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Numerical study on seismic response of the reactor coolant pump in Advanced Passive Pressurized Water Reactor

Cheng De, Yao Zhen-Qiang*, Xue Ya-bo, Shen Hong

State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China

HIGHLIGHTS

- An artificial accelerogram of the specified **SSE** is generated.
- A dynamic FE model of the RCP in AP1000 (with gyroscopic and FSI effects) is developed.
- The displacement, force, moment and stress in the RCP during the earthquake are summarized.

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ABSTRACT

The reactor coolant pump in the Advanced Passive Pressurized Water Reactor is a kind of nuclear canned-motor pump. The pump is classified as Seismic Category I, which must function normally during the Safe Shutdown Earthquake. When the nuclear power plant is located in seismically active region, the seismic response of the reactor coolant pump may become very important for the safety assessment of the whole nuclear power plant. In this article, an artificial accelerogram is generated. The response spectrum of the artificial accelerogram fits well with the design acceleration spectrum of the Safe Shutdown Earthquake. By applying the finite element modeling method, the dynamic finite element models of the rotor and stator in the reactor coolant pump are created separately. The rotor and stator are coupled by the journal bearings and the annular flow between the rotor and stator. Then the whole dynamic model of the reactor coolant pump is developed. Time domain analysis which uses the improved state-space Newmark method of a direct time integration scheme is carried out to investigate the response of the reactor coolant pump under the horizontal seismic load. The results show that the reactor coolant pump responds differently in the direction of the seismic load and in the perpendicular direction. During the Safe Shutdown Earthquake, the displacement response, the shear force, the moment and the journal bearing reaction forces in the reactor coolant pump are analyzed.

1. Introduction

Advanced Passive Pressurized Water Reactor (PWR) which is also known as AP1000, developed by Westinghouse, is a two-loop 1000 MWe PWR with passive safety features and extensive simplification to enhance its competitiveness in cost and tariff (Schulz, 2006). It is the first Generation III+ reactor to receive final design approval from the U.S. Nuclear Regulatory Commission (NRC) (Ming-chang, 2005). There are four AP1000 power plants under construction at Sanmen in Zhejiang province and Haiyang in Shandong province in China.

The reactor coolant pumps (RCP) in AP1000 system which is hung below the steam generator by the inlet pipe are high-inertia, highly-reliable, low maintenance, hermetically sealed canned-motor pumps that circulate the reactor coolant through the reactor core, loop piping, and steam generators. The reactor coolant transfers heat from the reactor core to the steam generator to create high temperature and high pressure steam which is used to push the steam turbine to generate electricity. The reactor coolant pumps (RCP) are the only power source to circulate the reactor coolant and is the heart of the whole plant. The RCP is classified as Seismic Category I. The prediction of seismic response of the RCP in AP1000 is of great importance.

* Corresponding author at: School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. Tel.: +86 02134206583.
E-mail addresses: 0100209064@sjtu.edu.cn (C. De), zqyaosjtu@gmail.com (Y. Zhen-Qiang).

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The finite element method is used to model the rotor and stator of RCP in this article. The rotor in the RCP with the speed of 1800 cpm (circle per minute) has relatively large rotatory inertia. The model of the rotor using the finite element method must be carefully considered due to the presence of gyroscopic terms. Nelson (1980) generated the rotor element by utilizing Timoshenko beam theory including the effects of the rotatory inertia, gyroscopic moments, axial load, internal damping and the transverse shear. The elements used in this article are derived from the Timoshenko beam theory. Suarez et al. (1992) presented equations of motion of a rotor finite element subjected to six components of base excitation. The equations contained speed dependent gyroscopic terms, base rotation dependent parametric terms and several forcing function terms which depend upon the linear accelerations, rotational accelerations and a combination of linear and rotational velocities. They concluded that various parametric terms in the equation of motion can be ignored without affecting the response. The rotational input terms in the forcing function were important and could be ignored only when they are not strong. As the rotor axis in the RCP is perpendicular to the ground, the input acceleration wave is set to be horizontal which is the most vulnerable direction. So there is no rotational acceleration. Without the rotational acceleration input, linear dynamic model of the rotor in the RCP can be generated for the seismic response research. Leontiev and Degtiarev (2007) developed a methodology to analysis the rotor systems of general type being under horizontal seismic excitation using the finite element method. Chen and Zhu (2008) generate the matrix standing for the rotor by the finite element method and formulated the H2, $H\infty$ and mixed $H2/H\infty$ control strategies by the means of linear matrix inequality (LMI) to attenuate the transient vibration of the flexible rotor system under a nonstationary seismic excitation.

Su et al. (2000) investigated the seismic response of a critical rotating machine either rigidly attached to a floor or independently isolated housed within an initially seismically designed or uncontrolled structure. It is noteworthy that they considered the structure and different isolator into their model. Zhao and Maisser (2006) proposed a multi-body model of wind turbine towers with the consideration of soil–structure interaction (SSI) to investigate their dynamic responses under seismic excitations in time domain. Kostarev et al. (2007) presented a detailed seismic analysis of a powerful high-speed Russian turbine within a nuclear power plant including the building, vibroisolation pedestal and turbine. The rotor of the RCP is housed inside the stator and the whole RCP is hung below the steam generator. Due to the low stiffness, the stator of the RCP cannot be treated as the rigid base. In the analysis, the stator of the RCP is also included in the finite element model. The stator is also modeled by the beam element which is generated by the Timoshenko beam theory including the effects of the transverse shear.

As a canned pump, there is water circulating between the rotor and stator to cool down the motor part. The journal bearings are also lubricated and cooled by water. As the rotor and stator are modeled separately by the finite element method, they are coupled by the upper and lower journal bearings housed inside the RCP and by the annular flow between rotor core and the stator core. When the dynamic displacements are small, the load-deflection relationships of the journal bearings are assumed to be linear. The dynamic effects of the journal bearings are represented by the stiffness matrices and the damping matrices. Antunes et al. (1996) developed a theoretical model for predicting the dynamic behavior and stability of a rotating shaft immersed in concentric or eccentric fluid annulus. The mass, damping and stiffness matrices are generated by the theoretical model. The matrices which represent the force acted on the rotor by the annular flow are used in this paper.

When the dynamic model of the RCP is developed, the input artificial accelerograms need to be obtained. The Safe Shutdown Earthquake (**SSE**) of the AP1000 nuclear power plant can be defined by response spectra corresponding to the expected maximum ground accelerations. The response spectra are defined in the RG1.60 (NRC, 1973). Meng-jia (2008) studied the major features of seismic analysis and design of AP1000 including the seismic categories, response spectra of design ground motion, soil conditions and seismic margin analysis. A rational approach to designing the RCP against seismic excitations involves the use of floor design spectra. Higher floors showed higher amplifications in spectra. The RCP is at the bottom of the AP1000 reactor coolant system. The amplifications will be small. So the AP1000 certified seismic design response spectra (CSDRS) is used in the seismic analysis.

Kaul (1978) proposed a method to describe the relationship between the power spectral density function of the process and the response acceleration spectra. André Preumont (1984) proposed a method for the generation of spectra compatible accelerogram for the design of nuclear power plants by the inverse Fourier transform method with random phase. Ishihara and Sarwar (2008) presented investigations on wind turbine modeling technique for the time domain analysis by using the Newmark-Beta method. By using the inverse Fourier transform method with random phases, Ishihara and Sarwar (2008) also generated the seismic waves for target response spectra specified by the Building Standard Law (BSL, 2004) to simulate the common seismic load. Chen et al. (2010) presented a high precision time domain method, which is used to generate artificial earthquake wave. When the spectra of the **SSE** of AP1000 nuclear power plant are specified, the procedures stated above are used to generate the artificial accelerograms. The numerical procedure proposed in this article is also the main numerical procedure adopted by De Grandis et al. (2009), Perotti et al. (2013) and Carelli Mario (2009) in the computation of seismic fragility of base-isolated nuclear power plants buildings. There are many different synthetic accelerograms which are compatible with different phases, envelopes and durations. According to the numerical procedure presented by Perotti et al. (2013), about fifteen TH calculations should be carried out to get a statistically reliable estimate of the RCP seismic response.

Khulief and Mohiuddin (1997) developed a finite element dynamic model for a rotor-bearing system. The model accounts for the gyroscopic moments and anisotropic bearings. Two modal truncation methods were proposed to get the reduced order form the dynamic model. Kim and Lee (2005) presented a state space Newmark method that incorporates the average velocity concept, and can be applied to the analysis of general dynamic systems that are expressed by state-space first-order differential equations. They also study the transient response of a rotor system under a base-transferred shock force by applying the generalized finite element modeling method using the state space Newmark method of a direct time integration scheme. In this article, the modal truncation method is applied first to get the reduced order form. Then the state space Newmark method based on the average velocity concept is used in the time integration.

In this paper, a full finite element model of the reactor coolant pump in AP1000 with the consideration of rotor–stator interaction is proposed to investigate the dynamic responses to seismic excitations in the time domain. The rotor and stator of the pump are modeled separately and are coupled by the journal bearings and annular flow in the annulus between the rotor and stator. The reduced order model using complex (damped) modal truncation is obtained from the original finite element model. The state space Newmark method that incorporates the average velocity concept is applied to obtain the transient response under the seismic excitation. The numerical method is validated by calculating the example presented by Lee et al. (2006). The results obtained by the method proposed in this article are in good agreement with the result stated in the reference. During the earthquake, the