Forced Vibration Tests and Simulation Analyses of a PWR-Type Nuclear Reactor Building

G. Tanaka, S. Fujiwara
The Hokkaido Electric Power Co., Inc., Tokyo, Japan
S. Kawamura, M. Hisano, M. Takaki, S. Hazama, H. Ono
Taisei Corporation, Tokyo, Japan

ABSTRACT

Dynamic tests and analyses were conducted to investigate vibrational characteristics of the PWR type reactor building of Tomari Nuclear Power Plant Unit No.1 in Hokkaido, JAPAN, and to verify the adequacy of an analytical model adopted for the seismic design of this plant.

Vibrational characteristics were experimentally confirmed by forced vibration tests. The experimental results were well simulated by the lumped mass model adopted for the seismic design.

1. INTRODUCTION

Tomari Nuclear Power Plant Unit No.1 and Unit No.2 are constructed symmetrically. Each of them is pressurized water type with 2 loops of steam generators which generate 579MWe power. The Reactor building consists of an outer shield wall (O/S), an inner concrete structure (I/C) and a steel containment vessel (C/V), and is connected with adjacent enclosure building (E/B) and fuel handling building (FH/B), which are constructed on the same basemat. It is more simplified and rationalized in the layout of buildings than the conventional reactor buildings.

Therefore, to confirm the vibrational characteristics of this structure, dynamic tests and simulation analyses were performed. In this paper, the results of these tests and analyses are described.

2. OUTLINE OF BUILDING AND SITE

The Reactor building which comprises O/S, I/C and C/V, and adjoining E/B and FH/B are shown in Figure 1. O/S is reinforced concrete cylindrical wall, which is 80cm~130cm thick, 40.7m in diameter and 71.4m high. I/C consists of three walls enclosing two steam generators and pressurizer and three floors, made of reinforced concrete. The operating floor is 29m high from the bottom of basemat (EL+31.3m level). C/V, E/B and FH/B are made of steel. C/V is not connected with the floors of I/C. E/B and FH/B are connected with O/S at some floor levels. The total weight of the building is approximately 230,200 ton (including basemat weight, 101,900 tons). The basemat is 55m×74m in plan, which is placed on rock, whose shear wave velocity is about 1.4 Km/sec. The rock consists of tuff and tuff breccia.

3. VIBRATION TESTS

3.1 OUTLINE OF TESTS

The forced vibration tests were carried out in three directions applying sinusoidal excitation force by two kinds of exciters. The time was from April to May 1988, when most of the buildings, the machinery and piping system were completed, except reactor coolant pipe and steam generator supports. Exciters, of which maximum exciting forces are 10 ton and 50 ton, were set on the operating floor at EL+31.3m of I/C as shown in Figure 1. The building was excited in a frequency range of 2Hz to 8.6Hz by 50ton exciter and 3Hz to 25Hz by 10ton exciter.

Displacement was measured to obtain the following information.

(1) beam and oval mode of O/S
(2) beam mode of I/C
(3) vertical mode of O/S, I/C, E/B and FH/B
(4) cross-interaction of O/S, I/C, C/V, E/B and FH/B

Figure 2 shows the measuring points in the X direction test of O/S and I/C.

3.2 TESTS RESULTS

The results measured in O/S and I/C are mainly described in this paper. The resonance curves and phase lag curves on some levels of O/S are shown in Figure 3. The natural frequency of the O/S dominating mode is approximately 5.4Hz in X direction and 5.6Hz in Y direction. Natural frequencies of E/B and FH/B are same as O/S due to coupling. Their modal damping factors in X and Y direction, obtained by modal analyses using MDOF method, are 7.0% and 5.8% respectively. The mode shapes corresponding to the fundamental frequency are shown in figure 4. The ratios of the swaying and rocking displacement to the whole one at the top of the structure are 8.8%, 29.3% in X direction, and 7.9%, 16.3% in Y direction. The large radiation damping attributed to the soil-structure interaction can be expected, since the ratios of swaying and rocking displacement are large. The modal damping factor in Y direction is smaller than that in X direction due to the small contribution of the radiation damping.

The natural frequencies of the I/C dominating mode in X and Y direction are 11.9Hz and 12.9Hz respectively, as shown in Figure 5. Their modal damping factors are 4.6% and 2.9%. The ratios of the swaying and rocking displacement to the whole one at the operating floor of I/C are 4.1% and 8.4% in X direction, and 1.7% and 15.2% in Y direction. The radiation damping of soil-structure interaction can be hardly expected due to the small ratios of the swaying and rocking displacements, especially that of swaying displacement. Therefore it seems that the modal damping factors of I/C dominating mode is quite similar to that of the reinforced concrete structure itself. The repulsive mode among steam generator walls is obtained at 21.9Hz in Y direction.

The impedance functions and damping factors calculated by inertial force of the reactor building and soil deformations are shown in Figures 6 and 7. The impedance functions and damping factors obtained by tests are well coincident with theoretical results by half-space model. However, in details, test results decrease harder than theoretical results in real part of horizontal component.

4. SIMULATION ANALYSES

4.1 ANALYTICAL MODEL

Simulation analyses were performed by a lumped mass model as shown in Figure 8. This model is almost same as the analytical model adopted for the seismic design. However the model was modified regarding 5 items as indicated below, considering the difference of deformation level in tests and design and the difference of state during test and operation.

(1) Young's modulus of the concrete was decided as 340 ton/cm^2 based on the test results of the concrete test pieces taken during the construction. This Young's modulus used in analyses was 1.05 times the experimental value, since Young's modulus at small strain level and that obtained by dynamic loading test are generally somewhat larger than the usual secant modulus of elasticity.
(2) Stiffness of thin walls ignored in the seismic design was considered.
(3) Polar crane was modeled independently, connected with C/V by a spring, taking the clearance between Polar crane and C/V into consideration in the case of tiny deformation level.
(4) The weights of reactor coolant pipe, steam generator and tank were corrected, considering the machinery and piping not set up and less

volume of water at testing.

(5) Stiffness of steam generator supports was modified so that the fundamental frequency of S/G analytical model showed good coincidence with test results.

4.2 ANALYTICAL RESULTS

Fundamental frequencies of O/S and I/C obtained by analyses are compared with test results as shown in Table 1. The analytical results indicate good agreement with the test results in both X and Y directions.

Table 2 shows the modal damping factors corresponding to the O/S and I/C dominating mode comparing the analytical and experimental results . In these simulation analyses, the damping factor of 3.5% was used for reinforced concrete. The damping factors of I/C dominating mode obtained by tests were corrected so that the test results could be well simulated. This damping factor was adjusted to those of another reactor buildings. Another damping factors for steel and soil were same as the seismic design value. Analytical modal damping factors are somewhat smaller than test results in X direction and larger in Y direction.

The resonance curves and phase lag curves obtained at top dome of O/S and the operating floor of I/C are shown in Figures 9 and 10. The analytical results well coincide with experimental results. Especially, the resonance curves O/S obtained by analyses well simulate those of tests in detail. The phase lag curves of O/S and I/C calculated by analyses are in accord with test results up to 14Hz, but the differences between both results gradually increase in high frequency range above 14Hz.

5. CONCLUSION

Vibrational characteristics of a Nuclear Power Building were experimentally confirmed by forced vibration tests. The fundamental frequency of the O/S dominating mode is approximately 5.4Hz in X direction and 5.6Hz in Y direction. Their modal damping factors are estimated 7.0% and 5.8% respectively. The fundamental frequency and modal damping factor of I/C are 11.9Hz and 4.6% in X direction, and 12.9Hz and 2.9% in Y direction respectively.

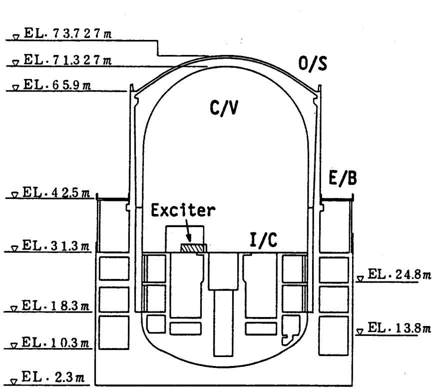
These experimental results were well simulated by the lumped mass model adopted for the seismic design. The natural frequencies of O/S and I/C calculated by analyses are 5.2Hz and 11.8Hz in X direction, and 5.5Hz and 13.0Hz in Y direction respectively. These frequencies indicate good agreement with those observed by tests. With the assumption that the damping factor of reinforced concrete is 3.5%, the modal damping factors estimated by analyses well coincide with experimental results.

Table 1 Comparison of Natural Frequencies between Experiment and Analysis

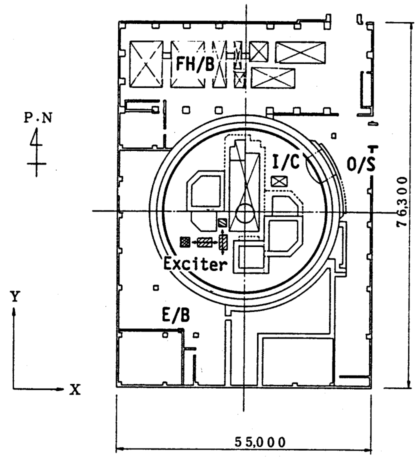
Direction	Part	Experiment (Hz)	Analysis (Hz)
X	O/S	5.36	5.21
	I/C	11.90	11.84
Y	O/S	5.63	5.52
	I/C	12.91	13.03

Table 2 Comparison of Modal Damping Factors between Experiment and Analysis

Direction	Part	Experiment (%)	Analysis (%)
X	O/S	7.0	6.3
	I/C	4.6	4.3
Y	O/S	5.8	7.5
	I/C	2.9	4.2

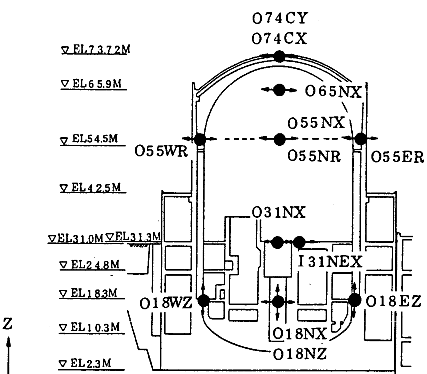


A-A Section

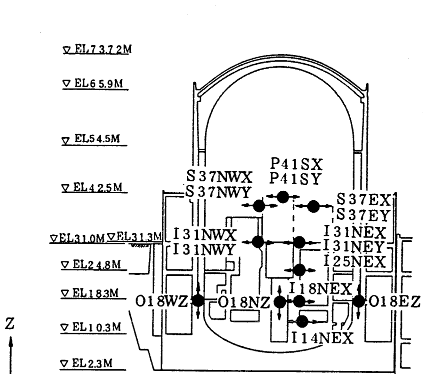


Plan at EL+31.3m

Figure 1 Outline of the Reactor Building

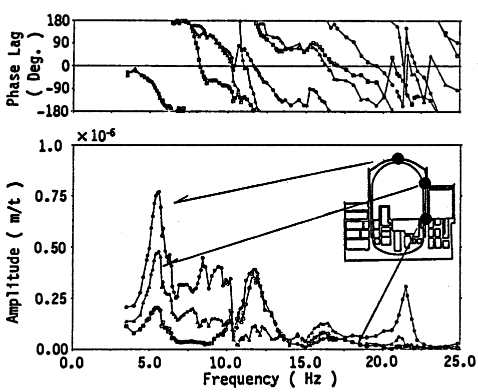


Case of O/S Measurement in X Direction

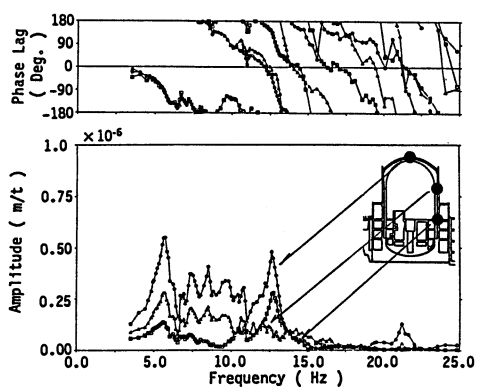


Case of I/C Measurement in X Direction

Figure 2 Example of Sensor Installation

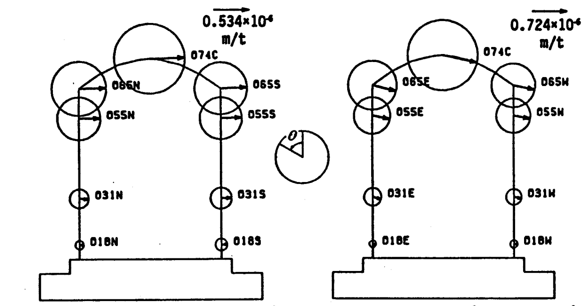


X Direction



Y Direction

Figure 3 Resonance Curve (O/S)



X Direction (5.4Hz)   Y Direction (5.6Hz)

Figure 4 Mode Shape

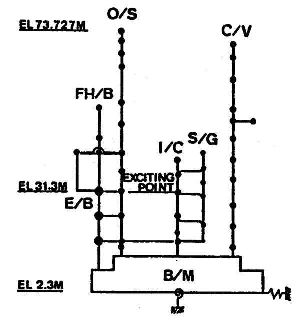
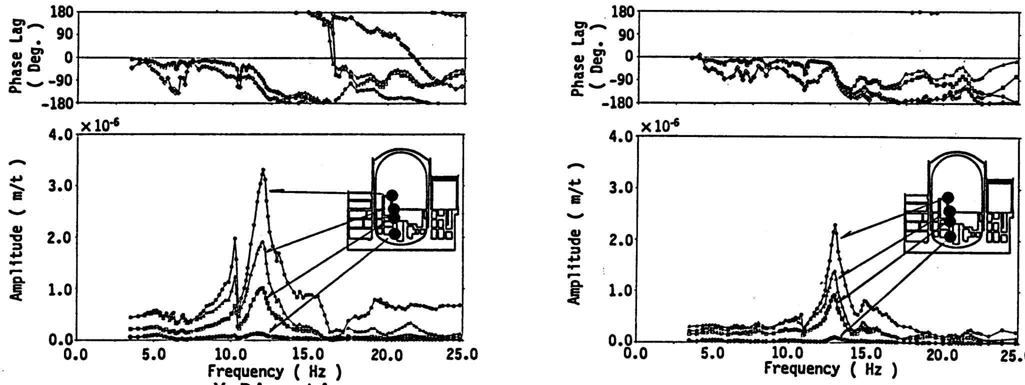
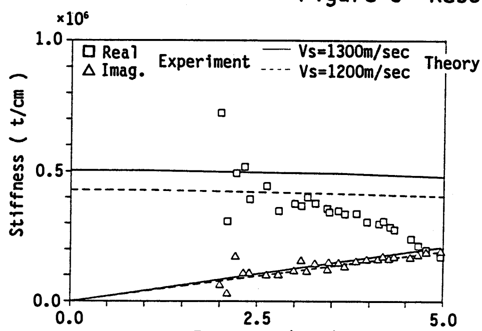


Figure 8 Analytical Model

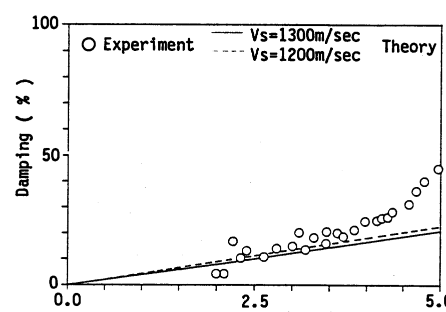


X Direction   Y Direction

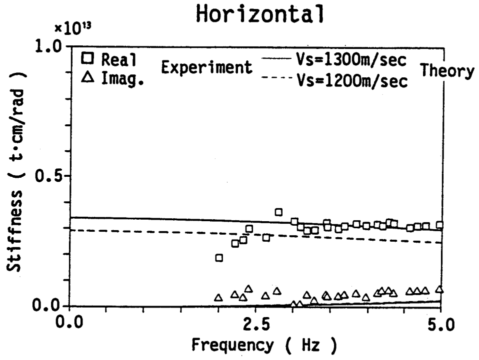
Figure 5 Resonance Curve (I/C)



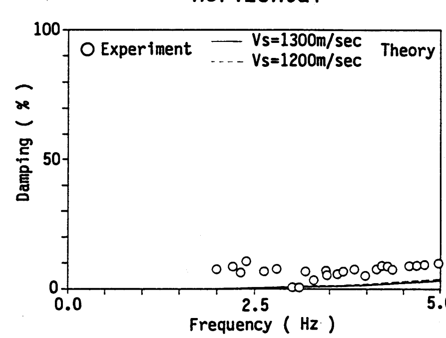
Horizontal



Horizontal



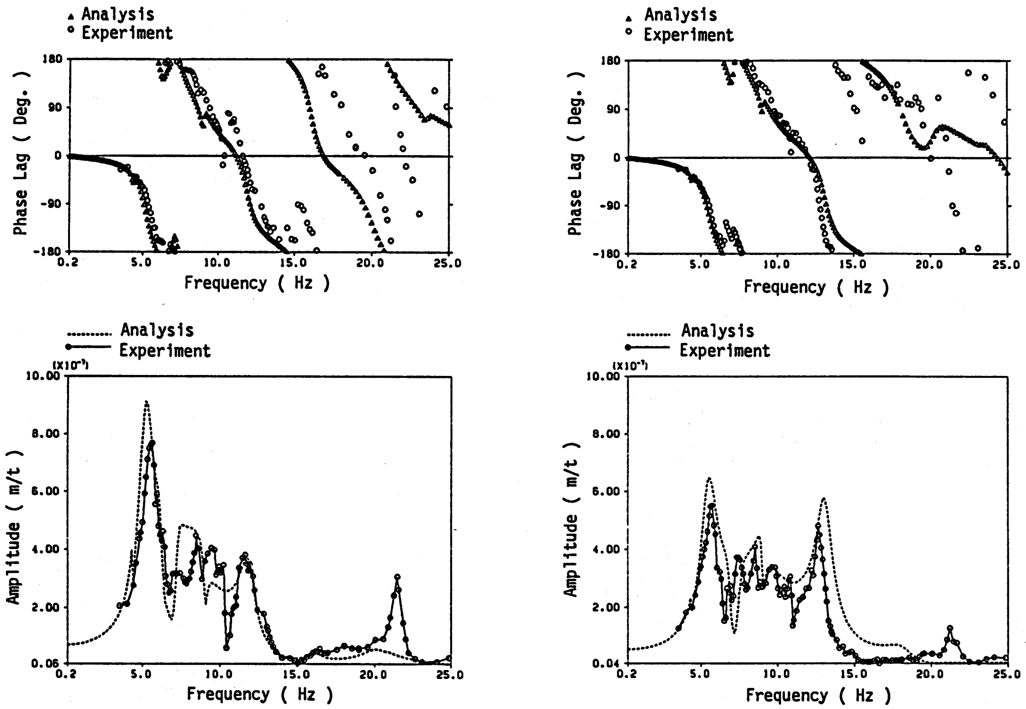
Rotational



Rotational

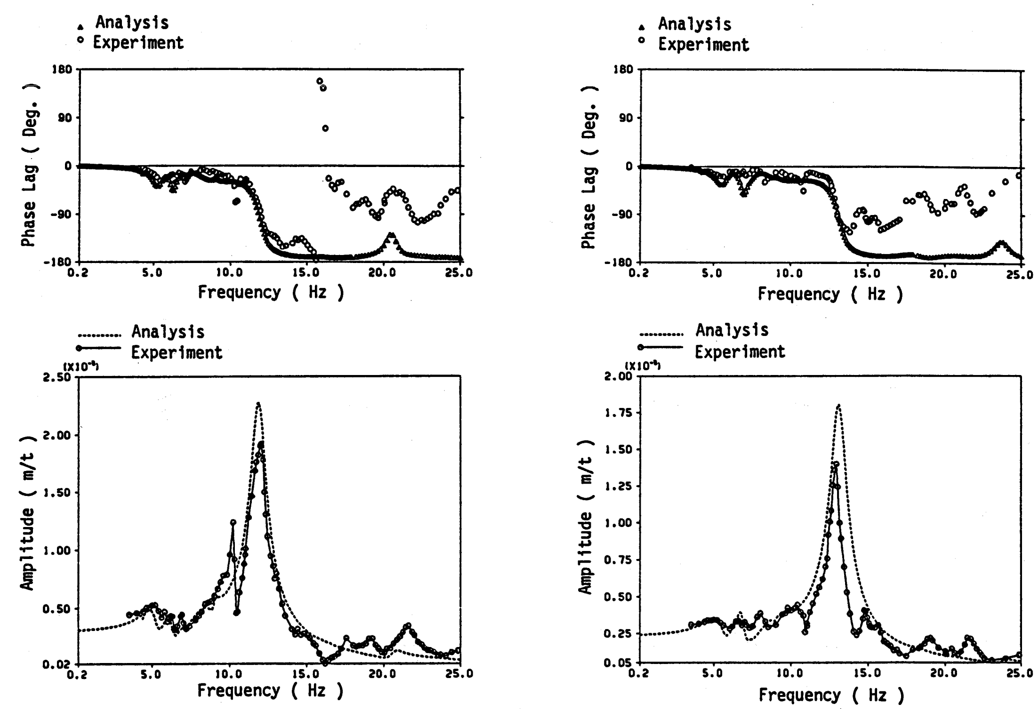
Figure 6 Impedance Function
(X Direction)

Figure 7 Damping Factor
(X Direction)



X Direction Y Direction

Figure 9 Comparison of Resonance Curve between Experiment and Analysis (O/S)



X Direction Y Direction

Figure 10 Comparison of Resonance Curve between Experiment and Analysis (I/C)