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Mass damper with convertible active and passive modes for response control of buildings

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ABSTRACT: With a view to improve habitability of tall buildings, a biaxially controlled mass damper with convertible active and passive modes has been developed. In this system, a passive mass damper is equipped with a hydraulic actuator to produce an active vibration control function. Against medium and weak earthquakes that occur frequently, this damper exhibits an active vibration control function, and when strong earthquakes that exceed the capacity of the actuator occur, the vibration control function switches from active to passive, thus permitting flexible system design. A 18m 6-story full-scale structure was constructed to verify the function of the mass damper developed. The weight of each story was 75 tonf and that of the mass damper was about 5 tonf.

INTRODUCTION

In general, the active mass damper is expected to exhibit a large vibration control effect. However, in view of economic efficiency and functions, it does not seem to be practical to adopt active vibration control, which requires large drive equipment and energy, to provide against strong earthquakes that seldom occur. To cope with such situations, an active-passive mass damper (hereinafter referred to as APMD) has been developed. APMD in an active mode exhibits a great vibration control effect against building vibration due to medium and weak earthquakes as well as strong wind that occur frequently.

When external force exceeding the capacity limit of actuators and other equipment is input during a severe earthquake, APMD switches over to a passive mode to dodge excessive load that will be otherwise applied to the equipment and controls the response of a building as a tuned mass damper. When the input force calms down within the allowable capacity of the equipment, APMD switches to the active mode with higher vibration control performance. Putting the two vibration control methods to proper use according to the magnitude of external force, the equipment capacity and applicable range of the active mode can be freely set in accordance with the design criteria, thus permitting formation of a flexible system.

APMD was installed in a full-scale structure constructed in the Institute of Technology, Toda Corporation, to confirm the vibration control performance in an active and passive modes and test the active-passive switching characteristics under forced vibration. This paper reports on the verified performance of APMD.

TEST BUILDING AND MASS DAMPER

The test building is of 6-story steel construction, shown in Photo 1, which is designed to be a comparatively long period

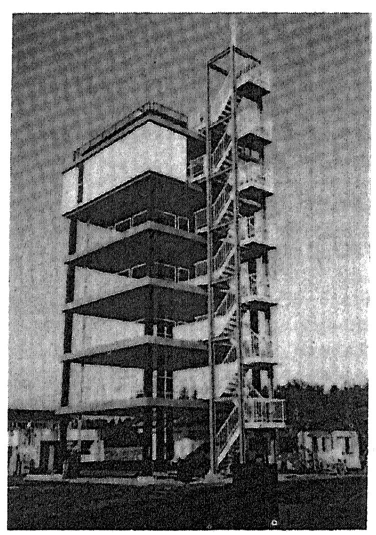

Photo 1 Large Scale Model Structure

structure assuming a tall building. The building measures 8m x 8m in the span and 18.9 m in height. The weight of the main construction is about 480 tonf. The superstructure is isolated from the vibration of steel stairs. Table 1 shows the fundamental frequency of the test building obtained from the forced vibration test. The damping constant in the first mode found in the test is 0.57% along the X axis and 0.65% along the Y axis.

APMD is installed outdoors on the highest story of the test building, while the pump unit used as a power source is installed on the story directly under the highest one. APMD shown in Fig. 1 is 3m both in width and depth and 1.8m in height. The moving mass in the Y direction is the upper mass shown in the figure and that in the X direction are the upper mass and intermediate frame mass. Each moving mass is independently supported by a linear motion mechanism. The moving mass is equipped with tension springs to allow APMD to have a passive vibration control function, and the natural period of the mass damper is synchronized with the primary natural period of the test building. The particulars of the mass damper is shown in Table 2.

A hydraulic (water-glycol) actuator is used as a drive unit in the active mode. The passive mode is created by opening the bypass valve mounted on the actuator cylinder and by releasing pressure from the cylinder. At that time, the actuator functions as an oil damper. Regulation of the valve opening causes variable damping by the mass damper system in the passive mode, thus permitting regulation for optimal damping. Table 3 shows the particulars of the actuator.

EQUATION OF MOTION

The respective equations of motion of the mass damper system, test building, and hydraulic actuator in the active mode are shown below.

$$m_d(\ddot{x}_r+\ddot{x}_d+\ddot{y})+k_d x_d=f \quad \text{.... (1)}$$

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{s\}(k_d x_d-f)+\{F\} \quad \text{... (2)}$$

$$r\cdot\dot{f}+1\cdot f+a^2\cdot\dot{x}_d=a\cdot b\cdot u \quad \text{.... (3)}$$

where m_d and k_d are the mass and spring rigidity of the mass damper; x_r is the displacement of the highest story of the test building; x_d is the displacement of the mass damper against the highest story of the test building; $\ddot{y}$ is ground motion acceleration; $\{F\}$ is input disturbance: $[M]$, $[C]$, and $[K]$ are mass, damping, and rigidity matrices; $\{x\}$ is the displacement

Table 1 Natural Frequencies of Structure

Mode	X-direction	Y-direction
1st	0.75 Hz	0.88 Hz
2nd	2.41	2.92
3rd	4.22	5.30
4th	6.07	8.01
5th	7.14	10.05
6th	8.00	11.69

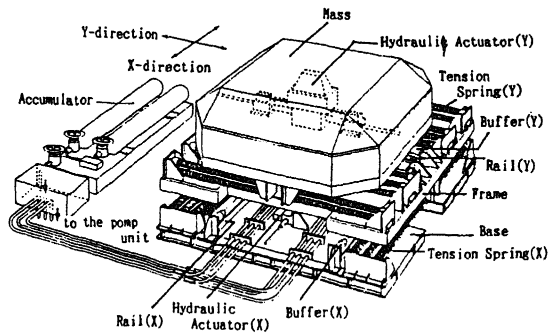

Fig. 1 Structure of Active-Passive Mass Damper

Table 2 Parameters of Mass Damper

	X-direction	Y-direction
Mass	5.59 ton	4.11 ton
Effective mass ratio (1st mode)	2.2%	1.6%
Natural frequency	0.83 Hz	1.04 Hz
Friction	7.9/1000	11.7/1000

Table 3 Dimensions of Actuator

Stroke	±35.0 cm
Max. velocity	1.00 m/s
Max. force	1.00 tf
Pump unit*	11.0 kW
Accumulator*	60.0 1x2

*: Used in common for both directions

vector of the building, $\{S\} = (10 \ldots 0)^T$; f is the controlling force (generated by the actuator); r, l, a, b, and u are constants representing the rigidity and leakage of the actuator, the sectional area of the cylinder, the flow rate gain of the servo-valve, and the control voltage for the servo-valve.

An equation of motion is derived from the above three simultaneous equations.

Of the members of equation (3), l and u are quantities changeable by the control system. Regulation of the opening of the actuator bypass valve changes the value l in the passive mode and vary the mass damper system damping. Change in the value u in the active mode permits operation of the actuator and controls the motion of the mass damper system.

CONTROL LAW

Fig. 2 shows the construction of the vibration control system. Observation items for control are velocity and displacement of each story of the test building, the velocity and displacement of APMD against the highest story of the test building, and actuator pressure.

In the current test, the response quantity of the 1st and 2nd modes of the test building is controlled. Equations (1) and (2) are represented as follows in the normal coordinates with the help of modal matrix.

$$\ddot{x}_d + t_{n1}\ddot{q}_1 + t_{n2}\ddot{q}_2 + \ddot{y} + \omega_d^2 x_d = f' \quad \ldots\ldots (4)$$

$$\ddot{q}_i + 2h_i\omega_i\dot{q}_i + \omega_i^2 q_i = \rho_i(\omega_d^2 x_d - f') - F' \quad \ldots\ldots (5)$$

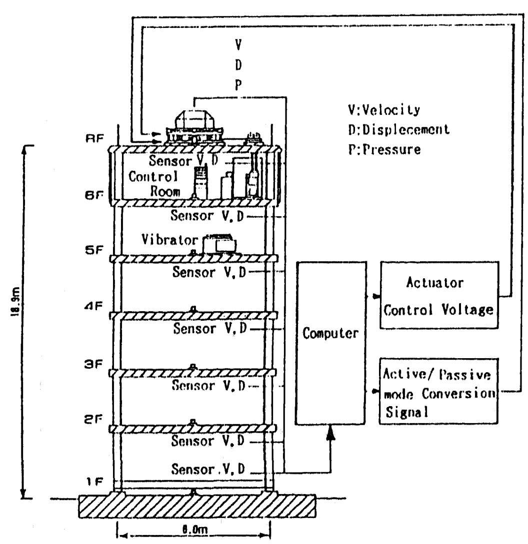

Fig. 2 Control System Diagram

where t_{ni}, is the i-mode component of the highest story of the building in the model matrix; ω_d is the natural circular frequency of the mass damper system; $f'=f/m_d$; q_i, h_i, ω_i, and ρ_i are the displacement, damping constant, circular frequency, and mass ratio of the test building in the ith mode; F' is the external force after coordinate transformation into the normal coordinates.

The control system is designed on the basis of simultaneous equations of (3), (4), and (5). State variables and the equation of state are represented as follows:

$$\{x\}=\{q_1\ q_2\ x_d\ \dot{q}_1\ \dot{q}_2\ \dot{x}_d\ f\}^T$$
$$\{\dot{X}\}=[A]\{X\}+\{B\}u+\{F\}$$

The control system is composed of optimal regulators.

It is impossible to directly observe the response quantity of the 1st and 2nd mode of the test building to be controlled. Therefore, a modal filter is used to analytically extract the velocity and displacement of the 1st and 2nd modes by using the velocity and displacement of each story of the test building, and 3rd and subsequent modes are eliminated. With the help of the response quantity of the 1st and 2nd modes thus obtained, the value u in equation (3), which is the control voltage to be output for the actuator, is calculated and used for controlling the actuator.

When either the control voltage to be output for the actuator or the internal pressure of the actuator exceeds the preset value, the mode switches from active to passive. When the above-mentioned value stays below the preset value for a particular period of time, the mode switches back to active.

TEST RESULT

Forced vibration tests were performed with the aid of an unbalanced mass type vibration generator installed on the 5th story of the test building. Fig. 3 shows the sweep test results in the X direction where acceleration response of the test building is standardized by means of exciting force.

In the passive mode represented by the broken lines, the vibration control effect is observed near the 1st mode on all stories, and the response quantity is about 60% less than that under the non-controlled vibration represented by the broken lines. In the active mode represented by the full lines, conspicuous vibration control effects are observed near the 1st and 2nd modes on each story, and the response

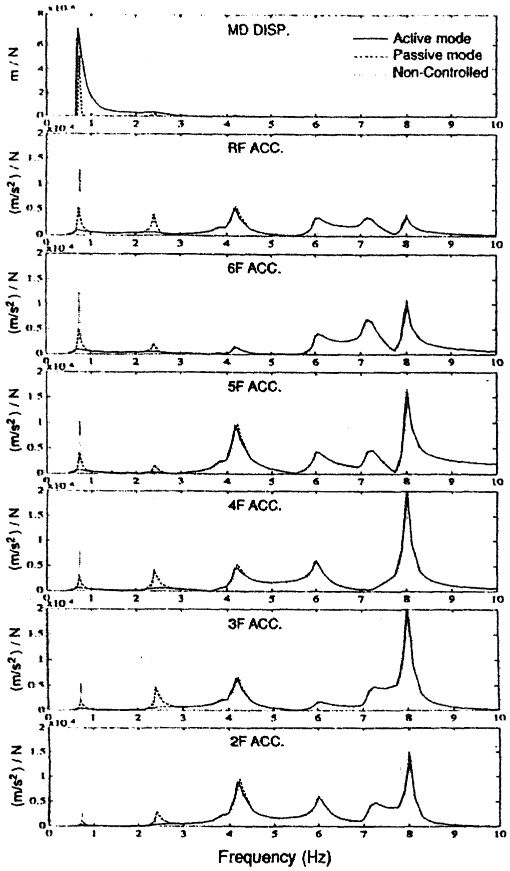

Fig. 3 Transfer Functions (X-direction)

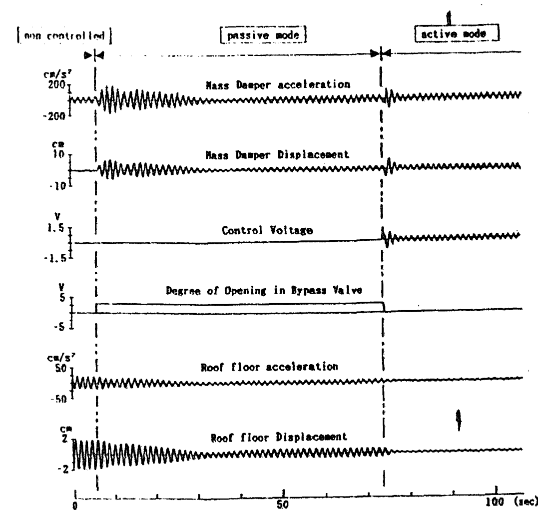

Fig. 4 Time Histories of Mode Conversion Test

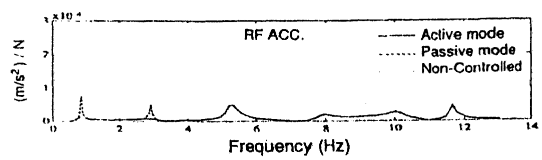

Fig. 5 Transfer Function (Y-direction)

quantity in the 1st mode is about 90% less than that under the non-controlled vibration represented by the dotted lines and the response quantity in the 2nd mode is about 80 to 90% less.

In the 3rd and subsequent modes in the active mode, which are out of the scope of the test, no meaningful difference is observed between the non controlled vibration, passive mode, and active mode, and thus stable control is materialized.

In the meantime, the action of the mass damper is effective in the 1st and 2nd modes of the test building in the active mode, and actions that coincide with the control system design are confirmed. While in the passive mode represented by the broken lines, the action of the mass damper is satisfactory in the 1st mode of the test building where the cycles of the mass damper system are synchronized. Near the 1st mode of the test building, the response of the test building is reduced in a wide frequency band, since the frequency band in the active mode represented by the full lines is wider than that in the passive mode represented by the broken lines.

Stationary vibration with the 1st resonant frequency of the test building was applied in the test, and the vibration control modes were switched in the order of the non-controlled vibration, passive mode, and active mode. Fig. 4 shows the time histories of response waveforms obtained through the said test.

According to the figure, switching from the non-controlled vibration to the passive mode is confirmed by the fact that the mass damper is actuated when the bypass valve is opened. It takes about 50 seconds for the highest story of the test building to be stabilized in the stationary state in the passive mode, and the response is reduced like in the case of the sweep test result. When the mode is switched from passive to active, the control voltage and mass damper response sharply increase and the response of the highest story of the test building becomes small instantaneously. For switching the mode from passive to active, the bypass valve is closed continuously over a certain period of time to avoid generation of shock response.

Fig. 5 shows the sweep test result of the highest story of the test building in the Y direction. In the active mode represented by the full lines, the response quantity is 90% less than that under non-controlled vibration represented by the dotted lines near the 1st and 2nd modes. While in the passive mode represented by the broken lines, the vibration control effect in the Y direction is not as great as that in the X direction because the mass ratio of the mass damper in the Y direction is smaller than that in the X direction. However, the response quantity is about 40% less than that under the non-controlled vibration represented by the dotted lines. The vibration control effect on other stories is the same as that on the highest story.

CONCLUSIONS

A full-scale structure was constructed to perform forced vibration tests. The results are summarized as follows:

1. In the active mode, satisfactory vibration control effect was obtained in the 1st and 2nd modes of the test building both in the directions of X and Y. In comparison with non-controlled vibration, the response quantity is about 90% less in the 1st mode and about 80 to 90% less in the 2nd mode. On top of that, unstable control is not observed in the 3rd and subsequent modes.
2. The vibration control effect in the passive mode is not as great as that in the active mode. However, the vibration control effect is satisfactory in the 1st mode of the test building where the cycles of the mass damper system are synchronized, and the response quantity is about 60% less in the X direction 2nd about 40% less in the Y direction, respectively, than that under non-controlled vibration.
3. The mode is smoothly switched from active to passive by continuously opening closing the bypass valves over a certain period of time.

The authors are presently observing earthquakes and wind, and the vibration control system in the test building is ready to be actuated by earthquakes and wind. Observation results will be reported successively hereafter.

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REFERENCES

Fujita et al. (1991). Fundamental Study of Active-Passive Mass Damper Using XY-Motion Mechanism and Hydraulic Actuator for Vibration Control of Tall Building. Transaction of Japan Society of Mechnical Engineers, 57, 543, pp3532-3539 (in Japanese)

Takanashi, Fujita et al. (1991). Study of Mass Damper with Convertible Active and Passive Modes. (Part 1 Shaking Table Test of Small Model Structure), Prepriuts of Annual Meeting of Architectural Institiue of Japan (in Japanese)