Seismic analysis model construction of the integrated reactor internals

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Abstract

The vibration assessment of the reactor should be performed on the design process in order to secure the safety. The seismic analysis, which is one of the main assessments, identifies dynamic behaviors of the reactor in respect of the seismic input. The accurate understanding of dynamic behaviors of reactor internals which include fuel assembly are especially important. In this research, we focus on the System-integrated Modular Advanced Reactor (SMART) developed in Korea. The 1/12 size scale-down model is manufactured for performing the modal test and the numerical analysis with the three-dimensional (3D) finite element model in order to identify the dynamic characteristics of the reactor internals. As a result, the simplified stick model is constructed reflecting obtained dynamic characteristics so as to perform the seismic analysis.

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1. Introduction

The reactor internals shows response behaviors when they are affected by various dynamic loads such as hydraulic load and seismic load. The vibration assessment evaluates these response behaviors in order to prevent critical accidents causing destruction of the reactor internals. The seismic analysis, which identifies the dynamic behaviors in respect of the seismic inputs, should be performed during the design process in order to secure safety of the reactor internals and the reactor should be manufactured reflecting the results of the seismic analysis. The System-Integrated Modular Advanced Reactor (SMART) developed in Korea is the integrated pressurized water reactor which contains main components such as the core, pressurizers, steam generators and reactor coolant pumps in the one reactor vessel. It means that the SMART doesn’t need primary pipe connections and it results in the elimination of the pipe break accident. However, these innovative structures makes that the SMART cannot use previous data of the seismic analysis which is used in the existing reactors. Thus, it needs original methodology of the seismic analysis for the SMART.

In the seismic analysis, the numerical analysis with the simplified equivalent model, which calls the stick model, is commonly performed because it is difficult to carry out the actual test with the real reactor. The stick model can provide primary low frequency bending modes which are affected by the seismic input and it has great advantage of reduction in analysis time and cost. However, it needs verification with more accurate methods such as the modal analysis with the detailed finite element model because of the uncertainty results from the simplification. Moreover, it should consider the added mass effect from the fluid-structure interaction (FSI) caused by the inner coolant which makes great changes in the dynamic characteristics of the reactor internals.

Lim and Choi manufactured the scale-down model of the SMART internals in order to obtain the dynamic characteristics of the primary internals [1-2]. They constructed the 3D finite element model of the scale-down model and performed the modal analysis. In addition, the extracted modal parameters from the modal test with the manufactured scale-down model are used for comparing the results from the finite element analysis (FEA).

In this paper, we extend the previous research in order to perform the seismic analysis of the SMART. The stick model of the reactor internals is designed reflecting obtained from the modal analysis with the scale-down model. The results of the modal analysis with the stick model compare with the results from the 3D finite element model.
2. Dynamic characteristics identification of the SMART

2.1. The scale-down model of the SMART

Fig. 1 shows the reactor vessel and the inner structures of the SMART. As shown in Fig.1, the SMART includes main components such as the reactor coolant pumps (RCP), pressurizer, steam generators, fuel assemblies in the one reactor vessel. This structure enhances the safety by preventing large break loss of coolant accidents with respect to eliminate the large size pipe connections.

In the seismic analysis, the structures which show dynamic behaviors affected by the low frequency seismic input are considered. In the case of the SMART, two coaxial cylindrical structures which are the CSB assembly including the fuel assembly and the UGS assembly show dominant behaviors in the low frequency. In addition, the inner coolant causes the added mass effect results dramatic decrease in the natural frequencies of the submerged structures and this phenomenon makes the fundamental modes of the structures under the seismic frequency range. Thus, the research focuses on the dynamic behaviors of these two coaxial structures. Fig. 2 represents the manufactured 1/12 size scale-down models of the SMART internals [2].

2.2. Modal analysis with the scale-down model of the SMART

For the seismic analysis, the simplified numerical analysis model should be constructed. It needs verification in order to confirm the reliability by comparing with more accurate methods. In this research, the scale-down model is used for obtaining reliable dynamic characteristics of the reactor internals. First, the 3D finite element models are designed considering detailed features of the scale-down model (Fig. 3). The ANSYS, which is the FE analysis software validated from many previous researches, is used in order to perform the modal analysis. The models also consider FSI effect by modelling the inner coolant using the acoustic fluid elements (FLUID30 in ANSYS). The results from the FEA retain the validity by comparing with the experimental data from the modal test with the scale-down model. In addition, the identified modal parameters from the FEA and the modal test are used for calculating the dynamic characteristics of the real reactor internals through the similarity analysis [2].

![Fig. 2. Scale-down models of SMART internals](image)
3. Equivalent stick model of the reactor internals

3.1. Description of the stick model

There are several methods for the seismic analysis; the time history analysis, response spectrum method of analysis and frequency domain spectral analysis. Among the rest, time history analysis is more accurate analysis method than other methods. Time history analysis is performed to obtain the response of structures for a specified time history of excitation. In the time history analysis, the simplified stick model that has the equivalent dynamic characteristics with the real structures is widely used. It has many advantages such as the reduction in analysis time and providing the clear conclusion about the seismic analysis.

In the stick model, each structure is composed of the beam and lumped mass elements, and boundary conditions are represented with spring elements. In addition, the inner coolant, which causes the added mass effect to the attached structures, is modelled by the lumped mass elements and the fluid elements. Fig.4 shows the stick model of the SMART internals. The primary structures such as the reactor vessel, UGS barrel, and CSB are established by using the beam elements (BEAM188 in ANSYS). These beam elements are divided into several parts in order to reflect the detailed geometric information of the structures which can affect to the dynamic characteristics by changing the stiffness of the structures. The lumped mass elements (MASS21) are used for the each plate in the UGS barrel and fuel assembly in the CSB. The flange part where the CSB assembly and UGS assembly are assembled is represented by the spring element (COMBIN14) considering the deflection of flange and hold-down ring. The spring elements are considered for axle spring and torsional spring and the spring constant is calculated from the results of the 3D FE model. The inner coolant in the reactor vessel is modelled by the lumped mass elements (MASS21) regarded as the added mass. And fluid elements (FLUID38) are adopted for the inner coolant located in the narrow gap between the barrel structures.
3.2. Results of the modal analysis

Table 1 lists the extracted modal parameters of the SMART internals in air from the 3D FE model and stick model. Fig.5 represents the related mode shapes of the SMART internals in air. Table1 shows that the natural frequencies extracted from the stick model are well matched with the 3D FE model. The mode shapes of the stick model depict the bending modes of the CSB assembly and UGS assembly well. Table 2 lists the extracted modal parameters of the SMART internals in water. Fig.6 shows the related mode shapes of the submerged internals. The natural frequencies of the submerged internals from the stick models are well matched with the 3D FE model. It means that the lumped mass elements and fluid elements in the stick model are well applied to represent the added mass effect. The stick model also represents the mode shapes (out-of-phase and in-phase bending mode) of the CSB assembly and UGS assembly well.
Fig. 5. Mode shapes of the reactor internals in air from the 3D FE model and stick model

Fig. 6. Mode shapes of the reactor internals in water from the 3D FE model and stick model

Table 1. Comparison of the modal parameters from the 3D FE model and stick model in air

| Mode Shape \ Mode (n, m) | Natural Frequency (Hz) | Error (%) |
|-------------------------|------------------------|-----------|
| CSB Assembly (1, 1)     | 7.12 3D FE model (a)   | 1.0       |
|                         | 7.05 Stick Model (b)   |           |
| UGS Assembly (1, 1)     | 11.44 3D FE model (a)  | -2.1      |
|                         | 11.68 Stick Model (b)  |           |

* In mode shape: n = the circumferential wave number, m = the number of nodal lines in the axial direction
* Error: (a - b) / a × 100%.
Table 2. Comparison of the modal parameters from the 3D FE model and stick model in water

| Mode Shape (n1, m1, n2, m2) | Natural Frequency (Hz) | 3D Finite element model (a) | Stick Model (b) | Error (%) |
|-----------------------------|------------------------|----------------------------|-----------------|-----------|
| (1, 1, 1, 1) Out-of-Phase   |                        | 3.82                       | 3.78            | 1.0       |
| (1, 1, 1, 1) In Phase       |                        | 6.62                       | 6.45            | 2.5       |

* In mode shape: n1, m1 = the numbers of circumferential waves and nodal line in axial direction of the CSB assembly
n2, m2 = the numbers of circumferential waves and nodal line in axial direction of the UGS assembly
* Error: (a – b) / a × 100%.

4. Conclusion

This research proposes the methodology for constructing the seismic analysis model of the reactor internals. This method makes up for the shortage of the reliability of the stick model from the simplification by using the dynamic characteristics of the real reactor internals extracted from the scale-down model. In this research, we designed the stick model with the beam, lumped mass, and spring elements. It also considers the FSI by using the fluid elements which are used for gap fluid between the structures. The results of the modal analysis with the stick model shows good agreement with the results extracted from the 3D detailed FE model. The natural frequencies of the fundamental modes from the stick model shows difference under 5% comparing with the natural frequencies of the 3D FE model. The mode shapes of the stick model also represent the dynamic behavior of the fundamental modes well including the FSI effect. It means that this stick model is suitable for performing the seismic analysis with the complicated structures such as the reactor internals.

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