Development of Tuned Active Damper for Skyscrapers

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Recently many types of structure controlling device for wind and earthquake disturbances have been developed for the purpose of improving the residential habitability. The authors developed the Tuned Active Damper (TAD) consisting of multi-stage-pendulum type Tuned Mass Damper (TMD) and controlled-driving device that drives the TMD's mass more effectively. This TAD was applied to the Yokohama Landmark Tower that is the tallest building in Japan, and moreover the vibration test and actual wind response observations were carried out. As a result of these tests and observations, it was confirmed that (1) TAD improves the equivalent structural damping factor to more than 10% in terms of the damping constant. (2) TAD reduces the structural vibrations in a strong wind to less than 40% of the case without control. (3) The performance of TAD is the same as that expected according to theory.

1. Introduction

Structural controls against wind and earthquake disturbances using active control techniques have achieved levels of full-scale application owing to recent progress in theoretical and experimental research. In particular, the active controlled mass damper is being put to practice to improve residential habitability against wind and earthquake disturbances of skyscrapers owing to a compact device, easy installation and high performance[1][2].

Mitsubishi Heavy Industries, Ltd. (MHI) has developed a Tuned Active Damper (TAD) consisting of a multi-stage-pendulum type Tuned Mass Damper (TMD) and controlled-driving device that drives TMD's mass more effectively to improve performance for skyscrapers and has thus far achieved practical results with 14 working units. The weight of this device has been reduced to 1/5 to 1/6 that of TMDs having the same control effect through the addition of controlled-driving device. Further, the devices can reduce power or power demand to about 1/5 that of the conventional Active Mass Damper (AMD) without frequency by making the most of the TMD.

Using the TAD installed in the Yokohama Landmark Tower, the tallest building in Japan, with the aim of improving the residential habitability of the building as an example, an outline is presented in this paper of the device and the structural control performance on the basis of vibration tests done on the actual building and records of the vibrations observed.

2. Outline of TAD

The TAD drives multi-stage hanging vibrators having the same frequency as that of the building using servo motors in two horizontal directions according to an optimal control algorithm. The structure and functions of the TAD have already been reported on[3], and in this paper its appearance and basic specifications are shown in **Fig. 1** and **Table 1**.

The operating system of the TAD is shown in **Fig. 2**. Usually the current of the motor is shut down and braking is applied to the vibrators, but when the TAD senses two cycles of building acceleration of 2 cm/s^2 or more, its operation is automatically started. Thereafter, the TAD is automatically switched over to an active control state, passive control state or brake applied state depending on the sway motion of the building and the vibrators to expand the range of wind velocity to be dealt with by the TAD and ensure safety. The TAD restrains the sway motion of the vibrators exceeding the criterion shown in ④, but when the sway motion of the vibrators becomes smaller, the TAD returns to the active control state after dozens of seconds and becomes a system capable of controlling residual vibrations after an earthquake.

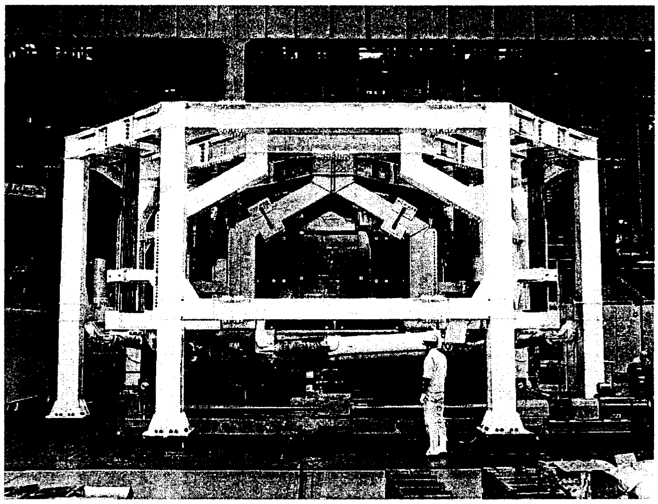

Fig. 1 TAD for skyscrapers
The photograph shows the appearance of the TAD using a multi-stage-pendulum.

Table 1 Specifications of TAD

Number of units	2 units
Dimensions ($D \times W \times H$)	9.0 × 9.0 × 4.9 m (per unit)
Weight of vibrator	170 t × 2 units = 340 t
Range of period adjustment	4.3 to 6.0 s
Max. amplitude	± 1.70 m
Max. controlling force	30 tf (one direction)

3. Vibration characteristics of building

The Yokohama Landmark Tower is 296 meters in height with 70 floors above ground and was completed in July 1993 making it the tallest building in Japan at present. In order to evaluate the building response and control effect of the TAD, vibration tests were carried out, and the vibration characteris-

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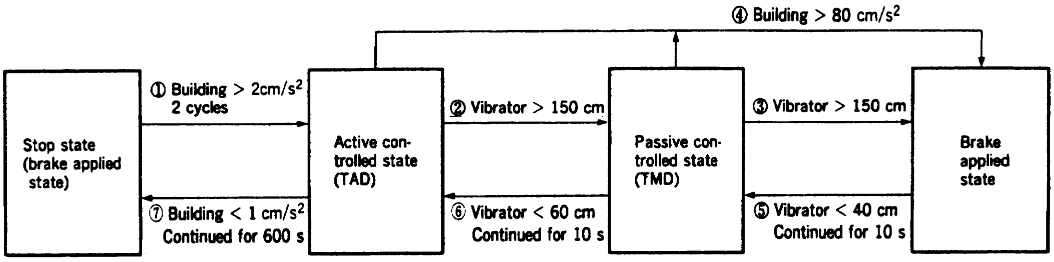
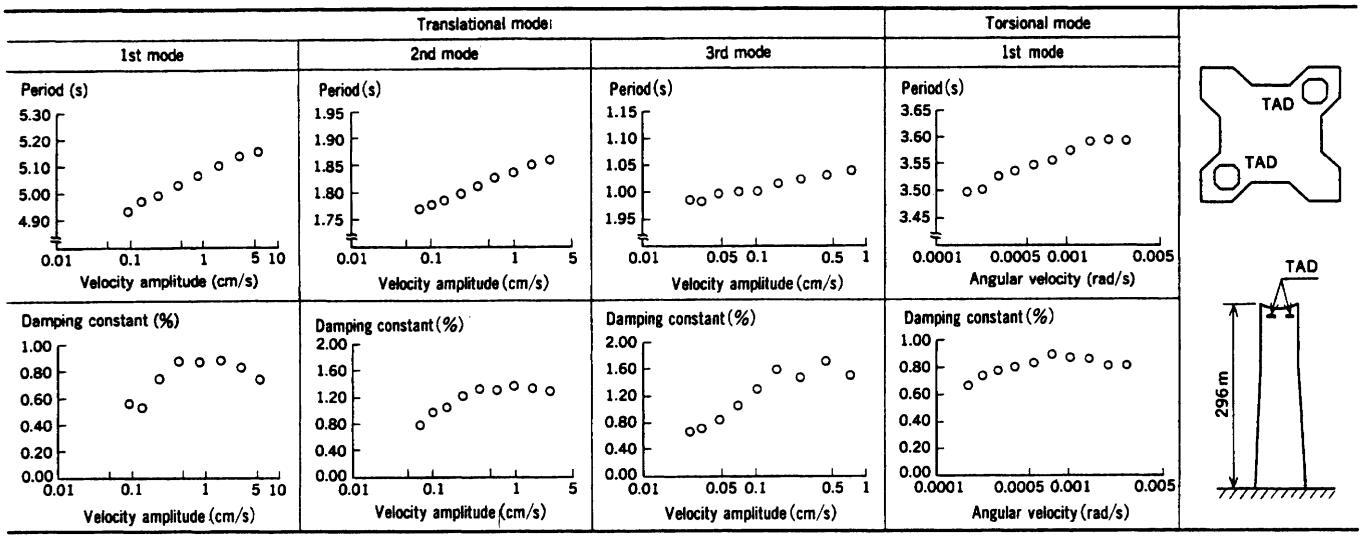


Fig. 2 Operating system of TAD
Block diagram showing switching system of the operating states on the basis of the motion of the building and the TAD is shown.

Table 2 Vibration characteristics of building



tics of the building were measured just before completion of the building. In the tests the TAD was used as an exciter. The natural period and damping constant were obtained from the free vibration wave form obtained by quickly stopping excitation after resonance of the building. The vibration modes measured in the test are the 1st, 2nd and 3rd modes in the translational vibration in the X and Y directions and the 1st mode in the direction of torsional vibration.

Table 2 shows the results of the tests. Dependency on the amplitude is observed in the natural period of the building, and the relation between the logarithmic values of the amplitude and period is roughly linear. A close look at the 1st mode in the translational vibration that is controlled shows a difference of about 4% between the maximum and minimum natural periods in the range of excitation amplitude in this test. The TAD can maintain a stable control effect even against such fluctuations in the period of the building. Furthermore, while dependency on the amplitude is observed in the damping constant, the relation between the logarithmic values of the amplitude and the damping constant is not necessarily linear. When the amplitude becomes larger, the damping constant tends to reach a limit.

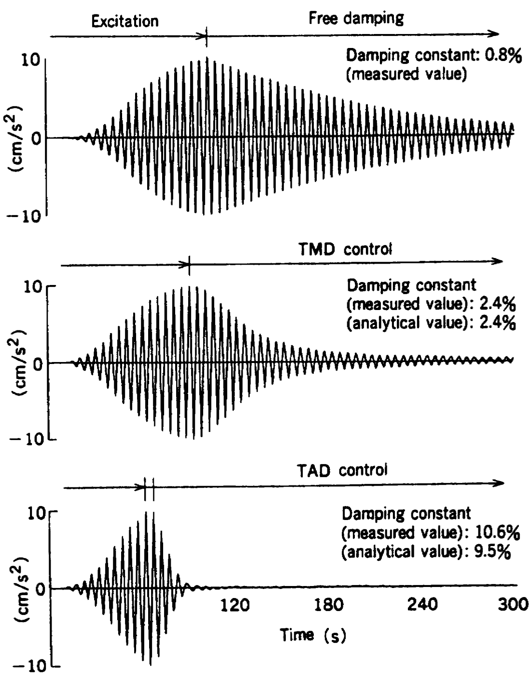


Fig. 3 Results of free vibration tests
Wave forms of free vibration after cessation of excitation showing that building damping becomes very large when the TAD is operated.

4. Performance tests of the TAD

4.1 Free vibration test

A free vibration test was carried out to verify the damping constant added to the building by the TAD. The testing method consisted of the building being excited in the 1st mode in the X and Y directions of the mode to be controlled, after which the devices were operated as a proper TAD and the free vibration of building was measured. In addition, the devices were also operated as a TMD by interrupting the power supply used for driving the device.

Fig. 3 shows the results of measurement in the X direction. The same results were obtained in case of the Y direction as well. Fig. 3 shows the analytical values and the free vibration wave form in the uncontrolled state in which the device is fixed after excitation. The damping constant of the building increases by about 10% due to the TAD and a large additional damping effect can be verified. Such results correspond well to the analytical results in both cases of control by the TAD and the TMD.

4.2 Forced vibration test

Excitation with random waves by simulating wind force was performed using one of the TAD as an exciter installed in the building for the purpose of verifying the control effect of the TAD against random vibration. The other unit was operated in two states: a state in which movement of the vibrators was fixed (without control) and the state in which the device was operated as a TAD (with control) and building vibration were measured, respectively.

Table 3 and **Fig. 4** show a comparison of the test and analytical results in cases without control and with control, respectively. While these results are in the X direction, the same results were obtained in the Y direction as well.

In the analysis the building was modeled as an one degree of freedom (1DOF) vibration system derived from equivalent vibration characteristics of the 1st mode measured in Chapter 3 and each two units of TAD were modeled as 1DOF and were coupled to the building model as a total 3DOF model. The vibration response of the building and the TAD was calculated with the driving force of the TAD that was used as an exciter. The analytical results correspond well to the test results, and it was confirmed that the TAD operated according to theory. The ratio of the measured values of building acceleration in the case of control to that in the case without control was reduced to 53% in the maximum value and to 52% in rms value. Such results show the control effect in the case of one TAD unit, and in case of two TAD units, the control effect on actual vibration becomes higher.

5. Observation of vibration

In order to examine and understand the properties of external forces such as the wind and earthquakes, the vibration response characteristics of the building to them, and the operating states of the TAD and its effect, observation of vibration has been performed using an integrated observation system[4].

According to observation records for a one year period from October 1993 through September 1994, the TAD worked a total of seven times for about three months in winter with a 10-minute mean wind velocity of about 20 m/s at the top of the building which seemed to be a seasonal wind. In this paper, the study of the control effect is done using two records in which the TAD was continuously operated for the longest period of time among the records of TAD operation.

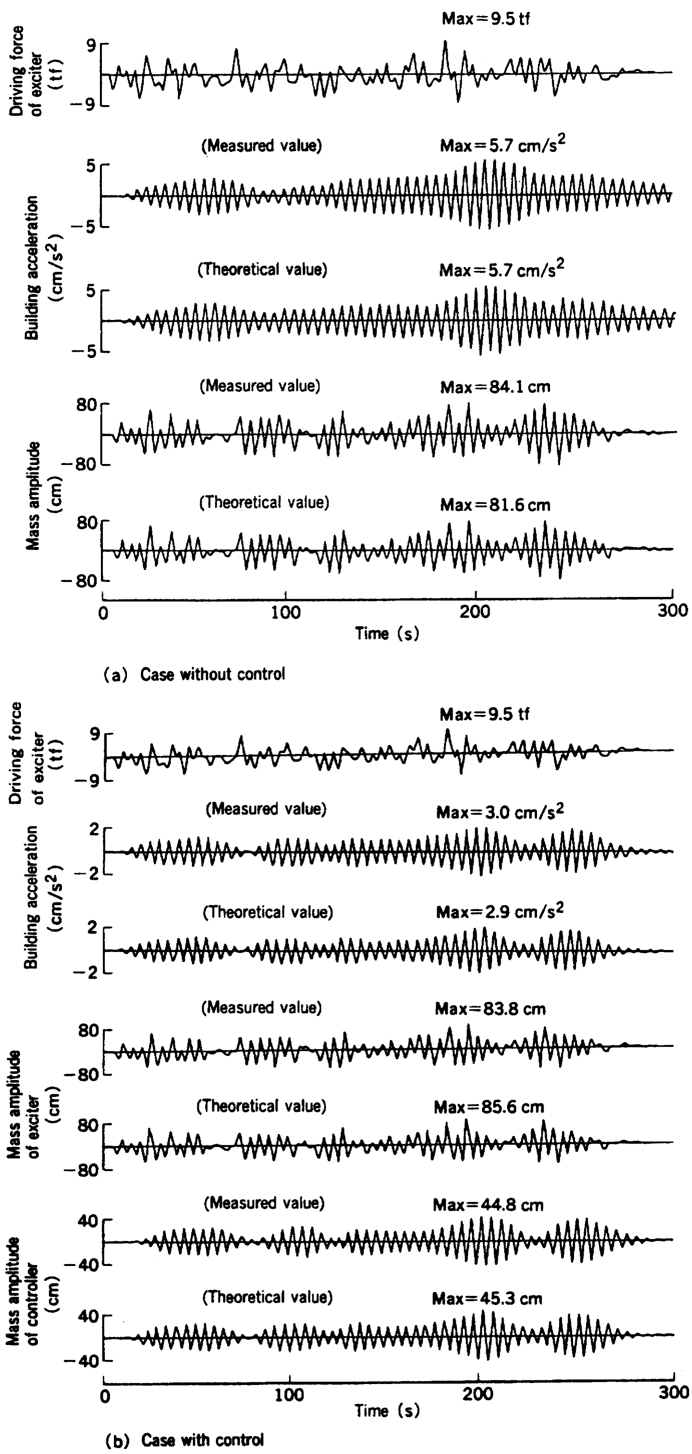


Fig. 4 Forced vibration test and theoretical results
The theoretical results correspond well to the test results and the control effect expected based on the theory is obtained.

Table 3 Results of forced vibration tests

	Measured value (cm/s²)	Theoretical value (cm/s²)
Without control		
Max. value	5.7	5.7
rms value	2.1	2.1
With control		
Max. value	3.0	2.9
rms value	1.1	1.1
Control ratio		
Max. value	0.53	0.51
rms value	0.52	0.52

5.1 Strong wind on February 21, 1994

According to the record, operation of the TAD was started

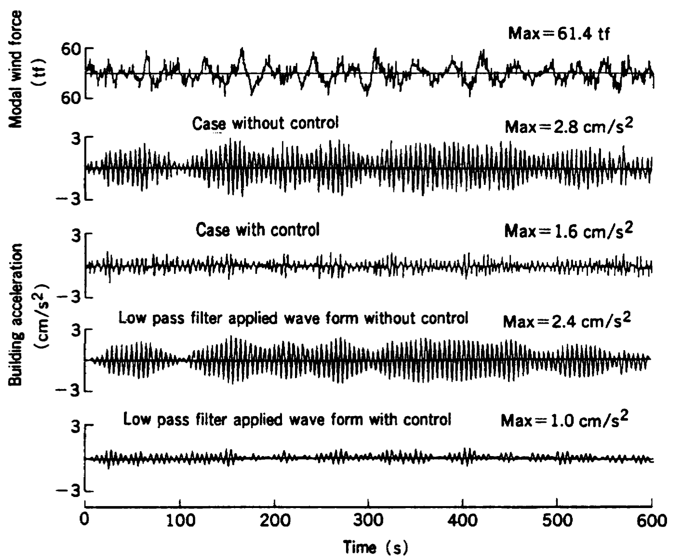


Fig. 5 Results of performance on wind observation
The vibration component of the 1st mode of the controlled building is reduced to 42% by the TAD.

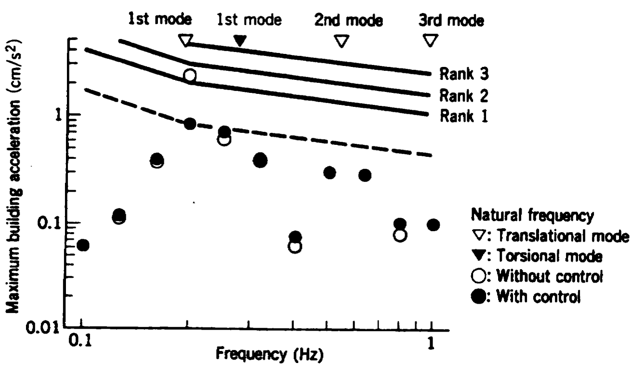


Fig. 6 Results of 1/3 octave band analysis of structural response
Building acceleration by frequency band is compared to the evaluation curve of residential habitability. The residential habitability depends on the vibration component of the 1st mode, and the effectiveness of the TAD can thus be understood.

at about 1340 hours and stopped at about 1520 hours. The 10-minute mean wind velocity at the top of the building was between 18 and 20 m/s and a maximum of 21 m/s at about 1400 hours. Study of the control effect was done on the basis of the building response records for 10 minutes starting from 1412 hours. First, an equivalent modal wind force F capable of reproducing the measured building response including sway motion in the higher mode was calculated in reverse with 1DOF vibration system derived from the building sway motion of the 1st mode.

$$F=M_s\ddot{x}_s+C_s\dot{x}_s+K_sx_s-R+U \quad (1)$$

Where,

$$R=C_d(\dot{x}_d-\dot{x}_s)+K_d(x_d-x_s)$$

M_s, C_s, K_s: generalized mass, damping factor and spring of building sway motion of the 1st mode

C_d, K_d: damping factor and spring of the TAD

U: controlling force of the TAD (measured value)

$\ddot{x}_s$: building acceleration (measured value)

x_d-x_s: relative amplitude of the TAD (measured value)

Then the extend of building acceleration in the case without control was obtained using the wind force as an external force and compared with the observation records in the case with control. **Fig. 5** shows the observed results. In Fig. 5, a 0.24 Hz low pass filter applied wave form is also shown in order to see the control effect for the vibration component of the 1st mode. The ratio of acceleration in the case with control to that of the case without control is 57% when the low pass filter is not applied and 42% when the low pass filter is applied considering only the vibration component of the 1st mode.

Fig. 6 shows the results of 1/3 octave band analysis for the observed results. From this figure it can be seen that the control effect due to the TAD is for the vibration component of the 1st mode. Furthermore, the solid line in Fig. 6 shows the vibration criteria in the guidelines for evaluating residential habitability[5] as set forth by the Architectural Institute of Japan. When this linear gradient is compared with the results of 1/3 octave band analysis, it can be said that the vibration component of the 1st mode is dominant in residential habitability.

In other words, in the case of this building it is adequate to focus on the vibration component of the 1st mode as a scale for evaluating of the control effect of TAD, and a reduction ratio of 42% was obtained. The control effect, as supposed by the observation results in the typhoon case mentioned below (**Fig. 7**), is generated at the vibration level at which the control effect being to appear. It is expected that the higher the vibration level is, the higher the control effect will be.

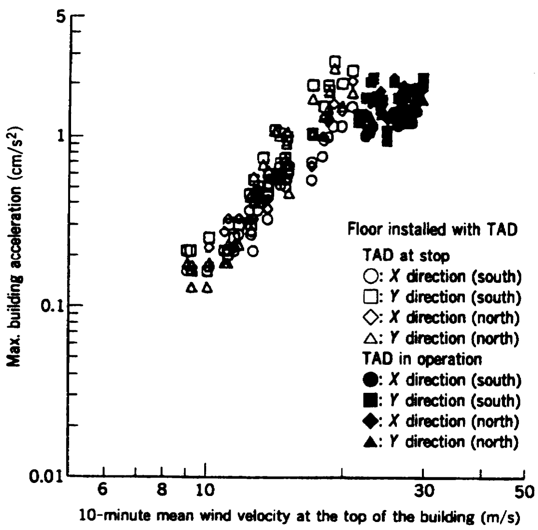


Fig. 7 Results of observations during Typhoon No.26 on September 30, 1994
Building acceleration increases rapidly in direct proportion with an increase in wind velocity when the TAD stops, but the increments of increase reach a limit with the starting of the TAD and vibration amplitude also decreases.

5.2 Typhoon No.26 on September 30, 1994

Typhoon No.26 passed approximately 300 km at its shortest distance from Yokohama. The TAD began to be operated at about 0020 hours when the 10-minute mean wind velocity at the top of the building reached about 21 m/s and continued operating for about three hours thereafter. During that period the mean wind velocity at the top of the building gradually increased reaching a maximum of 29.6 m/s at about 0200 hours.

Fig. 7 shows the relation between the 10-minute mean wind velocity at the top of the building and the maximum building acceleration. In this figure the records before the TAD began operating are shown as well. In the case without control before the TAD began operating, the building acceleration rapidly increased with a rise in the wind velocity, but when the TAD began starts to operate, the increments of building acceleration became smaller. The building acceleration becomes somewhat smaller than the building acceleration at a wind velocity of about 20 m/s just before the TAD begins to operate in spite of the higher wind velocity during TAD operation. It was therefore possible to confirm the control effect of the TAD in strong wind conditions.

6. Conclusion

It was confirmed from full-scale tests of the structure controlling device developed for skyscrapers and vibration observation records that the TAD has the sufficient levels of control performance as indicated by theory. Actual data will continue to be collected in the future, and the extent of control performance at the higher vibration levels during earthquakes and typhoons will be verified. Furthermore, it is expected that a device capable of dealing with earthquake control including vibration components in higher modes will be developed by employing a linear motor that is superior in controllability and response to the driving device.

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