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Seismic analysis of the APR1400 nuclear reactor system using a verified beam element model

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HIGHLIGHTS

- A simplified beam element model is constructed based on the real dynamic characteristics of the APR1400.
- Time history analysis is performed to calculate the seismic responses of the structures.
- Large deformations can be observed at the in-phase mode of reactor vessel and core support barrel.

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ABSTRACT

Structural integrity is the first priority in the design of nuclear reactor internal structures. In particular, nuclear reactor internals should be designed to endure external forces, such as those due to earthquakes. Many researchers have performed finite element analyses to meet these design requirements. Generally, a seismic analysis model should reflect the dynamic characteristics of the target system. However, seismic analysis based on the finite element method requires long computation times as well as huge storage space. In this research, a beam element model was developed and confirmed based on the real dynamic characteristics of an advanced pressurized water nuclear reactor 1400 (APR1400) system. That verification process enhances the accuracy of the finite element analysis using the beam elements, remarkably. Also, the beam element model reduces seismic analysis costs. Therefore, the beam element model was used to perform the seismic analysis. Then, the safety of the APR1400 was assessed based on a seismic analysis of the time history responses of its structures. Thus, efficient, accurate seismic analysis was demonstrated using the proposed beam element model.

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1. Introduction

Today, nuclear power generation occupies a large part of electrical energy generation. However, when an accident occurs, a nuclear power generation system can be the most dangerous system because, via radioactivity, it may cause detrimental effects from generation to generation over an extensive area. Thus, nuclear power plants should be designed robustly and securely. To achieve this, the dynamic behaviors should be determined precisely when reactor internal structures are exposed to external vibration sources, such as seismic loads.

Prior to performing any seismic analysis of nuclear reactor internals, it is important to define their dynamic characteristics, such as the natural frequencies and the vibratory mode shapes, because they are used as bases for such seismic analyses. On that account, many researchers have studied the dynamic characteristics of reactor internals by considering the fluid–structure interaction (FSI) effect, as this considerably affects the natural frequencies of the structures. Some researchers approached to the dynamic characteristics in numerical aspects. Kim studied the dynamic characteristics of reactor internals considering fluid effects in a finite element analysis (Kim et al., 2001). Also, Sigrist applied the fluid–structure interactions to the finite element model and studied how the fluid effects influence the dynamic characteristics of the structures (Sigrist and Garreau, 2007; Sigrist et al., 2006, 2007). However, these analytical methods are hard to consider the complex structural shapes and to verify the validity of the numerical analysis. Thus, in order to improve the accuracy of finite element analysis, Choi proposed a methodology for identifying the dynamic characteristics of a small modular reactor by adjusting analytical and experimental methods (Choi et al., 2013). Park identified the dynamic characteristics of a commercial nuclear reactor and constructed finite element models with experimental verification (Park et al., 2014).

Seismic responses of the nuclear reactor internals are affected largely by the gap fluid effect. Thus, this effect should be considered in any finite element analysis. However, extensive computational time and storage space are needed to perform time history seismic analysis based on a three-dimensional (3D) finite element model considering the fluid elements. To solve the problem, some researchers focused on the specific components under the seismic loads because the time history analysis including the many components was hard to be controlled. Recently, Jendzelovsky studied about the response of a cylindrical tank containing the fluid under the seismic loads (Jendzelovsky and Balaz, 2016). Brunesi deducted the numerical outcomes of storage steel tanks by using the finite element analysis (Brunesi et al., 2014). On the other hands, in order to analyze the complex structures, seismic analysis models have been developed based on lumped mass elements because a lumped mass element model can depict the bending modes that have a decisive effect on seismic analysis results; also, this simplified seismic analysis model is useful for quickly extracting seismic responses, such as maximum acceleration and relative displacement. Thus, many researches have been conducted based on lumped mass element models for seismic analysis. Jhung focused on the detailed behaviors of commercial nuclear reactor internal structures (Jhung and Hwang, 1996). Lee performed a time history acceleration response analysis for the upper internal structure of a liquid metal reactor (Lee and Koo, 2001). Koo investigated the fluid effects on the dynamic behaviors of a liquid-metal fast-breeder reactor (LMFBR) and performed a seismic analysis of an entire nuclear power plant system (Koo and Lee, 2004, 2007). Also, Lee simplified the geometry of power plant systems and performed seismic analysis based on lumped mass models, by considering components such as the main steam system, shielding wall, and piping system as non-structural components (NSCs) (Lee et al., 2015). However, most finite element models have not been supported by experimental verification. Moreover, the complex boundary conditions of the reactor internal structures have not been reflected properly in finite element models. Boundary conditions and fluids affect the dynamic characteristics significantly; thus, they should be defined exactly to enhance the accuracy of numerical approaches.

The main purposes of this research are to suggest a methodology for the seismic analysis of nuclear reactor internals and to confirm the accuracy of seismic analyses using beam elements. Based on the dynamic characteristics of a detailed 3D finite element model and experimental verification (Park et al., 2014), a lumped mass element model of an Advanced Power Reactor 1400 MWe (APR 1400) was constructed in steps to replicate precisely the boundary conditions for each assembled condition. Also, the gap fluids were considered because the added mass effect and dynamic coupling of structures from the gap fluid largely affect to the dynamic behaviors of the structures. From this process, a more accurate lumped mass element model was constructed, compared with the other lumped mass element models. Then, time history seismic analyses were performed and the responses of the structures were analyzed. Based on the results, a low-cost, efficient methodology for seismic analysis was proposed for precise determination of the dynamic characteristics of real reactor systems. By applying this methodology to next generation nuclear reactor systems, the safety of the structures can be secured more efficiently.

2. Research target

The APR1400 is a standard advanced pressurized light water reactor developed in the Republic of Korea. The APR1400 was designed to provide enhanced safety and economic efficiency.

Fig. 1 shows the reactor vessel and the internal components of the APR1400 (IAEA, 2011). The reactor vessel (RV) is cylindrical with a hemispherical lower head and contains a core support barrel (CSB). The RV and the CSB assembly have a high slenderness ratio. The lower support structure (LSS), the core shroud (CS), the inner barrel assembly (IBA), and the upper guide structure (UGS) assembly are included in the reactor system.

The nuclear reactor system contains reactor coolant; this coolant causes FSI effects that decrease the natural frequencies throughout the entire system. Generally, a nuclear reactor system has natural frequencies in the seismic frequency range

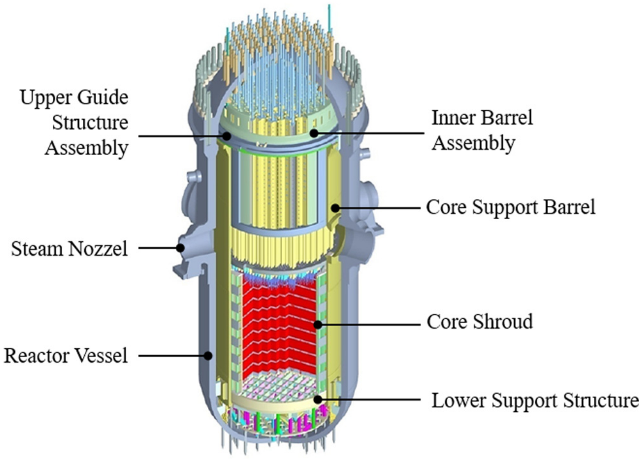

Fig. 1. Schematic configuration of the APR1400 nuclear reactor (IAEA, 2011).