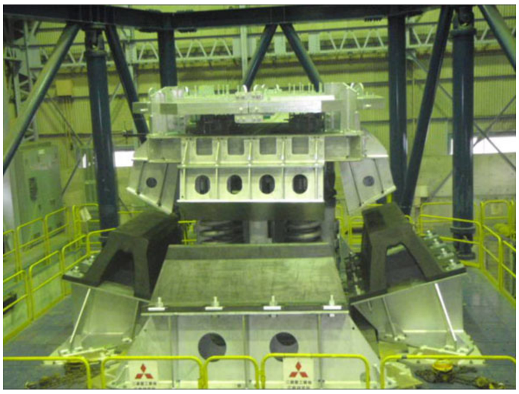
Development of a Wind Vibration Control Device for the Tokyo Sky Tree



KUNIHIRO MORISHITA[*1] KEISUKE SASAJIMA[*2]
YUJI TOMITANI[*3] RYOJI TASAKA[*4]
ATSUSHI KUBO[*5]

Buildings and towers are becoming increasingly taller, as demonstrated by the Tokyo Sky Tree, which is operated by Tobu Railway Co., Ltd. and Tobu Tower Sky Tree Co., Ltd., was designed and administrated by Nikken Sekkei Co., Ltd., and was contracted by Obayashi Corporation. The installation of wind vibration control devices is an indispensable technology for buildings. The assured vibration control performance and safety of these devices, particularly during a large earthquake (including long-period ground motion), is desirable. Mitsubishi Heavy Industries, Ltd. (MHI) and Mitsubishi Heavy Industries Bridge & Steel Structures Engineering Co., Ltd. (MBE) have installed in a wind vibration control device developed for the Tokyo Sky Tree a stopper mechanism that ensures safety of the device even when excessive vibration amplitudes occur due to an earthquake. MHI and MBE verified its wind vibration control performance through shaking tests using a large shaking table. This paper describes the development and verification of these vibration control devices.

1. Introduction

Many active and passive devices have been used as wind vibration control devices for ultra-tall buildings, such as the Yokohama Landmark Tower, Shanghai World Financial Center, and other tower buildings. For the supporting structure (gain tower) of the digital broadcasting antennas on the Tokyo Sky Tree, which will become the world's highest (634 m) self-standing broadcasting tower, MHI and MBE have developed a wind vibration control device with a mechanism that can handle longer periods of vibration than conventional passive devices and that ensures safety of the device even when excessive vibration amplitudes occur under earthquake. We have already installed 40-ton and 25-ton versions of these devices at the tip of the gain tower. We have also verified that the required wind vibration control performance is attained through actual shaking tests using a large shaking table.

2. Structural Overview of the Vibration Control Device

The developed vibration control devices have been installed at two levels on the tip of the gain tower on the top of the Tokyo Sky Tree; one is at an altitude of 625 m (25-ton version), and the other at an altitude of 620 m (40-ton version), as shown in **Figure 1**. These devices were required to have compact structures because there was a structural restriction limiting the installation height to 5 m or less. Additionally, the devices had to perform for a longer period of vibration (approximately 5 seconds) than conventional passive vibration control devices. We developed a device that satisfies this restriction and achieves the required characteristics by employing an inverted pendulum passive vibration control device, as shown in **Figure 2**, and making improvements to its conventional structure.

*1 Research Manager, Hiroshima Research & Development Center, Technology & Innovation Headquarters
*2 Research Manager, Takasago Research & Development Center, Technology & Innovation Headquarters
*3 Hiroshima Research & Development Center, Technology & Innovation Headquarters
*4 Manager, Architectural Structures Headquarters, Mitsubishi Heavy Industries Bridge & Steel Structures Engineering Co., Ltd.
*5 Engineering Department, Mitsubishi Heavy Industries Bridge & Steel Structures Engineering Co., Ltd.

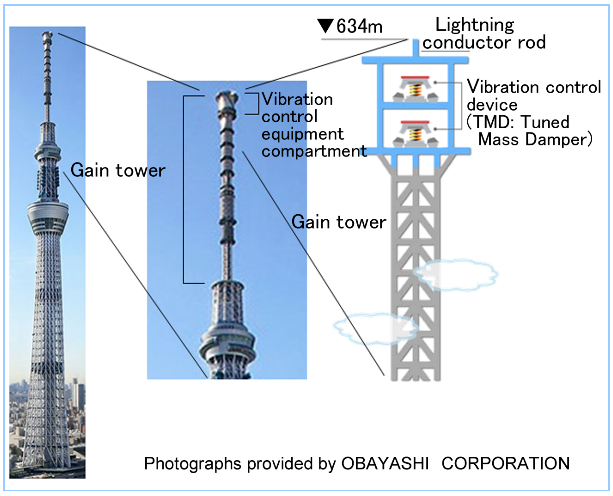


Figure 1 Installation locations of the vibration control devices
Vibration control devices are installed at the tip of the gain tower on the top of Tokyo Sky Tree to safeguard the gain tower against the wind.

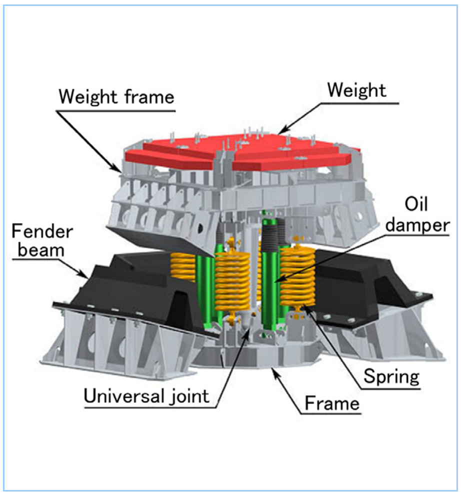


Figure 2 Structural overview of the vibration control device
The device consists mainly of weights, springs, and oil dampers. It has a stopper mechanism that uses fenders for safety in case excessive displacement is encountered.

The developed device has a structure such that the base of a vibrating body consisting of a weight and a weight frame is supported by universal joints, including components such as push and pull springs and oil dampers. A mechanism that can adjust the vibration characteristics on site is incorporated in the structure because it is necessary to tune the vibration characteristics of the device depending on the vibration characteristics of the actual constructed building. Additionally, as a stopper mechanism, we developed and applied a fender structure that absorbs a certain level of displacement while performing displacement control even if unexpected external forces such as those from an earthquake are applied, resulting in excessive vibration amplitudes of the device; this prevents sudden braking that could cause a destructive impact.

3. Performance Verification Tests

3.1 Overview of the large shaking table

We conducted performance verification tests of the vibration control device using a large shaking table, as shown in **Figure 3**, on which the actual device to be tested was mounted. The shaking table had the following specifications: maximum loading weight of 1,000 kN, maximum test-piece size of 7 × 7 × 6 m (L × W × H), maximum shaking force of ±300 kN, and maximum stroke of ±1,000 mm, with two simultaneously shaking directions.

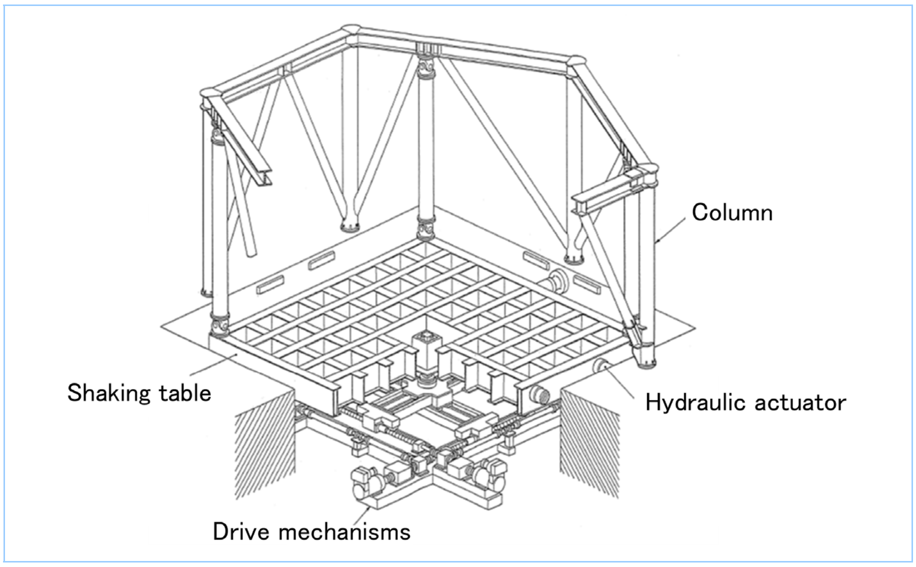


Figure 3 Large shaking table
The table has a maximum loading weight of 1,000 kN and a maximum stroke of ±1,000 mm.

3.2 Test overview

The performance verification tests were conducted to confirm the following two required characteristics related to the vibration characteristics of the vibration control device.

(1) Confirm the frequency range that the device can handle (should be adjustable in the range of ±15% or more of the target frequency)

(2) Confirm the damping factor within the above frequency range (should be within a maximum of ±15% of the target damping factor)

In these verification tests, the device was shaken sinusoidally for various positions of the springs and oil dampers using the vibration-characteristic adjusting mechanism, and the resulting frequency and damping constant were measured. The eigen frequency was obtained from the frequency at which the phase lag of the weight vibration of the test device to the vibration of the shaking table was 90 degrees. The damping factor was obtained from the relationship between the slope of the phase curve and the eigen frequency.

3.3 Test results

Figure 4 shows an example of the test results. The horizontal axis gives the ratio of the frequency to the target value, and the vertical axis is the phase difference. **Figure 5** shows photographs indicating the vibrating states of the vibration control device. **Figure 6** shows a plot of the frequency versus ratio of the damping constant to the target value; the hatched area is the expected performance range of the device, and circles indicate the test results. **Figure 7** shows a comparative example of the behavior of the actual test device and model analysis results using random waves instead of sine waves; the vertical axis gives the ratio of the displacement time-history to its maximum value. Based on these results, the following findings were obtained.

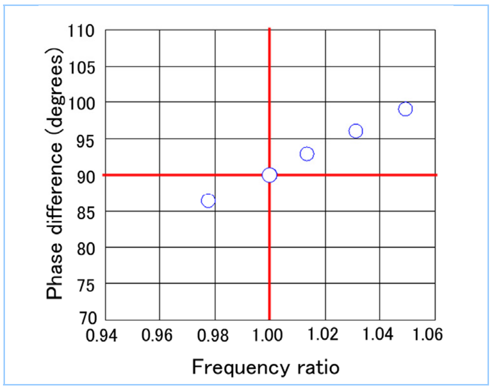


Figure 4 Relationship between frequency and phase difference
Resonance points are obtained from the relationship between various shaking frequencies and the phase difference during testing.

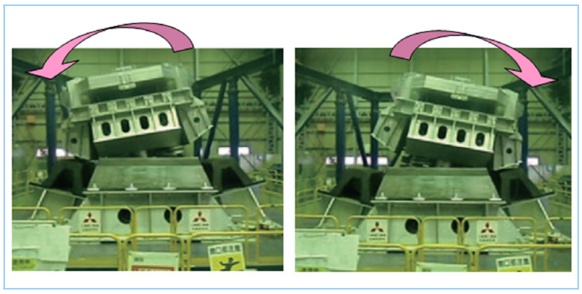


Figure 5 Vibrating states of the vibration control device
The vibration control device employs an inverted pendulum structure such that the upper weight sways from side to side around the fulcrum, or the universal joint, to generate a damping effect.

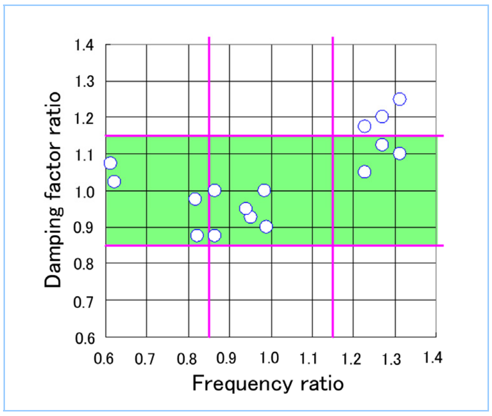


Figure 6 Relationship between expected performance and the test results
The hatched area indicates the expected performance range. The circles indicate test results.

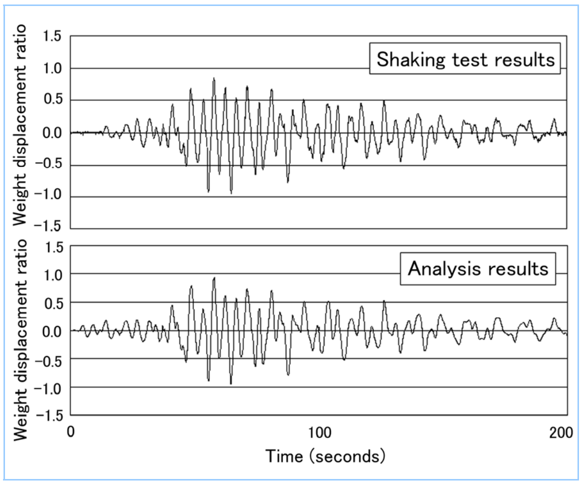


Figure 7 Comparison between shaking test results and an analysis for a random wave
For a random wave, the shaking test results almost conform to analysis results based on a vibration control device model.

(1) Figure 6 indicates that the frequency could be adjusted over a range of at least ±15% of the target frequency, which was the expected performance. However, for the damping factor, some higher frequency ratios departed from the expected performance range. But as the positions of the springs and oil dampers can be adjusted through on-site tuning, these results can be also adjusted to the expected performance range. Thus, we verified through testing that the vibration control device has the required performance characteristics.

(2) The comparison shown in Figure 7 indicates that vibration continues at the eigen frequency of the vibration control device, even when a random vibration is applied. The analysis model behaved similarly.

(3) Based on the above analysis model, an analytic study of a case with an unexpected disturbance (i.e., an underlying fault earthquake defined for design of the Tokyo Sky Tree that is unforeseeable with the building code) found that the weight could hit the fenders but that the impact force did not exceed the acceptable bearing force of the fender. Thus, the safety of the device is assured.

4. Conclusion

We have developed a vibration control device that can safeguard the gain tower of the Tokyo Sky Tree against wind vibrations. This device satisfies the installation height restriction and can handle longer periods of vibration compared with conventional vibration control devices. We conducted performance verification tests of the actual device on a large shaking table and verified that its expected performance for both frequency and damping factor could be met by using the adjusting mechanism for on-site tuning.

In response to expectations of requirements for more and more ultra-tall buildings and hyper buildings in the future, we will continue to develop vibration control devices that not only meet their required performance standards but also ensure safety of the devices during unexpected disturbances to safeguard buildings against wind vibration.