Development of Active-Damping Bridges and Its Application to Triple High-Rise Buildings*

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The X-, Y- and Z-Tower office buildings of the Harumi Island Triton Square are located very close to one another. The distance between two of the three towers is as narrow as 13 meters. To increase the habitability of these buildings when they vibrate during a strong wind, they are equipped with active-damping bridges. Each active-damping bridge connects one building to another and actively controls expansion and contraction to reduce vibrations. In this paper, a general description of the buildings and equipment will be presented, following which an applied control system design method will be related. The paper will conclude with a report of tests on the actual buildings conducted to verify performance.

Key Words: Vibration Control, High-Rise Building, Active-Damping Bridge, Wind-Induced Vibration

1. Introduction

High-rise buildings must be equipped with systems to reduce vibration during strong winds in order to ensure a high degree of habitability⁽¹⁾. For this purpose, many actively controlled mass damper systems, such as active mass dampers (AMD) and hybrid mass dampers (HMD), utilizing the inertia force of

moving mass have been applied⁽²⁾. However, when multiple buildings are constructed near one another, damping can be achieved by connecting the buildings with dampers, actuators and other vibration control devices and utilizing the mutual interaction between the buildings. Kunieda was one of the first to study this method, proposing a system called the “shared” system in which tower structures are connected with dampers that possess appropriate damping coefficients⁽³⁾. Seto has developed an active type system for connection and damping. Numerical simulations and model experiments have been conducted to study damping performance when twin, triple and other structures arranged in parallel are connected to one another using actuators^{(4),(5)}. Subsequently, Ikawa et al. conducted research into active systems⁽⁶⁾.

The X-, Y- and Z-Tower office buildings of the Harumi Island Triton Square, completed in April 2001 in Tokyo, are high-rise buildings that have been constructed very close to one another. To reduce vibrations during strong winds and thus increase the habitability of these buildings, the buildings are connected with two bridges that actively expand and contract. As damping is actively performed by

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bridges connecting the buildings, these units are called active-damping bridges. They represent the world's first use of the active system for connection and damping.

This paper will begin by presenting a brief outline of the buildings and numerical calculations of damping performance. Next, it will give an outline of the equipment and the results of verification tests of damping performance conducted after the equipment was installed on the buildings. The paper will conclude with an overall evaluation of the system based on the results of actual measurement.

2. Outline of Buildings and Control Target

Harumi Island Triton Square, which opened in April 2001, was planned under the Harumi 1-chome Block Class 1 Urban Redevelopment Project as a tri-functional community incorporating business, residential and amusement facilities. The complex comprises office buildings, commercial and service facilities, exhibition facilities, a concert hall, housing complexes and other facilities. Counting all of the blocks, the complex has a lot area of approximately 84 800 m² and a total floor area of 671 900 m². The triple office

Fig. 1 General view of triple office towers X, Y and Z

Fig. 2 Arrangement of vibration control devices

towers X, Y and Z have heights of 195 m, 175 m and 155 m, respectively. These three towers form a new landmark for the area (see Fig. 1).

The above-ground section of each office tower is a four-cornered structure measuring 54 meters square. The office towers are grouped together in triangular fashion around the hall building. Accordingly, towers X and Y and towers Y and Z are located extremely close to one another. Bridges that can expand and contract in the axial direction have been provided between the towers, and an active control system for axial expansion and contraction has been employed to damp each of the three towers (see Fig. 2). The connecting heights are 162.4 m between X- and Y-Tower, and 138.4 m between Y- and Z-Tower, respectively.

The control target for this system is to increase building damping by two to three times, and to ensure that the maximum bi-directional acceleration for each building will satisfy habitability performance evaluation criterion H-3 of the Architectural Institute of Japan⁽¹⁾.

To confirm the damping performance of this system, a time history response analysis during strong winds was performed. The values in Table 1 were used as the values for the building, and all damping ratios were set to 1%. The modal external force for the 1st mode, derived from the results of wind tunnel tests, was used as the external force of the wind. The return period was one year, and the mean wind velocity at the top of the X-Tower (height: 194.9 m) was

Table 1 Designed natural periods and generalized masses of towers

Tower	Natural period s			Generalized mass	
	x-direc.	y-direc.	Torsion	Horizontal t (x and y-direc.)	Torsion t·m ²
X-Tower	4.9	5.0	2.7	27 300	2.3×10^7
Y-Tower	4.1	4.1	2.4	24 500	2.0×10^7
Z-Tower	3.9	3.7	2.6	24 000	1.8×10^7

Fig. 3 Orbit of acceleration response for the Y-Tower (wind direction: 285 degrees)

Fig. 4 Analytical results of habitability evaluation

27.7 m/s.

Figure 3 shows the orbits of acceleration response for the Y-Tower for a wind direction of 285 degrees (north-northwest), which has a high probability value. For purposes of comparison, the value for no damping (when damping is not applied) is also shown. From this figure, it can be seen that the scope of the whirling during damping was reduced to about half of the value when no damping was applied.

Figure 4 shows the performance evaluation standard, on top of which the maximum acceleration corresponding to a return period of one year is plotted. From this figure it can be seen that, with the exception of the x direction for Z-Tower, all of the values for when no damping was conducted exceed evaluation standard H-3. However, when damping is performed, the values satisfy H-3 in all cases.

3. Configuration of Vibration Control Devices

Figure 5 shows a general view of the vibration control device and the key components making up this device. The device is a telescopic structure made up of two main structures: an inner structure and an outer structure. Both structures are supported by rollers, enabling the device to expand and contract. For connections with buildings, spherical bearings on the inner structure and orthogonal bearings on the outer structure are used to eliminate constraint with respect to relative displacement between buildings in two horizontal directions and the vertical direction. On the inner structure, two clamping devices driven by electric motors and ball screws are provided, one above and one below. When these clamping devices hold the retaining plates, the inner and outer structures can be expanded and contracted by the electric motor. Ordinarily, when the wind is not blowing, and in the event of a strong earthquake or storm, the clamping devices are released to allow the inner and outer structures to expand and contract freely. When

(a) General view

(b) Key components

Fig. 5 Vibration control device

the building begins to vibrate as a result of a strong wind, the clamping devices begin to exert following control with respect to the relative displacement between the inner and outer structures, holding the retaining plates and commencing damping action. The control stroke during damping is ± 0.1 m, while the effective stroke between the inner and outer structures when the clamping devices have been released is ± 2.4 m. Two units of 37 kW AC servomotor are adopted as electric motor, and the maximum control force applied by two motors is 340 kN. Overall mass of vibration control device is 80 tons.

Before installation into the building, functional tests were conducted for individual units at the factory to confirm basic performance. Figure 6 shows the measured hysteretic curve of vibration control force, using a test unit shown in Fig. 7, when the device is set to vibration control mode and the inner structure is subjected to forced sinusoidal vibration by the excitation moving mass. The vibration control force was detected by load cells, installed in the bearings for supporting the outer structure, as well as in the two motor axes. The frequency was set at 0.25 Hz and two values for amplitude were used: approximately ± 0.02 m and approximately ± 0.04 m. From this figure, it can be seen that the result was almost ideal linear viscous damping that was not affected by

amplitude. Measurements of the maximum coefficient of static friction between the inner and outer structures with the clamps released were on the order of 10^{-3} , and the movement of the inner and outer structures with respect to one another was confirmed to be smooth.

The arrangement of control system is shown in Fig. 8. The power panels for each of the devices are located on the top floors of the X- and Z-Tower, while

Fig. 6 Measured hysteretic curve

Fig. 7 Configuration of functional test unit

Fig. 8 Arrangement of control system

the control panel is located on the top floor of the Y-Tower. Calculations needed for vibration control are performed by the controllers housed in the control panel. Accelerometers are provided in the two horizontal directions of the floor on which the equipment is installed in each tower to detect building vibration. The signals from these units and the signals relating to the devices are sent from the transfer control panel to the control panel on the top floor of the Y-Tower via composite fiber-optic cable.

4. Control System Design

The dynamic model of three towers, connected by vibration control devices, is shown in Fig. 9. This model is a physical model of multi-degree of freedom system, in which each mass point has two horizontal directions, and the control force direction affected by triangle placement of the buildings is considered. The equation of motion for this system is written as follows:

$$M(\ddot{\mathbf{x}}) + C(\dot{\mathbf{x}}) + K(\mathbf{x}) = \mathbf{f} + \mathbf{U}(\mathbf{f}_{c1}) \quad (1)$$

where M , C and K are the mass matrix, damping matrix and stiffness matrix, respectively, $\mathbf{x}$ and $\mathbf{y}$ are the displacement components of each mass point in two directions, $\mathbf{f}$ is a external force vector and $\mathbf{U}$ is a matrix for determining the applying point and direction of control forces.

Fig. 9 Dynamic model of three towers

The modal analysis technique is used for control system design. For this purpose, Eq.(1) is transformed into Eq.(2) by using modal coordinate η :

$$\mathbf{M}_m \ddot{\eta} + \mathbf{C}_m \dot{\eta} + \mathbf{K}_m \eta = \mathbf{U}_m \mathbf{f}_c + \mathbf{F}_m \mathbf{f} \quad (2)$$

where $\mathbf{M}_m$, $\mathbf{C}_m$ and $\mathbf{K}_m$ are the modal mass matrix, modal damping matrix and modal stiffness matrix, respectively. And $\mathbf{U}_m$ and $\mathbf{F}_m$ are the matrices concerning control forces and external forces.

The diagram of control method is illustrated in Fig. 10. In this system, two vibration control devices are controlled independently for the purpose of simplifying the control system; the two directional accelerations of the X- and Y-Tower are used for controlling the device between the X- and Y-Tower and the two directional accelerations of the Y- and Z-Tower are used between the Y- and Z-Tower. As the above system formulated in Eq.(2) is a 2-input system, the partial model given in Eq.(3), which is extracted from Eq.(2), is used for designing the independent control system.

$$\mathbf{M}_{m_i} \ddot{\eta}_{_i} + \mathbf{C}_{m_i} \dot{\eta}_{_i} + \mathbf{K}_{m_i} \eta_{_i} = \mathbf{U}_{m_i} \mathbf{f}_{ci} + \mathbf{F}_{m_i} \mathbf{f}_{_i} \quad (3)$$

This equation is of a 1-input system and $i(=1, \text{ or } 2)$ denotes the connection condition of the vibration control devices.

The H_∞ control theory is adopted in the control system design in an effort to avoid the spill-over phenomena with respect to higher modes and to improve the robustness of parameter variation. According to the H_∞ control theory, the control input $u_i(=f_{ci})$ is given by the observation output $\mathbf{Y}_i$ and the controller $\mathbf{K}_i(s)$ shown in the following equation:

$$u_i = \mathbf{K}_i(s) \mathbf{Y}_i \quad (4)$$

where the building acceleration is adopted as $\mathbf{Y}_i$, and it has four components consisting of two directional

Fig. 10 Diagram of control method

accelerations in buildings connected by vibration control device.

5. Verification Tests of Damping Performance

After the vibration control devices were installed in the buildings, a vibration control test was performed at the site to confirm damping performance.

A dynamic model for the control system design was created from the modal parameters and the controllers were determined. The modal parameters up to secondary mode in two horizontal directions for each tower were obtained by sine wave sweep tests using vibration control devices. In the design procedure, in order to provide damping during the primary mode and robust stability from the secondary mode on, a reduced-order model was devised in which the full-order model included up to the aforementioned

Fig. 11 Bode diagram of additive error and weighting functions used for the device between Y- and Z-Tower

Fig. 12 Bode diagrams of controller used for the device between Y- and Z-Tower

Fig. 13 Measured free vibration responses of three towers

secondary mode was truncated to remove the secondary mode, and the H_∞ control system was designed for reduced-order model. Figure 11 shows the bode diagrams of the additive error and of the weighting functions used for the controller between the Y- and Z-Tower. The curves $W_{si}(i=1$ to 4), W_t and Δ_p are the weighting functions for the Y- and Z-Tower accelerations, the weighting function for the control input and the additive error, respectively. The bode diagrams of the controller obtained for the above-mentioned weighting functions are shown in Fig. 12. The 10th order controllers were used both between the X- and Y-Tower and between the Y- and Z-Tower. The controller was converted into a discrete system and implemented.

Figure 13 shows the results of the free vibration test. The free vibration test was performed by measuring the free vibration waves when the mode was changed to vibration control mode following forced excitation of the building by the vibration control devices. The damping characteristics were then compared with the values for no damping when the clamping device was released. When excitation was performed with both of two devices at the same time, considering the fact that all three towers would be excited, the excitation frequency was set to 0.243 Hz for the device between the X- and Y-towers and 0.303 Hz for the device between the Y- and Z-towers, and an excitation force of ± 58.8 kN was used in each case. From this figure, it can be seen that the acceler-

Fig. 14 Measured frequency responses of Y-Tower 38th floor

ation in two horizontal directions for each tower was reduced more quickly when damping was applied than when damping was not applied, and that damping was approximately two to three times greater. Moreover, Figure 14 shows the frequency response for the Y-Tower 38th floor obtained in the sweep test. A comparison was conducted with the device between the X- and Y-towers used as the exciting device and the device between the Y- and Z-towers both damped and not damped. As the figure shows, although only a single damping device was used, the resonant peak value was reduced by about half for each direction.

These results demonstrate that this device can make building damping two to three times as much as when vibration control is not performed, and that the device can be predicted to satisfy H-3, the habitability performance evaluation criterion.

Also, for a background noise of 32 dB, the indoor acoustic noise level when damping was applied was less than 40 dB throughout all of the tests, demonstrating that there would be no impact on building residential areas.

6. Conclusion

Active-damping bridges were used to connect the three high-rise towers of the Harumi Island Triton Square. Verification tests of damping performance were performed at the site. These tests confirmed that the devices demonstrate damping performance capable of meeting the target habitability performance standard. The vibration control device described in this paper is a vibration control system that does not require a moving mass, and it can be expected to find applications in a variety of fields. System vibration control performance during actual strong winds is planned to measure for the future.

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