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Active mass damper using multistage rubber bearing and hydraulic actuator

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ABSTRUCT: An mass damper with a newly developed active strutcure has been developd to provide active vibration control for tall buildings. This device, supports a moving mass with four multistage rubber bearings. One major adantage of this new mass damper is that its structure allows for installation on building roofs thus eliminating the need for indoor space usage. The structure can also reduce operational friction and mass acceleration distortion. For damper control, a variable gain control law was formulated, with which the damper can protect against strong earthquakes in addtion to high winds and weak earthquakes. This is accomplished by keeping its displacement within the strong limit of two hydraulic actuators. Excitation tests were carried out for an experimental model of the damper, in which a 5300 kg of mass was supported by four multitage rubber bearing and horizontal movement was controlled by two hydraulic actuators. Through tests and simulation studies, we confirmed that the structure and control law effectively provided active vibration control for tall buildings.

INTRODUCTION

Recently, studies have been extensively conducted on the active mass damper, which prevents vibration of a building mainly caused by wind and earthquake of small magnitude. The active mass damper is therefore one of the effective measure to upgrade living comfort of the tall building. There have been several cases of actual use of the equipment.

An appropriate measure against medium- and large-scale earthquakes must be taken when designing an active mass damper for the Japanese buildings. Because a large number of small earthquakes occur in Japan every year.

Furthermore, there is a considerable possibility of the occurrence of medium and large scale earthquakes. The amplitude of the mass damper is inevitably large when a medium or large-scale earthquake occurs. The most popular measure to cope with this was automatically fixing a mass damper when the displacement of the damper reached the limit. However, the mass damper could not control any vibration when being fixed. In addition, it was disadvantageous because an unnecessary mass derived from the damper fixation was added at the top of the building.

This paper describes our studies on the possibility of application of the active control method to cope with a large-scale seismic vibration. As a result, it is revealed that the effective method has been achieved by making the best use of the actuator within a limited displacement.

That was achieved by switching several feedback gains. From the viewpoint of the effective use of a building's floor area, the mass damper should be installed at the roof of the building.

In our research, a multistage rubber bearing was incorporated into the active mass damper.

2 BASIC STRUCTURE OF ACTIVE MASS DAMPER

Figure 1 shows the basic structure of the active mass damper with the multistage rubber bearing incorporated. The mass damper features a heat storage tank to effectively use the mass of the system.

The passive mass damper which we have already reported has the following two advantages:

(1) It is easily installed on the roof of the building, and

(2) Less operational friction is caused.

Advantage (1) is endorsed by the fact that the multistage rubber bearing works well even under a severe operating condition like outside installation.

This type of rubber bearing is widely used for seismic vibration isolation equipment. Concerning Advantage (2), the multistage rubber bearing is less affected by friction caused due to material deformation, allowing the high frequency component of mass damper acceleration to be maintained a low level.

Our mass damper incorporates a hydraulic actuator. Since it generates relatively large power per unitary mass, the larger the capacity of the actuator becomes, the more effective it is.

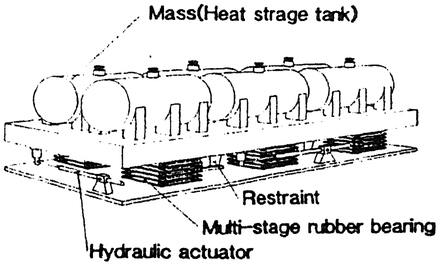

Figure 1. Basic structure of active mass damper using multistage rubber bearings

3 CONTROL LAW FOR MULTISTAGE RUBBER BEARING ACTIVE MASS DAMPER

3.1 Basic theory for active mass damper

An analysis model of the active mass damper is shown in Figure 2. Assuming that a tall building is an n material point corollary, a mass damper is installed at the s floor of the building, while the external force is impressed by earthquake or wind, the following two equation of motion are achieved:

The equation of motion of the building is defined by Eq.(1).

$$[M](\ddot{x})+[c](\dot{x})+[K](x) =(s)(c_d\dot{x}_d+k_dx_d-F)-[M](1)\ddot{z}+(w) \qquad (1)$$

Also, the equation of motion of the mass damper is defined by Eq. (2).

$$m_d(\ddot{x}_s+\ddot{x}_d+\ddot{z})+c_d\dot{x}_d+k_dx_d=F \qquad (2)$$

Where, [M], [C] and [K](n x n) represent the building's mass matrix, damping matrix and stiffness matrix, respectively.

The vector representing the building's relative displacement against the ground is defined by (x)(n x 1); whereas that representing the floor at which the damper is installed is defined by $(s) = (0...1...0)^T(n \times 1)$, $(1)=(1...1)^T(n \times 1)$, the acceleration of the ground caused by earthquake is defined by $\ddot{z}$. The external force vector derived from the wind is given as $(w)=(w_1,w_2,...,w_n)^T(n \times 1)$. x_d is a relative displacement of the floor at which the damper is installed against the ground. m_d, c_d and k_d correspond to the mass damper mass, the damping ratio and the spring ratio, respectively.

Also, the relative displacement of the mass damper against the floor surface where it is installed is defined as x_d; whereas the actuator control force is expressed by F.

The characteristics of the hydraulic actuator is defined by the equation described below;

$$a^2\dot{x}_d+r\dot{F}=abi-lF \qquad (3)$$

Where, the cross section area of the piston is represented by a. The cylinder's stiffness constant is represented by r. l is the decreasing rate of output flow by leakage inside the servo valve b is a flowing amount gain at the servo valve. i represents the controlling input.

Feedback gain was determined by the following process. The low-order components of Equations (1), (2) and (3) extracted by mode analysis prior to the application of the optimum regulator theory.

As the evaluation functions, the following items were considered:
-First-order components of the acceleration,
-Displacement occurring at the top floor of the building, and -Controlling input.

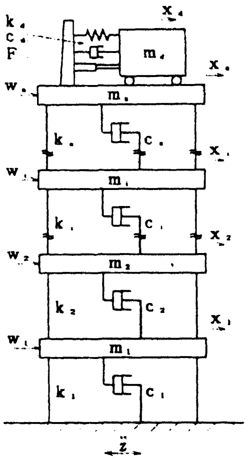

Figure 2. Analysis model

3.2 Feedback gain switching

If the active control of the mass damper is conducted by a single feedback gain, the displacement of the mass damper tends to be large when the gain with favorable vibration control performance is used. As a result, the displacement easily reaches the limit even though the external force is comparatively small.

One effective method to cope with this problem is a use of variable feedback gain method. By selecting the most appropriate feedback gain among the gains prepared, it is possible to effectively control the mass

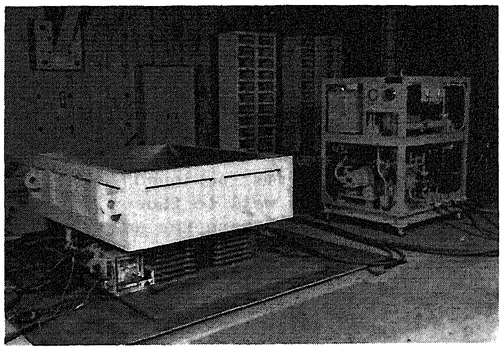

Figure 3. Active mass damper experimantal model

Table 1. Building model parameters

Mode	**1st**	**2nd**	**3rd**	**4th**	**5th**
Natural Frequency(Hz)	**0.55**	**1.57**	**2.47**	**3.64**	**3.15**
Damping Ratio (%)	**1.00**	**2.83**	**4.45**	**6.58**	**5.71**

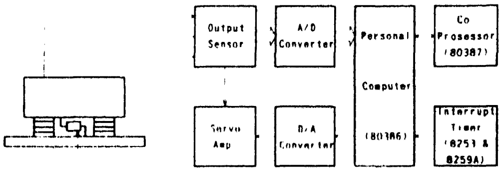

Figure 4. Control system

damper under a larger external force input without exceeding the displacement limit of the mass damper.

The gain switching is conducted in accordance with the displacement and the velocity of the mass damper.

Four types of the feedback gains were used. The smaller the gain was, the smaller the control current became. In other words, the evaluation function of the optimum regulator was more dependent upon the control input as the gain became small.

Furthermore, if an excess of the displacement limit is anticipated even with the smallest gain chosen, the system is designed to turn off the control current and stop the mass damper.

The switching conditions used in the experiment is defined in the region of $x_d>0$ as follows. Where, the displacement and the velocity of the mass damper, and time required to switch the gain are represented by x_d, $\dot{x}_d$ and delta t.

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if $x_d \geqq 9$cm or ($x_d \geqq 5$cm and $\dot{x}_d \geqq 25$cm/s)
        Gain1→Gain2
  then  Gain2→Gain3   and   $\Delta t=0.3$sec
        Gain3→Gain4

if $x_d \geqq 8$cm  and $\dot{x}_d \geqq 20$cm/s
  then  Gain1→Gain4   and   $\Delta t=0.2$sec
        Gain2→Gain4

if ($x_d \geqq 11$cm and $\dot{x}_d \geqq 5$cm/s)

or ($x_d \geqq 9$cm and $\dot{x}_d \geqq 15$cm/s)
  then  Gain3→Gain4   and   $\Delta t=0.5$sec

if $x_d \leqq 3$cm  for  2.5sec
        Gain4→Gain3
  then  Gain3→Gain2   and   $\Delta t=0.5$sec
        Gain2→Gain1
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4. EXPERIMENT EQUIPMENT AND CONTROL SYSTEM

The experimental model of the active mass damper is shown in Figure 4.

In this model, the mass of 5,300 kg is supported by four multistage rubber bearings. The two hydraulic actuators incorporated are unidirectional. The natural frequency of the mass damper without the actuators incorporated is 0.50 Hz. The damping ratio is 2 %. The maximum displacement is 12 cm. A couple of the actuators generate the maximum output of 9.8 kN x 2.

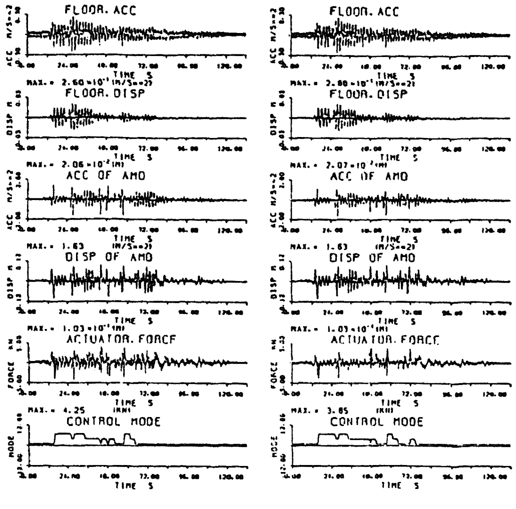
A building model was assumed as a subject of control. It was a five-story stiffness proportion type. The mass of each story accounts for 200 tons. The natural frequencies and the damping ratios of the building model are shown in Table 1.

The mass damper model was designed so that it had a natural frequency similar to that of the optimal passive mass damper against the first-order natural frequency of the building model. The experiment was performed assuming the mass damper model was installed at the roof floor of the building model. Also, the first-order component of the roof floor acceleration, which was generated when the ground acceleration caused by an earthquake, was used as an input wave form to the shaking table.

As shown in Figure 4, the control system consists of the sensor, the AC/DC conversion board and other equipment. The measurement processing was conducted by a personal computer with 32-bit CPU (80386 + 80387). The sampling time was 5 msec.

5 RESULTS OF EXPERIMENT AND ANALYSIS

Figure 5 shows the response wave achieved when the 0.2 m/s^2 Akita NS wave (an



experiment simulation

Figure 5. Active mass damper response

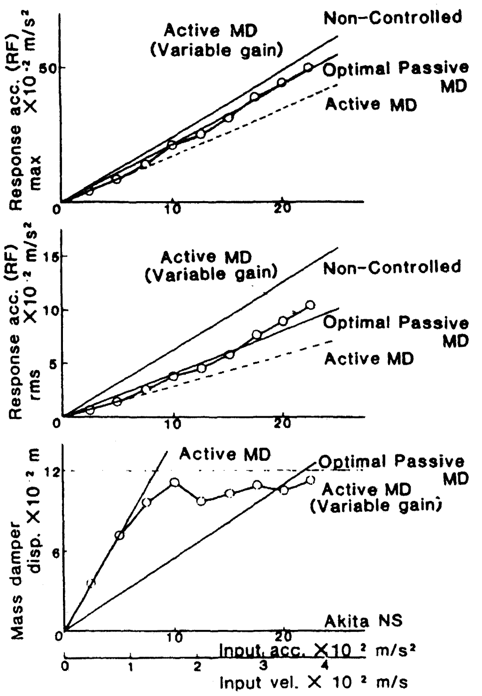


Figure 6. Active mass damper vibration contarol characteristics

earthquake wave form recorded in Japan) was applied to the building model as a ground vibration input.

The six graphs on the left represent the wave forms achieved by the experiment; whereas the right six graphs shows wave forms simulated based upon acceleration, velocity and displacement of the shaking table. The graphs are the wave forms of acceleration of the top floor, mass damper acceleration, mass damper displacement, actuator force and actuator control mode in the order from the top to the bottom.

All the wave forms achieved in the simulation conformed well to those achieved in the experiment, showing the adequacy of the analysis model.

Then, another simulation was conducted using the same analysis model. In the simulation, all the responses of the building model from the first- to fifth-orders were taken into consideration while the actuator control was performed only in the first-order.

Figure 6 shows the relationship between input acceleration/velocity and the mass damper's maximum displacement and anti-vibration characteristics. In this case, Akita NS wave was applied as an earthquake input wave.

The unrealistic control with the displacement limit set at mere 12 cm made resulted that the effective area of the active control became very small.

However, the mass damper displacement remained 10.4 cm against the earthquake acceleration of 0.20 m/s^2. This figure is favorably compared with 28.6 cm achieved using a single gain active mass damper and 10.8 cm achieved using an optimal passive mass damper.

This means that the variable gain active mass damper is capable of controlling the vibration within a small external force range more effectively than the optimal passive mass damper. At the same time, even against a larger external force input, it can effectively control the vibration within the displacement limit.

6. CONCLUSIONS

We developed the active mass damper using hydraulic actuators in order to study the control law with the mass damper displacement limit positively considered.

As a result, it is confirmed that the switching of several gains enabled the effective vibration control even against a large external force input.

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