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Fluid-Induced Vibration Analysis for Reactor Internals Using Computational FSI Method

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1. Introduction

Reactor coolant flow makes Reactor Vessel Internals (RVI) vibrate and may affect the structural integrity of them. U.S. NRC Regulatory Guide 1.20[1] requires the Comprehensive Vibration Assessment Program (CVAP) to verify the structural integrity of the RVI for Fluid-Induced Vibration (FIV). The hydraulic forces on the RVI of OPR1000 and APR1400 were computed from the hydraulic formulas and the CVAP measurements in Palo Verde Unit 1[2] and Yonggwang Unit 4 for the structural vibration analyses. In this method, the hydraulic forces were divided into deterministic and random turbulence loads and were used for the excitation forces of the separate structural analyses. These forces are applied to the finite element model and the responses to them were combined into the resultant stresses. This paper introduces a fluid-induced vibration analysis method which calculates the response of the RVI to both deterministic and random loads at once and utilizes more realistic pressure distribution using the computational Fluid Structure Interaction (FSI) method.

2. Methods and Results

Since the measured displacements of the RVI were less than 1mm, the flow section and path are not changed due to the flow-induced vibration. Therefore, one way FSI method is used for this study. For this method, a fluid analysis is carried out first and then a structural analysis is performed using the force from the fluid analysis result.

The 1/2 symmetric RVI model, which has one outlet nozzle and two inlet nozzles, is developed to account for the dynamic characteristics of the RVI. The analysis condition for this study is set to be under 4 pump pre-core and uniform temperature conditions.

To simplify the model, the fluid analysis model has only the main flow region excluding the bypass flow region. The bypass flow is less than 5% of the entire flow so that it doesn't give a large influence on the flow in the Reactor Vessel (RV). The geometries in the bypass flow region are very complicated and have many small geometric features. These complicated geometries make the fluid analysis more difficult because they require many small elements which make it harder to get the solution. Though the fluid analysis model excludes the bypass flow region, the structural analysis model contains the entire fluid region inside RV below RV flange. The procedure of fluid-induced vibration analysis for RVI is shown in Fig. 1.

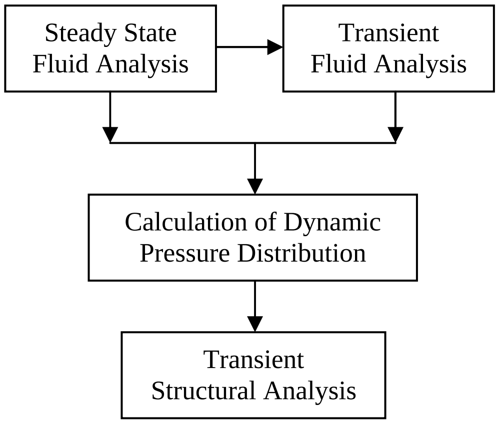

Fig. 1. FIV Analysis Procedure for RVI

2.1 Fluid Analysis

The Computational Fluid Dynamic (CFD) analysis in this paper uses the method that can calculate all hydraulic forces of the RVI at once. The hydraulic static load is calculated from the steady state fluid analysis. The periodic pressure wave is simulated with the combination of forcing functions from the transient fluid analysis. The random pressure in the RV is generated by the CFD methodology.

The time history transient fluid analysis is done with the initial steady-state flow distribution and transient forcing function. This paper uses the forcing function derived by a time history method to simulate Reactor Coolant Pump (RCP) pulsation. The forcing function at RCP discharge nozzles is derived with the operating pressure and pressure pulsation at each forcing frequency as Eq. (1).

$$P_{tot}(t) = P_o + \sum_{n=1}^{m} P_n(t) \qquad (1)$$

where,
$P_{tot}(t)$: total forcing pressure
P_o : static pressure
t : time
$P_n(t)$: periodic forcing pressure
$= A_n \times \sin(\omega_n \cdot t - \theta_n)$
n : type number of force

m : total number of force
A_n : amplitude
ω_n : frequency
θ_n : angle

The computer program STAR-CCM+[3] is used for the fluid transient analysis to get flow and pressure distributions. Fig. 2 shows the pressure distribution at outlet and lower plenums from the transient fluid analysis.

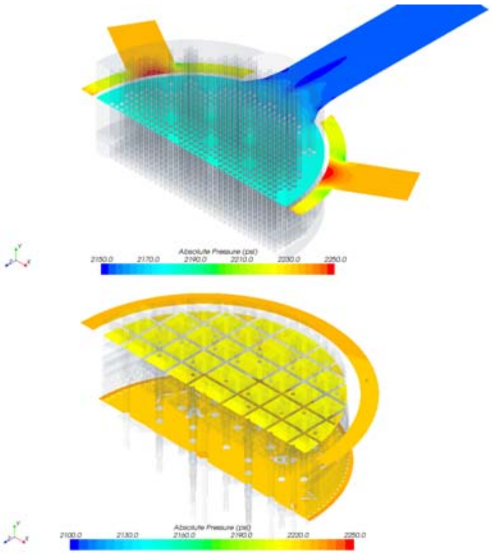

Fig. 2. Pressure Distribution

2.2 Structural Analysis

The conventional structural analysis method uses the harmonic analysis for deterministic loads and the spectrum analysis for random turbulence loads for each component. Then the responses from two dynamic analyses are combined into the resultant stresses.

This paper uses a new method which integrates all hydraulic loads, including deterministic and random turbulence loads. The structural analyses apply the time history of pressure distributions to the surface of the RVI directly with one way FSI, while the conventional method applies loads with the conservative method to the surface of the structures. The structural analysis considering FSI can get more detailed responses by using 3-dimensional solid model and fluid elements in the finite element model. The structural analysis considering FSI also uses the entire RVI, not separate components. It makes the boundary conditions more realistic and makes the analyses for all components integrative.

The dynamic structural analysis is performed using the dynamic loads from the fluid analysis results. The dynamic loads are calculated by subtracting the initial pressure distribution from the transient pressure distribution at each time step. These pressure distributions are applied to the surface of the RVI directly with one way FSI.

The computer program used to perform the structural analysis is ANSYS[4]. The stress level from the structural analysis as shown in Fig. 3 is similar to the measured data of CVAP[2].

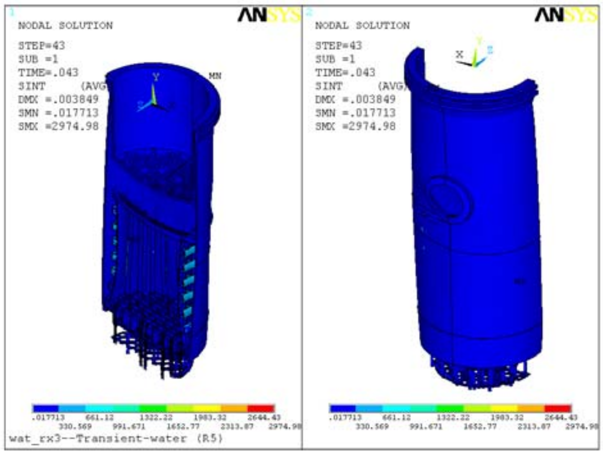

Fig. 3. Stress Intensity

3. Conclusions

As addressed above, the FIV analysis for the RVI was carried out using the computational FSI method. This method calculates the response to deterministic and random turbulence loads at once. This method is also a simple and integrative method to get structural dynamic responses of reactor internals to various flow-induced loads. Because the analysis of this paper omitted the bypass flow region and Inner Barrel Assembly (IBA) due to the limitation of computer resources, it is necessary to find an effective way to consider all regions in the RV for the FIV analysis in the future.

REFERENCES

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[4] User's Manual for ANSYS 14.0, ANSYS Inc.