Random Vibration Analysis for Random Excitation at APR1400 Reactor Vessel Closure Head in Normal Operating Condition

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1. Introduction

The coolant flow has the characteristics of pulsation and turbulence by reactor coolant pumps (RCP) operation in APR1400 normal operating condition (NOP). The pulsation and turbulence induces fluctuations causing acoustic induced vibration (AIV) and flow induced vibration (FIV) on wetted surfaces of reactor internals (RVI). These periodic and random fluctuations are transmitted to the reactor vessel closure head (RVCH). They affect the structural integrity of the control element drive mechanism (CEDM) and functionality of the reed switch position transmitter (RSPT). In the APR1400 design, periodic and random vibration loadings at the RVCH are used as the design data for the CEDM and the equipment qualification (EQ) for RSPT vibration aging. However, the design data is generated by scaling methods based on the test measurement.

In this study, as a new methodology to generate the design data, the random vibration response at the RVCH is calculated by using the structural analysis method and applying the random fluctuation into inside of the reactor vessel (RV). The analysis results are compared and reviewed to design data to confirm the adequacy of the methodology.

2. Structural Analysis

2.1 RCS Model

Modeling and structural analysis have been performed with ANSYS Mechanical 18.0 [1]. In order to get the precise dynamic results, the RV modeling sets on those of the main NSSS components (steam generator (SG) and RCP), main piping (Hot leg, Cold leg and Crossover leg) and other components (CEDM and Integrated Head Assembly (IHA)). The analysis model is shown in Fig. 1. RCP and SG are implemented as the lumped mass corresponding to the weights of them. The RVI, coolant and ICI nozzles are reflected as the lumped mass considering their weights and center of gravity.

Table I: Primary modal frequency of the RV

No.	X-dir.	Z-dir.
1	11.3 Hz	11.9 Hz
2	13.3 Hz	13.6 Hz
3	-	21.2 Hz

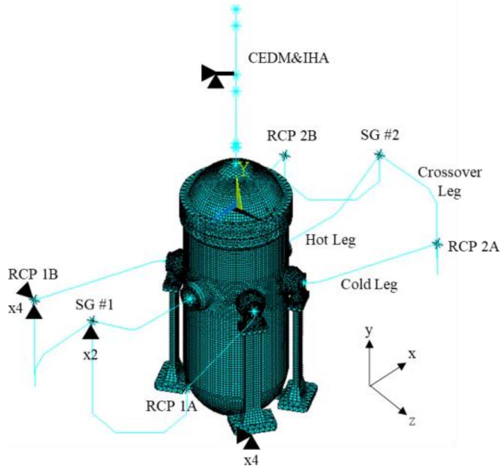

Fig. 1. RCS model.

The CEDM and IHA are added as beam element, mass element and spring element to the analysis model. The main piping connects the main components by beam element. The total number of nodes and elements for the analysis model are respectively 297,681 and 105,348.

The bottoms of RV support columns are fully fixed as the boundary conditions of analysis model. The IHA is connected with the seismic restraints to the reactor building. The SG is placed on the sliding base plate, so the thermal movement is allowed in the horizontal direction. The RCP movement can be accommodated in the horizontal and vertical directions by the link supports during normal operation.

The modal analysis with the Block Lanczos method is performed to extract the dynamic characteristics of analysis model. Table I and Fig. 2 present the major modes of RV for horizontal direction. The cumulative mass fraction is more than 99 % within 100 Hz mode of the analysis model.

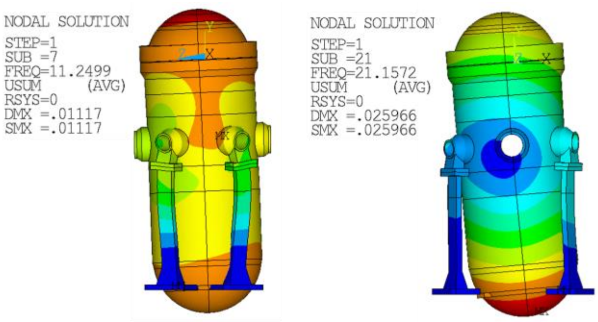

Fig. 2. Modal analysis results of RCS model.

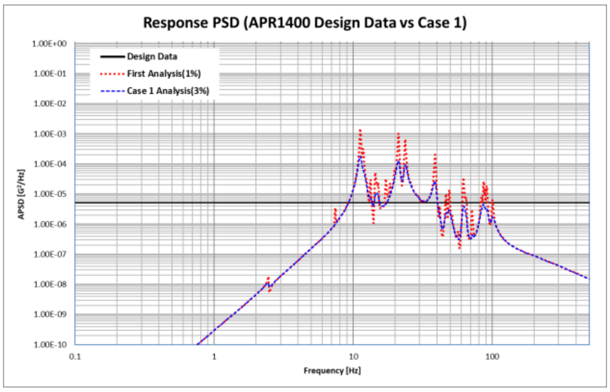

Fig. 3. Comparison of design data and Case 1 analysis result.

2.2 Random Vibration Analysis

The power spectral density (PSD) for acceleration response at the RVCH is calculated through the PSD random vibration analysis. The damping ratio 1 %, which is conservatively used for the RVI CVAP analysis is applied to the analysis [2]. The PSD for random turbulence and the coherence area of the APR1400 core support barrel (CSB) are used as the analysis inputs. The inner surface of RV cylinder is divided into patches corresponding to the size of coherence area, and the PSD for random turbulence are applied to the corresponding patches separately.

3. Analysis Results

As a result of the analysis, it turns out that the PSD response for acceleration at the RVCH is amplified in major modal frequencies of the RV, and the peak response of the PSD and root mean square of acceleration, g (GRMS) greatly exceed the design data as shown in Fig. 3 and Table II. Consequently, three case studies have been performed to find the reasons why the analysis results are larger than the design data with respect to the analysis model and the turbulence PSD input.

3.1 Case 1: Consideration on structural damping ratio

To take into account the energy transfers to the RVI and the energy dissipation by structural non-linearity, the structural analyses have been performed by increasing the structural damping ratio to 2 % and 3 %. Using 3 % structural damping ratio reduces the analysis results to about 71 % level of the first analysis result, but still significantly exceeds the design data.

Table II: GRMS per damping ratio variation (0 to 100 Hz)

	Design Data	Analysis Result	
		ζ=1%	ζ=3%
GRMS	0.23	1.27	0.90

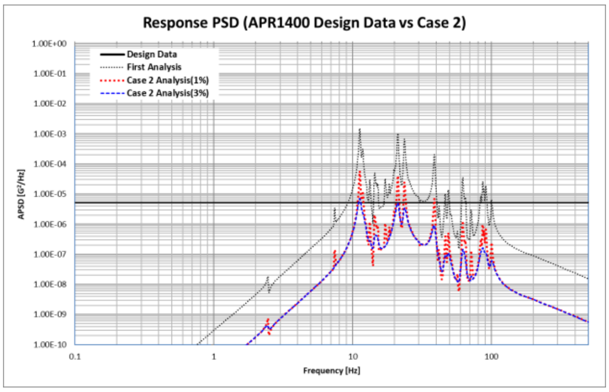

Fig. 4. Comparison of design data and Case 2 analysis result.

3.2 Case 2: Consideration on size of coherence area

The second analysis case is about the coherence area. The coherence length used in the first analysis was conservatively determined for the design considering the random nature of turbulence. It has been replaced to the new coherence length by applying 0.4 times the hydraulic radius of channel, which was experimentally discovered by M.K. Au-Yang [3].

The change in the coherence area reduces the first analysis GRMS result to 24 % level of the first analysis result. When the effect of increase in structural damping ratio is considered with the reduction in coherence area, the analysis result is enveloped with the design data as shown in Fig. 4.

3.3 Case 3: Consideration on combination method

The individual responses for each coherence area generated by the random vibration analysis for PSD are combined by the square root of the sum of the squares (SRSS). Since turbulent loading do not occur simultaneously in all the area, the SRSS combination method which appropriately considers the simultaneous and asynchronous responses is mainly used for the design. However, combining the responses of all coherence area patches may results in a highly conservative result. In the third case study, the reduced number of patches are applied to the analyses and the individual responses have been combined by SRSS.

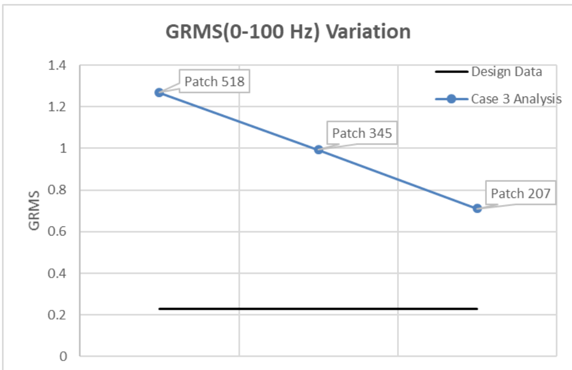

Fig. 5. Comparison of design data and Case 3 analysis result.

As shown in Fig. 5, it is confirmed that it can be reduced to about 56 % level of the first analysis GRMS result.

4. Conclusions

In this study, to generate the design data for random excitation at the RVCH, the adequacy of structural analysis using finite element method(FEM) has been reviewed. The GRMS of analysis result performed by using the turbulent PSD loading and the general design process exceeds 5.5 times of the design data. To find the reasons of the large difference between the design data and the analysis result, three case studies such as changes in the structural damping ratio, size of coherence area and the number of responses for combination have been performed. They confirm that the optimization of analysis model and turbulent loading are necessary. Additionally, their optimizations should be accompanied by the correct test plan and accurate measurements.

However, though the optimizations can enhance the possibility of analysis methodology, the analytical results must have conservatism in the input loading, the coherence area and the response combination method due to the random nature of turbulence. The conservatism may make the design of components located on the RVCH difficult.

In conclusion, this study reveals the difficulty of application of structural analysis method to the design data generation due to the analytical limitations.

REFERENCES

[1] ANSYS Manual 18.0.
[2] US NRC, Regulatory Guide 1.20, Rev.4.
[3] M.K. Au-Yang, “Flow-Induced Vibration of Power and Process Plant Components”, ASME, 2001.