The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

Vibration Tests on Nuclear Power Station Stacks Equipped with Structural Control Oil Dampers

Ryu Shimamoto[1], Fukashi Mori[2], Tomonori Kitaori[2], Satoru Aizawa[3], Yukio Naito[4] and Haruhiko Kurino[4]

[1] *Civil & Architectural Engineering Dept., Chubu Electric Power Co., Inc. Nagoya, Japan*
[2] *Hamaoka Nuclear Power Station, Chubu Electric Power Co., Inc. Shizuoka, Japan*
[3] *JFE Engineering Corporation, Tokyo, Japan*
[4] *Kajima Corporation, Tokyo, Japan*
Email: Shimamoto.Ryuu@chuden.co.jp

ABSTRACT :

This paper presents forced vibration tests conducted on a 100m-high steel stacks at Hamaoka Nuclear Power Station, whose seismic margin has been widely enhanced through an upgrading project using structural control techniques. For this project, a new target earthquake load that is much stronger than the original design loads was set up. The original stack was designed as free-standing without any supporting frames, and we planned to link the with a supporting tower via oil dampers to improve structural damping as well as strength. In order to examine the dynamic characteristics of the stacks with the oil dampers, forced vibration tests were carried out before project completion by introducing three slide-mass-type exciters on the top level of the supporting tower. Although the observed displacement at the top of the stack was less than 10mm, which is much smaller than the response to the target design earthquake, the test results showed damping ratios of about 9% In addition, it was confirmed that the test results were well simulated by the numerical model used for seismic design by simply introducing a small friction element to the damper portion. This paper first describes the specification of the stack with oil dampers, and presents the results of vibration tests. Next, it presents simulation results and discusses the control effect of the oil dampers.

KEYWORDS: Structural control, Oil damper, Nuclear power plant, Stack, Forced-vibration test

1. INTRODUCTION

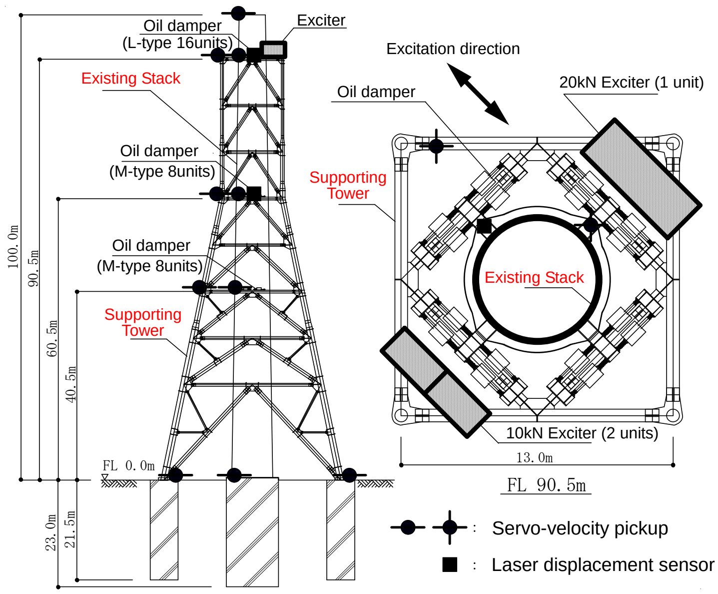
This paper presents forced vibration tests conducted on 100m-high steel stacks in an actual nuclear power station, whose seismic margin has been widely enhanced through an upgrading project using structural control techniques. The target, Hamaoka Nuclear Power Station, consists of five reactor buildings, and three stacks (Units-3, 4 and 5) are included in this project. A new target earthquake load that is much stronger than the original design loads was set up. The original stacks were designed as free-standing without any supporting frames, and we first examined the possibility of conventional reinforcement by building up a new supporting tower around the existing stack. However, it became apparent that several difficult problems would remain unsolved with such a simple technique. Thus, we planned to link each stack with a supporting tower via oil dampers to improve the structural damping as well as the strength. This project is the first full scale application of structural control technology to an actual nuclear power plant facility in Japan, and was completed in December 2007. We have presented this seismic upgrading project in detail in another paper [Shimamoto et al. 2008].

In order to examine the dynamic characteristics of the stacks with the oil dampers, forced vibration tests were carried out before project completion. Since a large structural damping is expected compared with ordinary structures, and at least a few millimeters of stroke should be generated in the damper portion to avoid an undesirable effect such as a friction force in the oil damper between the piston and the cylinder, a large excitation force was required for this test. Therefore, we set three slide-mass-type exciters on the top level of the supporting truss-tower (maximum excitation force is about 40kN when the three exciters are operated synchronously). The vibration tests were conducted on all stacks included in the upgrading project, but this paper focuses on Unit-4. We first describe the stack with oil dampers, and present the results of the vibration test. Next, we present simulation results and discuss the control effect of the oil dampers.

2. OUTLINE OF STACK

Figure 1 outlines the structural design of Unit-4. The existing tube-shaped steel stack is about 100m high with a diameter from 8.8m at the base to 5.6m at the top. We built a new supporting truss-tower 90.5m high to surround the existing stack, and connected the two structures via oil dampers. The details of the joint part are described in Figure 1(b). The oil dampers were inserted between a connecting arm attached to the existing stack and a bracket of the newly built supporting tower. We arranged three connecting levels (FL+90.5m, 60.5m and 40.5m) in considering various obstacle attachments of the existing stack. The oil damper generates a reaction force against a relative velocity between the existing stack and the supporting tower, and augments a damping effect to both structures to reduce the response vibration. The parameter of the damper is carefully examined by considering the response of both the stack and the damper portion. According to the complex eignvalue analysis using a simple vibration model, about 10% of damping augmentation is expected [Shimamoto et al. 2008]. Table 1 summarizes the specifications of the damper, and Table 2 shows the damper distribution. Figure 2 shows the installed actual oil dampers.

(a) Overview (after upgrading)



(b) Structure and vibration test settings

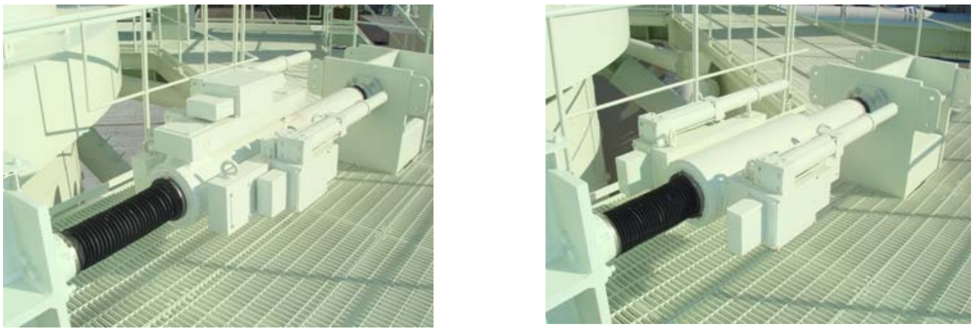
Figure 1 Outline of the Stack (Unit-4)

Table 1 Specifications of oil damper

Damper type	Damping coefficient	Stiffness	Permissible velocity	Stroke
L	5.0kNsec/cm	80kN/mm	180cm/s	±300mm
M	7.5kNsec/cm	110kN/mm	120cm/s	±200mm

Table 2 Damper distribution

Vertical level	Damper type	Number
FL 90.5m	L	16
FL 60.5m	M	8
FL 40.5m	M	8



(a) L-type (b) M-type

Figure 2 Oil Dampers

3. VIBRATION TEST

3.1. Test and Measuring Description

In order to obtain a large excitation force, we set three slide-mass-type exciters on the top level of the supporting tower (FL+90.5m), and shook the tower with a sinusoidal excitation force. The maximum excitation force capacity was about 40kN when the three exciters were operated synchronously. Figure 3 is a photo of the exciters used here. We selected four different excitation force levels named “Full”, “1/2”, “1/5” and “1/10” in order to examine the force level dependency (or deformation level dependency), and the excitation force amplitude “Full” is about 40kN, but the exact excitation force in the test could be accurately calculated by the measured acceleration of the sliding mass. The distribution of the servo-velocity pickup and the location of the exciters are also shown in Figure 1(b). The obtained velocity converted to displacement based on the excitation frequency, and normalized by the excitation force when we discuss the resonance curves of the displacement amplitude in a later chapter. In addition to the servo-velocity pickup, we set the laser displacement sensors at FL+90.5m and 60.5m levels to measure the relative displacements between the stack and the tower directly.

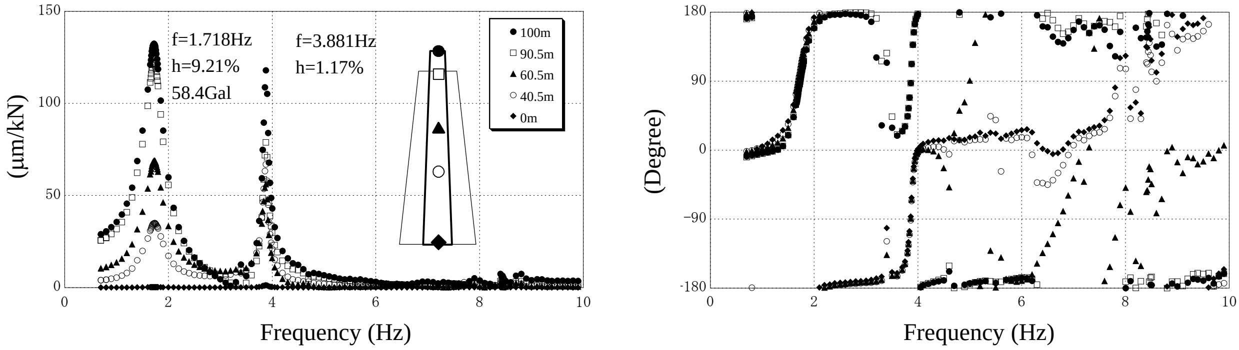
3.2. Test Results

Figure 4 and Figure 5 show resonance curves of the existing stack and the supporting tower, respectively, for the “Full” excitation case. In both figures, (a) shows displacement amplitude normalized by excitation force, and (b) shows phase lag between excitation force and the response at several measuring points. Peaks for the first and second vibration modes are clearly recognized from the figures, and the resonance frequencies and damping ratios for the first and the second modes, which were evaluated by the curve fitting method, are also shown in the figures. Although the displacement of the top of the existing stack is less than 10mm, which is much smaller than the response for the target design earthquake, the structural damping ratio reached 9%. Compared with an ordinary structure, this ratio is quite large, and this is obviously the oil damper’s effect. The 1st peak acceleration of the top of the existing stack (FL+100m) is also indicated for information.

Figure 6 shows resonance curves at the top of the stack (FL+100m) for different excitation forces. The change of resonance frequencies, damping ratios and accelerations at the top level of the existing stack are summarized in Table 3. It can be seen that the resonance frequency and damping ratio depend on the response displacement (or excitation force), and there is a tendency for the resonance frequency to become low and the damping ratio to become large when the excitation force becomes large. Figure 7 shows the relative displacement between the existing stack and the supporting tower, which is equal to the damper’s stroke, for “Full” excitation. A symbol means the directly obtained displacement by the laser sensors and block line shows the displacement calculated from the velocity measured by the servo-velocity pickups, and the two results agree closely. A possible reason why the relative displacement is almost zero when the excitation frequency is lower than 1.5Hz is the friction between the piston and the cylinder of the oil damper. This friction force is assumed to cause the excitation force dependency seen in Table 3. In the next chapter, we discuss the effect of the friction force of the oil damper through the simulation analysis.

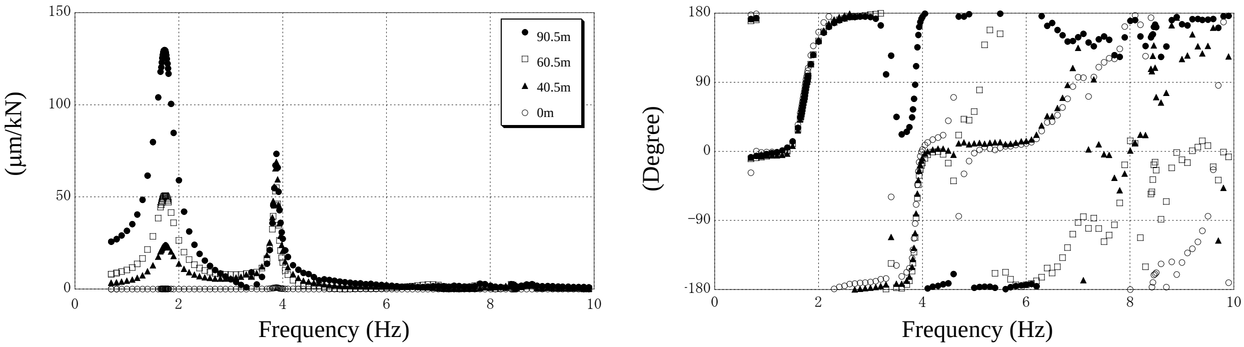
(a) 20kN type (1 unit) (b) 10kN type (2 units)

Figure 3 Exciters (slide-mass type)



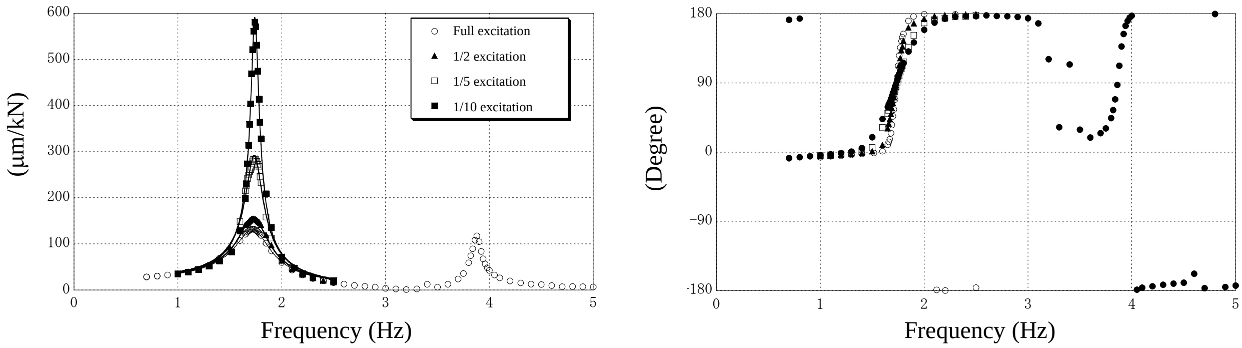
(a) Normalized displacement (b) Phase lag (degree)

Figure 4 Test results of existing stack for “Full” excitation



(a) Normalized displacement (b) Phase lag (degree)

Figure 5 Test results of supporting tower for “Full” excitation



(a) Normalized displacement (b) Phase lag (degree)

Figure 6 Test results of at the top of the existing stack for various excitation level

Table 3 First mode frequency and damping ratio for various excitation level

Excitation case	1st mode frequency (Hz)	1st mode damping ratio (%)	Acceleration of top of the stack (cm/s^2)
Full	1.718	9.21	58.4
1/2	1.725	8.06	36.8
1/5	1.736	4.55	22.5
1/10	1.742	2.15	15.5

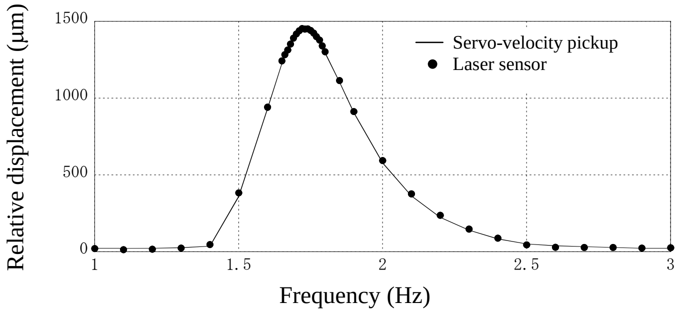


Figure 7 Relative displacement between existing stack and supporting tower (FL+90.5m)

4. SIMULATION ANALYSIS

4.1. Analytical Model

Figure 8 shows the vibration model used for the simulation analysis. The stack and the supporting tower are modeled as lumped mass bending shear elements. We consider the mass of the exciters and some additional equipment for the vibration test for this simulation. The soil portion is modeled as a multi-degree-of-freedom lumped-mass model. Although viscous boundaries were introduced to the model for the seismic design in order to consider energy dissipation effects [Shimamoto et al. 2008], we omit it in this study.

The oil damper is expressed as a series of a springs and a dashpots (Maxwell model), and inserted between the stack and the tower at the connection level. Figure 9 shows a force-velocity relation (damping coefficient) of an L-type oil damper. The plots are the means of the performance test conducted on all the devices before shipping, and the block line shows the specification. From the right figure, it is confirmed that the damper’s performance agrees closely with the specification over a wide range of velocities. However, from the left figure, which is a magnification of a very small velocity, it can be seen that the damper’s performance differs slightly from the specification. This is caused by friction between the piston and the cylinder of the oil damper as well as the small nonlinearity of the valves. In order to take this characteristic accurately into consideration, we separated the constant resistant force, i.e., friction force, from the total damper force, and slightly modified the damping coefficient over the low-velocity range, as shown in the left figure. When the velocity becomes large, this nonlinearity is negligible. The friction element is introduced in parallel with the Maxwell model (as for an M-type device).

4.2. Simulation Method

Because the nonlinear element was introduced into the analytical model, the time domain step-by-step response analysis method was employed to obtain the resonance curves. We first calculated the time history of displacement by considering the sinusoidal excitation force at point A in Figure 8 where the exciters were set in the vibration test. When the response time history became steady state, we normalized the displacement amplitude by the excitation force. By repeating this calculation at various frequency points, we simulated the resonance curve. This simulation procedure is almost the same as the signal processing in the actual vibration test.

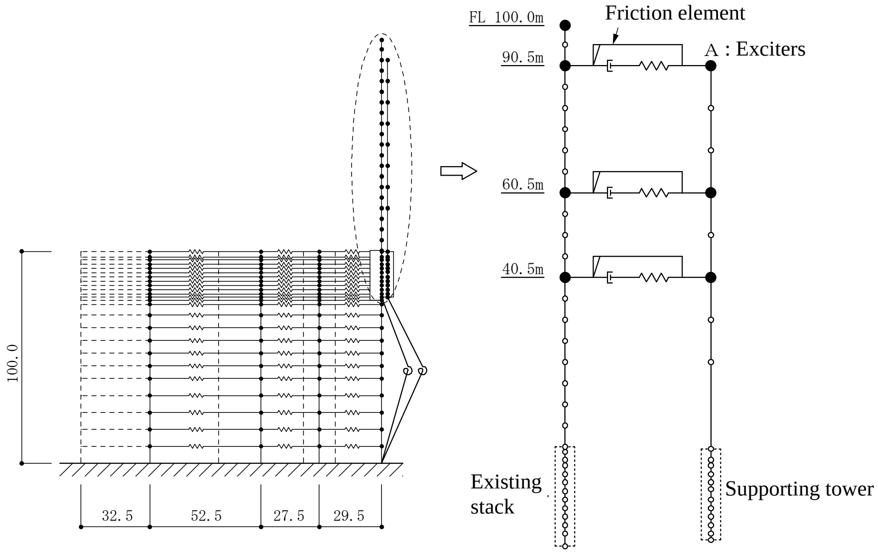


Figure 8 Analytical model for simulation

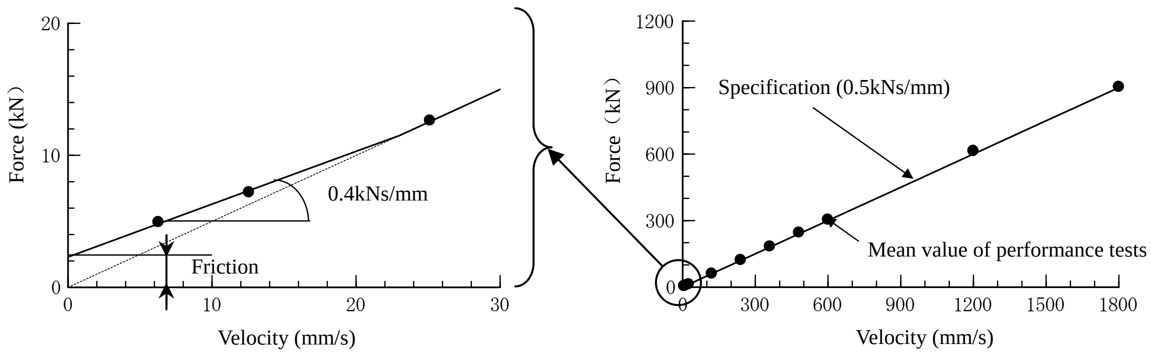
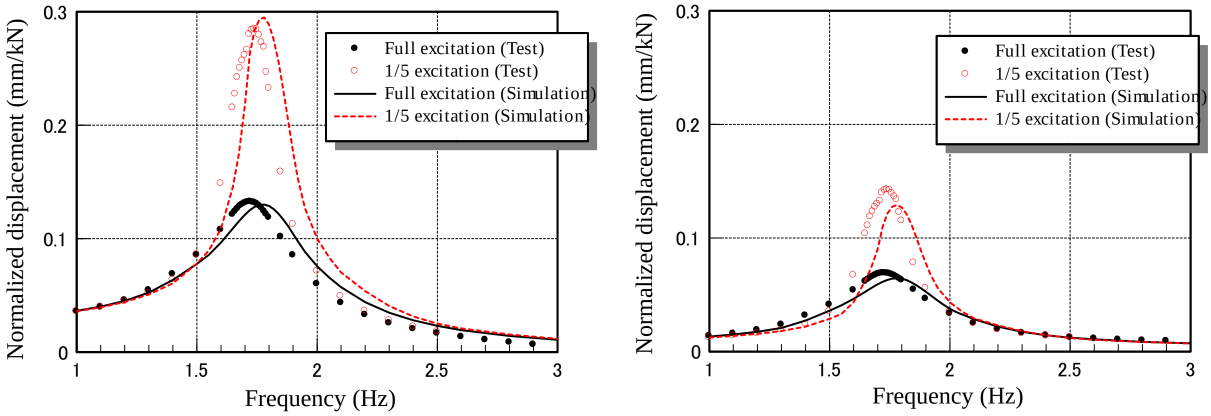


Figure 9 Force-velocity relations (L-type)

4.3. Simulation Results

Figure 10 shows the normalized displacement amplitude of the existing stack at FL+100m and 60.5m for "Full" and "1/5" excitations. The test results are also shown. The overall shape of the resonance curves including peak frequency and the height of the curves as well as the force level dependency are well simulated by the analytical model shown in the previous chapter. Table 4 compares the peak frequencies of the test and the simulation. Figure 11 shows the normalized displacement of the existing stack and the damper stroke (relative displacement between the existing stack and the supporting tower) at the peak frequencies shown in Table 4. It is confirmed that the damper stroke as well as the mode shape are well simulated for both "Full" and "1/5" excitations. As can be seen in Figure 11(b), the maximum damper stroke is only about one millimeter even for Full excitation.

Because the only nonlinearity introduced into the analytical model is a friction element of the oil damper, we can conclude that the observed force level dependency was caused by the friction of the oil damper. As can be seen in Figure 9, the damper's performance agrees well with the specification when the velocity becomes larger than that in the vibration test, which confirms the validity of the analytical model used for seismic design.

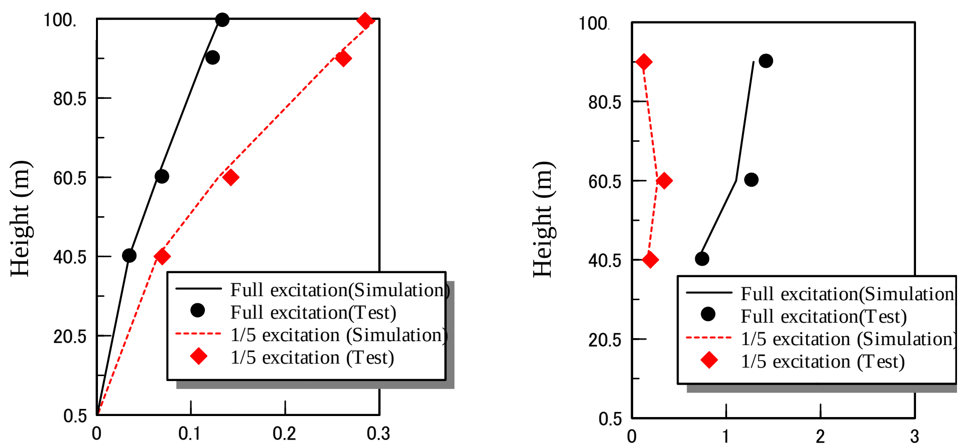


(a) FL+100m (b) FL+60.5m

Figure 10 Displacement amplitude of existing stack (simulation and test results)

Table 4 First mode peak frequency

Excitation case	Test (Hz)	Simulation (Hz)
Full	1.72	1.78
1/5	1.74	1.78



(a) Normalized displacement (mm/kN) (b) Damper stroke (mm)

Figure 11 Distribution of displacement of existing stack and damper stroke

5. CONCLUSION

This paper has presented forced vibration tests conducted on 100m-high steel stacks at Hamaoka Nuclear Power Station, whose seismic margin has been widely enhanced through an upgrading project using oil dampers. Since the original stacks were designed as free-standing without any supporting frames, a new supporting tower was constructed to surround the existing stack, and both structures were linked via oil dampers to improve structural damping as well as strength. Although the observed displacement at the top of the stack was less than about 10mm, which is much smaller than the response to the target earthquake, damping ratios of about 9% were shown by the test results. In addition, it was confirmed that the test results, including the overall shape of the resonance curves, mode shapes and damper stroke, could be well simulated by the analytical model used for seismic design by simply introducing a friction element to accurately express the oil damper's characteristics at very low velocities. The damper's performance agrees well with the specification at higher velocities, which confirms the validity of the analytical model used for seismic design.

REFERENCES

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