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Application of the active mass driver (AMD) system to structural active seismic response control

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ABSTRACT: The active mass driver (AMD) system, an active seismic response control system, has been applied to an actual 11-story office building completed in Tokyo in August 1989. The AMD system suppresses the vibrations of a structure by the operation of an active control force. The practical application of the active seismic response control system is the first of its kind in the world. Observation data was shown that the AMD system effectively reduces the response vibration of a building subjected to not only earthquake motion but also strong wind motion.

1 INTRODUCTION

Research and development of a new type of structural response control system named the Active Seismic Response Control System was proposed by Kobori (1986).

The active mass driver(AMD) system, which is classfied as a response control force type system, aims to suppress building vibration caused by earthquakes and strong winds by controlling an auxiliary mass installed in the building, by operating an actuator. In August 1989, this AMD system was installed and put into operation in a building in Tokyo. This paper outlines the building, the AMD system, and the control effect under actual earthquakes and strong winds.

2 OUTLINE OF THE BUILDING

The AMD system was installed in an 11-story steel-frame building. A typical floor plan and cross section are shown in Figure 1. It is a very slender building, 4m wide, 12m long and 33m high. The structure of the building above ground comprises a rigid framework of four structural steel box columns and "I" shaped beams. The total weigth of the building estimated at the time of structural design is about 3.92MN.

In the initial design process, there was some anxiety about vibration of the building during earthquakes and strong winds because of its large slenderness ratio and the small damping factor of its structural steel beam column framework. Thus, to reduce vibrations and increase serviceability, it was decided to install the AMD system.

3 CRITERIA OF VIBRATION CONTROL

Japan frequently experiences moderate earthquakes of a maximum acceleration of about 10

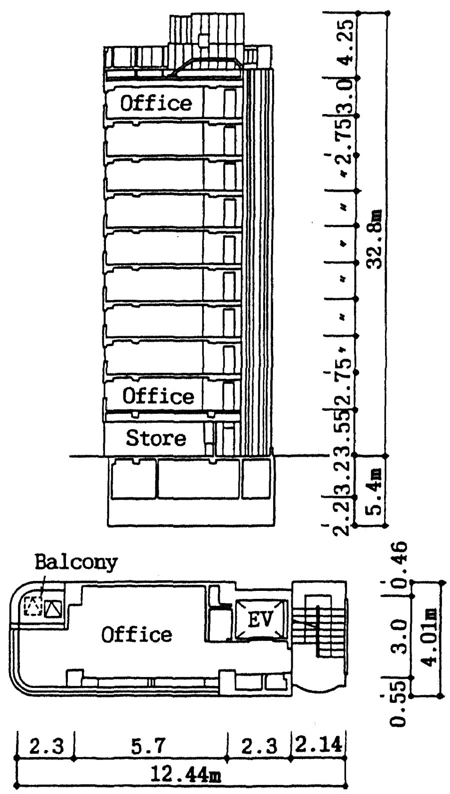


Figure 1 Outline of the building

cm/sec^2. The criteria for this AMD system was to reduce the maximum response accelerations of an uncontrolled structure by about 1/3 through 1/2 during these frequent earthquakes. In other words, its purpose was to improve the comfort of the building when subjected to such external excitations as earthquakes or strong winds.

4 CONTROL ALGORITHM

The matrix equation of motion for the vibration controlled structure can be expressed as

$$M\ddot{q}(t)+C\dot{q}(t)+Kq(t)=Uu(t)+f(t) \quad (1)$$

in which q(t) is the displacement vector relative to the base, u(t) is the control force vector, f(t) is the external force vector, U is the location matrix of controllers, and M, C,and K are the mass, damping, and stiffness matrices, respectively.

The control force u(t) is regulated linearly by the relative velocity vector $\dot{q}(t)$, i.e.,

$$u(t)= G\dot{q}(t) \quad (2)$$

where G is the feedback gain matrix, that is simplified and regulated by certain relative velocities to have a control effect equivalent to that obtained by the optimal control theory for all components of the state vector.

5 COMPOSITION OF THE AMD SYSTEM

The entire composition of the AMD system for the building is shown in Figure 2. Two AMD units provide the controlling force. The center unit(auxiliary weight of 39.2KN) acts to suppress the large lateral vibrations in the transverse width direction, and the end unit (auxiliary weight of 9.8KN) acts to suppress the torsional vibrations.

To confirm the control effect and to obtain data for utilizing in development henceforth, an observation system is also installed in the building. The accelerations at the basement, 6+h, and 11th floors are measured, as well as the accelerations and relative displacements of the weight.

The AMD system is composed of a driver unit, a hydraulic supply unit, and a control computer.The details of each component are described below.

5.1 Driver unit

For realizing the objective of the control system, the required maximum control forces determined were 9.8KN for lateral vibration and 2.45KN for torsional vibration. The driver unit that was designed based on above conditions is shown in Figure 3. The driver unit consists of a steel weight suspended by steel

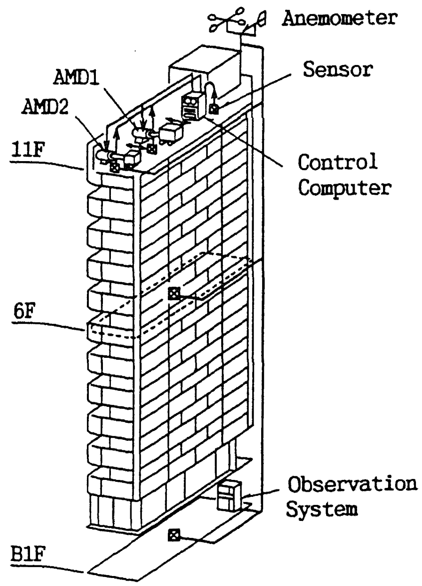


Figure 2 Composition of AMD system

cables, an electro-hydraulic actuator, and a reaction block that connects the building and the actuator. The natural frequency of the suspended weight is approximatly 0.4Hz, which is much lower than the building's natural frequency. Control forces are applied according to the feedback signal of acceleration and displasement of the weight.

5.2 Hydraulic power unit

The hydraulic power unit consists of 2 pumps, one of 1.5Kw and the other of 22Kw; an oil tank; a filter; an accumlator and a fan cooler. The 1.5Kw pump operates constantly. It provides pressure storage to the accumlator and gives coverage to the rise of the 22Kw pump, which enables instant operation when an earthquake hits. This dual pump system makes it possible to save electric power.

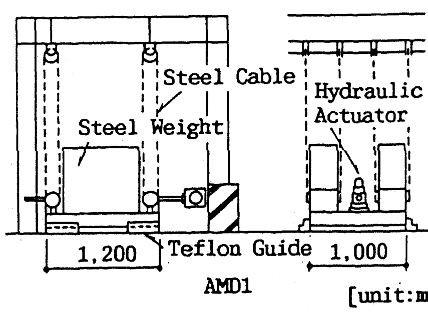


Figure 3 Datails of the driving unit

5.3 Control computer

The control computer system is made up of an analog type control circuit, which creates commands (by processing the signals from the sensors), and a controller for the actuator. The applied control method is expressed by equation(2) and this equation is expressed concretely as follows:

$$u_{AMD1}(t)=g_1\dot{q}_1(t)+g_2\dot{q}_{AMD1}(t) \quad (3)$$

$$u_{AMD2}(t)=g_3(\dot{q}_2(t)-\dot{q}_1(t))+g_4\dot{q}_{AMD2}(t) \quad (4)$$

where $u_{AMD1}(t)$ and $u_{AMD2}(t)$ are control forces of the AMD, $\dot{q}_1(t)$ and $\dot{q}_2(t)$ are relative velocities at the 11th floor, ($\dot{q}_1(t)$ is at the center, and $\dot{q}_2(t)$ is at the end), $\dot{q}_{AMD1}(t)$ and $\dot{q}_{AMD2}(t)$ are relative velocities of the AMD weight, and g_1, g_2, g_3, g_4 are feedback gains determined by the preliminary analysis.

5.4 Safety systems for the building

In this system, two types of safety mechanisms are provided. One is to limit the maximum action of the devices and the other is to prevent them from causing excitations to the building.

Table 1 Resonance periods and damping factors

Direction	Mode No.	Test: Resonance period (sec)	Test: Damping factor (%)	Analysis: Resonance period (sec)
Transverse	1	0.94	0.77	0.93
	2	0.25	1.35	0.27
	3	0.12	2.26	0.13
Torsion	1	0.54	1.96	0.54
	2	0.17	2.43	0.17

6 FORCED VIBRATION TEST

To confirm the dynamic characteristics of the structure, a forced vibration test was conducted on the building in controlled(AMD ON) and uncontrolled(AMD OFF) states.

6.1 Dynamic characteristics of the structure

As the test results, resonance periods and modal damping coefficients estimated from waveforms of free vibration are indicated in Table 1. A typical resonance curve of displacement measured at the 10th floor with the AMD OFF is shown in Figure 4(a). From the figures and table, the following effects are apparent.

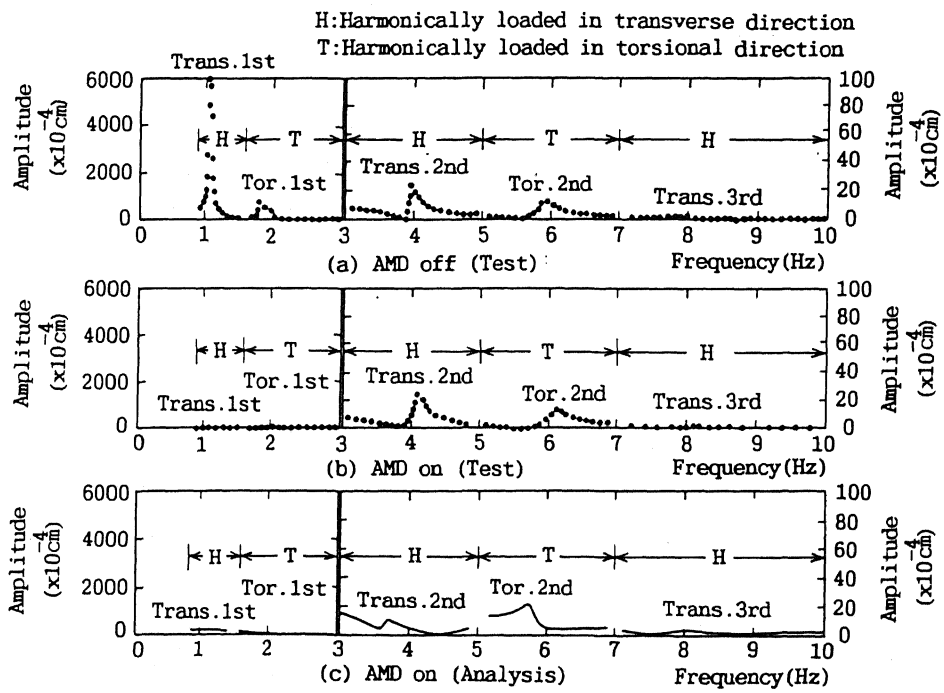


Figure 4 Resonance curve of displacement(10th floor)

1. Vibration modes in the transverse and torsional directions are excited independently.
2. Modal damping coefficients of the torsional modes are larger than those of the transverse modes.

6.2 AMD performance under stationary excitation

A resonance curve of displacement measured at the 10th floor of the controlled structure with the AMD ON is shown in Figure 4(b). This shows a notable control effect in comparison with Figure 4, especially at the resonance peak of 1.07Hz for the first mode in the transverse direction, and 1.85Hz for the first mode in the torsional direction.

7 EATHQUAKE OBSERVATION RECORDS

After completion of the building, earthquake records of more than 3 cm/sec^2 acceleration at the basement floor were recorded as shown in Table 2. From these records, the following effects were noted.
1. When the magnitude of the earthquake was larger than M_{JMA}6(90/Feb./20,Jun./1), or the seismic center was relatively shallow(90/Aug./5), the earthquake spectra had a wide range of power from 0.2 to 1.0sec in natural period.
2. In other earthquakes, when the magnitude was less than M_{JMA}6, or the seismic center was relatively deep, the earthquake spectra had a predominant power at a natural period of 0.2-0.3sec.

8 SIMULATION ANALYSIS

To confirm the AMD performance during earthquakes, analyses were carried out to compare the responses of the structure in the uncontrolled and controlled states.

8.1 Analytical model of the building

The objective building is modeled as a 3-D frame that consists of columns, girders and joint panels. Based on the assumption of a rigid floor slab, deformations of each story are considered in two horizontal directions, and in the torsional direction at the gravity center. The generalized stiffness matrix is derived from the transformation calculation of the local stiffness matrix and the compatibility conditions at each floor level. The frames and stiffnesses of partition walls around the elevator are also considered in addition to the main structural elements. The building frame is assumed to be fixed at the first floor level in the analytical model.

Table 2 Earthquake observation records

Date	Epicenter	Magnitude M_{JMA}	Focal depth (km)
89. 9. 5	Central Chiba Pref.	4.5	70
10.10	Central Chiba Pref.	4.8	78
10.14	Off Izuohshima	5.7	21
90. 2.20	Off Izuohshima	6.5	6
6. 1	Eastern Off Chiba Pref.	6.0	59
6. 5	Kanagawa Pref.	5.4	123
8. 5	Off Ibaraki Pref.	5.8	39
8. 5	Western Kanagawa Pref	5.1	14
8.23	Central Chiba Pref.	5.4	50
8.23	Central Chiba Pref.	5.2	50
91. 7.14	Wastern Nagano Pref.	5.4	80
9.29	Nothern Chiba Pref.	4.9	80
11.19	Coast of Chiba Pref.	4.9	80

Natural periods and vibration modes obtained by the eigenvalue analysis of the analytical model are shown in Table 1 and Figure 5 and compared with the test results. The vibration mode shapes were normalized relative to the amplitude of the 11th floor. These table and figures show that the analytical model is appropriate to be used for the simulation analysis of vibration tests and earthquake responses.
In the analysis for AMD1 and AMD2, whose weights were modeled as a mass point, the dynamic characteristics of the control circuits and actuators in the frequency domain are considered.

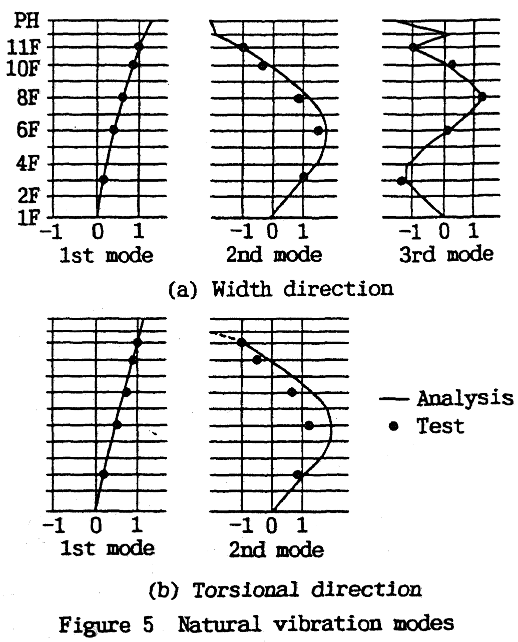
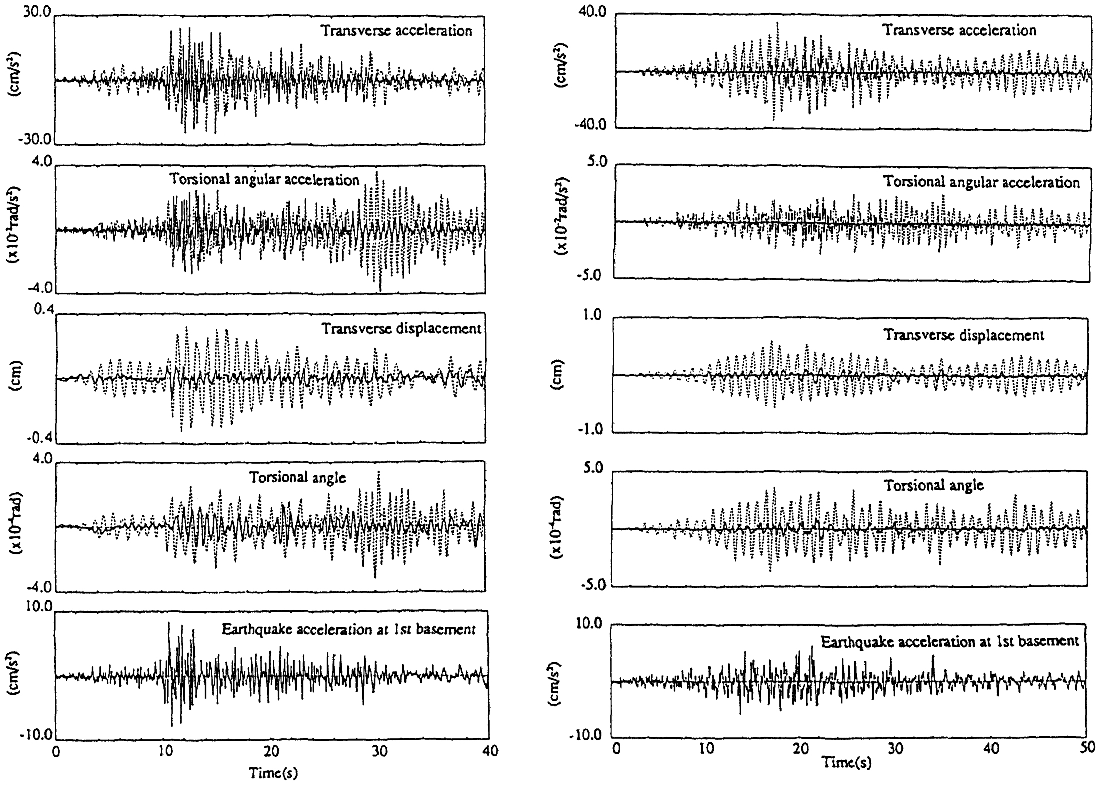


Figure 5 Natural vibration modes



(a) October 14, 1989

(b) June 1, 1990

Figure 6 Control Effect in Response Time Histories

8.2 Simulation analysis of vibration test

A resonance curve of displacement of the 10th floor, evaluated from the analysis using the analytical model subjected to an exciting force of 0.98KN at the 10th floor, is shown in Figure 4(c).

Comparison between the analytical results and test results shows that the analytical model is appropriate because the analysis simulated the experimental amplitude of the first transverse direction mode near 1Hz and the first torsional mode near 1.8Hz, which can be controlled mainly by AMD.

8.3 Simulation analysis of earthquake responses

Using the verified analytical model, analyses were carried out to compare the responses of the uncontrolled and controlled structure for two typical earthquakes taken from the records of Table 2. One is the earthquake of October 14, 1989, as shown in Figure 6(a), and the other is that of June 1, 1990, as shown in Figure 6(b). In the former, the control effect is seen to be efficient for the overall time history of the figure, except for the parts of insufficient control effect at the first large wave of horizontal vibration and at the beginning of the torsional vibration. However, the latter showed a remarkable decrease in the amplitude due to the AMD in each time history of the figure. The difference between these control effects seems to be caused by the relation between the dynamic characteristics of the structure and the spectra of the earthquake. As the AMD system mainly controls the 1st mode of the structure (1.0 sec natural period), it showed a good control effect for the earthquake of June 1, 1990 in which the long period component predominated.

9 STRONG WIND OBSERVATION RECORDS

The response of the building during several strong winds after the building was completed are shown in Table 3. The strong wind record of August 10, 1990 (Typhoon 11) is shown in Figure 7. In this case, the AMD's operation was suspended in order to compare the responses of the structure in the uncontrolled and controlled states. Under almost the same conditions of wind direction and velocity, the response of the building was observed in

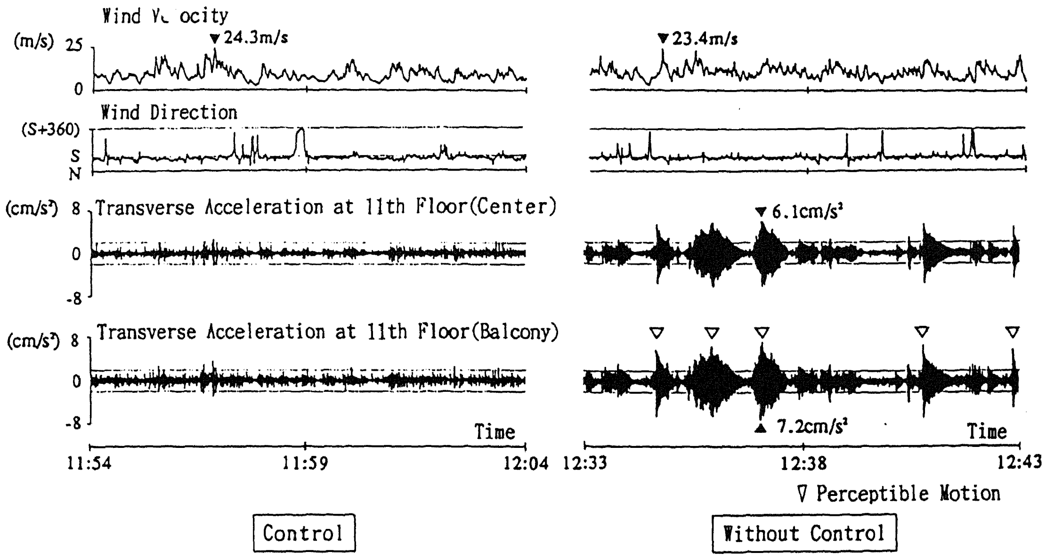


Figure 7 Observation Records of Typhoon 11 on August 10, 1990

Table 3 Strong wind observation records

Date	Type of wind	Max.wind velocity (m/sec)	Note*
89. 8. 6	Typhoon 13	19.3	NC and C
8.27	Typhoon 17	18.2	C
9. 3	seasonal wind	16.7	C
9.20	Typhoon 22	19.9	C
90. 2.11	seasonal wind	19.0	NC and C
4.29	seasonal wind	20.1	C
6. 9	seasonal wind	18.1	C
8.10	Typhoon 11	24.3	NC and C
8.23	Typhoon 14	18.2	C
91. 2. 8	seasonal wind	24.9	C
2.16	seasonal wind	22.6	C
8.31	Typhoon 14	19.5	C
9.28	Typhoon 19	25.2	C

* NC:without control, C:with control

the AMD power-on state and the AMD power-off state.

The acceleration responses of the 11th floor were generally less than 1 cm/sec^2 in the controlled state (Figure 9(a)), and 6 to 7 cm/sec^2 in the uncontrolled state(Figure 9 (b)). The maximum response in the controlled state was reduced to 1/3 of that in the uncontrolled state. Moreover, no uncomfortable vibration was felt in the controlled state even though there were many noticeable vibrations in the uncontrolled state.

10 CONCLUSIONS

The active mass driver(AMD) system, which has been applied to an actual 11-story office building in Tokyo, is an active seismic responce control system. The practical application of the AMD is the first of its kind in the world. The AMD system is verified to achieve a remarkable vibration control effect.

However, as the goal of seismic response control is to reduce earthquake disasters, there are many problems in practical seisimic control systems like control energy, etc.. Therefore, we shall continue to make efforts to find new solutions to future problems.

REFERENCES

Kobori,T., et al.,1986, Approach to dynamic intelligent building-A new development in seismic response controlled structure-, Proc. Annual Meeting of A.I.J.:891-898

Kobori,T., et al.,1990, Study on active mass driver system(Part 1),(Part 2)- Active seismic response controlled structure-, 4th World Congress of the Council on Tall Buildings and Urban Habitat.