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EARTHQUAKE RESPONSE OBSERVATION OF A VERIFICATION TOWER WITH ACTIVE MASS DAMPER SYSTEM

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ABSTRACT

An active/passive mass damper is developed as a response reduction device for tall or slender buildings subjected to ground motions and wind excitations. This system is a hybrid mass damper adopted variable gain control algorithm and it also works as a passive system in case of exceeding the limits of active control. In order to confirm the practical performance of this system, a series of experiments and response observation of a prototype system on 31m height experimental tower has been carried out. Through these experiments and observations, validity of the proposed control algorithm and the response reduction effect are verified.

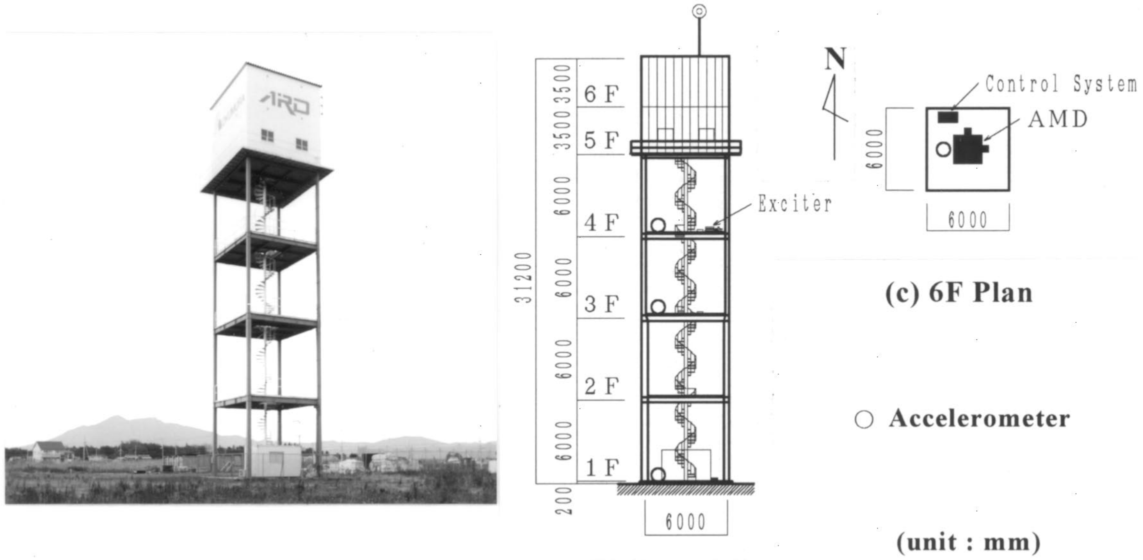
KEYWORDS

active mass damper; hybrid mass damper; optimal feedback regulator; variable gain control; earthquake and wind response observation;

INTRODUCTION

The authors have developed an active/passive mass damper system supported by special roller bearings and variable gain control algorithm. This system is a hybrid mass damper driven by AC servo motor, and it works as a passive mass damper in case of exceeding the limits of active control. Although the feedback control on the optimal regulator is basically used as a control algorithm, variable gain control is applied in order to improve the performance and expand the controllable region. In this algorithm, an appropriate control gain is selected among the several levels of prepared gains according to the velocity and the displacement of the moving mass. A prototype system is produced and a series of verification tests is carried out. In order to confirm the basic performance of the system, the shaking table tests are conducted. Then the forced vibration tests and the earthquake and wind response observations on the verification tower are performed to verify its response reduction effect and applicability. In this paper, the outline of system, observed earthquake and wind response and simulated results are described.

OUTLINE OF VERIFICATION TOWER



(a) View of the tower (b) Elevation (c) 6F Plan

○ Accelerometer

(unit : mm)

Fig. 1 Verification Tower

The verification tower has been constructed in Research Institute of Okumura Corp.. This tower is a 6 story and 31.2m high steel frame structure. Weight of the tower above ground level is 100tf. The elevation and plan of the tower are shown in Fig.1. The active mass damper and control system are installed on the 6th floor. The forced vibration tests and free vibration tests are carried out with a hydraulic exciter on the 4th floor. The natural periods of the tower are shown in Table 1. Because the plan of the tower is square, the dynamic characteristics of X and Y directions are same.

Table 1 Natural Periods of Experimental Tower

Mode No.	Obserbed	Analisys
1	0.5	0.5
2	1.9	1.9
3	3.6	3.7
4	5.8	5.9
5	6.5	6.6
6	**.*	11.1

OUTLINE OF PROTOTYPE MASS DAMPER SYSTEM

Outline of the Mass Damper

The mass damper system is shown in Photo 1. This system is originally developed as a tuned mass damper and advanced to be active mass damper by applying AC servo motors. The mass is supported by the special roller bearings set up in two orthogonal layers, so it swings as a pendulum in any direction with no strings. Fig.2 shows the principle of the system. The bearing consists of a roller and two, upper and lower, circular rails. The natural period is independent on the supporting weight and is given only by the radii of both rails and roller as

$$T = 2\pi\sqrt{\frac{2(r_2 - r_1)}{g}} \tag{1}$$

where T is the natural period, r_2 and r_1 are the radii of rails and roller respectively and g is gravity acceleration.

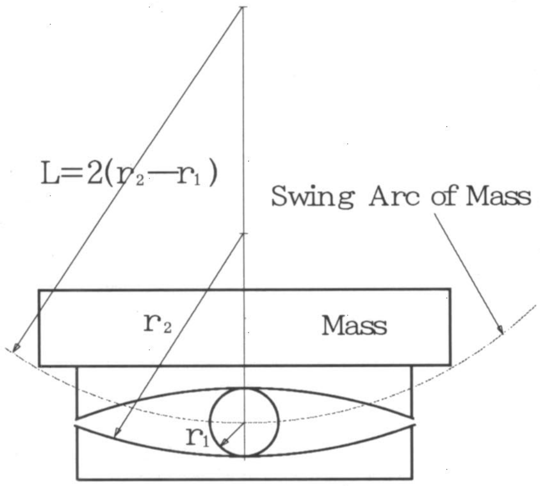


Fig.2 Principle of Roller-Pendulum

It is essential that the coefficient of friction of this roller bearing is small of 0.0006 and its characteristic is very stable.

A set of motor and ball screw is employed in each direction as an actuator. The motor is controlled by the velocity signal from the computer, so the velocity of the mass is used as the control value, instead of the control force. When the torque-free mode is selected, the rotor in motor becomes free to turn and the system acts as a passive mass damper. In case that the displacement of mass damper or the temperature of the motor reaches each limit due to extreme winds or earthquakes in excess of the design level, the computer turns the mode from active to passive. When the electric failure happens, the status is torque-free mode and it works as the passive system. It should be noted that, for the active system with motor and others, the natural period is evaluated taking into consideration the inertia moments of those additions. As for the damping device within the system, a rotational viscous damper is attached at an end of the ball screw.

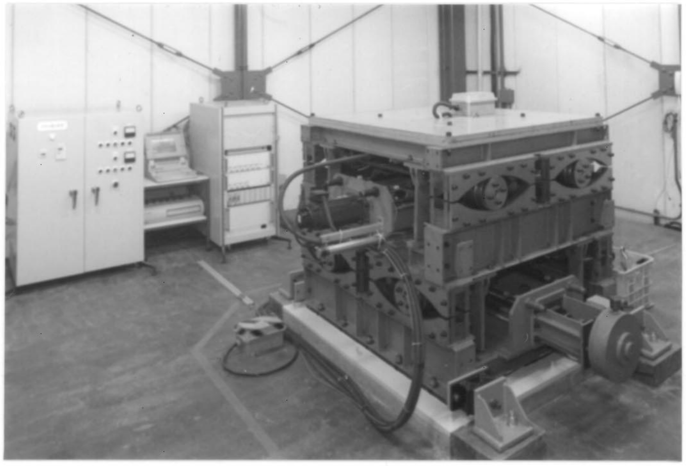


Photo 1 View of Prototype System

Table 2 Specifications of Prototype System

	Upper	Lower
Shape (cm)	$150^{(W)}\times 150^{(B)}\times 120^{(H)}$	
Weight of Mass (tf)	**1.0**	**2.3**
Natural Period (sec)	**2.0**	**2.0**
Power of Motor (kW)	**0.8**	**3.7**
Max. Displacement (cm)	**35.0**	**35.0**
Max. Velocity (cm/sec)	**83.3**	**83.3**
Time Constant (sec)	**0.005**	**0.005**

A prototype mass damper system is designed to be installed on the verification tower. The specifications of the system are given in Table 2. One mass is supported by both upper and lower systems. The weight of a mass in lower system includes the intermediate frame and others. The power of motor is intentionally contrasted to compare the difference of the power ratio.

Control Algorithm

Modal Optimal Control In our control algorithm, an optimal feedback regulator is basically used. The modal responses of the structure are used as the state values. This is because the response of the structure is mainly dominated by a few principal modes and modal control is advantageous to reduce the number of the dimension of the control matrix and the sensors. A feedback gain is obtained from minimizing a quadratic performance index assuming the weight values against the modal response of the structure and the control velocity.

On the verification tower, the accelerometers in NS and EW direction are distributed on the 6th, 4th, 3rd floors and ground level of the tower, and the relative responses are obtained through the integration amplifiers. These relative responses of three floors against the ground can be converted to the first through third modes. The first and second modes are used in control, and the response of the third mode are ignored in order to cut off the higher order mode response not to be controlled and the signal noise. The mass damper has no degrees of freedom and the servo motor is controlled by the velocity signal. From the fundamental test, the response velocity of this system against the control velocity is estimated as the first order time lag, where the time constant is 0.005second.

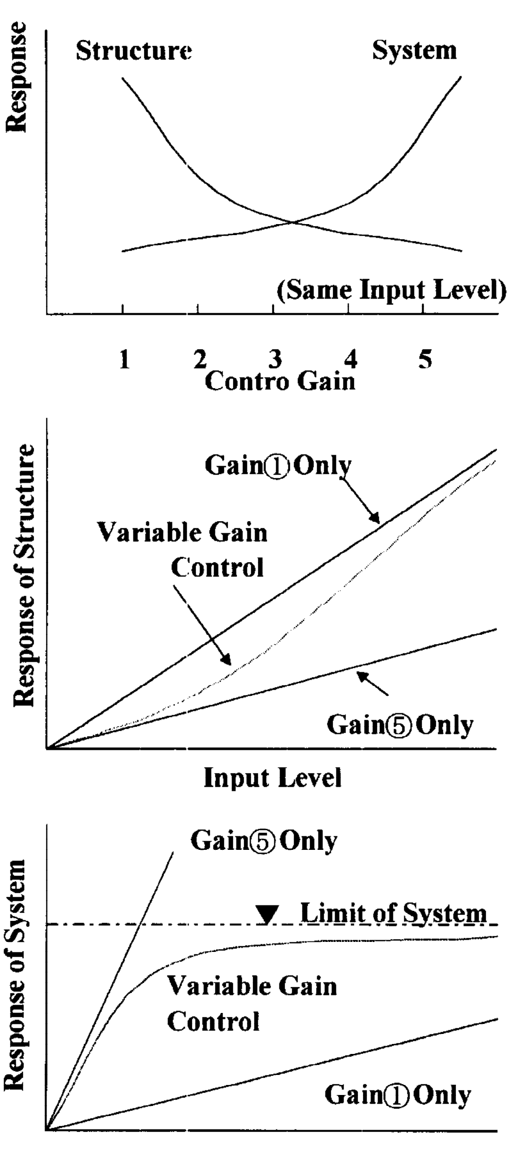
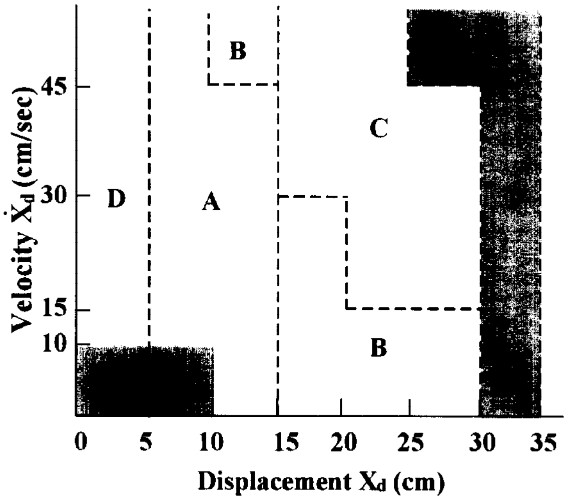


Fig.3 Concept of Variable Gain Control



<Gain Switching>

Region	Condition of mass	Switching
A	$(X_d \leqq 10)$ $or(X_d \leqq 15.and.\dot{X}_d \leqq 45)$	non (± 0)
B	$(X_d \geqq 10.and.\dot{X}_d \geqq 45)$ $or(X_d \geqq 15)$	1 lebel down (-1)
C	$(X_d \geqq 15.and.\dot{X}_d \geqq 30)$ $or(X_d \geqq 20.and.\dot{X}_d \geqq 15)$	go to No.1 (⇒1)
D	$X_d \leqq 5$ for 1.0sec	1 lebel up (+1)

<Active/Passive Conversion>

Region	Condition of mass	Switching
P	$(X_d \geqq 25.and.\dot{X}_d \geqq 45)$ $or(X_d \geqq 30)$	Active ⇒ Passive
Q	$X_d \leqq 10$ and $\dot{X}_d \leqq 10$ and $\dot{X}_d^* \leqq 10$ (cont. velocity) and $T_p \geqq 4$ (passage time in Passive)	Passive ⇒ Active

* if $Xd \leqq 0.0$ then $\{Xd,\dot{X}d\} \times (-1.0)$

Fig.4 Judgement to Variate Gain

Variable Gain Control Although this feedback gain is optimal for a particular condition, it is not best for other conditions. Moreover, the system has several limits in the velocity and the displacement of the mass and the torque and the temperature of the motor. If only one gain is used, the system easily reaches its limits by the external force over the design level. The developed "Variable Gain Control Algorithm" is one of the solution of this problem. A concept of this algorithm is illustrated in Fig.3. For the same input force, in general, the larger the gain is, the smaller the response of structure become and the larger the response of the system becomes. If only gain No.5 is used, the response of the structure is expected to be magnificently reduced, but the control can not be provided continuously. By the variable gain control, an appropriate gain is selected among the five gains and the active control operation is maintained within the limit of the system. To make it clear, the switching rules for the prototype system are introduced here in Fig.4. Because the purpose of this algorithm is to maintain the active control operation, switching is conducted according to the response of the system only. The limits of the mass damper are 35cm in displacement and 83cm/sec in velocity. When the responses are in the region A, the gain is not switched. When the response become larger in region B, the gain is switched to one level below. In region C, the gain directly goes to No.1, the lowest one. If the displacement is under 5cm in region D for one second, the gain should be increased one level. It is noted that the control signal should be smoothed for 0.1second between old and new gains.

The conversion regions between active and passive modes are arranged outside these gain switching regions. Besides these rules shown in this figure, the temperature of the motor is considered as the judgment factor for active passive conversion.

Table 3 Damping Constants(%) for Each Gain

Gain No.	Upper 1st	Upper 2nd	Lower 1st	Lower 2nd
1	5.9	7.0	5.9	7.1
2	7.1	8.2	8.3	9.3
3	7.8	8.8	11.5	12.3
4	8.7	9.7	12.8	13.5
5	10.0	10.9	14.7	14.7

The control gains are prepared in five levels, and their equivalent damping constants of the structure are shown in Table 3 corresponding to the effects of each gain.

OBSERVATION

A prototype system is installed on the verification tower, in order to verify its response reduction effect for ground motions and wind excitations. On the tower, the state of the mass damper system and the responses of the tower are recorded simultaneously. Absolute acceleration and displacement of the tower, the motion of the mass and the control gain etc., total number of 30 components are recorded when earthquakes or winds affect the tower.

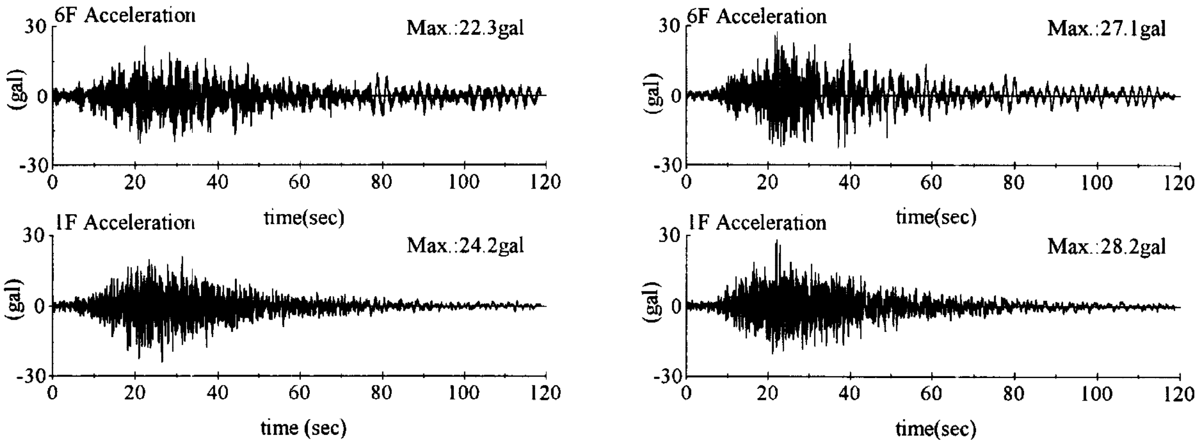
The Earthquake Observation

The response observation has been conducted, and several earthquake responses have been recorded. East Off Hokkaido Earthquake (October 4, 1994 (Mj=8.1)) is the largest one and the maximum ground acceleration is about 30cm/s2. The maximum displacement and velocity of the mass damper were about 10cm and 25cm/s in EW-direction and about 7cm and 25cm/s in NS-direction,. In this earthquake, the mass damper works with only gain.5. The time histories of the response acceleration at the 6th-floor and ground motion are shown in Fig.5. From this earthquake record , it can be recognized that system works as expected.

Model of the Tower In the simulation, the tower is modeled 6-story shear spring model same as the control one. Damping of structure is taken as a type of proportional to stiffness, and the damping ratio was set at 0.5% by the free vibration test results . The eigenvalues of this model are shown in Table 1 together with the results of forced vibration tests. It seems that this model well describes the dynamic characteristics of the tower.

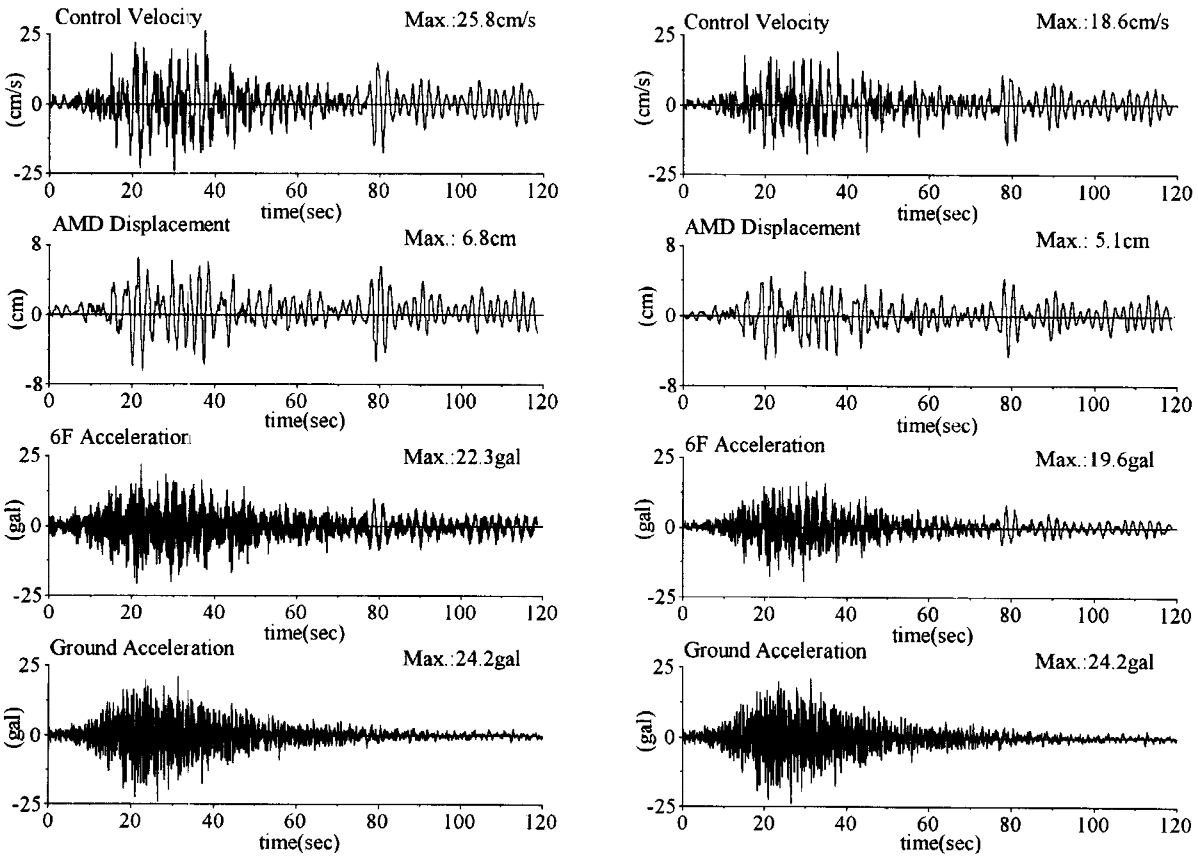
Results of Simulation Among the numerical results, the time histories of acceleration at the 6th-floor and the control velocity and the relative displacement of the mass are shown in Fig. 6, compared with the observed data. As for the acceleration of the tower, the peak values of the simulated data were smaller than the observed values. This is because the non linearity of the system is not considered in the simulation model. But for the amplitude, phase and envelope shape of the waves, the simulated results agree well with the observed data. For the motion of the mass damper, the simulates results and observed data are almost the same. Therefore it is clear that the behavior of the tower and the mass damper under an earthquake load can be pursued through a relatively simple linear numerical vibration model and forced vibration tests results.

Effectiveness of Mass Damper In order to estimate the effectiveness of the mass damper in vibration control, the response of the tower without AMD under the same earthquake load were calculated and compared with the observed result. The simulated time histories and spectrum of acceleration at the 6th-floor of the tower are shown in Fig.7 and Fig.8. In time history, the maximum accelerations are almost same. As for the active control effect, RMS. value of the observed response acceleration under active control is below the half of the simulated response of that without AMD. On the other hand, in the spectrum value, the response of the first mode with AMD is less than about one tenth of that without AMD. The response of the second mode is also reduced effectively.



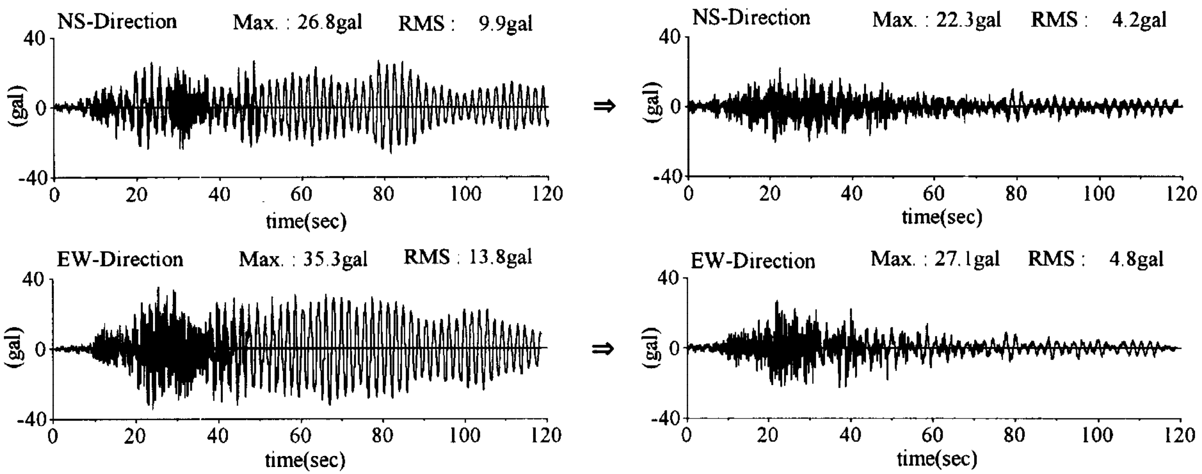
NS-Direction **EW-Direction**

Fig.5 Observed Earthquake Response of the Tower



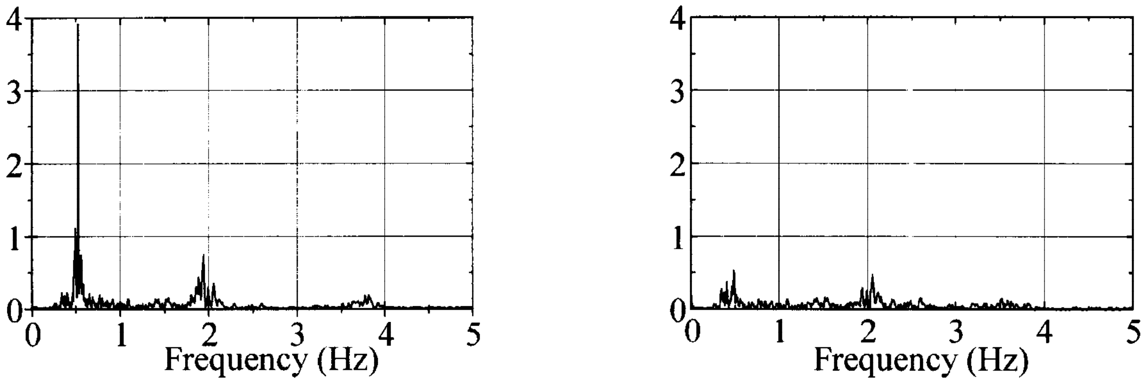
Observed **Simulated**

Fig.6 Comparison with Observed and Simulated Results (NS-Dir.)



Without AMD (Simulated) **With AMD (Observed)**

Fig.7 Effectiveness of the Mass Damper (acceleration on 6F)

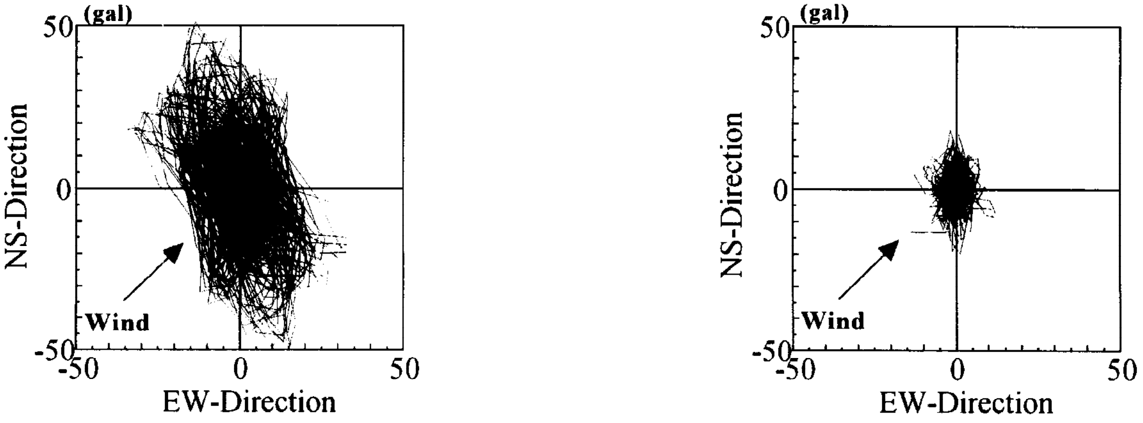


Without AMD (Simulated) **With AMD (Observed)**

Fig.8 Effectiveness of the Mass Damper (acceleration on 6F in NS)

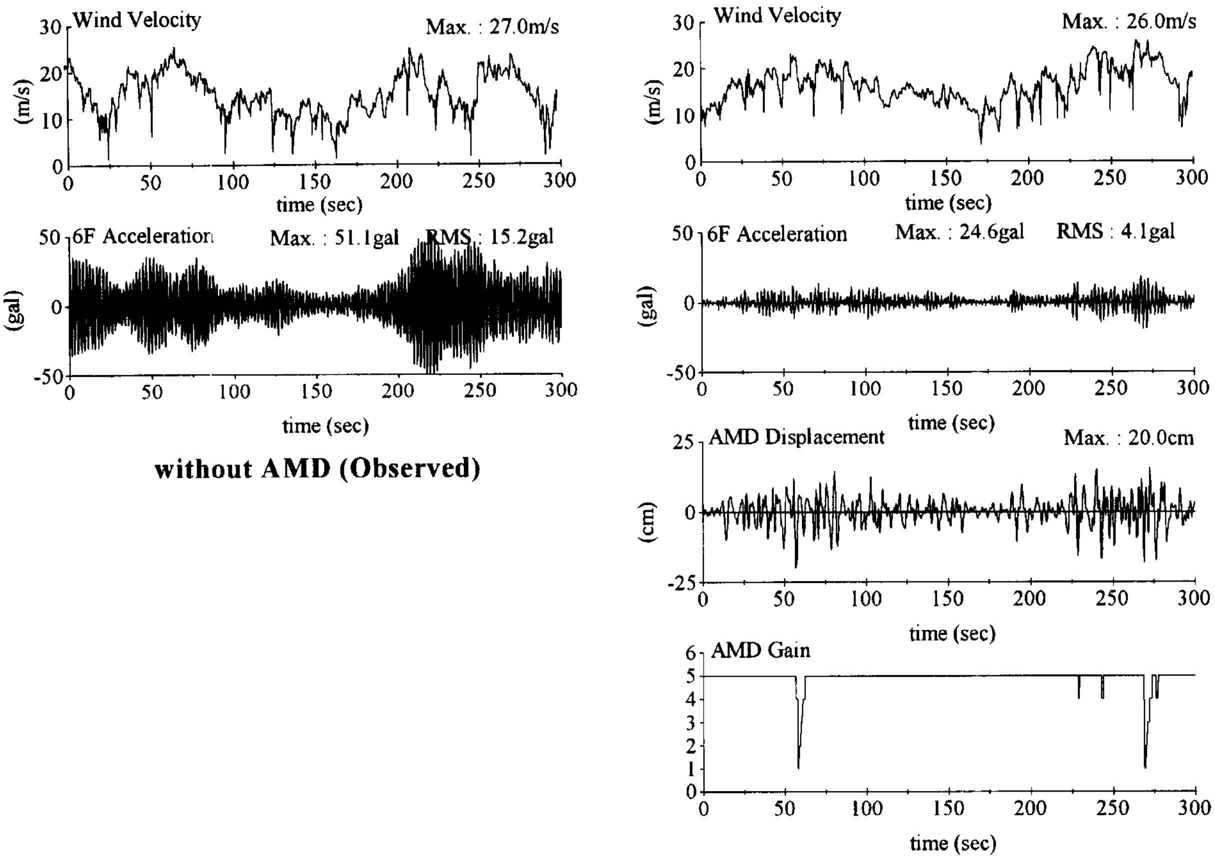
The Wind Response Observation

Fig.9 and Fig.10 show the typical wind response recorded on February 22 in 1994. The tower vibrates orthogonally to the direction of the wind as shown in Fig.9. Comparing the controlled response with the uncontrolled, in almost the same wind conditions, the maximum accelerations are significantly reduced in any direction by applying the active control. It is important to note that the gains are smoothly switched from No.5 to No.1 and up to No.5 again as shown in Fig.10.



Without AMD (Observed) **With AMD (Observed)**

Fig.9 Orbit of Wind Response Accelerations on 6F



without AMD (Observed)

with AMD (Observed)

Fig.10 Wind Response Time Histories

CONCLUSIONS

An active/Passive mass damper driven by AC servo motor has been developed. This system works not only as an active (hybrid) mass damper but also as a passive system. A modal optimal control law combined with proposed variable gain control is used as control algorithm. A prototype system is produced and installed on a verification tower. It is confirmed that the variable gain control algorithm contributes to improvement of the performance and expansion of the control level region within limits of the system. Through the earthquake and wind response observations, it is also verified that this system is sufficiently applicable to the actual structures for the validity of the variable gain control algorithm and the remarkable response reduction effect.

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REFERENCE

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