Investigation of the dynamic characteristic similarity of the experimental reactor for comprehensive vibration assessment program (CVAP)

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1. Introduction

The comprehensive vibration assessment program (CVAP) is a specialized experimental facility designed to investigate the dynamic behavior of structures subjected to vibrational loading. It was proposed by the U.S. Nuclear Regulatory Commission (NRC) as a standardized approach to evaluating flow-induced vibration in nuclear reactor components. The CVAP framework is conducted by Regulatory Guide 1.20, which outlines the necessary procedures for assessing structural responses under vibrational conditions [1]. By providing an assessment testing environment, CVAP enables researchers to accurately measure key dynamic characteristics such as natural frequencies, mode shapes, and damping properties, ensuring a comprehensive understanding of structural behavior.

Various tests are performed in CVAP, including modal analysis, harmonic excitation tests, and vibration fatigue assessments, to evaluate structural integrity and dynamic stability. A critical aspect of CVAP testing is ensuring that the natural frequency of the experimental setup closely matches that of the actual reactor system. This similarity is crucial because discrepancies between the test facility and the real structure could lead to inaccurate predictions of resonance effects, structural reliability, and operational performance. Since the natural frequency significantly influences vibration characteristics and structural behavior, ensuring similarity between the experimental facility and the real reactor is essential for validating numerical models and predicting real-world vibrational responses. In this study, we investigated the natural frequency of the experimental reactor model and then assessed whether the results aligned with the designed similarity law.

2. Materials and Methods

This study investigated the natural frequencies of the experimental reactor model designed with 1/5 scale of the actual one. The experimental facilities are designed based on the actual nuclear reactors. However, the designs are necessarily modified to install devices required for experiments, such as sensors. While the actual one consists of one part, the experimental reactor model is designed to be separated into three parts to insert various sensors at the exact locations, and they were assembled with flanges (Fig. 1). While carbon steel is used for the actual reactor, stainless steel is used for the experimental model because of the difference in the manufacturing method.

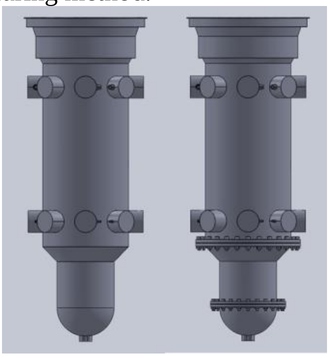

Fig. 1 The geometries of the actual (left) and experimental (right) models of the reactors.

Table 1. Material properties for the actual and experimental reactor models

	Actual model	Experimental model
Material	Carbon steel	SUS304
Density	7.87 g/cc	8.0 g/cc
Elastic modulus	200 GPa	193 GPa
Poisson's ratio	0.29	0.29

The similarity between the actual reactor and the experimental model for CVAP is calculated based on the theoretical natural frequency, assuming that the experimental model has the same shape as the actual reactor.

$$k_1 = \frac{A_1 E_1}{L_1}$$

$$m_1 = \rho_1 \cdot V_1$$

$$\omega_1 = \sqrt{\frac{k_1}{m_1}} = \sqrt{\frac{A_1 E_1}{L_1} \cdot \frac{1}{\rho_1 \cdot V_1}}$$

$$k_2 = \frac{A_2 E_2}{L_2} = \frac{(\lambda_S^2 \cdot A_1) \cdot (\lambda_E \cdot E_1)}{\lambda_S \cdot L_1} = (\lambda_S \cdot \lambda_E) \cdot k_1$$

$$m_2 = \rho_2 \cdot V_2 = (\lambda_\rho \cdot \rho_1) \cdot (\lambda_S^3 \cdot V_1) = (\lambda_\rho \cdot \lambda_S^3) \cdot m_1$$

$$\omega_2 = \sqrt{\frac{k_2}{m_2}} = \sqrt{\frac{(\lambda_S \cdot \lambda_E) \cdot k_1}{(\lambda_\rho \cdot \lambda_S^3) \cdot m_1}} = \frac{1}{\lambda_S} \cdot \sqrt{\frac{\lambda_E}{\lambda_\rho}} \cdot \omega_1$$

where k_1, A_1, E_1, L_1, ρ_1, V_1, m_1, and ω_1 are stiffness, cross-sectional area, elastic modulus, length, volume, mass, and angular velocity of the original model, respectively. k_2, A_2, E_2, L_2, ρ_2, V_2, m_2, and ω_2 are are for those for the scaled model. λs, $\lambda \rho$, and λ_E are the ratios of the size, density, and elastic modules between two models.

Because of the additional flanges, the natural frequencies of the experimental model could not align with the similarity law. Finite element models for the actual reactor and experimental one were developed using bilinear tetrahedral elements. To investigate the dynamic characteristics of the reactor body, the cylindrical body was left, and all others, including lugs, were neglected. Material properties of carbon steel and SUS304 were applied for the actual and experimental models, respectively. The modal analyses were conducted using a commercial finite element analysis software, Abaqus Standard ver. 2022.

3. Results

Based on the equations, the natural frequencies of the experimental model for CVAP should be 4.87 times greater than the actual one's natural frequencies.

The predicted natural frequencies from the first to the fifth eigenmodes in the actual model were 31.2 Hz, 31.3 Hz, 43.5 Hz, 43.6 Hz, and 48.3 Hz, respectively. In the experimental model, they were 153.1 Hz, 153.6 Hz, 213.4 Hz, 213.5 Hz, and 226.6 Hz, respectively. Thus, the ratios of the natural frequencies between the two models were 4.90, 4.91, 4.90, 4.90, and 4.69 in the first five eigenmodes. The shapes in the 2nd and 4th eigenmodes are identical to the first and third, respectively (Fig. 2).

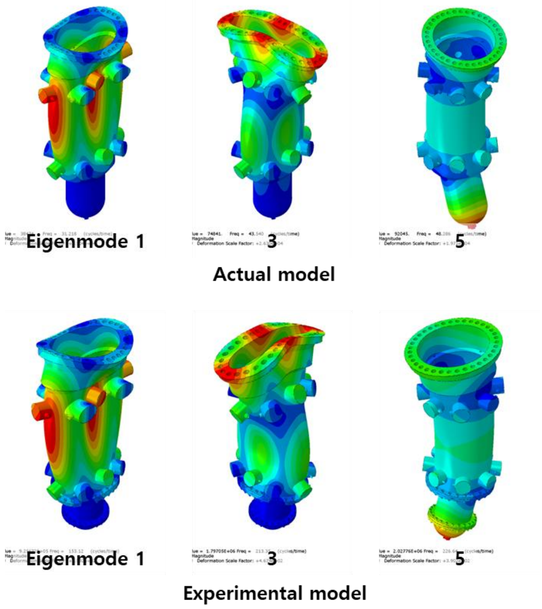

Fig. 2 The first five eigenmode shapes of the actual and experimental models of the reactor.

Table 2. The predicted natural frequencies from the first to the 5th eigenmodes.

Eigne mode	Actual model (A)	Experimental model (B)	Ratio (B)/(A)
1	31.2	153.1	4.90
2	31.3	153.6	4.91
3	43.5	213.4	4.90
4	43.6	213.5	4.90
5	48.3	226.6	4.69

4. Discussion and Conclusion

This study investigated the similarity of the dynamic characteristics between the actual and experimental reactor models. Even though the experimental model has the flanges to install the experimental devices, the effects of the flanges on the dynamic characteristics were neglectable, and the natural frequencies of the experimental model showed good agreement with the theoretical calculations. Therefore, the authors believe the design of the experimental reactor model reflects its design intent well.

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[1] U.S. NRC, Regulatory Guide 1.20, 2017, Comprehensive Vibration Assessment Program for Reactor Internals during Preoperational and Startup Testing, Regulatory Guide 1.20(Rev.4), Washington, D.C