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Hybrid mass damper system for response control of building

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ABSTRACT : A Hybrid Mass Damper (HMD) system is proposed to suppress the response of a tall building against strong wind and moderate earthquake loads to meet the requirement on the vibration level for comfort. A prototype of an HMD system has been installed in an actual building to verify its capability. To find out the dynamic characteristics of the HMD system and the building, forced vibration tests were conducted. From the tests and observations during strong winds, the HMD system has been verified to be suitable for suppressing the vibration response of tall buildings against strong wind and moderate earthquake loadings.

1 INTRODUCTION

Recently several vibration control systems have been developed for vibration control of high-rise buildings and slender structures like view towers. Among these systems, passive mass damper systems such as a Tuned Mass Damper (TMD) system and a Tuned Liquid Damper (TLD) system are typical and have reasonable capability to reduce vibration response. While an Active Mass Damper (AMD) system, which is defined by a mass damper powered by actuators and has no spring or damper, also has excellent capability to suppress vibration response, it requires large amounts of power to operate when applies to high-rise buildings, especially buildings over 50 stories high.

Therefore, we have developed a Hybrid Mass Damper (HMD) system which makes use of its capability to suppress vibration as a TMD system, and is much more energy efficient than an AMD system while maintaining the same performance.

In order to compare the vibration control capability between an HMD and AMD, numerical simulations to control lateral and torsional modes of high-rise buildings not only in fundamental modes but also higher order modes were conducted by Kaneko and Mita.

From their results, control force and control power of an HMD required for vibration control can be about 1/3 - 1/4 those of an AMD. And it has become obvious that for lateral or torsional higher order modes of building, control force and power of an HMD are still less than those of an AMD.

A prototype of an HMD system has been installed in an actual building for the first time in the world. Forced vibration tests were conducted to evaluate the dynamic characteristics of the building and the HMD system. The observation system has accumulated precious response data during typhoons. From these tests and observations, the HMD system has been verified to suppress vibration response of the building against strong wind and moderate earthquake loadings. Also, some remarkable points have become clear from applying the system to an actual building.

A large scale genuine HMD system has been installed in an actual tall building. This is the largest HMD system in the world and has made good use of the prototype's experiences.

2 HYBRID MASS DAMPER SYSTEM

2.1 *Outline of system*

A prototype of an HMD system employed in an actual building is described in Fig.1. The system consists of an auxiliary mass supported by multi-stage rubber bearings and actuators driven by AC servo motors. Control force generated by AC servo motors is transmitted to the mass by timing-belts and ball screws. Using two AC servo motors, this system can control the response in two horizontal directions independently. Table 1 shows specifications of an HMD system.

2.2 *Control algorithm*

Although various algorithms for the control system have been investigated, the optimal control theory has been selected to the current system. From a simplified model consisting of a building and an HMD shown in Fig.2, the state equation can be expressed as follows,

$$\begin{aligned} \dot{X}(t) &= A\,X(t) + B\,u(t) \\ X(t) &= [\dot{x}_s(t),\ \dot{x}_d(t),\ x_s(t),\ x_d(t)]^T \end{aligned} \tag{1}$$

where,

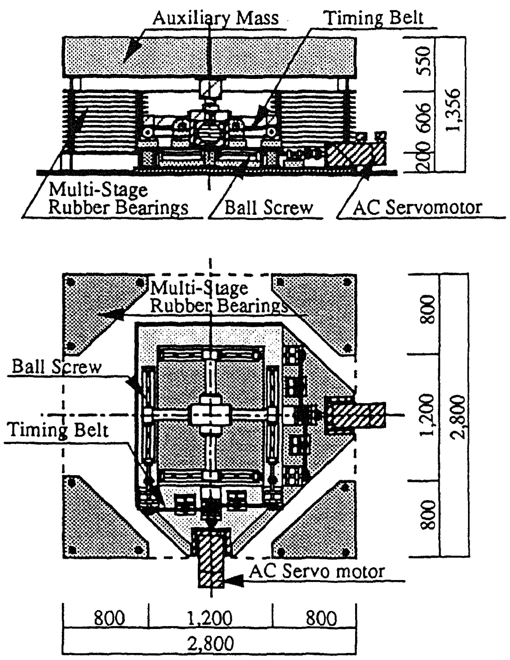


Fig.1 Description of HMD system

Table 1 Specifications of HMD system

weight of auxiliary mass (including the mass effect of inertia moment of actuator)	: 4.95 tonw
horizontal stiffness	: 0.140 tonf/cm
natural period	: 1.19 sec
damping ratio	: 0.10
stroke	: ± 23cm
maximum control force	: 1.2 tonf
maximum power	: 7.5 kw

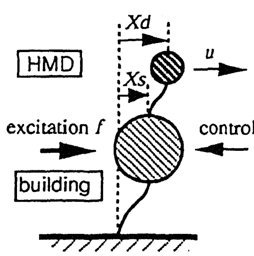


Fig.2 Reduced model for control design

Table 2 Dynamic characteristics of the building (eccentric moment mr = 20 kgm)

1-st mode	X-dir.	Y-dir.	Torsion
natural period (sec)	0.88	1.05	0.66
damping (%)	2.8	5.1	4.1

X : state vector of building and HMD
u : control force
$\dot{x}_s$: absolute velocity of building
$\dot{x}_d$: absolute velocity of HMD
x_s : absolute displacement of building

The system matrix A and the control matrix B are expressed as,

$$A = \begin{bmatrix} -(c_s + c_d)/m_s & c_d/m_s & -(k_s + k_d)/m_s & k_d/m_s \\ c_d/m_d & -c_d/m_d & k_d/m_d & -k_d/m_d \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$B = [\ -1/m_s \quad 1/m_d \quad 0 \quad 0\ ]^T$$

where,
m_s : generalized mass of building
k_s : generalized stiffness of building
c_s : generalized damping coefficient of building
m_d : mass of HMD
k_d : stiffness of HMD
c_d : damping coefficient of HMD

The cost function is expressed by

$$J = \int_0^\infty (q\ x_s^2 + r\ u^2)\, dt \tag{2}$$

where,
q, r : weight coefficients

Minimizing the cost function J given by Eq.(2) derives the following feedback control system.

$$u = g_1 \dot{x}_s + g_2 \dot{x}_d + g_3 x_s + g_4 x_d \tag{3}$$

where,
$g_{i\ (i=1,2,3,4)}$: feedback gains for each state values

3 APPLICATION TO AN ACTUAL BUILDING

3.1 *Outline of target building*

The HMD system described in Chap.2 has been installed in an actual 7-story building completed in 1991 at the Institute of technology of Shimizu Corporation, Tokyo.

The building is 30m high and 6m by 11m in plan dimension as shown in Fig.3. The total weight excluding the under ground portion is about 400 tons. The 7-th floor is allocated for the HMD system, the 6-th floor for exciters employed in forced vibration tests, the 5-th floor for vibration perception tests, the 4-th floor for the control room of the HMD system and the observation system for winds and earthquakes.

Because of its slender shape and stiffness changeable columns, natural periods of the building are much longer than those of similar height buildings. (Table 2)

Seismometers have been set up at -40m in the ground, 1-st, 3-rd, 5-th and 7-th floors of the building and an anemometer placed on the roof. The observation systems are currently accumulating response data for strong wind and earthquake loadings. The entire building is shown in Fig.4.

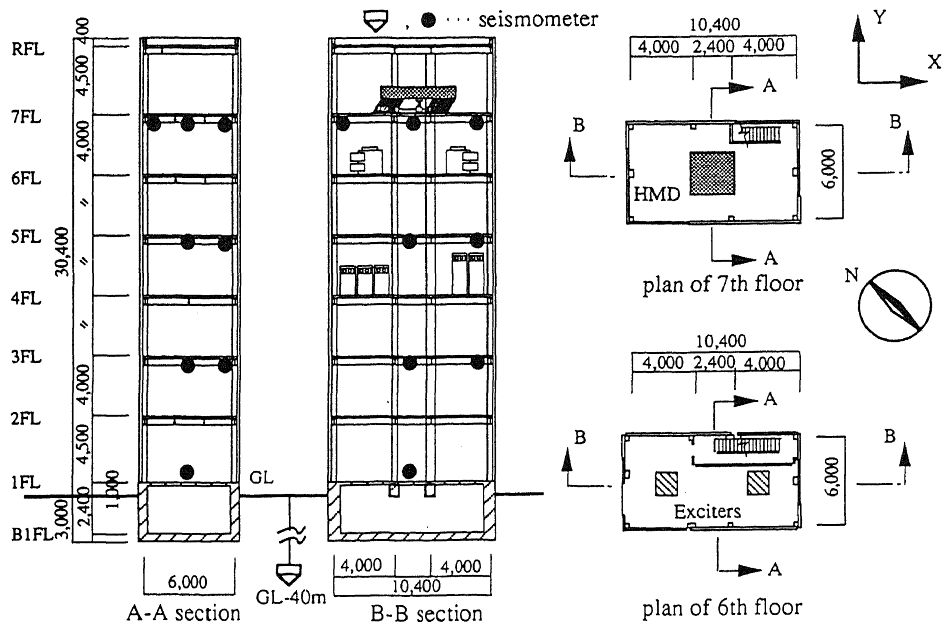


Fig.3 Outline of the building

3.2 *Control system*

After installing the HMD system shown in Fig.1, the multi-stage rubber bearings and the auxiliary mass were carefully adjusted to match the system frequency of the HMD to the first frequency of the building.

A whole HMD system composes of sensors, a control system and drive system. Four vibrometers, which are indispensable for measuring the state values of the building and the HMD for calculation of control forces, are set up on the 7-th floor and on the auxiliary mass. Using these measurement data, the control system on the 4-th floor calculates control forces and operates the drive system on the 7-th floor.

The HMD system usually keeps the state that control force is zero and watches the building responses (waiting mode), and when the responses exceed the prescribed levels against strong wind or earthquake loadings, the actuators starts to move automatically (control mode). If the responses become small and keep the quiet state over certain period, the system return to waiting mode again. When the motion of the auxiliary mass becomes unexpectedly large, the mechanical stoppers become active.

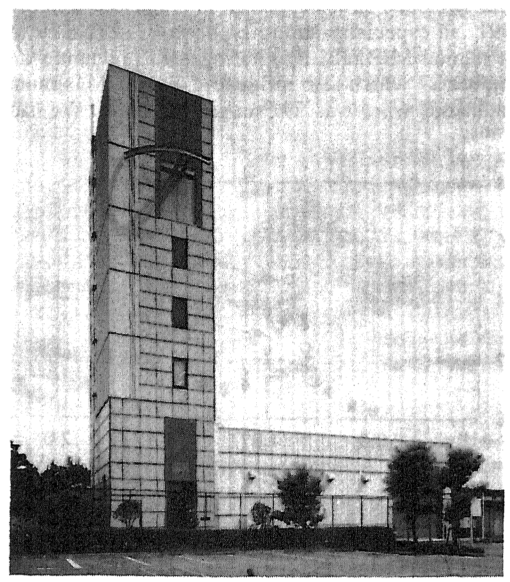


Fig.4 Exterior of the building

3.3 *Forced vibration test*

In order to find out the dynamic characteristics of the building and HMD system, forced vibration tests have been conducted.

Acceleration response of each floor, control force, strokes and acceleration response of the auxiliary mass were measured to evaluate the behavior of the HMD system and the building. Forced vibration directions were both in X- and Y-direction of the building.

Assuming two sets of weight coefficients, (q=1,r=50)

Table 3 Forced vibration test cases

Case	dir.	mr	feedback gain	fre.range(Hz)
1	Y	20	B1	0.5 - 2.95
2	Y	100	A1	0.5 - 1.4
3	Y	100	B1	0.5 - 1.4
4	Y	200	B1	0.5 - 1.4
5	X	100	B2	0.5 - 1.45

mr : eccentric moment of exciter (kgm)

and (q=1,r=1), for the cost function defined by Eq.(2), feedback gains named gain A1 (Y-dir.), gain A2 (Y-dir.), gain B1 (Y-dir.), gain B2 (X-dir.) are calculated. Test cases are shown in Table 3. Sinusoidal sweep tests have been conducted and response amplitude and phases against vibration force for each frequency are measured. Minimum pitch of vibration frequency is 0.01 Hz.

Typical resonant curves of velocity response at the 7-th floor are shown in Fig.5 (a). It shows that the response amplitude at the resonant frequency of the building when the HMD is operated is much smaller than that when the HMD is cramped. The effectiveness of the HMD is conspicuous. It is also evident that the response suppression depends on the value of gain factor for the HMD.

Simulation results are shown in Fig.5 (b). The building and HMD are modeled into a multi-lumped-mass system. Although horizontal stiffness and damping factor of the building depend on the forced vibration amplitude, they are assumed to be close to the experimental data when the forced vibration moment is 100kgm. Fig.5 shows the simulation results agree well with the experiments.

3.4 *Performance during typhoons*

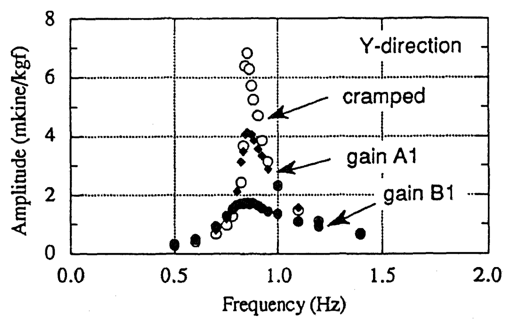
Several typhoons struck Japan from August to October in 1991, an especially strong typhoon 9119 (No.19 in 1991, named MIREILLE) hit Nagasaki prefecture on September 27 which also influenced Tokyo. Maximum instantaneous wind was 29.5 m/sec in Tokyo. We had the good opportunity to confirm the effectiveness of the HMD system installed in the 7-story building for strong wind loads.

Fig.6 shows maximum instantaneous wind velocity, mean wind velocity and wind direction observed at the building when MIREILLE came up. From 1:00 a.m. to 5:00 a.m. on Sep. 28 1991, verification tests were conducted by changing the HMD system to be cramped or to be operated every 15 minutes and response data of the building were accumulated. Feedback gains C1 (Y-dir.) and C2 (X-dir.) based on weight factors (q=1,r=0.5) were used after 2:30 a.m.

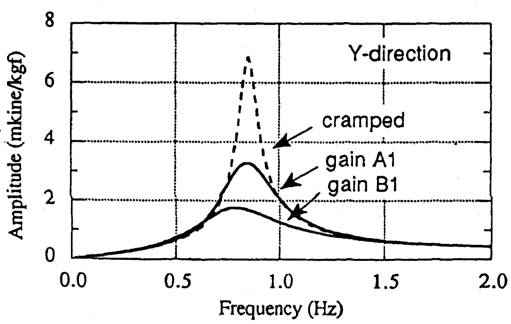
Fig.7 shows the response time histories of the 7-th floor when the HMD system was cramped in comparison with when it was operated. Both data were obtained under virtually the same condition, that is, the mean wind velocity was approximately 15 m/sec. As is evident from Fig.7, r.m.s. response values of the building was suppressed to about one half by operating the HMD system.

Relationships between the mean wind velocity and the r.m.s. acceleration response at the 7-th floor for every 4 minutes are shown in Fig.8. Exponential regression line obtained from the observed data (solid line) and building response against wind calculated by AIJ code (broken line) are also shown in Fig.8. The damping factors of the building were estimated from the forced vibration tests.

From the Fig.8, it is recognized that observed data agree well with the AIJ code. In the region where the mean wind velocity is larger than 12-14 m/sec, the response of the building have been effectively suppressed by operating the HMD system.



(a) test



(b) simulation

Fig.5 Resonant curves (Y-direction)

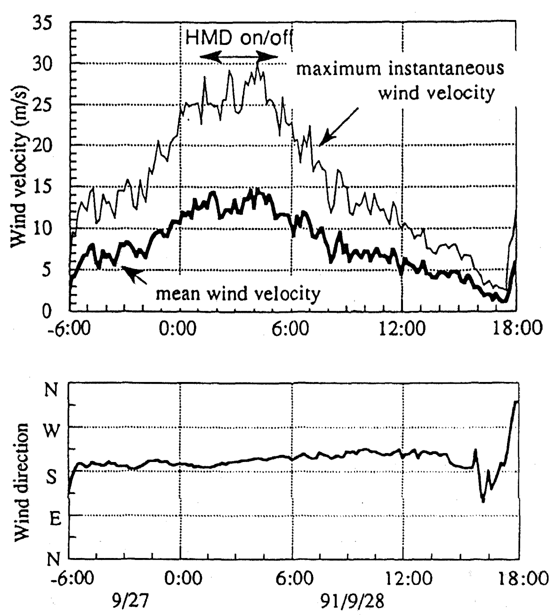
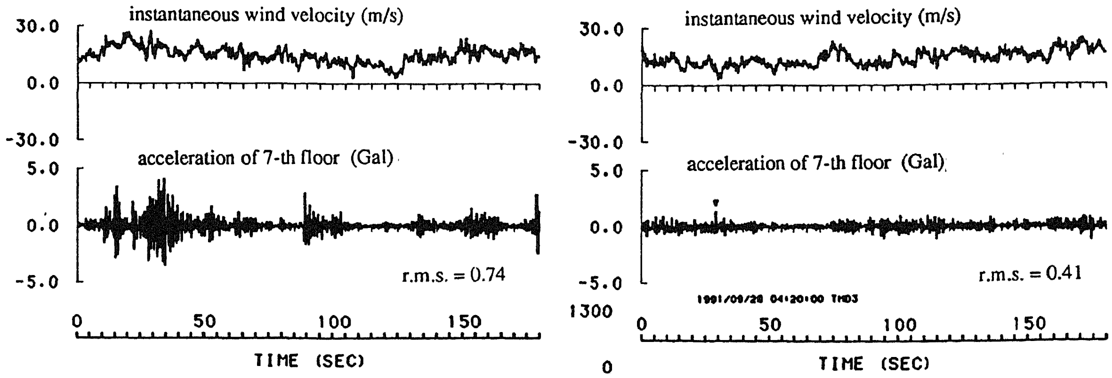


Fig.6 Strong wind record (Sep. 27 - 28, 1991)



(a) HMD cramped (b) HMD operated

Fig.7 Comparison of response

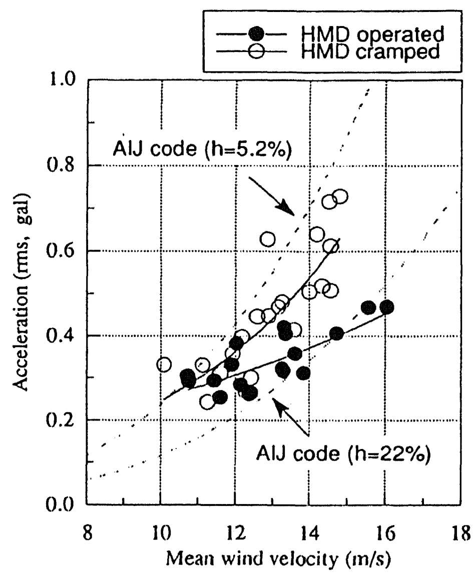


Fig.8 Relationship between wind velocity and acceleration response

3.5 *Remarks*

After conducting the several tests and observations for an actual building, it has become clear that the some problems such as nonlinearity of dynamic characteristics of the building or noise tolerant system should be carefully taken into account for designing a control system for vibration suppression devices.

4 APPLICATION TO TALL BUILDING

4.1 *Outline of target building*

After confirming the excellent capability of the HMD system through several tests and observations at the 7-story building, two large HMDs have been designed for a high-rise building which will be completed in 1992. The building is a 50-story, 200m-high structure. The upper part plan dimension is shown in Fig.9 and specifications are shown in Table 4. The height and rectangle plan of the building make it prone to cause lateral vibration to transverse direction as well as torsional vibration against strong winds.

4.2 *Control system*

In order to suppress the lateral and torsional vibration to meet the requirement on the vibration level for comfort, two HMDs have been installed on the top floor of the building.

The description of the HMD system is shown in Fig.10. An auxiliary mass is supported by multi-stage rubber bearings which make it possible not only to have large deformation but also to achieve the long natural period of the system. An AC servo motor has been placed on the mass to avoid transmitting the high frequency vibration of the device to downstairs. The mass is controlled actively in the transverse direction, but is not controlled in the longitudinal direction. It acts

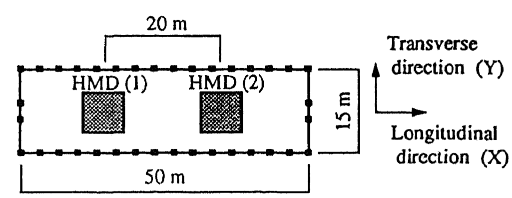


Fig.9 Plan dimension of building

Table 4 Specifications of building

Height	: 200 m (50-story)
Total weight	: 60,000 ton
Fundamental period	
Transverse direction	: 3.8 sec
Longitudinal direction	: 4.2 sec
Torsional direction	: 3.7 sec

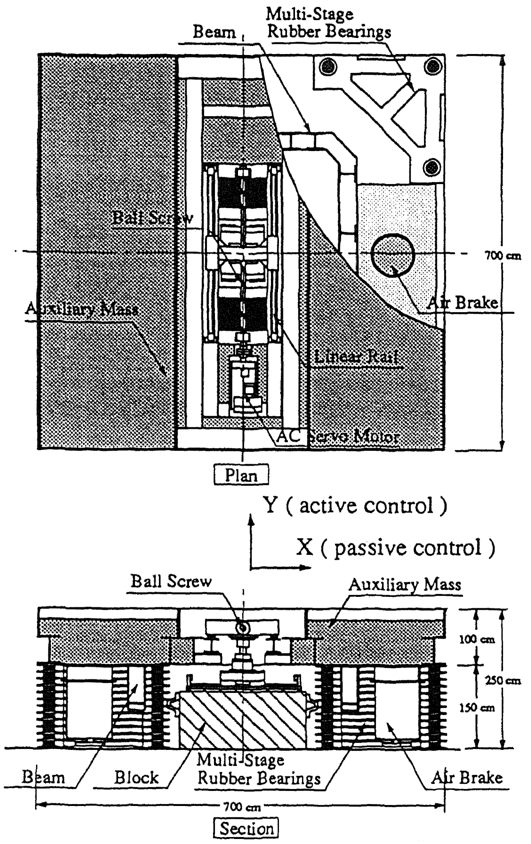


Fig.10 Description of HMD system

Table 5 Specifications of HMD system

weight of auxiliary mass	: 100 tonw
natural period	: 3.3 - 4.0 sec
damping ratio	: 0.06
maximum stroke	: ±100 cm (Y-dir.)
	: ± 50 cm (X-dir.)
maximum control force	: 7.5 tonf
maximum power	: 55 kw

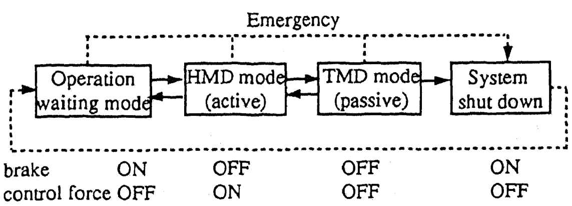


Fig.11 Concept of control modes

as a TMD in the longitudinal direction. When the deformation of the mass increases to exceed the prescribed value, two air brake systems will be activated to stop the mass automatically. Table 5 shows the specifications of the system.

The whole HMD system consists of a sensor system, computer system, drive system and air brake system. The system are designed as follows. The mass has usually anchored by the air brake system (waiting mode), and when the responses of the building exceed the prescribed level, the system starts to operate automatically (HMD mode). In this mode, the control gain is changed according to the amplitude of lateral and torsional responses. If the responses exceed the allowable level, the system changes to a TMD system (TMD mode). When the responses reach the limit level, the system is shut down and is anchored by the air brake system (shut down). The concept of control modes is shown in Fig.11.

5 CONCLUSION

A Hybrid Mass Damper system has been installed in an actual building to verify its capability. From forced vibration tests and observation data, the HMD system is found suitable for suppressing the vibration response of buildings against large wind and moderate earthquake loadings.

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