

Structural Analysis of Reactor Vessel Internals under Random Hydraulic Loads with Fluid–Structure Interaction

Chiwoong Ra^a, Hyungyu Roh^a, and No-cheol Park^{a*}

^aDepartment of Mechanical Engineering, Yonsei Univ., 50, Yonsei-ro, Seoul, 03722, Republic of Korea

*Corresponding author: pnch@yonsei.ac.kr

***Keywords :** Fluid-induced vibration, Reactor vessel internals, Turbulent buffeting, Random vibration

1. Introduction

Reactor vessel internals (RVIs) are continuously exposed to hydraulic excitations generated by turbulent coolant flows, making their structural integrity a critical safety consideration for nuclear power plants. Although numerous studies have examined fluid-induced excitations, the geometric complexity of RVIs and the high computational cost of fully coupled fluid–structure interaction (FSI) analyses remain significant challenges [1].

Most previous research has focused on individual internal components [2,3] rather than the entire integrated assembly [4]. While such component-level studies provide insights into local responses, they may fail to capture the coupled dynamic behavior of the overall RVI system under turbulent hydraulic loads. Consequently, these approaches have limitations when evaluating system-level integrity, particularly when spatial correlations and stochastic characteristics of coolant-induced loads are significant.

To overcome these challenges, the present study proposes an alternative methodology that balances computational efficiency with physical fidelity. Specifically, power spectral density (PSD)-based hydraulic load analyses derived from integrated FSI models are compared with structural responses from previous studies in which coolant effects were represented qualitatively. This comparison aims to evaluate the adequacy of earlier approaches and provide a more robust framework for assessing stochastic responses of RVIs under turbulent buffeting.

2. Methods

2.1 Analysis Procedure

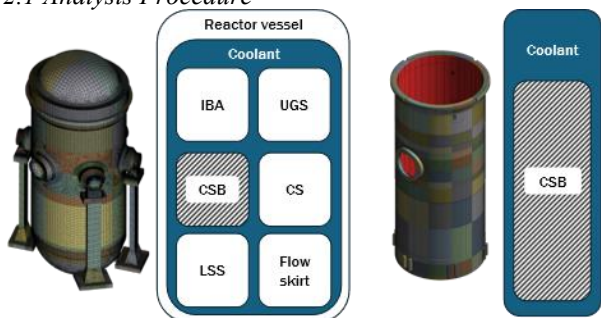


Fig. 1. Schematic of finite element models for reactor vessel assembly(left) and a single core barrel support(right).

Analyses were conducted using ANSYS Mechanical version 19.2 and two types of structural models were employed, as illustrated in Figure 1.

Integrated RVI model (Model 1, left in Figure 1): This model includes all reactor vessel internals (RVIs) and surrounding coolant. It allows direct incorporation of fluid–structure interaction (FSI) effects but can impose substantial computational demands as geometric complexity increases.

Single CSB model (Model 2, right in Figure 1): This model focuses solely on the Core Support Barrel (CSB) with surrounding coolant. While it cannot fully capture the fluid effects as accurately as the integrated model, it allows highly detailed representation of the CSB geometry and local structural features. In this model, coolant effects are represented qualitatively.

2.2 Fluid–Structure Interaction Considerations and hydraulic Load Application for Random Vibrations

Finite element (FE) models were constructed using acoustic elements for the fluid domain and solid elements for structural components. The fluid domain represented light water at the operating temperature. Fluid–structure interfaces were defined to enforce equilibrium of normal direction loads and displacements. Modal analysis and PSD analysis were performed on both models: the integrated RVI assembly and the single CSB model.

Turbulent buffeting loads were applied as PSD-based random excitations. Spatial correlation of loads was explicitly considered. In this study, fully correlated conditions were assumed for all points to evaluate the maximum potential structural response, providing a conservative assessment compared with simplified global analyses. Turbulent buffeting loads were applied as power spectral density PSD-based random excitations. Spatial correlation of loads was explicitly considered, with fully correlated conditions assumed for all points to evaluate the maximum potential structural response.

3. Results and Conclusions

For the CSB, fluid-structure integrated model analyses predicted a maximum stress of approximately 9.6 MPa. Analyses with fully correlated loading with only CSB model increased the predicted maximum

stress to 13 MPa, an amplification of nearly 45%. This stress amplification results from localized stress concentrations at the nozzle vessel regions near the Control Element Assemblies(CEA) guide tubes. Both the integrated and individual CSB models identify the same vulnerable locations, indicating that the observed maximum stresses are primarily dictated by the modal behavior of the CSB in these specific nozzle areas. The analyses highlight that these nozzle regions near the CEA guide tubes represent the most critical locations for structural integrity under turbulent buffeting. The observed amplification is a direct consequence of modal-induced load alignment rather than interactions with other RVI components, emphasizing that the CSB's local geometry and modal characteristics dominate its response under fully correlated excitation.

This study establishes a practical and conservative methodology for evaluating the response of RVIs, with a focus on the CSB, under turbulent buffeting loads. Analyses incorporating full FSI effects were compared with those using PSD-based loads with considered spatial correlations. Both approaches identified the same critical stress locations at the nozzle regions near the CEA guide tubes and yielded comparable maximum stress magnitudes. Fully correlated loading conditions provide a conservative bounding scenario, ensuring that structural vulnerabilities are not underestimated. Overall, the methodology captures the significant stress amplification in the CSB due to correlated turbulent loads while offering a computationally efficient alternative to direct FSI simulations.

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