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Analysis of dynamic characteristics of reactor vessel including adjacent equipment

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ABSTRACT

A nuclear power accounts for a large portion of today's energy production. Many countries are pursuing the construction of nuclear power plants to meet the energy demand. However, the issue of risk to nuclear power plants certainly exists. The reactor vessel must be demonstrated to be safe against earthquakes. Some equipment adjacent to the reactor vessel can affect the dynamic characteristics and seismic response of the reactor vessel. Therefore, seismic analysis of the reactor vessel should be performed including the adjacent equipment. In this study, dynamic characteristics of reactor vessel including adjacent equipment were investigated. In addition, as a essential and fundamental step for seismic analysis of the reactor vessel including adjacent equipment, seismic input wave was generated in consideration of the seismic waves caused by the height difference of each equipment. The results of this study provide the dynamic characteristics of the reactor vessel including adjacent equipment. In addition, this study provides a methodology for generating the seismic input wave for seismic analysis of reactor vessel including adjacent equipment. Ultimately, this study can contribute to deriving an accurate seismic response of the reactor vessel and improving the structural integrity of the reactor vessel.

INTRODUCTION

After the Fukushima nuclear accident caused by the Great East Japan Earthquake (GEJE) in 2011, interest in the seismic safety of nuclear power plant has increased. Since the reactor vessel is a large structure, structural integrity is evaluated using finite element analysis and computational simulation rather than experiment on prototypes. In order to verify the structural integrity of reactor vessel, seismic analyses using the finite element (FE) model were performed by many researchers. For example, Park et all. (2017) constructed a beam model for reactor vessel and analyzed the seismic response. In addition, Park et all. (2019) and Lee et all. (2019) derived the seismic response considering the hydraulic loads (periodic hydraulic load and random hydraulic load) by the internal coolant assuming the reactor operating conditions. And Lee et all. (2019) studied the methodology for analysis considering the effects of neutron irradiation of nuclear fuel. Recently, Lee et all. (2021) analyzed the plastic behavior of the reactor vessel for excessive earthquakes. However, although the reactor vessel is connected and fastened to adjacent equipment, independent analyses of the reactor vessel were performed in most studies.

The equipment adjacent to the reactor vessel include steam generator (SG), reactor coolant pump (RCP) and pressurizer (PZR) as shown in Figure 1. These adjacent equipment are connected to the reactor vessel by large-diameter pipes. So, the dynamic characteristics of the reactor vessel are changed by the interaction of the stiffness and mass effect with the adjacent equipment. In addition, the reactor vessel vibrates and interacts with the adjacent equipment. The interaction of the reactor vessel with adjacent equipment can serve to reduce the seismic response of the reactor vessel and, conversely, to amplify it. Therefore, in order to derive an accurate seismic response of the reactor vessel and perform a structural integrity evaluation, it is necessary to analyze the system including adjacent equipment rather than an individual analysis of the reactor vessel.

In order to perform the reactor coolant system (RCS), the heights of the supports of the adjacent equipment should be considered. According to the APR1400 Design Control Document (APR1400 DCD, 2014), it is necessary to secure design certification by applying the floor response spectrum (FRS) that are amplified differently by the height differences of each support. For the individual reactor vessel, seismic analysis can be performed using the 94 ft floor response spectrum, which is the height of the support column. However, since the reactor coolant system includes supports of various heights, the floor response spectrum of each height must be considered. If only the low-height floor response spectrum is considered, non-conservative analysis results can be derived. However, since there is no phase information in the floor response spectrum, the time histories generated based on the floor response spectrum are random. Therefore, the time histories generated by the floor response spectrum for each support height of the adjacent equipment have random relative displacements. This relative displacement shows an unrealistically excessive relative displacement between each support. For this reason and conservative analysis, Korea Institute of Nuclear Safety (KINS, 2016) suggests using a single response spectrum that can envelope the floor response spectrum of all support heights. However, this method ahs the potential to derive unreasonably high seismic responses.

Therefore, this study aims to investigate the effect of the adjacent equipment on the dynamic characteristics of the reactor vessel. In addition, for seismic analysis of the reactor vessel including the adjacent equipment, this study intends to suggest a methodology for deriving a reasonable floor response spectrum considering the difference in support height. In this study, the adjacent equipment, steam generator, reactor coolant pump, and pressurizer, were additionally extended to the reactor vessel constructed by the previous studies of Park (2014) and Choi (2016). Thereafter, mode analyses were performed on the individual reactor vessel model and the reactor vessel model including adjacent equipment. Based on these analysis results, the change in dynamic characteristics were analyzed. In addition, for the seismic analysis of the reactor vessel including the adjacent equipment, a methodology for generating a floor response spectrum reflecting the dynamic characteristics of the adjacent equipment was presented.

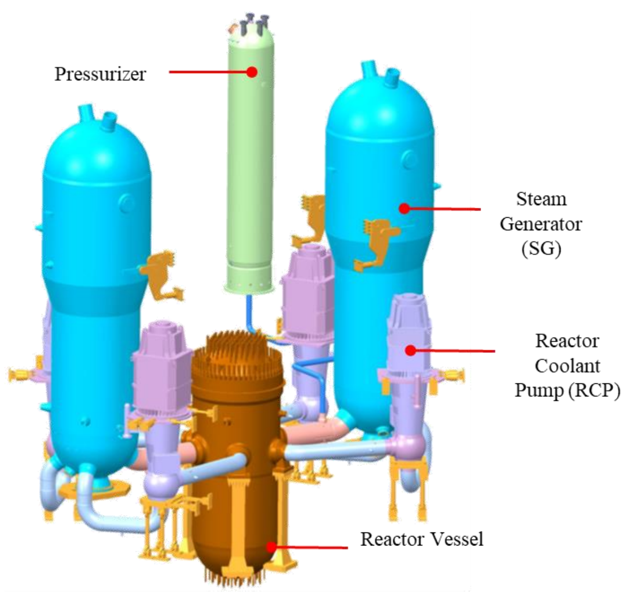


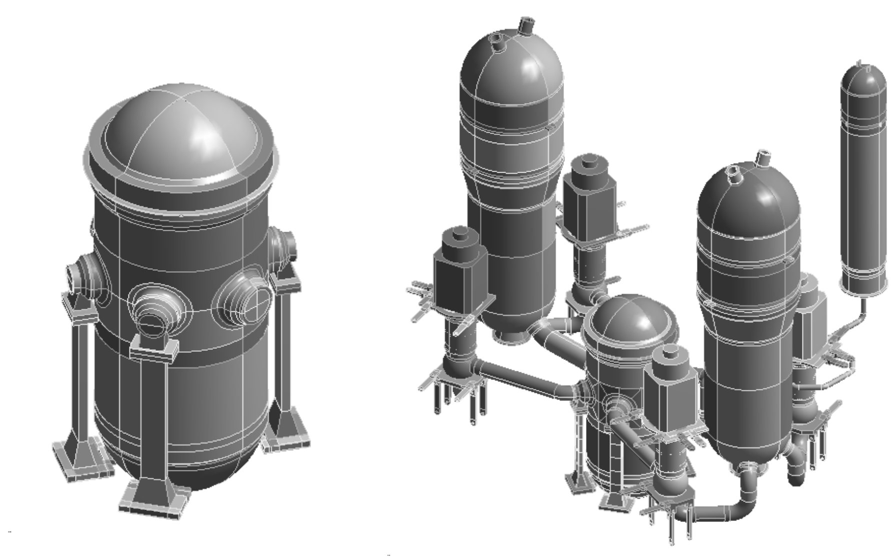
Figure 1. Scheme of equipment adjacent to the reactor vessel.

FINITE ELEMENT MODEL

As mentioned earlier in the introduction, the finite element model of reactor vessel was constructed through the previous studies. The reactor vessel model consists of not only the reactor vessel (RV) but also internal structures such as core support barrel (CSB), lower support structure (LSS), core shroud (CS), upper guide structure (UGS) and inner barrel assembly (IBA). The internal nuclear fuel was simulated as lumped mass considering only the mass effect. The main boundary conditions of the internal structures were applied in consideration of the operating mechanism. For example, the lug of core shroud and fuel alignment plate only couple the lateral degree of freedom between adjacent nodes because they restrict only the lateral motion by thermal expansion. In addition, the fixed condition was applied assuming that the bottom surface of the support column of the reactor vessel is fixed to the primary shield wall. The constructed reactor vessel model was verified comparing natural frequencies and mode shapes through a scaled model test.

For the adjacent equipment such as steam generator, reactor coolant pump and pressurizer, since the behaviors of the internal structures of each equipment are not of interest, it is simulated with concentrated mass and only the outer shell-type structures were modeled in detail. The four snubbers of the steam generator limit the lateral movement and the skirt at the bottom is fixed. The ten supports of the reactor coolant pump were simulated in a pin-fixed to limit the translation behavior and enable rotation. Finally, the snubber of the pressurizer was also designed to limit the lateral movement. Two steam generators and four reactor coolant pumps connected the hot leg and cold leg of the reactor vessel using large diameter pipes, respectively. The pressurizer is connected to the hot let pipe by a surge line. All finite element models for steam generator, reactor coolant pump and pressurizer were verified by referring to the previous studies of Yu (2011) and Lee (2015).

All of the finite element models were constructed using ANSYS Mechanical 2021R2 version, a commercial finite element analysis program which is pre-verified computation code. The constructed finite element model is shown in Figure 2. The reactor vessel model consists of a total of 1,308,540 elements, and the reactor vessel with the adjacent equipment consist of a total of 1,868,482 elements. Table 1 shows the material properties applied to each equipment. The materials of reactor vessel and steam generator are SA 508 Gr. 3 Class 1, and the materials of internals structures, reactor coolant pump and pressurizer are SA 240 TP 304.



(a) (b)

Figure 2. Constructed finite element models (a) Reactor vessel (b) Reactor vessel with adjacent equipment.

Table 1: Material properties used in the finite element model.

	Reactor vessel	Internals	Steam generator	Reactor coolant pump	Pressurizer
Material	SA 508 Gr.3 Class 1	SA 240 TP 304	SA 508 Gr.3 Class 1	SA 240 TP 304	SA 508 Gr.3 Class 1
Density [kg/m^3]	7750	8030	7750	8030	7750
Young's modulus [GPa]	171.4	172.5	171.4	172.5	171.4
Poisson's ratio	0.3	0.31	0.3	0.31	0.3

MODAL ANALYSIS

In order to investigate the change of dynamic characteristics according to the adjacent equipment, modal analyses were performed for reactor vessel with all equipment, except for pressurizer and surge line, except for steam generator, except for reactor coolant pump and excluding all equipment. The connection section created by excluding each equipment was analyzed as fixed. The natural frequencies for each analysis are shown in Table 2, and the graph is shown in Figure 3 to confirm the tendency change.

In or cases, the natural frequency change of the reactor vessel vertical bending mode is insignificant. This is because the vertical eigenmode of reactor vessel is affected by the bending stiffness of a large-diameter pipe, which has relatively lower stiffness than the axial stiffness. For each equipment, reactor coolant pump, steam generator and pressurizer have a significant influence on the dynamic characteristics of the reactor vessel in that order. In the case of excluding the pressurizer and surge line, the result of modal analysis is not significantly different from the case including all equipment. On the other hand, when steam generator and reactor coolant pump are excluded, the maximum change in dynamic characteristics are 11.7% and 32.3%, respectively. Especially, in the case of individual reactor vessel modal analysis, the natural frequency of 1st mode shows a difference of 30.0%, the 2nd mode shows 43.4% and the 4th mode shows 35.0% compared to the case that includes all adjacent equipment. The natural frequency changes of the 1st and 2nd bending mode of reactor vessel are significant, which is included in the strong seismic frequency band. In addition, the low frequency bending modes have a dominant influence on the seismic response. Therefore, in the seismic response analysis of the reactor vessel, it is necessary to perform an analysis including steam generator and reactor coolant pump to accurately investigate the behavior of the reactor vessel.

Table 2: Natural frequency change according to the adjacent equipment.

Mode #	Mode shape	Natural frequency [Hz]				
		RV including all equipment	w/o PZR & SL	w/o SG	w/o RCP	Only RV
1	RV bending (NS)	8.992	8.992	9.5811	11.18	11.69
2	RV bending (EW)	16.31	16.31	18.21	21.44	23.39
3	RV vertical	21.56	21.56	21.80	21.59	21.83
4	RV twist	23.45	23.46	24.17	31.02	31.65

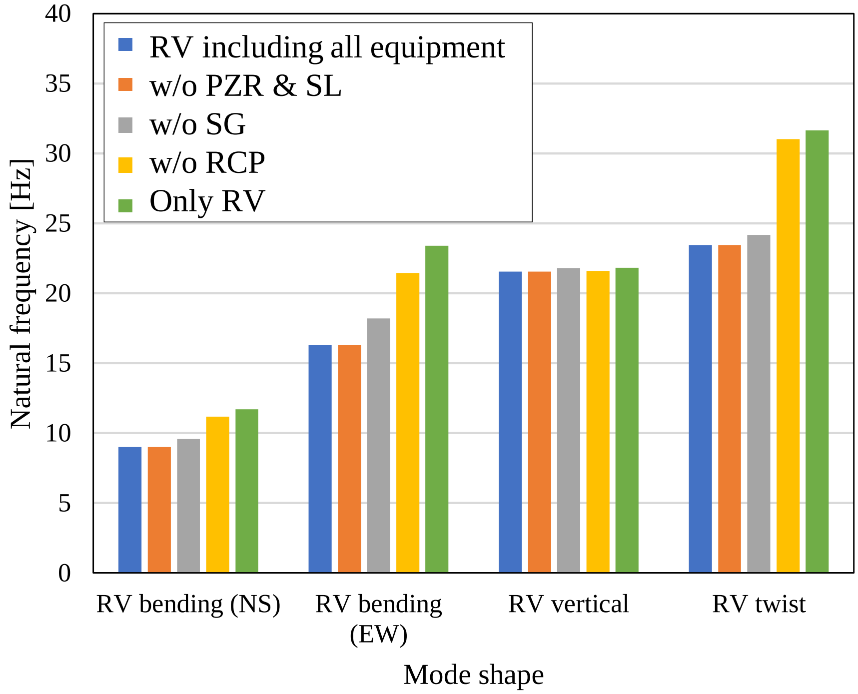


Figure 3. Natural frequency change according to the adjacent equipment.

SEISMIC INPUT WAVE

As mentioned in the introduction, for seismic analysis of reactor vessel including the adjacent equipment, seismic input wave is required in consideration of the different floor response spectra of the support heights of adjacent equipment. The different heights of the supports of the adjacent equipment are shown in Figure 4. The floor response spectrum by height differs not only in the level of the spectrum but also in the main frequency band. Since the equipment of interest is reactor vessel, the 94 ft floor response spectrum, which is the height of the support column of the reactor vessel, is used as the base floor response spectrum. And the floor response spectra for each support height are selectively combined. Depending on the spectrum input for each height, the mode of the equipment mainly expressed also varies. Therefore, in this study, a methodology for selectively combining floor response spectra for each support height with respect to the main mode frequencies of each equipment is presented. This methodology was described in detail in this section.

First, the main modes of stream generator, reactor coolant pump and pressurizer which are adjacent equipment are derived. Table 3 shows the main mode frequencies with effective mass of 3% or more for each direction 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 that directly connected, the main modes for the surge line replaced the main modes of the pressurizer. As can be seen from the results of the modal analysis in the previous section, the equipment that have a dominant influence on the dynamic characteristics of reactor vessel are the steam generator and reactor coolant pump. Therefore, the main modes for steam generator and reactor coolant pump were mostly selected as the dynamic characteristics of adjacent equipment for generating the seismic input.

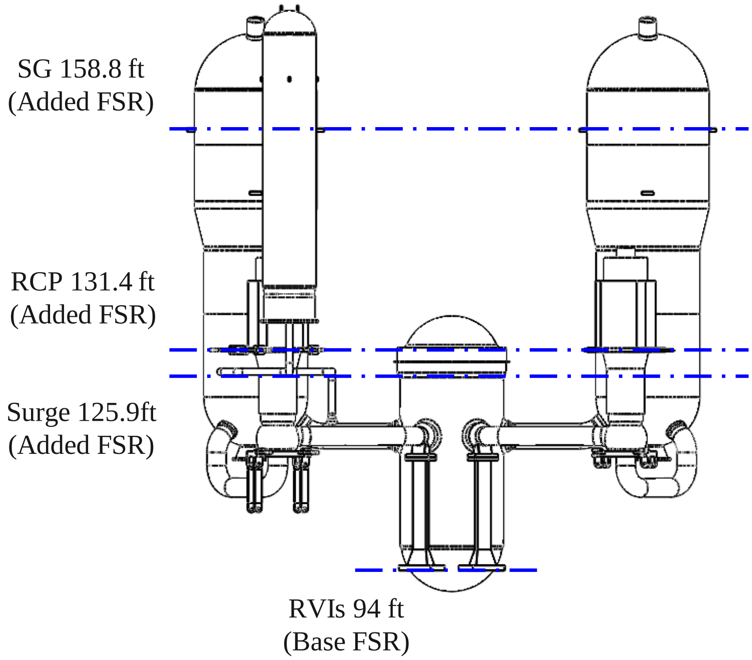


Figure 4. Examples of support heights of reactor vessel, steam generator and surge line.

Table 3: Main mode of adjacent equipment for selective floor spectrum response combination.

	Natural frequency [Hz]	Equipment	Height [ft]
EW	14.9	Steam generator	158.8
	16.3	Reactor coolant pump	131.4
	26.3	Steam generator	158.8
	31.8	Surge line	125.9
NS	13.1	Steam generator	169.7
	8.99	Reactor coolant pump	131.4
	12.3	Reactor coolant pump	131.4
	62.2	Steam generator	169.7
	39.0	Reactor coolant pump	131.4
	48.5	Steam generator	169.7
	24.3	Reactor coolant pump	131.4
Vertical	32.9	Steam generator	112.2
	21.5	Surge line	125.9
	25.0	Reactor coolant pump	131.4

After selecting the main mode of the adjacent equipment, the response spectrum values corresponding to the main mode frequency are extracted from the floor response spectra for each height. As shown in Figure 5, the values corresponding to the main mode frequencies of the adjacent equipment in Table 3 are extracted from the floor response spectrum for each equipment height. And the extracted values are combined with the floor response spectrum of 94 ft height, which is the base floor response spectrum. And for the peak values of the combined spectrum, 15% peak broadening was performed according to U. S. NRC Reg. 1.122. Figure 6 shows the floor response spectra selectively combined in consideration of the dynamic characteristics of adjacent equipment in the EW, NS and vertical direction.

In order to verify the appropriateness of response level, the response spectrum analysis results of the 94 ft spectrum and the spectrum enveloping all floor response spectra of each height were compared. For the reference responses, multi-point response spectrum analysis was performed with the input of the different spectra according to height of adjacent equipment. When the spectrum of 94 ft, which is the height of the support column of reactor vessel, we used as an input, the response was about 38% to 48% lower than the reference response. On the other hand, when a enveloped floor responses spectra were used as an input, too excessive response of about 125% to 182% compared to the reference response was derived. However, when the spectrum generated by the methodology presented in this study is used as an input, it shows a difference of about 3% to 7% from the reference response. Therefore, it was confirmed that the methodology presented in this study can derive a reasonable level of seismic response.

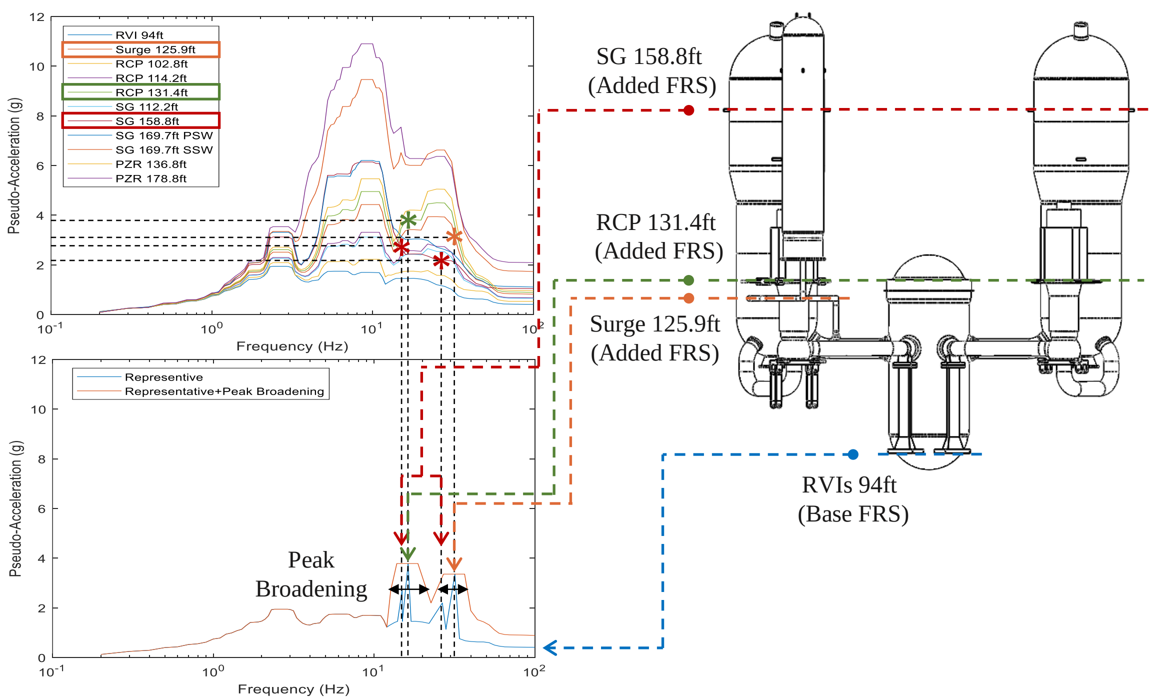
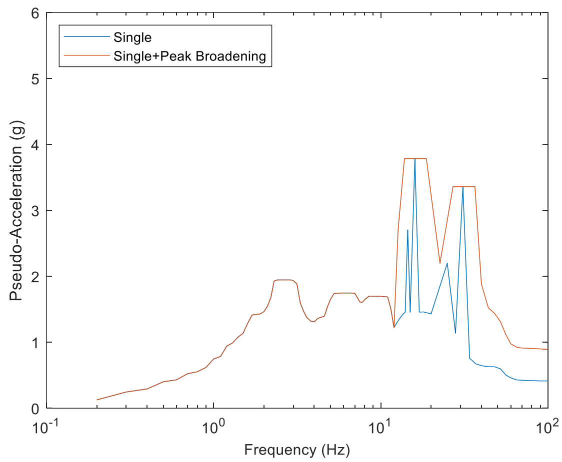
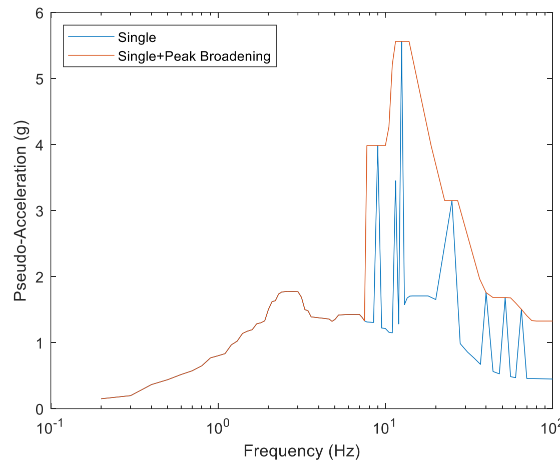


Figure 5. Example of a methodology for generating a selective floor response spectrum.



(a)



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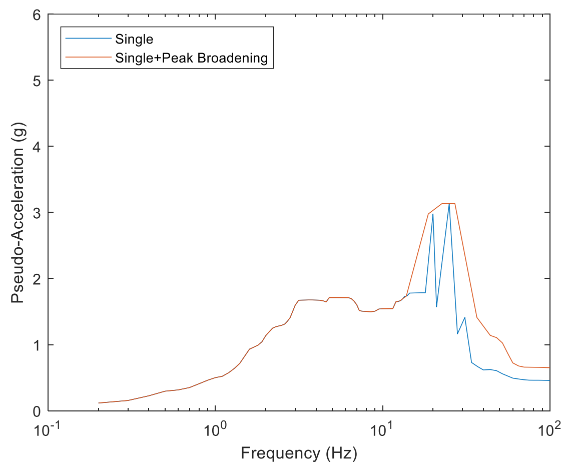

(c)

Figure 6. Floor response spectrum generated by selective combinations (a) EW direction (b) NS direction (c) Vertical direction.

CONCLUSION

In this study, the effect of adjacent equipment on the dynamic characteristics of the reactor vessel was investigated. Although the pressurizer does not have a significant effect on the dynamic characteristics of the reactor vessel, steam generator and reactor coolant pump have a significant effect on the 1st and 2nd bending modes of the reactor vessel. Therefore, the steam generator and reactor coolant pump are equipment that must be included in seismic analysis. In addition, in this study, a methodology for generating the floor response spectrum to be used as an input for seismic analysis was presented in consideration of the dynamic characteristics of adjacent equipment. This methodology was verified to be a reasonable level of input.

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