



## **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**





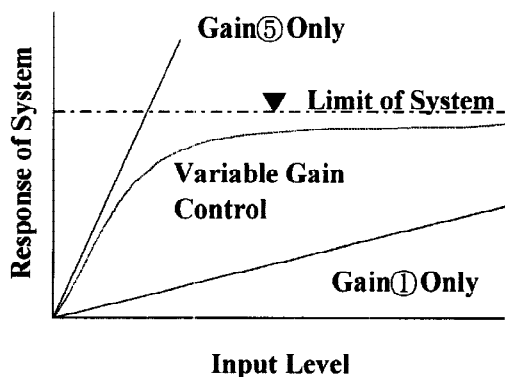
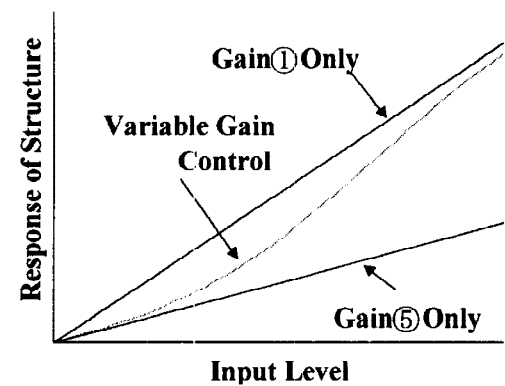
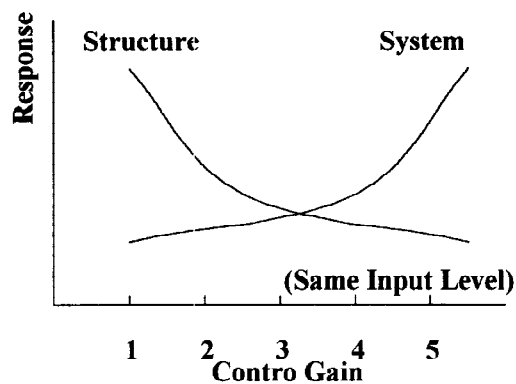
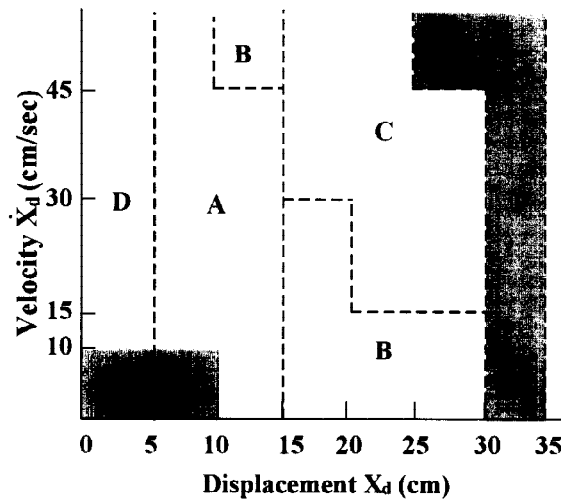


Fig.3 Concept of Variable Gain Control



<Gain Switching>		
Region	Condition of mass	Switching
A	$(X_d \leq 10)$ or $(X_d \leq 15 \text{ and } \dot{X}_d \leq 45)$	non ( $\pm 0$ )
B	$(X_d \geq 10 \text{ and } \dot{X}_d \geq 45)$ or $(X_d \geq 15)$	1 level down (-1)
C	$(X_d \geq 15 \text{ and } \dot{X}_d \geq 30)$ or $(X_d \geq 20 \text{ and } \dot{X}_d \geq 15)$	go to No.1 ( $\Rightarrow 1$ )
D	$X_d \leq 5$ for 1.0sec	1 level up (+1)

<Active/Passive Conversion>		
Region	Condition of mass	Switching
P	$(X_d \geq 25 \text{ and } \dot{X}_d \geq 45)$ or $(X_d \geq 30)$	Active $\Rightarrow$ Passive
Q	$X_d \leq 10$ and $\dot{X}_d \leq 10$ and $\dot{X}_d^* \leq 10$ (cont. velocity) and $T_p \geq 4$ (passage time in Passive)	Passive $\Rightarrow$ Active

\* if  $X_d \leq 0.0$  then  $\{X_d, \dot{X}_d\} \times (-1.0)$

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		Lower	
	1st	2nd	1st	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/s<sup>2</sup>. 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.

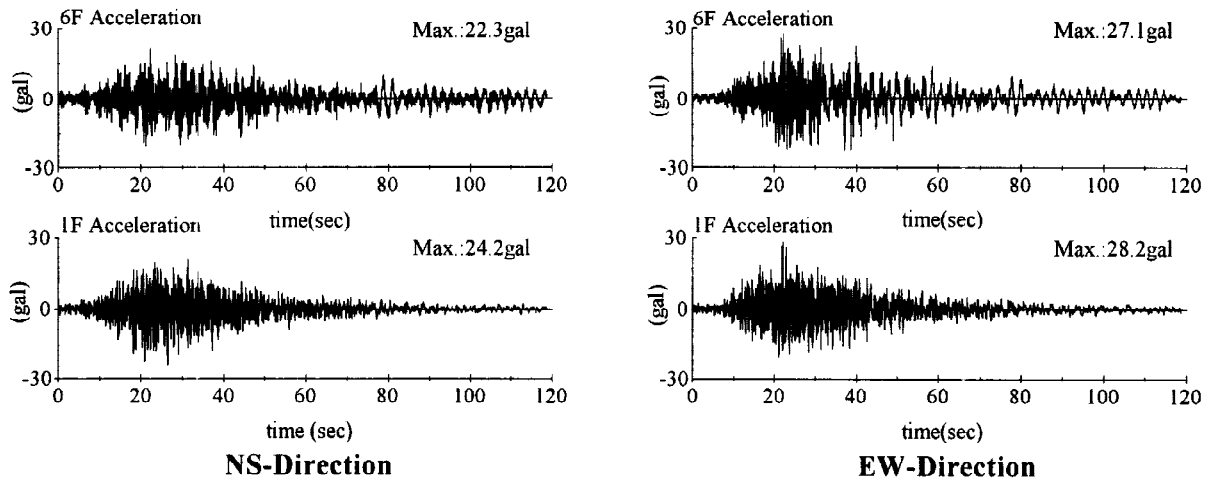


Fig.5 Observed Earthquake Response of the Tower

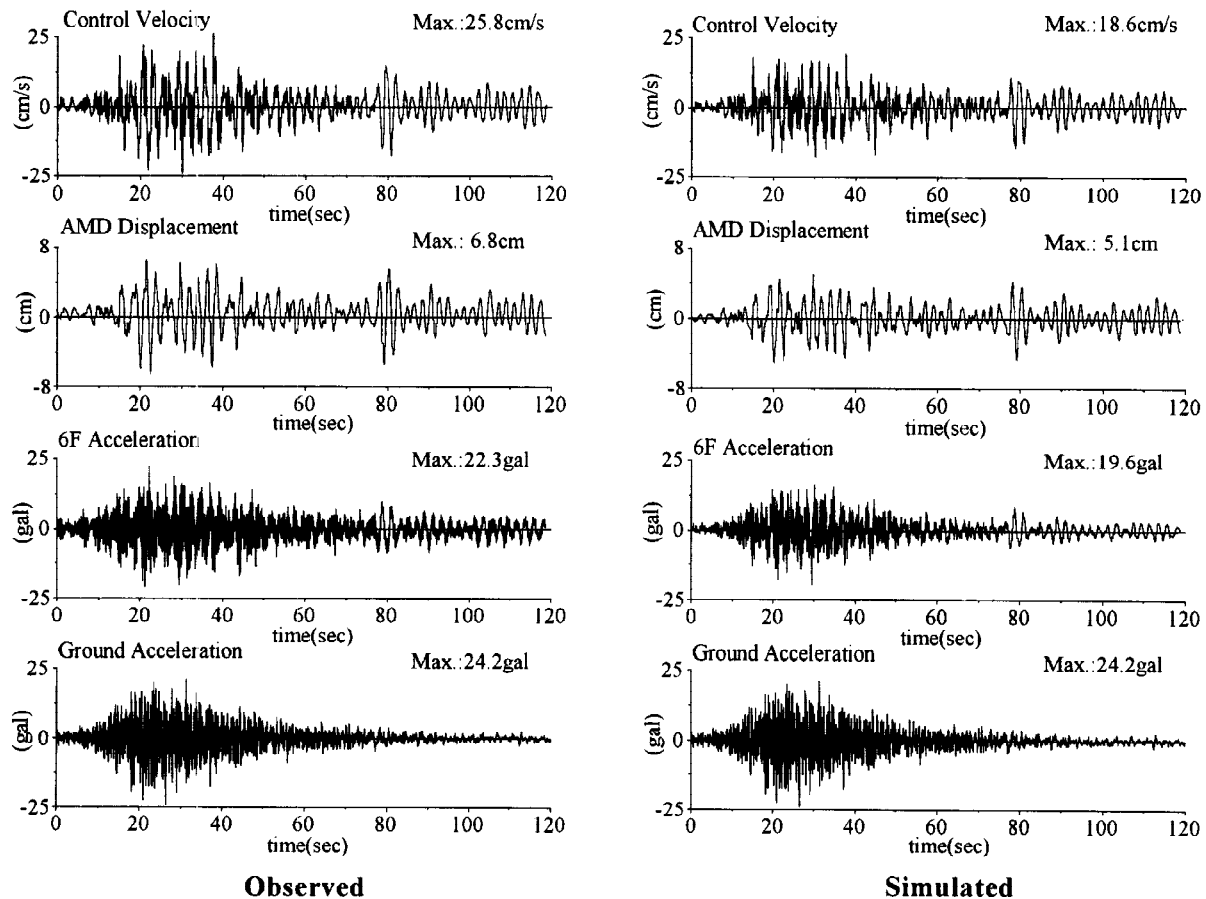
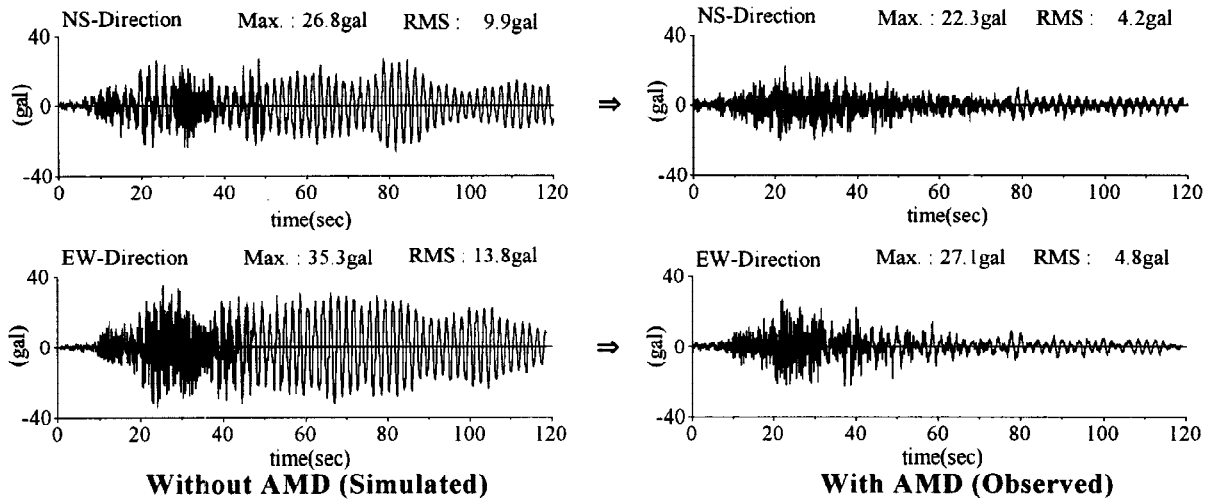
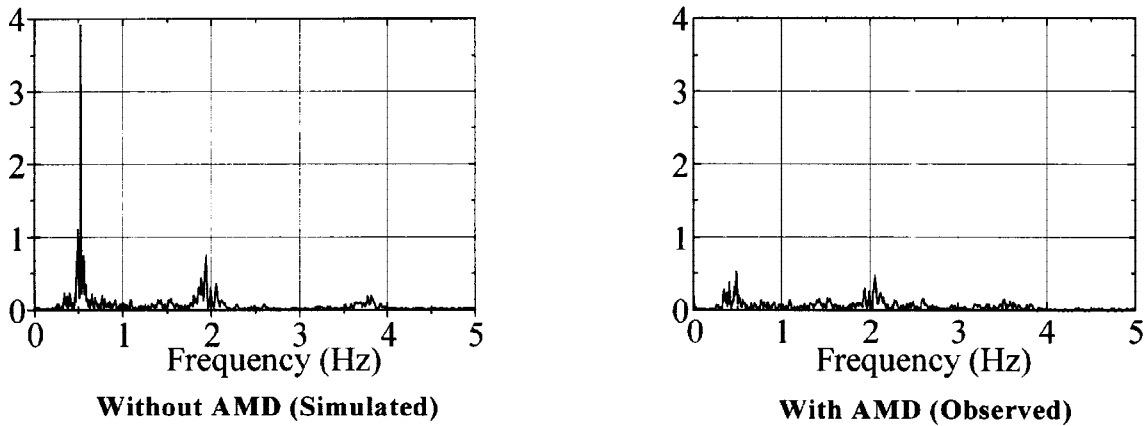


Fig.6 Comparison with Observed and Simulated Results (NS-Dir.)



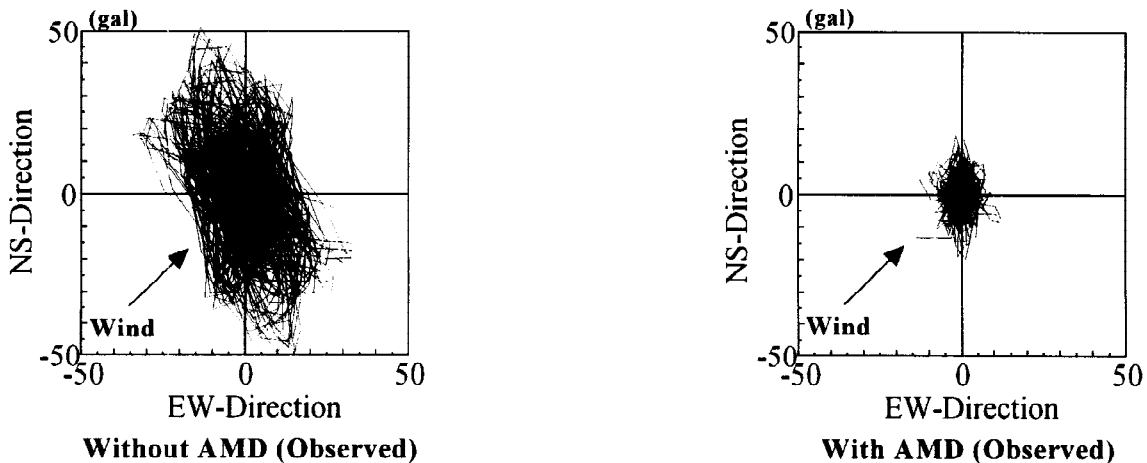
**Fig.7 Effectiveness of the Mass Damper (acceleration on 6F)**



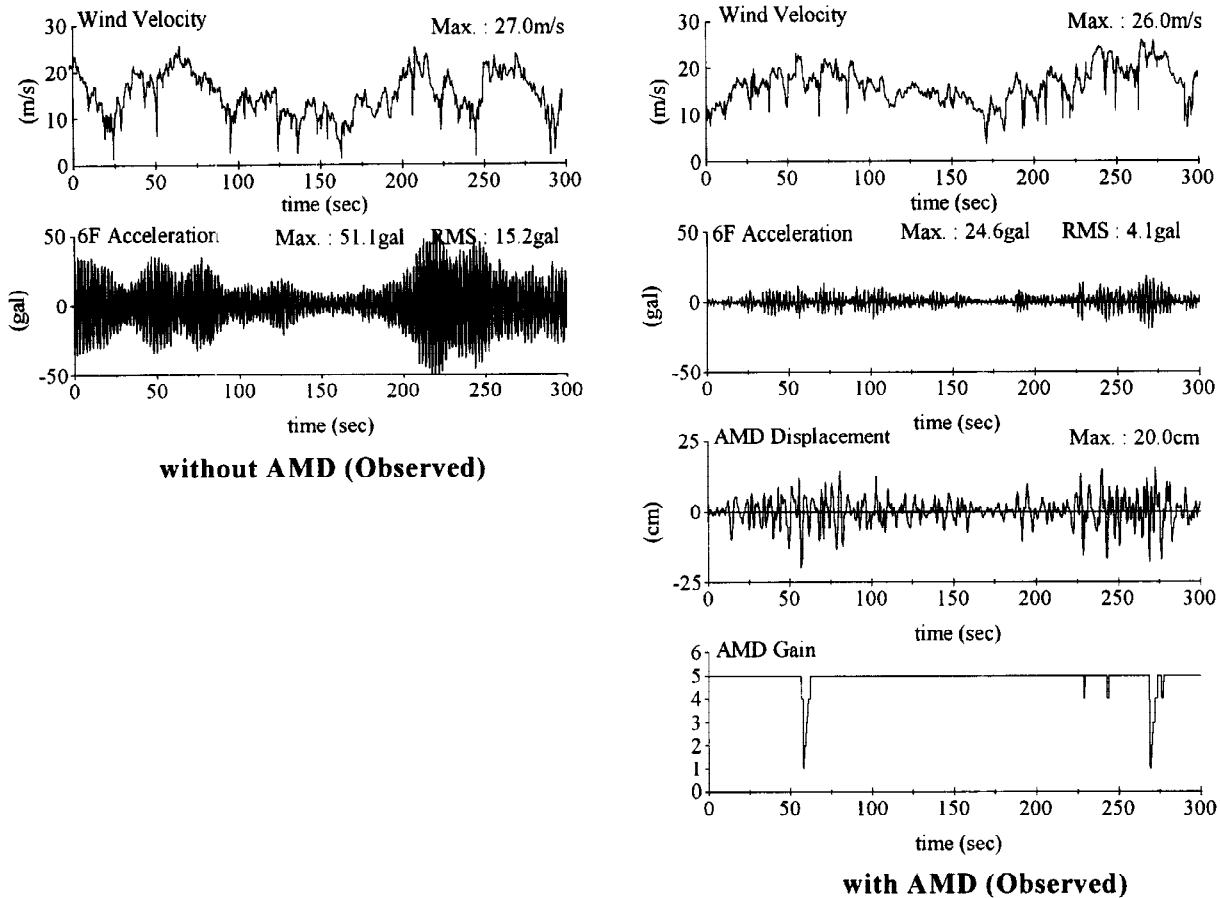
**Fig.8 Effectiveness of the Mass Damper (acceleration on 6F in NS)**

*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.



**Fig.9 Orbit of Wind Response Accelerations on 6F**



**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.

## ACKNOWLEDGMENTS

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## REFERENCE

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