DEVELOPMENT OF A SEISMIC ANALYSIS MODEL FOR SMART

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ABSTRACT

KAERI has been developing SMART(System-integrated Modular Advanced ReacTor) as an environment-friendly reactor that gives freshwater from the sea as well as electric power. The purpose of this study is to develop a seismic analysis procedure and assess the structural safety of SMART against the seismic. The finite element models of the reactor vessel and the internal structures have been simplified as a stick model. The stick model is composed of beams, lumped masses, rigid beams and spring-damper elements, and the analyses were performed by a general purpose finite element program, ANSYS. Since the stick model is required to be equivalent to the solid model, it is derived from the modal and static analyses of the solid models of critical structures by evaluating their natural frequencies and stiffness. Results of every stick model are compared with those of the respective solid model, and then this study developed the seismic analysis model for SMART via the equivalent constraints or the coupling conditions between components. Finally, this study shows the results of the modal and seismic analysis to evaluate the safety of the reactor structure.

INTRODUCTION

Since a reactor always has the potential to encounter an earthquake that causes severe damage to the structure, it is necessary to assess the structural safety against the seismic loads in the design process [1]. It is generally performed either by the seismic test, analysis or comparison with past experience. Of them, the assessment by analysis using the finite element method (FEM) is the most common approach used in practice [2,3]. The reliability of the analysis depends on the FE modeling of the structural components. The seismic analysis of a large structure especially, like the reactor, is usually performed by modeling the structure as a stick model not a solid model. Since the accuracy of the stick models is generally dependent on intuition or engineering judgment, it has been known that it is very difficult to match the boundary and coupling conditions. The initial stick model possesses a lot of assumptions and idealizations such as boundary conditions and constraint conditions between its components in order to simplify an installed structure. Hence, the initial stick model should be updated based on the experimental data or the analysis result obtained from the detailed solid model so that the FE model can be used with confidence for spectrum or transient analyses.

The purpose of this study is to develop a stick model in order to assess the structural safety of SMART against the seismic. The FE models of the reactor vessel and the internal structures have been simplified as a stick model. Since the stick model is required to be equivalent to the solid model, it is derived from the modal and static analyses of the solid models of critical structures in consideration of their natural frequencies and stiffness. The results of all stick models are compared with those of the respective solid models, and then this study integrates every stick model with the equivalent constraint or coupling conditions. Finally, this study shows the brief results of the modal and seismic analyses.

ANALYSIS OF SOLID MODEL

Fig. 1 and Fig. 2 show the external appearance and the internal components of SMART. In this paper, the critical structures have been selected as RVA(reactor vessel assembly), CSB(core support barrel), UGS(upper guide structure), CRDM(core rod drive mechanism), SG(steam generator), FMHA(flow mixing header assembly), FWN(feed water nozzle), flow-skirt and ICI(In-Core instrument) support structure, which governs the natural frequencies and the mode shapes of SMART as a whole. Above 3D solid FE models will be substituted with 3D elastic beam elements which are able to consider the shear deformation effects. This chapter deals with the modal analyses of the solid models so as to get the natural frequencies and the mode shapes of the internal components. FWN(feed water nozzle) will be modeled as a spring element having the stiffness from the static analysis with the solid model, and the connection between RVA and FWN/SN(steam nozzle)/RCP(reactor coolant pump) will adopt a rigid beam element.

RVA, CSB, UGS, CRDM, FMHA , Flow-Skirt and ICI support structure

Table 1 and Fig. 3 show the natural frequencies and the mode shapes of the respective components by modal analysis with 3-D solid model. The shell modes of RVA, CSB and UGS should be excluded since the responses due to the shell modes are negligible compared to the deformation caused by the translation or bending modes. Therefore, the representative mode shapes of RVA are the translation modes in the horizontal(X, Y) directions, tilting one and the translation mode in the vertical(Z) direction. The modal analyses for CSB, UGS and CRDM indicate that the primary vibration modes are bending ones as illustrated in Fig. 3. The 1st mode shapes of these components are shown in Fig. 3 respectively. In the cases of FMHA and flow-skirt, their natural frequencies are higher than the others because the ratio of diameter to height is much higher than other components. On the other hand, the 1st-natural frequency(18.2Hz) of ICI support structure was lower than those of FMHA(61.5Hz) and flow-skirt(76.7Hz). The reason is that ICI support structure is able to move freely like a rigid body only with the fixed boundary conditions on the ends of the legs.

SG and FWN

SMART has 8 sets of SGs consisting of 375 tubes, in which there are two important regions; the effective heat transfer region plays a role heat transfer from a primary coolant system to a secondary one, and the routing region connects the effective heat transfer region with FWN and SN as illustrated in Fig. 4(b). It is assumed that the effective heat transfer region acts as a rigid body of coiled tube bundles and the routing region is attached to FWN and SN only by 375 tubes. Therefore, the effective heat transfer region is modeled as the rigid beam elements with the lumped mass elements as shown in Fig. 4(a). The routing region adopts the Timoshenko beam element, and all 375 tubes are modeled to accurately simulate the motion of SGs. The 1st vibration mode shape of SG is the translation one in the vertical direction(Z). In addition, the 2nd and 3rd mode shapes are translation ones in the circumferential and radial directions.

We adopt the spring elements for the stick model of FWN in the circumferential and radial directions. The static analyses have been done in order to get the spring constants of FWN in the vertical and tangential directions as shown in Fig. 5(a), which were utilized for a spring element in the stick model as shown in Fig. 5(b).

DEVELOPMENT OF STICK MODEL

Stick Model for Each Component

The seismic analysis of a large structure like the reactor usually employs the stick model rather than the solid model. Since the stick model is composed of many beams, lumped masses, rigid and spring elements, it cannot help but have a lot of assumptions and idealizations on imposing the section information, the boundary or constraint conditions between components so as to simplify the installed structure. Since it is very difficult to match such conditions directly, the modal and static analyses with the solid model prior to the development of the stick model have been performed.

RVA, CSB, UGS and CRDM

These components can be characterized as the main parts for the function of the reactor. Since the ratio of the diameter to the height for RVA is about is 0.33, and those of CSB, UGS and CRDM are slightly lower than that

Fig. 1: External appearance of SMART

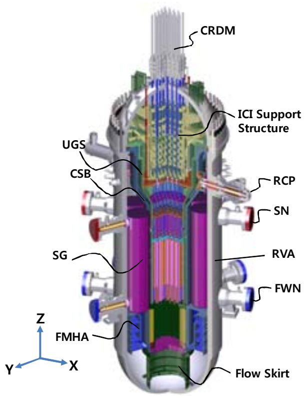


Fig. 2: Internal components of SMART

of RVA, these components are able to be categorized as stubby and thick structures. Hence, this study employs a 3D elastic beam element which includes shear deflection effects. The shear deflection effect is often significant in the lateral deflection of short beams, and it is activated in the stiffness matrix by including proper shear deflection coefficients. The shear deflection coefficients in the section are defined as Eqn. (1).

$$F_i^S = \frac{A_z}{A_i} \quad i = x,\ y \tag{1}$$

where F_i^S and A_i are the shear deflection coefficient and the shear area in the 'i' direction respectively, and A_z is the cross sectional area of the structure. Shear deflection coefficients for common sections are as follows;

$$F^S = \frac{7+6\nu}{6(1+\nu)} \text{ , for circle} \tag{2}$$

$$F^S = \frac{(7+6\nu)(1+m^2)^2+(20+12\nu)m^2}{6(1+\nu)(1+m^2)^2} \text{ , for hollow circle} \tag{3}$$

where ν is the poisson's ratio, and $m(=R_i/R_o)$ means the ratio of inner radius to outer radius of the hollow circle.

And the mass of the respective structures are distributed at the corresponding positions as the lumped mass elements so that the center of the mass and the moment of inertia of mass for each structure can be kept as Eqn. (4)~Eqn. (6).

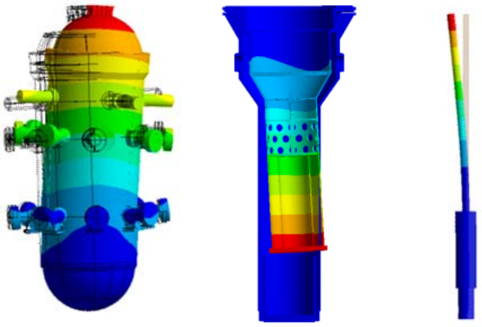
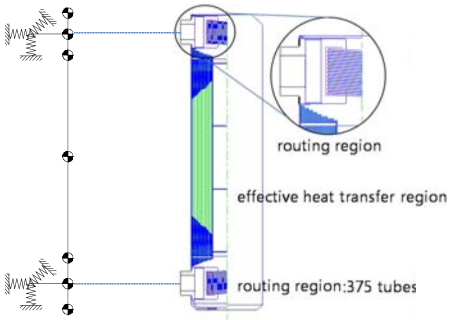
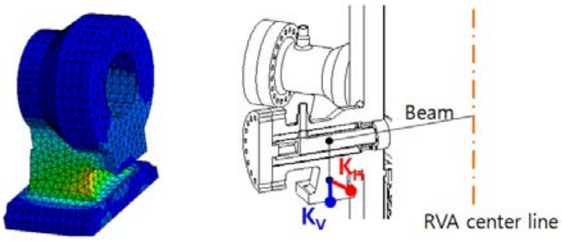

(a) (b) (c)

Fig. 3: Representative mode shapes of the components: (a) 1st mode shape of RVA; (b) 1st mode shape of CSB and UGS; (c) 1st mode shape of CRDM.



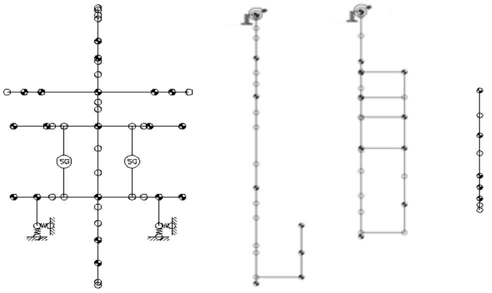
(a) (b

Fig. 4: Stick and detail models of SG: (a) Stick model; (a) Drawing view of SG.



(a) (b)

Fig. 5: Solid and stick models of FWN: (a) Static analysis for getting the directional stiffness; (b) Stick model of FWN modeled as two spring elements.



(a) (b) (c) (d)

Fig. 6: Stick models of the components: (a) RVA and FWN; (b) CSB; (c) UGS; (d) CRDM.

Table 1 Percent errors of the natural frequencies of initial stick and updated stick models with respect to those of solid models.

RVA	Mode shape		translation(X,Y)	torsion(z)	tilting(X,Y)	translation(Z)	1st bending
	FE model	Initial stick model	-13.0	-31.9	-22.4	22.7	15.8
		Updated stick model	-1.9	0.5	4.5	4.1	2.1
CSB	Mode shape		1st bending	extension(Z)	2nd bending		
	FE model	Initial stick model	-20.7	-4.9	-21.4		
		Updated stick model	0.5	0.2	0.0		
UGS	Mode shape		1st bending	extension(Z)	2nd bending		
	FE model	Initial stick model	-6.5	14.6	-4.3		
		Updated stick model	-0.1	0.1	0.0		
CRDM	Mode shape		1st bending	2nd bending	3rd bending		
	FE model	Initial stick model	-8.1	-6.3	-16.9		
		Updated stick model	0.0	3.5	-6.4		
SG	Mode shape		translation(Z)	tranlation(θ)	translation(r)		
	FE model	Initial stick model	-2.8	-1.7	-3.3		
Flow Skirt	Mode shape		tilting(X)	tilting(Y)	torsion(Z)	translation(Z)	
	FE model	Initial stick model	0.0	0.0	0.0	0.0	
FMHA	Mode shape		translation(Z)	tilting(X)	tilting(Y)		
	FE model	Initial stick model	0.0	0.1	0.0		
ICI support structure	Mode shape		tilting(X)	torsion(Z)	translation(Z)	tilting(Y)	
	FE model	Initial stick model	0.0	-0.1	0.3	-1.4	
Fuel Assembly	Mode shape		1st bending	2nd bending	3rd bending	4th bending	
	FE model	Initial stick model	-4.4	-0.3	4.9	0.0	

$$\sum_{i=1}^{N} m_i = M \tag{4}$$

$$\sum_{i=1}^{N} m_i y_i = 0 \tag{5}$$

$$\sum_{i=1}^{N} m_i y_i^2 = I_{CG} \tag{6}$$

where m_i , y_i and N are the lumped mass on the i-node, the location from the mass center and the number of the lumped mass elements respectively. And M and I_{CG} are total mass and the mass moment of inertia of the structures. Fig. 6(a-d) illustrates the beam element, the location of the lumped mass element of RVA, CSB, UGS and CRDM, respectively.

FWN, FMHA, Flow-Skirt, SG and ICI support structure

While RVA, CSB, UGS and CRDM can be assumed to be deformable as mentioned in the previous section, others such as FWN, FMHA, flow-skirt, SG and ICI support structure are modeled as a combination of rigid, spring and lumped mass elements.

In the case of FWN, the previous section has already simulated the static analysis for obtaining the equivalent stiffness in the cylindrical coordinate. Fig. 5(b) and Fig. 6(a) show the two spring elements are connected to the vertical and tangential directions of the respective FWNs, which are linked up with the center line of RVA as a rigid beam element. In the cases of FMHA, flow-skirt, SG and ICI support structure, their natural frequencies are to some extent higher than those of RVA, CSB, UGS and CRDM, and their ratios of the diameter to height is about is 1.0. Therefore, it has been assumed that these components act like the rigid bodies in comparison to other components and this study estimated the stiffness for the spring element as expressed in Eqns. (7, 8) [4].

$$k_I = (2\pi f_I)^2 \cdot M \tag{7}$$

$$k_{\theta,J} = (2\pi f_J)^2 \cdot I_J \tag{8}$$

where k_I, $k_{\theta,I}$, M and I_J denote the spring constants for translation and rotation, mass and mass inertia of moment, respectively.

FE Model updating method

The initial stick models were constructed on the basis of highly idealized engineering designs that may not truly represent all the dynamic aspects of an actual structure. These models often show some deviations from the actual responses and, therefore, need to be updated to match the actual physical data. The FE model updating entails tuning the model so that it can better reflect the actual responses. The problem of how to modify the analytical model from the actual data is known as the FE model updating in structural dynamics[5].

Table 1 shows the results of the modal analysis of the major components. There are deviations of the natural frequencies between the solid models and initial stick ones in RVA, CSB, UGS and CRDM, but the other components are in good agreement with the solid model and stick model. It is necessary to update the stick models in RVA, CSB, UGS and CRDM to get more accurate results. This paper adopts the FE model updating method to produce more acceptable and reliable natural frequencies and mode shapes[5], and uses the analysis results of the solid model as the reference data for the update. The FE model updating procedure is carried out by using a least-square approach which is efficient and common way to solve the updating problem[6]. The objective function, Π, is defined as a sum of the squared differences of the natural frequencies as shown in Eqn. (9).

Objective Function

$$\min \Pi(F_i^S, k_H, k_V) = \sum_{i=1}^{N} \alpha_i \left(\frac{f_{ai} - f_{ei}}{f_{ei}} \right)^2 \tag{9}$$

$$\text{such that} \quad \text{Lower Limit} \le F_i^S, k_H, k_V \le \text{Upper Limit}$$

where, f_{ai} : the natural frequency of the initial FE model

f_{ei} : the target natural frequency of the updated FE model

α_i : the weighted factor of the respective modes

k_H : the stiffness of FWN in the circumferential direction

k_V : the stiffness of FWN in the vertical direction

Design variables are selected as the shear deflection coefficient and the spring constants, and are subjected to constraints with upper and lower limits as shown in Eqn. (9). The optimization is performed by using the sub-problem method in ANSYS. The results of the initial stick models and the updated ones are compared in Table 1. Table 1 shows the deviations in the natural frequencies of the initial stick and updated stick ones with respect to those of the solid models, which are calculated by Eqn. (10).

$$e_i = \frac{f_i - f_{ei}}{f_{ei}} \times 100\ (\%) \tag{10}$$

where, f_i : the natural frequency of the initial or updated FE model

f_{ei} : the referential natural frequency of the solid FE model

Results shows that the natural frequencies from the FE model updating method give a good agreement in comparison with the solid model.

SEISMIC ANALYSIS MODEL

Integration of updated stick models

So far, this study has explained the development procedure of the stick model for each component based on the solid model. Fig. 7 shows the integrated seismic model based on the updated stick model of each component. Components, except for SG, are connected by the given constraint conditions between each component so that their assembled positions can be coaxial as illustrated in Fig. 7. And 8-SGs are linked up with the spring elements on the rigid beams between FWN and RVA.

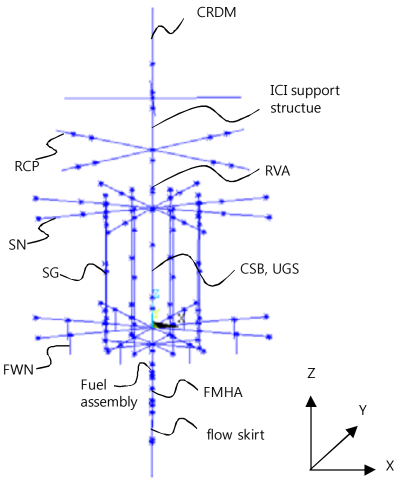


Fig. 7: Seismic analysis model of SMART

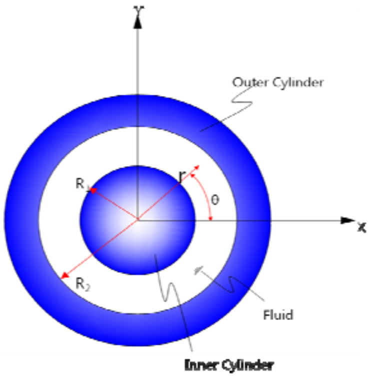


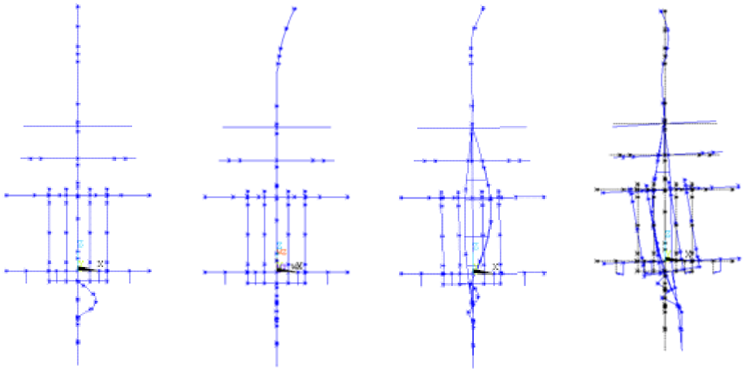
Fig. 8: The fluid in two concentric cylinders

Fluid-structure interaction

SMART includes fluid-coupled cylindrical structures between CSB-UGS, RVA-CSB and CSB-FMHA. It is reported that the fluid-structure interaction may significantly reduce the natural frequencies of such structures due to the hydrodynamic mass of fluid[6,7]. In this paper, the FE model of the fluid-structure interaction adopts a dynamic fluid coupling element whose theory is based on Fritz's work[7]. Fritz suggested the element using a potential flow theory in the two concentric cylinders as illustrated in Fig. 8 assuming that the flow is irrotational, inviscid and incompressible. The element is applicable to the problem where the axial flow in two concentric cylinders is insignificant[7]. Since the assembled configurations of CSB-UGS, RVA-CSB and CSB-FMHA are coaxial as shown in Fig. 2, their axial flows are negligible so that it is acceptable to employ the dynamic fluid coupling element. Fig. 7 shows the seismic analysis model of SMART including the fluid-structure coupling conditions. The residual fluid mass which is not modeled by the dynamic fluid coupling element is considered as the lumped mass element at the corresponding position so that the center of mass for each fluid can be kept.

Nonlinearities

One of the most critical challenges for the seismic analysis of the reactor's structure is how to deal with the nonlinearities of the system. Although it is also common sense that the nonlinear analysis might provide more realistic responses than the linear one, it has been reported that the linear analysis introduces more conservative responses [8]. Hence, this paper deals with the linear response of the reactor based on the above fact. In future, the nonlinear analysis in a sub-system level will be performed so as to obtain more realistic results for the nonlinearities such as contact and slide and so on.



(a) (b) (c) (d)

Fig. 9: Representative mode shapes of SMART: (a) 1st mode of fuel assembly; (b) 2nd mode of CRDM; (d) out of phase bending mode between CSB and UGS; (d) in phase bending mode between CSB and UGS.

MODAL ANALYSIS

In Air

The stick model without the dynamic fluid coupling element was used for the modal analysis, and the fixed boundary conditions are imposed on the ends of the spring elements for FWM as Fig. 6(a). The 1st mode is the bending of the fuel assembly and the 2nd one is the bending of CRDM. These frequencies are lower than those listed in Table 1 because the bottom of the fuel assembly and CRDM is not fully a fixed boundary condition. For RVA, the frequencies of translation modes in the horizontal and vertical directions are also lower than those shown in Table 1. The reason is that the mass of internal structures are added to the RVA. The frequencies of the tilting modes of RVA are slightly decreased, compared to the tilting modes of RVA only. SG is tilted in the horizontal direction and translated in the vertical direction with a higher frequency. The connection between SG and FMHA tends to raise the frequencies of SG. The frequencies of CSB and UGS are 47.10Hz with an in-phase bending mode and 57.56Hz with an out-of-phase bending mode respectively, and ICI support structure showed the translation mode in the vertical direction with lower frequencies than those in Table 1.

In Water

A modal analysis of SMART (including fluid-structure interaction) was performed, which representative mode shapes are illustrated in Fig. 9. The stick model and the boundary conditions are also the same as the ones in air. As a result, the 1st mode is the bending of fuel assembly and the 2nd mode is the bending of CRDM. These frequencies are almost the same as the results (not considering the fluid-structure interaction). The natural frequencies of SG are slightly lower than results in air condition. For RVA, the frequency of the translation modes in the vertical directions is also slightly lower than that in air condition. The reasons are that the masses of the fluid are added to the RVA. However, the frequencies of CSB and UGS are 15.18Hz with out-of-phase and 34.78Hz with the in-phase, respectively. The fluid-structure interaction between CSB and UGS reduced the frequencies about 73% and 26% in the out-of- phase mode and the in-phase mode. Since the 1st through 23th modes of SMART were found to be lower than 33Hz, these should be considered as important vibration modes in the sense of a seismic response. Though the frequencies of the 24th through 37th modes are higher than 33Hz, this study took these into consideration as critical modes because the mass participation ratio from the 1st through 37th modes is about 90%.

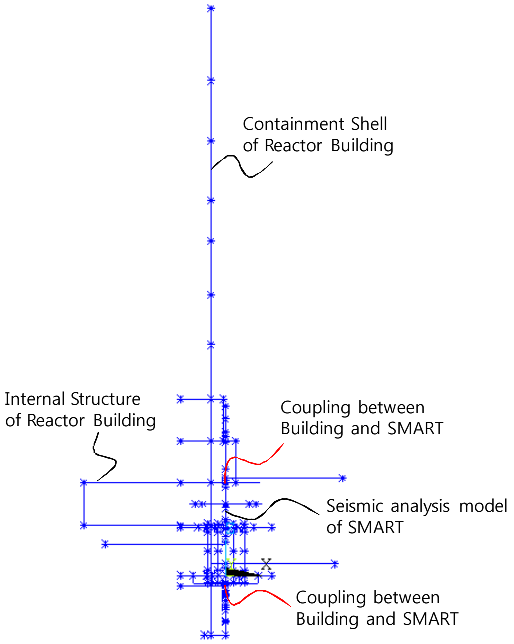
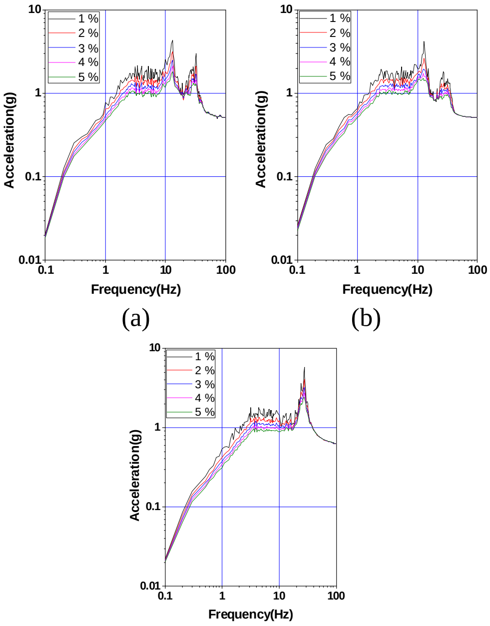


Fig. 10 Seismic analysis model of the reactor building and SMART.



(a) (b)

(c)

Fig. 11 Floor response spectra at the top of fuel assembly: (a) X-direction (horizontal); (b) Y-direction (horizontal); (c) Z-direction (vertical).

SEISMIC ANALYSIS

The seismic analysis model for SMART has been developed as mentioned above, and it is expected to be reliably used for seismic analysis and the design modifications. Above FE model and the results of modal analysis were used for the seismic response evaluation. In addition, we have coupled a reactor building model with the integrated seismic model for SMART using the spring elements which have the local stiffness of the reactor building as shown in Fig. 10. The seismic analysis is carried out by the transient analysis with the acceleration time history of the earthquake with ZPA of 0.3G.

Fig. 11 illustrates the floor response spectra at the top of the fuel assembly with respect to the damping ratios as the results of the seismic analysis. The current design of the fuel assembly is acceptable in terms of the maximum response acceleration. The maximum deflection occurs at the end of CRDM and the top of SG. And the responses of the other components are acceptable. Since the free boundary condition on the body of CRDM results in a higher response, there is a need to add a support structure for CRDM. These results can be considered for the design justification for each component. The design modification for operating the reactor safely can be done in future, and the response against the seismic load can again be simulated.

CONCLUSION

This paper presents the development procedure of the reactor stick model for a seismic. Since there were deviations of the natural frequencies between the solid models and initial stick models of RVA, CSB, UGS and CRDM, the FE model updating method was adopted to get accurate stick models. The stick model for SMART includes fluid-coupled effects between CSB-UGS, RVA-CSB and CSB-FMHA with the dynamic fluid coupling element. The fluid-structure interaction between CSB and UGS reduced the major frequencies about 73% and 26% in the out-of- phase and the in-phase modes, respectively. As a result of the seismic analysis, this study shows that it is preferable to install the support structure for CRDM such as a integral head package.

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