Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Methodology for generating single spectrum considering height of reactor coolant system

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1. Introduction

Reactor coolant system (RCS) consists of a reactor vessel (RV), steam generator (SG), reactor coolant pump (RCP), and pressurizer (PZR). These components have supports of various heights (Fig. 1). Therefore, according to the APR1400 Design control document (APR1400 DCD), it is necessary to secure design certification by inputting the floor response spectra (FRS) that are amplified differently by the height differences of each support [1]. However, there is a problem in performing seismic analysis using the floor response spectra for each support height. For time history analysis (THA), time history inputs corresponding to each floor response spectra are required. At this time, since there is no phase information in the floor response spectrum, if an artificial time history is created with the floor response spectrum of each height, excessive relative displacement between each support can occur. For this reason and for a conservative analysis, Korea Institute of Nuclear Safety (KINS) suggests using a single spectrum that can envelope all of the floor response spectra [2]. However, this method has the potential to derive an unreasonably high seismic response.

Therefore, this study intends to suggest a methodology for generating a single floor response spectrum considering the various support heights of the RCS. For a reasonable level of input, the floor response spectrum for each height is corrected in consideration of the dynamic characteristics of the RCS. The level of response for the generated floor response spectrum and the frequency domain response are verified using FE model.

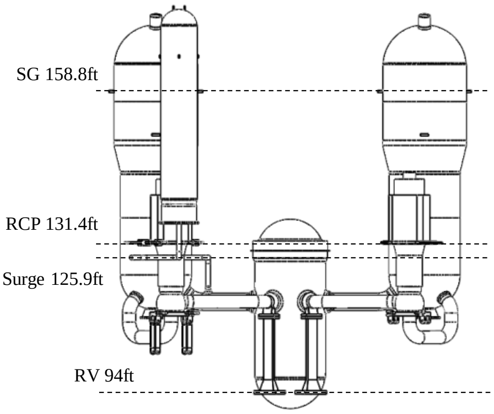


Fig. 1. Examples of support heights.

2. Single FRS generation methodology

2.1 Dynamic characteristics of RCS

In order to secure the dynamic characteristics of SG, RCP, and PZR, in this study, FE models of each component were constructed with reference to previous studies [3-5]. FE models were constructed using ANSYS Mechanical 2021R2 version, a commercial finite element analysis program, and the constructed FE model is shown in Fig. 2. Table I shows the main mode frequencies with effective mass of 3% or more for each axis of EW, NS, and Vertical. The natural frequency of the pressurizer belongs to a relatively high-frequency band. In addition, since the reactor vessel is excited by the surge line, the main modes for the surge line were derived in Table 1.

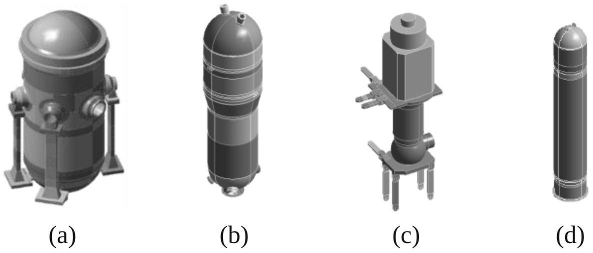


Fig. 2. RCS components (a) Reactor vessel (b) Steam generator (c) Reactor coolant pump (d) Pressurizer.

Table I: Dynamic characteristics of RCS devices for EW, NS, and Vertical direction

Dir.	Eff. Mass [%]	Freq. [Hz]	Device	Height [ft]
EW	51.4	14.9	SG	158.8
	12.2	16.3	RCP	131.4
	8.06	26.3	SG	158.8
	2.72	31.8	Surge line	125.9
NS	29.0	13.1	SG	169.7
	22.2	8.99	RCP	131.4
	8.34	12.3	RCP	131.4
	6.84	62.2	SG	169.7
	4.52	39.0	RCP	131.4
	4.50	48.5	SG	169.7
	2.75	24.3	RCP	131.4
Vertical	43.8	32.9	SG	112.2
	28.0	21.5	Surge line	125.9
	18.1	25.0	RCP	131.4

2.2 FRS extraction

In order to generate a single FRS, the most basic FRS must be selected. Since the target component of this study is the reactor vessel and internals, 94 ft FRS, which is the height of the reactor vessel support, is selected as the base FRS.

After that, it is necessary to selectively correct the FRS in consideration of the dynamic characteristics of the RCS components in the base FRS. Therefore, the spectrum value corresponding to the natural frequencies of each component height in Table I are extracted and summed on the base FRS. In addition, 15% peak broadening is performed for conservative analysis considering the uncertainty of seismic input [6]. This procedure is shown in Fig. 3. Fig. 3 is an example of the EW direction. If this method is applied to the three directions of EW, NS, and Vertical, three independent single FRS are calculated (Fig. 4). These spectra can be effective seismic inputs that can express the behavior of the main modes of each component because the FRS corresponding to the main mode frequencies of SG, RCP, and PZR are selectively corrected.

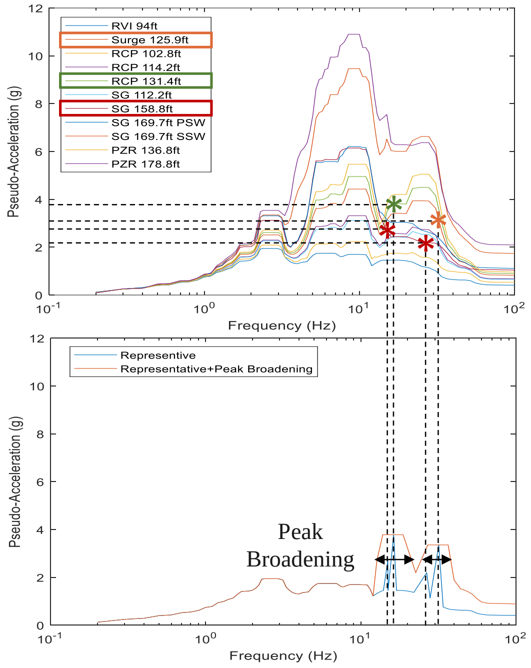
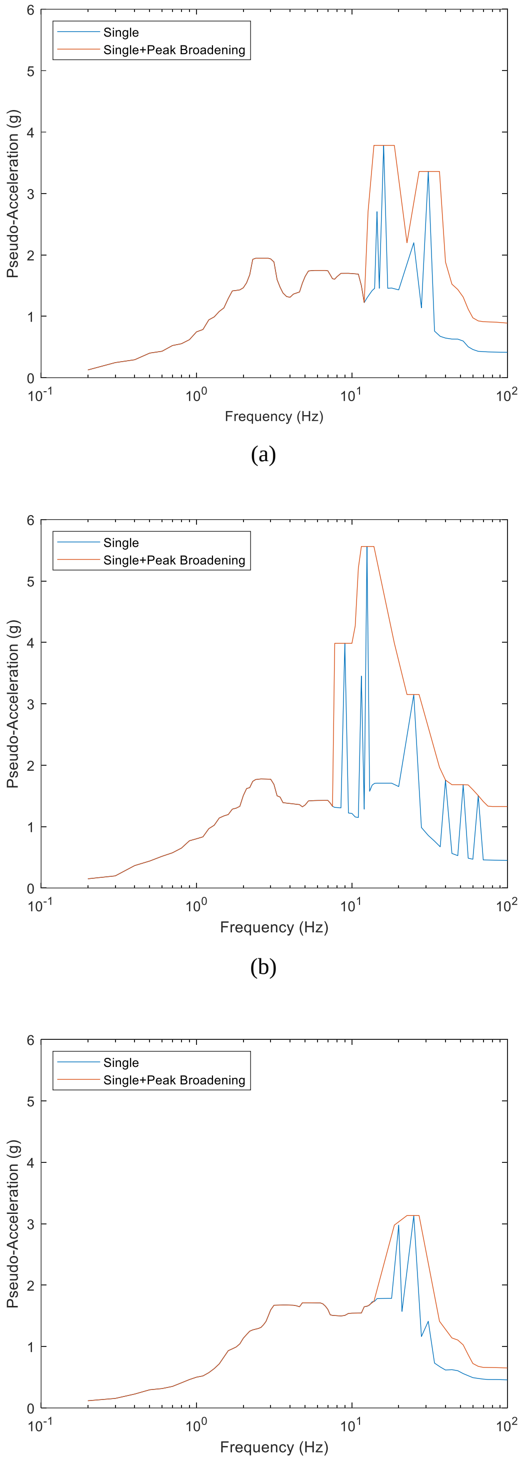


Fig. 3. Application example of single FRS generation methodology



(a)

(b)

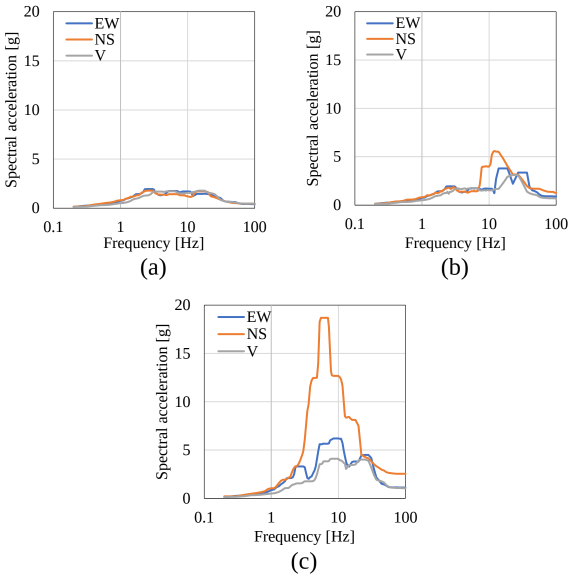
(c)

Fig. 4. Single FRS in direction (a) EW (b) NS (c) Vertical

3. Validation

3.1 Level of response

In order to verify the validity of the single spectral input level generated by the methodology suggested in this study, the response spectrum analysis (RSA) responses to a total of three spectral inputs in Fig. 5 were compared. The SRSS (Square Root of Sum of Squares), known as the most conservative mode superposition method, was applied to combine the responses for each mode. The result of inputting the spectra for each height of the RCS support were used as a reference value. For the reference responses, multi-point response spectrum analysis was performed. Table II shows the results of inputting the 94 ft spectrum of the reactor vessel support height, the single spectrum presented in this study, and the maximum enveloped spectrum of each floor height. When the spectrum of 94 ft, which is the height of the reactor vessel support, was used as an input, the response was about 38~48% lower than that of the reference response. On the other hand, when a maximum FRS enveloped spectrum was used as an input, excessive response of about 125~182% compared to the reference response was shown. When the single FRS suggested in this study is used as an input, the response of upper guide structure (UGS) is low by about 24%, but the difference between the responses of reactor vessel, core shroud (CS), and core support barrel (CSB) is about -7 to 3%. This is a reasonable response level compared to the reference response.



(a)

(b)

(c)

Fig. 5. Input spectrum for comparison (a) RV (94 ft) (b) Single FRS (c) Max. envelop

Table II: Response spectrum analysis results

Input spectrum	Equivalent stress [MPa]			
	RV	CS	CSB	UGS
Reference	267.1	58.42	39.42	36.64
RV (94 ft)	153.2	36.06	24.21	18.87
Single FRS	247.4	60.17	38.95	27.64
Max. envelop	754.9	159.2	109.9	82.64

3.2 Frequency characteristics

To check whether the single FRS suggested in this study is an input that reflects the dynamic characteristics of the RCS components, the single response spectrum was converted into a time history artificial earthquake. Then, time history analysis was performed with the converted artificial earthquake as input. In addition, as shown in Fig. 6, the top displacements of SG, RCP, and PZR were analyzed in the frequency domain using Fast Fourier Transform (FFT). The red line is the 94 ft spectrum response, which is the height of the RV support, and the blue line is the single spectrum response suggested in this study. Comparing the FFT peaks, it can be confirmed that the dynamic characteristics of RCS components are well reflected in the single spectrum response. In addition, due to the effect of peak broadening, a mode of a component with a natural frequency other than the extracted FRF is also expressed. This result allows for a conservative analysis.

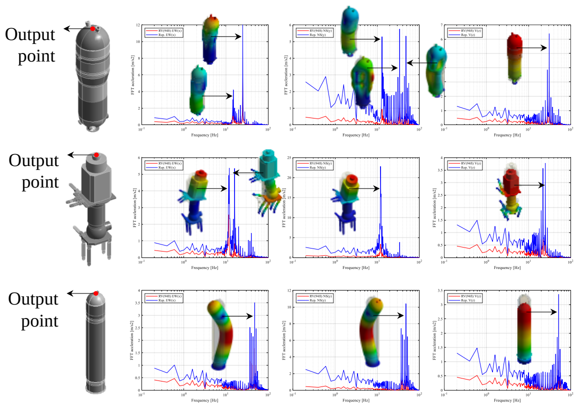


Fig. 6. FFT results for top of SG, RCP, and PZR

4. Conclusions

In this study, a methodology for generating single FRS was investigated to analyze the seismic response of RCS with supports of various heights. This methodology can derive a reasonable response level of reactor vessel and internals and reflect the dynamic characteristics of RCS components. However, it is necessary to supplement the conservatism because non-conservative responses can be derived for some structures.

ACKNOWELEDGEMENT

This research was supported by the Nuclear Safety research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (grant number 1805005-0522-WT121).

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