# Methodologies of Added Mass Consideration in Fluid–Structure Interaction and Its Influence on Reactor Vessel Internal Dynamics

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## 1. Introduction

The accurate identification of dynamic characteristics for reactor vessel internals (RVIs) is of paramount importance to ensure the structural integrity and operational safety of nuclear power plants under various loading conditions, including seismic events and flow-induced vibrations. A key challenge lies in properly accounting for the significant changes in dynamic properties caused by the surrounding coolant. Previous studies have commonly assumed rigid-body behavior of the structural components and approximated the coolant effect by applying a representative added-mass value calculated independently as an external force term based on simplified potential-flow theory [1,2]. Although this approach is computationally efficient, it becomes highly limited when applied to RVIs, which consist of multiple concentric cylindrical structures with narrow annular gaps. In such geometries, the added-mass coefficient increases exponentially as the gap size decreases, resulting in substantial underestimation of natural frequencies and stress predictions [3].

To overcome these limitations, the present study proposes a three-dimensional modeling approach that directly computes the hydrodynamic pressure field using acoustic fluid elements [4]. Because all RVI components are fully immersed in coolant on both inner and outer surfaces, the proposed model incorporates the flexible behavior of every internal structure through an integrated fluid-structure interaction (FSI) analysis that includes the reactor pressure vessel (RPV) and the entire coolant domain.

In this research, recognizing the high computational cost associated with full integrated models, we considered an efficient methodology that can achieve comparable accuracy even when analyzing a single internal structure. Such a streamlined approach can be readily considered for structural integrity evaluations, including the Comprehensive Vibration Assessment Program (CVAP).

## 2. Methodologies

### *2.1 Patch Test Validation of Fluid Structure Interaction Modeling Assumptions*

**Table 1.** Natural frequencies [Hz] of each analysis cases

| Mode shape \ Patch test | | (1) | (2) | (3) |
|---|---|---|---|---|
| Inner cylinder | (2,0) | 0.5874 | 0.5984 (+1.873%) | |
| | (3,0) | 2.327 | 2.368 (+1.762%) | |
| | (4,0) | 5.741 | 5.835 (+1.637%) | |
| Outer cylinder | (2,0) | 8.984 | | 2.916 (-67.54%) |
| | (3,0) | 25.44 | | 11.24 (-55.82%) |
| | (4,0) | 49.00 | | 26.78 (-45.35%) |

*Note : The notation (m,n) indicates the number of circumferential and axial nodal lines*

A patch test was performed on a narrow annular gap representative of the core support barrel (CSB) to RPV geometry. The inner radius is 1.989 m, the outer radius is 1.994 m, and the height is 3.069 m. Three patch test cases were examined using acoustic fluid elements for the gap coolant. The examined cases were: (1) both cylinders flexible (reference), (2) flexible inner and rigid outer cylinders, and (3) rigid inner and flexible outer cylinders. The modal analysis results are summarized in Table 1.

When the inner cylinder was modeled as flexible and the outer cylinder as rigid (case 2), the natural frequencies of the inner cylinder are within 2% compared with the fully flexible case (case 1) across all dominant modes. These results confirm that treating only the internal structure as flexible while assuming the external structure as rigid produces natural frequencies that are nearly identical to those of the fully flexible reference case. Therefore, structures located internally with respect to the gap fluid must be modeled with flexible behavior, whereas the flexibility of the outer structure has negligible influence on the dynamic characteristics of the inner structure for the present geometry and modeling conditions.

### *2.2. Construction of the CSB Analysis Model*

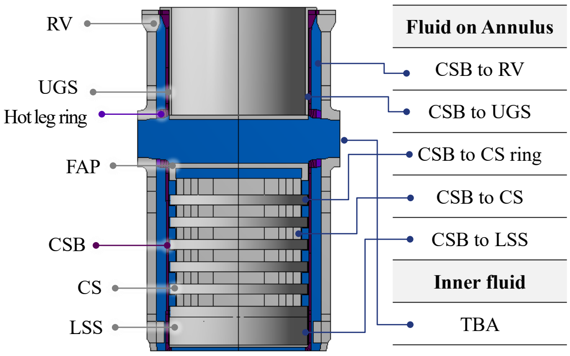


**Figure 1.** Schematics of analysis model for CSB

Based on the findings from the patch test, a modeling strategy was established to efficiently represent fluid–structure interaction effects while minimizing computational cost. The analysis methodology proposed

following key concepts:

- Only the surrounding coolant domain that directly encloses the target internal structure is included in the model. The structural components in direct contact with this coolant are also incorporated. These components are either the internal structures themselves or the reactor pressure vessel.
- The structures are modeled under both flexible-body or rigid-body assumptions. Their results are then compared with the full integrated analysis model that includes all RVIs, the RPV, and the entire coolant domain. In this way, consistency is verified.

For example, the analysis model for the CSB can be constructed as illustrated in Figure 1. The coolant regions in contact with both the inner and outer surfaces of the CSB correspond to the blue-colored domains in Figure 1. In addition to these coolant regions, a total of six structural components that influence the pressure field in the coolant are incorporated into the analysis model.

## 3. Results and Conclusions

The mode shapes of the CSB obtained using the proposed method were consistent with those from the fully integrated model. The corresponding natural frequency was predicted to be 24.94 Hz, compared to 26.08 Hz from the fully integrated model, showing good agreement within 4.4%. This result confirms the validity of the proposed methodology for predicting the dynamic characteristics of a single RVI component.

The main conclusions of this study are summarized as follows:

- An efficient analysis methodology was established to evaluate the dynamic characteristics of a single reactor vessel internal (RVI) while accurately reflecting the coupled fluid–structure interaction behavior of the fully integrated system. The proposed approach enables accurate representation of added-mass effects without explicitly modeling all internal structures and the entire coolant domain.
- Through patch test analysis of a representative narrow annular gap configuration, it was confirmed that the flexible-body behavior of structures located internally with respect to the coolant domain should be properly considered to accurately capture the hydrodynamic coupling effect. This result provides a physically justified modeling basis for the proposed methodology.
- The application of the proposed methodology to the CSB demonstrated excellent agreement in both mode shape and natural frequency compared to the fully integrated model. In particular, the natural frequencies corresponding to the matched mode shapes showed high consistency, confirming that the proposed approach accurately reproduces the dynamic characteristics of the full system.

## REFERENCES

[1] American Society of Mechanical Engineers. (2010). ASME boiler and pressure vessel code, Section III, Division 1 – Rules for construction of nuclear facility components, Nonmandatory Appendix N: Dynamic analysis methods. ASME.

[2] Fritz, R. J. (1972). The effect of liquids on the dynamic motions of immersed solids. *Journal of Manufacturing Science and Engineering*, *94*(1), 167–173.

[3] Je, S. Y., Chang, Y. S., & Kang, S. S. (2017). Dynamic characteristics assessment of reactor vessel internals with fluid-structure interaction. *Nuclear Engineering and Technology*, *49*(7), 1513-1523.

[4] Park, J. B., Choi, Y., Lee, S. J., Park, N. C., Park, K. S., Park, Y. P., & Park, C. I. (2014). Modal characteristic analysis of the APR1400 nuclear reactor internals for seismic analysis. *Nuclear Engineering and Technology*, *46*(5), 689-698.