteristics of control system including the filters and dynamic absorbers are confirmed in this section. The relationships between relative velocity frequency response of the added mass and input signal to the filter for the translational model are shown in Fig.9 In this figure circular marks are measured and the rigid line is calculated result. In this calculation the model parameters were modified slightly in order to fit the calculated result to the measured. Dynamic characteristics of control system for torsional model is confirmed in the same way.

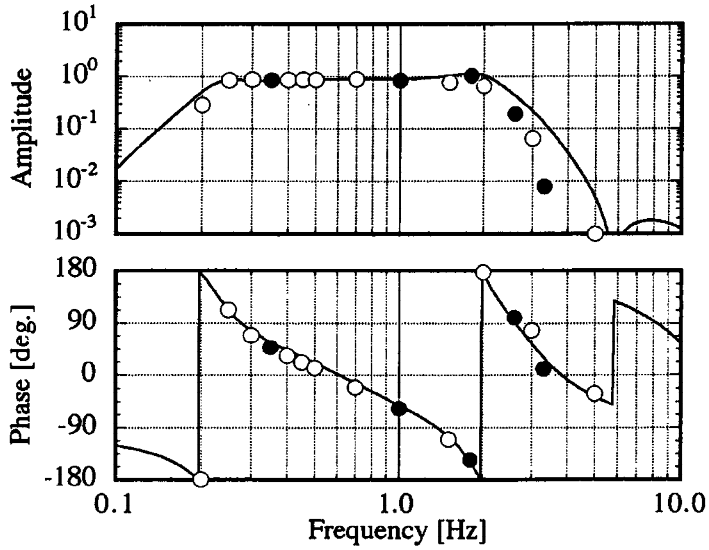

Fig.9. Frequency response characteristics of the added mass to the input signal

VIBRATION CONTROL EFFECT VERIFICATION EXPERIMENT

The experiment was based on a method whereby first the dynamic absorbers were used as vibrators to achieve a steady vibration state at the natural period of the building, next the dynamic absorbers were stopped, and then a switch over to the control mode was carried out. Here, the vibration control effect on the translation modes is shown as an example of the experimental result. Fig 10 shows translational free vibration waveforms at a non-control time; since the first to the third modes have a damping factor of about 1%, the vibration durations are long. Fig.11 shows experimental results at the time of translational vibration control obtained by using the feedback gain computed with the velocity state variable of the building as a criterion function. The results of Fig.11 at the time of vibration control show that approximately 10 percent is secured as damping factor for the first to third vibration modes, thereby realizing multi-mode control. Fig.12 shows experimental results of 1st translational and 1st torsional modes in controlled case at small response amplitude. The results of Fig.12 indicates that very large damping effect which is over 20 percent damping factor can be obtained within the small response amplitude.

From these results, the control method for variable gain and varing force in accordance to the response amplitude of the building is secured.

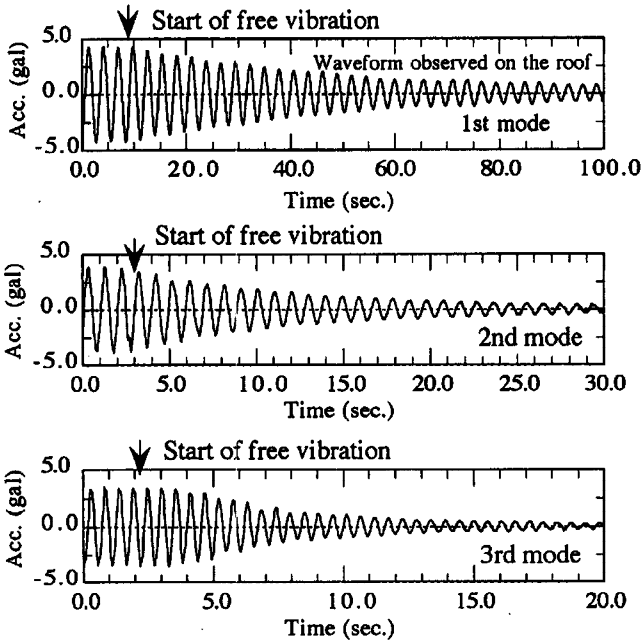

Fig.10. Free vibration waveforms without control

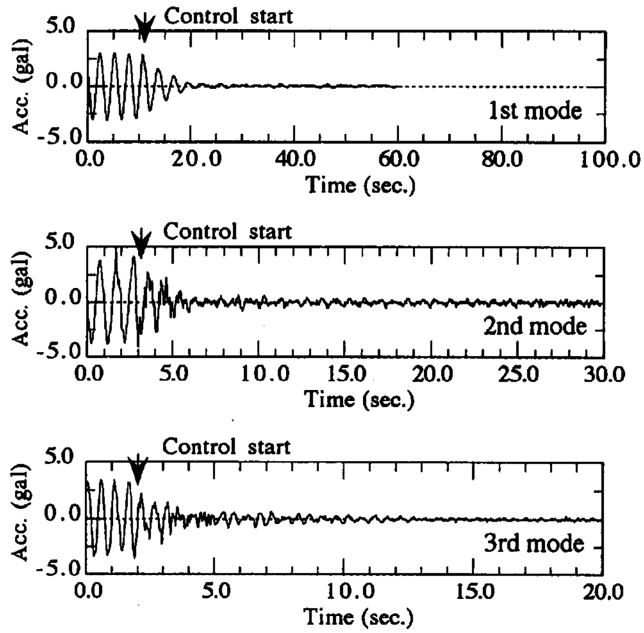

Fig.11. Waveforms with control

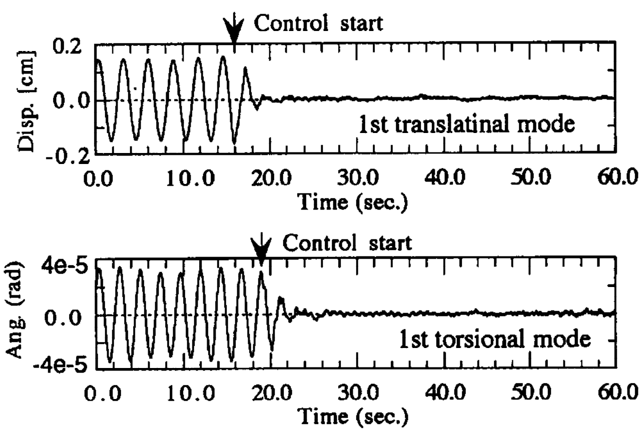

Fig.12. Waveforms with control in small amplitude

VIBRATION CONTROL EFFECT DURING EARTHQUAKE

Strong wind and earthquake obserbations have been continued since the structure was completed on August 8,1994. Many earthquake response obserbations were recorded. One of the earthquake response recorded on January 10,1995 is shown in Fig.13 and 14. The JMA seismic intensity in Tokyo was Ⅱ. Fig.13 shows the input wave, accelerations of the roof with and without control, and displacement of AMD. The acceleration without control was calculated using obserbed data and analytical building model. After 50 secons of the system starting, the vibration control system reduced the acceleration amplitude to about 2/3 of that without control. In Fig.14 Fourier spectra of acceleration of the roof with and without control are shown. Compared to the 1st to 3rd modes peaks of Fourier spectrum without control, those with control are about 1/3. From these results, vibration control effect during earthquake was verified.

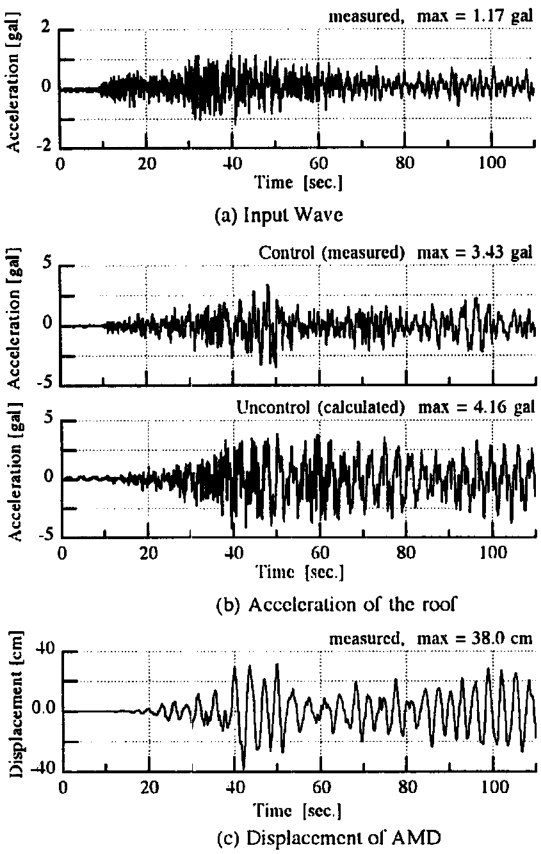

Fig.13. Earthquake responces of the structure and AMD

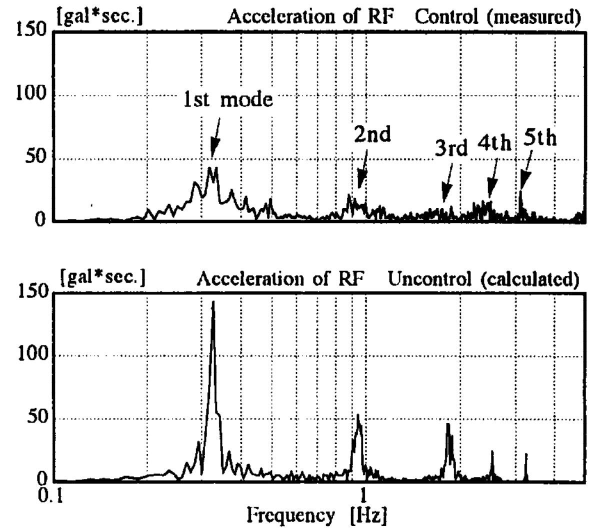

Fig.14. Fourier spectra of acceleration of the roof

CONCLUSIONS

Outline of the active vibration control system applied to an actual building and its control effects were described. One of the features of this system is to control multiple vibration modes without causing spilover, which was verified by vibration control experiment and observation results during earthquakes.

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