

A Structural Analysis Methodology for Reactor Vessel Internals under Flow-Induced Vibration Considering Spatial Partial Correlation

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1. Introduction

Reactor vessel internals (RVIs) are exposed to a severe environment of high-temperature and high-pressure coolant flow. Flow-induced vibration (FIV) caused by high-speed coolant is a critical factor that can lead to fatigue failure and wear of the structures. Therefore, a Comprehensive Vibration Assessment Program (CVAP) is essential at the design stage to accurately predict the dynamic characteristics and responses of the internal structures throughout the design life of the nuclear power plant [1].

In conventional APRI400 CVAP analyses, the fluid-structure interaction has been simplified by applying an equivalent added mass, calculated from representative mass values to the structural wall surfaces [2,3]. However, such simplified models introduce significant errors in the prediction of natural frequencies and damping characteristics of the structures. In particular, they fail to adequately capture the complex coupling effects between the coolant and the reactor vessel, necessitating a more precise integrated analysis that includes the coolant flow characteristics and the vessel itself [4].

Moreover, in the process of defining CVAP loads, turbulent pressure is converted into equivalent loads. Although a partially correlated model is employed to reflect the spatial correlation of the loads, the correlation area is typically determined using representative characteristic lengths such as the inner and outer diameters of the vessel. This approach has limitations in accurately reflecting the local pressure fluctuation characteristics acting on complex geometries. Consequently, to precisely evaluate the influence of the spatial distribution of loads on structural responses, it is necessary to establish correlation relationships based on actual geometric positions rather than simplified characteristic lengths [5].

2. Research Objectives and Methodology

The objective of this study is to establish a structural analysis methodology for RVIs under turbulent flow-induced dynamic loads that directly utilizes pressure power spectral density (PSD) data while precisely reflecting spatial partial correlation based on actual geometry. The research procedure consists of two main parts: (1) construction and verification of a partially

correlated structural analysis methodology through patch tests, and (2) derivation of RVIs responses considering center-to-center distances of load application areas.

2.1. Theoretical background of spatial correlation

In the modal superposition-based PSD analysis, the cross-modal correlation is expressed by the product of conjugate transfer functions. The spatial correlation of input loads is defined by an exponential decay function of the correlation length with respect to the distance between load application locations. When the number of divided areas is r , the load matrix becomes an $r \times r$ matrix. The correlation coefficient between each area is given by an exponential function of the ratio of the center-to-center distance to the correlation length [5].

Because the built-in command in ANSYS is limited to a matrix size of 200×200 , a more scalable approach based on LU decomposition was developed (where U is the transpose of L in the symmetric case). By decomposing the correlation matrix into a lower-triangular matrix L and an upper-triangular matrix U , the partially correlated response can be obtained by superposing independent (uncorrelated) responses of the column vectors of the decomposed matrix. This formulation yields responses identical to those of the original partially correlated load matrix while remaining applicable to a large number of loadings.

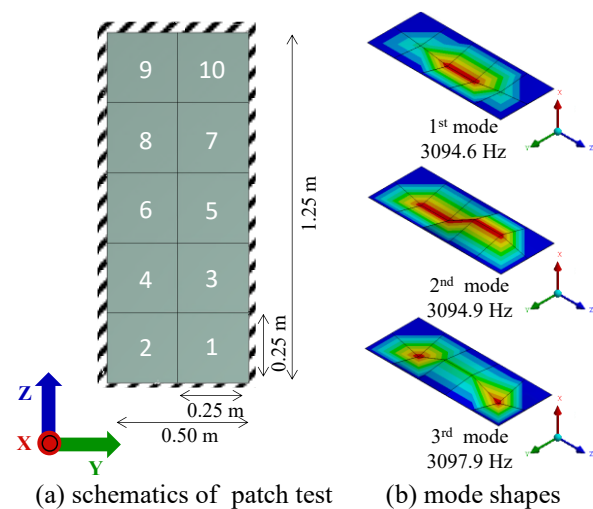


Fig 1. FE model for verification of LU decomposition

2.2. Verification with patch test

A simple plate model consisting of ten element faces was constructed for the patch test as shown in figure 1 (a). The plate dimensions were 1.25 m (Y) $\times$ 0.5 m (Z) with a thickness of 3 mm. Material properties of steel ($E = 200$ GPa, $\nu = 0.3$, $\rho = 7800$ kg/m³) and a damping ratio of 2 % were considered. A flat PSD spectrum ranging from 1 Hz to 10 kHz was applied. As shown in figure 1. (b), the three modes were considered. Center-to-center distances were calculated for all pairs of patches, and the corresponding correlation coefficient matrix was formed using an exponential decay model. Both the analysis using built-in command and the proposed LU-decomposition method produced identical 1- σ deformation responses, thereby verifying the mathematical equivalence and numerical accuracy of the LU-based approach.

3. Application to Reactor Vessel Internals

We built an integrated finite element model containing the reactor vessel, all internal components, and the coolant domain. 3D fluid elements were used to capture the added mass effect inside narrow gaps, avoiding the rigid-body assumptions of older added-mass methods. We used a substructuring workflow: dynamic analysis was first run on a coarse global model including FSI, and the resulting displacements and forces were mapped onto a refined structural model. Mapping errors were kept under 1% across both structural and fluid interfaces.

The core support barrel (CSB) was selected for detailed evaluation. Turbulent PSD loads were applied across six surface groups. Correlation lengths were set to 10 inches (both axial and hoop) for outer surfaces and 2.6 inches for the inner surface. Mapping down to element faces resulted in roughly 500 to over 1,000 load patches per group. Accounting for partial correlation reduced the predicted maximum 3- σ deformation to 1.331×10^{-2} mm (about 70% lower than the fully correlated case). Given that the axial correlation length is only about 2.5% of the total CSB height, this reduction aligns well with trends seen in simpler plate studies and does not appear overly non-conservative.

4. Conclusions

We developed an RVI structural analysis workflow that uses pressure PSD data directly and spatial partial correlation based on real distance coordinates. The LU-decomposition scripting bypasses commercial software limits on matrix size, allowing thousands of surface patches to be evaluated. Applying this method to an APR1400 CSB showed that accounting for partial correlation drops peak deformation predictions by roughly 70% compared to full correlation. Combined with 3D fluid modeling, this approach provides a more realistic, less overly conservative basis for RVI design and regulatory evaluation.

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