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Structural Response of the SMART Reactor Vessel Assembly under Postulated Dynamic Transients

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ABSTRACT

In this study, the dynamic analysis of the SMART (System-integrated Modular Advanced ReacTor) under postulated seismic events is carried out to review the response characteristics of major components. The dynamic analysis using an equivalent beam model is performed. The seismic input from the Korean Standard Nuclear Power Plant (KSNPP) is applied, since it represents typical site specifics in Korean peninsula. Responses in the horizontal direction are found to be slightly amplified, while those in the vertical direction are found to be suppressed. High acceleration level at the CEDM base shown in the resultant response spectra analyzed might call the minor design modification to enhance the integrity of subsystems.

INTRODUCTION

Korea Atomic Energy Research Institute (KAERI) has been carrying out the development of an advanced integral reactor, the SMART (System-integrated Modular Advanced ReacTor), to supply the energy for seawater desalination as well as for electricity generation [1]. The rated power of the SMART is decided to 330MWt.

The main design concept of the SMART is to install the major components in a single pressure vessel, so called reactor vessel assembly (RVA), as shown in the Fig.1 [2][3]. The pressure boundary consists of a pressure vessel and a pressurizer (PZR) cover. The PZR resides in the top space of the pressure vessel providing a common pressure boundary, and surge lines are installed inside the vessel. The pressure is regulated and controlled passively by the volumetric change of steam and nitrogen gas in the PZR. Total 12 cassettes of once-through type steam generators (SG) using helically coiled tubes are installed inside the vessel in a circular symmetric pattern about the center of reactor vessel [4]. Four main circulation pumps (MCP) are installed on the top of reactor vessel. Since steam generators (SG) and PZR are designed as in-vessel type components, the individual piping systems connecting the SG and PZR to reactor vessel can be eliminated. In this regard, the general arrangement of the NSSS is highly simplified, while the component layout becomes more complicated. The main purpose of preliminary design activities is to preserve the integrity of a reactor from daily loads and dynamic events such as seismic events or sudden failure of piping systems. Since most of primary piping systems are eliminated in the SMART, the design limit for the postulated dynamic transients shall be dominated by Safe Shutdown Earthquake (SSE).

In this paper, the response characteristics of the SMART under seismic event are investigated to review the validity of current design features. The equivalent beam model has been prepared[11] and dynamic analysis for the model is performed. The artificial time history, which was applied to the seismic analysis of the Korea Standard Nuclear Power Plant (KSNPP), is chosen as input. The responses of major components are then evaluated and the response characteristics are discussed.

METHOD OF ANLYSIS

Development of the Equivalent Model for the SMART

Generally, a nuclear power reactor has a complicated structure to be analyzed due to a large number of dynamic degrees of freedom. The most preferred method to minimize the degrees of freedom is to carry out analyses through an equivalent model consisting of beam elements. This method is based on the assumptions that the global mode of vibration for the major components can be represented by a beam type mode and that this introduces the conservative results[5][6]. However, the accuracy of the results is closely relevant to the adequacy of the equivalent model, although this method remarkably reduces analysis costs of dynamic analyses.

A detailed finite element analysis on the pressure vessel and PZR is preceded to establish target reference frequencies to be kept in the equivalent model. By defining specific mass systems for the pressure vessel and PZR, the equivalent model maintaining the representative frequencies from the detail analysis is developed. Also performed are detail analyses using refined beam elements with a distributed mass system to get the dynamic characteristics of the control element drive mechanism (CEDM), MCP and fuel assemblies (FA). Based on the results of these analyses, the equivalent element for each component is developed with proper mass system. The other components are directly converted to beams or piping elements with discrete mass system. Certain attachments or structures, which are irrelevant to the stiffness of the reactor, are considered as concentrated mass. The final equivalent model for the SMART is constructed by coupling all the component elements to the model for pressure vessel and PZR. Fig. 2 shows the equivalent model developed for this study, and Table 1 lists the natural frequencies and corresponding modal participation with dominating components.

The eigenvalue analysis is performed using ABAQUS Ver. 5.8 on the HP workstation [7]. Table 1 reveals that the fundamental frequency of the SMART resides around 20Hz for the horizontal direction, and about 60% of the total effective mass are appeared within 33Hz in the horizontal direction.

Seismic Analysis

A seismic input to reactor depends on many factors such as the geology of the construction site and design of the containment building affecting the dynamic characteristics of the plant. Generally, the coupling of the containment building with RVA is quite preferable to consider the interaction between both structures. Since the SMART is under basic design stage, specific information on the construction site and containment building is not fully established yet. The purpose of the current analysis is to pursue the responses of major components, the seismic analysis without the building model is still acceptable. Thus, a specific seismic input is directly imposed to the bottom of the support skirt without coupling the building model. The generation of artificial earthquake records is associated with the specific geology of construction site. To envelop wide range of site specifics in Korea, the acceleration time history applied to the KSNPP (Korean Standard Nuclear Power Plant) is adopted as the seismic input for the SMART. This time history is compatible with requirements presented by the US NRC regulatory guide 1.60 [8] and SRP 3.7.1 [9]. The peak ground acceleration for the SSE, i.e. the zero period acceleration, is designed to about 0.2g in the horizontal direction. The time history of 0.005 second sampling time and 25 seconds duration is available. Fig. 3 through 5 shows the input time histories and Fig. 6 indicates the raw response spectra of the time histories.

Because of the linear features in the current model, mode superposition method is chosen to reduce analysis time and cost. The dynamic analysis is carried out with 0% damping to generate conservative results compensating all the uncertainties introduced in the analyses. The integration time step (ITS) is defined as 0.0025sec throughout the duration. The number of modes considered in the dynamic analysis is limited to 30 modes because more than 90% of modal participation are appeared within 30 modes during eigenvalue analysis. All analyses are done by the ABAQUS Ver. 5.8 on the HP workstation.

RESULTS AND DISCUSSIONS

Table 2 and 3 list the peak acceleration and corresponding amplification factor of major components for each direction. In case of the horizontal direction, relatively high responses are monitored at the top of CEDM and bottom of the reactor vessel, while only small amplification is found in the vertical direction. This seems to be relevant to the natural frequencies of the major component vibration. The dominating natural frequency of the RV and CEDM in the horizontal direction lies around 20Hz and 11Hz respectively. As shown in Fig. 6, the response spectra for the input has a plateau of acceleration between frequencies 2 to 20Hz, modes within the range can be easily excited. Although the MCP has bigger modal participation than the CEDM as shown in Table 1, relatively small amplification is monitored in comparison with the CEDM since the natural frequency of the mode resides away from the plateau. Table 1 indicates that all the vertical modes appear above 33 Hz except the FA. Therefore, small responses in the vertical direction are quite explainable. The amplification factors of internal structures such as PZR, SG and core support structures (CSB) are also believed to be reasonable comparing the response of the RV. Then, any anomalies forcing the design modification of internal structures from a viewpoint of response characteristics is not expected. Table 4 lists the maximum relative displacement occurring on each component location. The excitation is applied at the bottom of the support skirt where fixed boundary is applied. Though the maximum displacement occurring at the top of CEDM is less than 2mm in the horizontal direction, the ratio to the displacement at the bottom of RV supports the possibility of an excessive response at the CEDM. Fig. 7 and 8 show the response spectra at each component level. The peak in responses are shown at frequencies where the natural frequency of each component. In the horizontal direction, the response of the CEDM shows only one sharp peak around its fundamental frequency, and relatively high level of acceleration above 30Hz is maintained. The response of the MCP shows reasonable level of acceleration up to 100Hz except typical peaks caused by resonant frequencies. Because various kinds of equipment and cables are installed on the CEDM, a hefty design activity is inevitable to guarantee the integrity of such structures. Therefore, a design modification to moderate the response of the CEDM seems to be necessary in the future design stage. Adding an additional support structure to CEDM can adjust the fundamental frequency and modal participation to reduce the responses to a reasonable level.

CONCLUSION

The seismic analyses for the SMART are performed to review the response characteristics of major components. Although amplified responses are monitored in the horizontal direction, the response acceleration and amplification factor support the fact that global response characteristics of major components are acceptable. Since a high level of acceleration is monitored from the response spectrum on the top of CEDM, a proper design modification to enhance the integrity of subsystems on the CEDM is expected. Because the frequencies of vertical direction are higher than 33Hz, only small amplification factors are delivered.

ACKNOWLEDGEMENT

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Table 1 Results of eigenvalue analysis

Freq.(Hz)	Modal Participation (%)		Note*
	Horizontal	Vertical	
2.25	2.9	-	Fuel Assembly
10.92	4.2	-	CEDM
20.40	55.5	-	Reactor Vessel
33.09	-	6.1	Fuel Assembly
46.80	11.9	-	MCP
51.85	3.3	-	Internal Structures
58.87	2.2	-	PZR
61.31	-	26.7	SG
69.08	-	16.3	Internal Structures
82.17	-	34.4	Reactor Vessel
82.25	13.7	-	Reactor Vessel

*Mode of major component vibration

Table 2 Response acceleration of components

Location	X(g)	Y(g)	Z(g)
Top of RV	0.23	0.22	0.26
Bot. of RV	1.40	0.30	0.92
Top of MCP	0.78	0.23	0.57
Top of CEDM	3.41	0.23	4.35
Top of SG/CSB	0.55	0.29	0.38
Bot. of PZR	0.66	0.28	0.52
Top of SCN	0.92	0.28	0.62

Table 3 Amplification factors of components

Location	X	Y	Z
Top of RV	1.0	1.1	1.1
Bot. of RV	6.2	1.4	4.1
Top of MCP	3.8	1.1	2.5
Top of CEDM	15.0	1.1	19.2
Top of SG/CSB	2.4	1.4	1.7
Bot. Of PZR	2.9	1.3	2.3
Top of SCN	4.1	1.4	2.7

Table 4 Relative displacement of components

Location	Horiz.	Vert.
Top of RV	0.003	0.001
Bot. of RV	0.112	0.002
Top of MCP	0.018	0.001
Top of CEDM	1.289	0.002
Top of SG/CSB	0.017	0.001
Bot. Of PZR	0.043	0.001
Top of SCN	0.07	0.001

Unit) mm

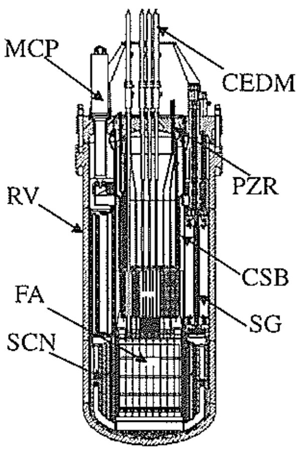

Fig.1 The arrangement of the SMART RVA

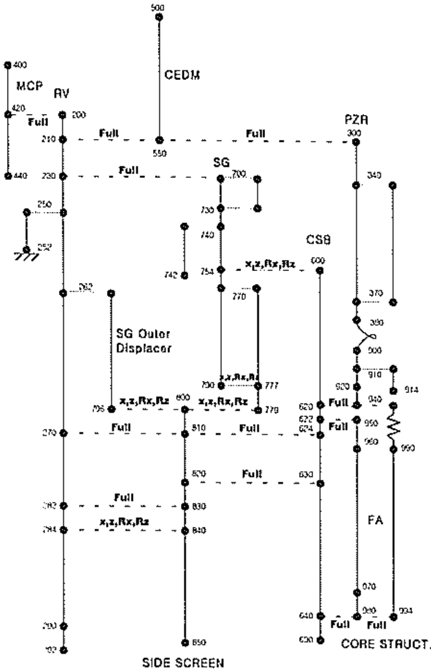

Fig. 2 The equivalent beam model for RVA

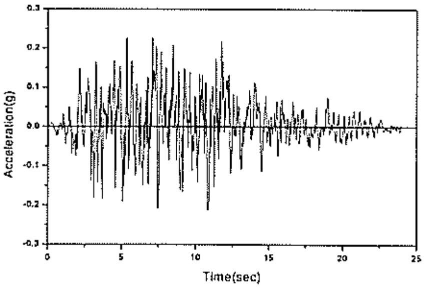

Fig. 3 Time history for NS (X) direction

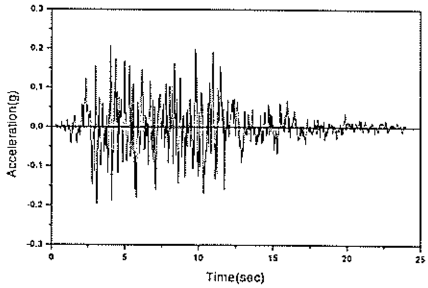

Fig. 4 Time history for Vertical (Y) direction

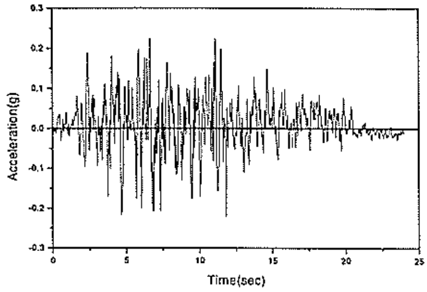

Fig. 5 Time history for EW (Z) direction

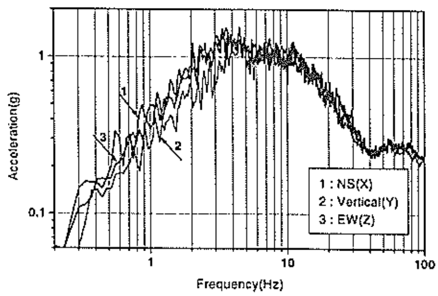

Fig. 6 Response spectra of input T. H. (1% Damping)

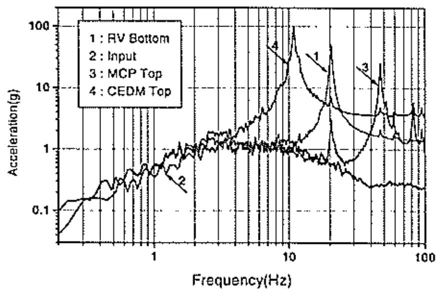

Fig. 7 Response spectra for NS (X) direction (1% Damping)

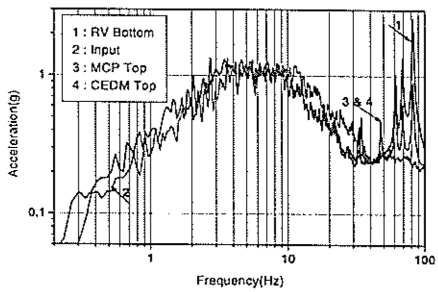

Fig. 8 Response spectra for Vertical direction (1% Damping)