Analysis of Seismic Performance of Nuclear Power Manipulator Based on ANSYS

Shanshan Zhang\textsuperscript{1*}, Wenman Du\textsuperscript{1}, Qian Li\textsuperscript{1}, Yongqiang Gao\textsuperscript{1}, Guohui Hu\textsuperscript{2}, Guoliang Sun\textsuperscript{1}

\textsuperscript{1}China Telecommunication Technology Labs, China Academy of Information and Communications Technology, Baoding, 071000, China.
\textsuperscript{2}China Nuclear Power Engineering Co., Ltd., Beijing Nuclear Chemical Research and Design Institute

*Corresponding author e-mail: zhangshanshan1@caict.ac.cn

Abstract. Nuclear power manipulator is mainly used in the work of radiation or other human cannot come to the site to operate the environment, the seismic performance has received great attention. In this paper, the modal test of manipulator prototype is carried out by hammering method, combined with ANSYS software, the dynamic response of manipulator model was obtained by response spectrum analysis. The accuracy of the simulation model was calibrated by comparing the experimental and simulation results, to provide a reference for the seismic structure design of nuclear power manipulator in the future.

Keywords: Manipulator, Seismic Performance, Test, Response Spectrum Analysis

1. Introduction
Nuclear power plant structure is a kind of special structure, the safety directly affects the surrounding environment, and even the entire region in which it is located. The accidents at Three Mile Island, Chernobyl and the JCO nuclear power plant all illustrate the risks faced by the nuclear power industry, Therefore, the seismic performance of nuclear power plant structure has been paid great attention. It is of great significance to conduct complex structural dynamic analysis of nuclear power plant structure and related substructures.

Nuclear power small master slave manipulator is a kind of joint master slave manipulator, used for remote operation. It is characterized by small shape and light weight, which can realize fine operation of small operating range, Replace the sword manipulator in use for the small compartment, Aiming at the defects of the sword manipulator used in the protective work box in the field of radiochemical laboratory and isotope production in the reprocessing plant of nuclear power plants in China, a better remote operation tool is provided[1]. In order to research the seismic performance of manipulator, In this paper, ANSYS software is used to conduct static analysis and response spectrum analysis of the manipulator, and to assess stress condition under combined working conditions.
2. Principle of response spectrum analysis
Response spectrum analysis is used in this paper, response spectrum analysis (RSM) is a technique used to estimate the maximum response of a structure in a transient state, the maximum displacement, maximum stress and maximum force of the structure can be obtained by response spectrum analysis. The response spectrum analysis technique combines the response spectrum of a given dynamic load with the modal analysis results[2]. Response spectrum describes the relationship between the maximum response of a single degree of freedom system under a given dynamic load and the natural frequency. They can be used to calculate the maximum modal response of the structure in each mode. These modal maximum response values are then combined using some method (such as a sum of absolute values or a complete quadratic combination (CQC)) to estimate the peak response of the structure.

There are two types of response spectrum calculation, namely single point response spectrum (SPRS) and multi-point response spectrum (MPRS). The seismic analysis of nuclear power plant generally adopts single point response spectrum analysis, therefore, this paper adopts the single-point response spectrum analysis.

The response values (displacement, velocity, and acceleration) for each mode can be obtained from the natural frequency, the mode system, and the mode shape. After obtaining the response values of each mode, in order to obtain the total response value, the response value of each mode needs to be combined in some way.

Each mode is assumed to be a single degree of freedom system, and the transient response of each degree of freedom is expressed as follow:

\[ u_k = \sum \phi \psi X \]

(1)

Where, \( \{ \phi \} \) is the eigenvector, \( \{ \psi \} \) is the modal participation factor, \( (X) \) is the response spectrum.

For the load generated by acceleration, the modal participation factor can be expressed as follow:

\[ \psi = -(\phi)^T (M)^{(T)} \]

(2)

Where, \( \{ \phi \} \) is the eigenvector, \( (M) \) is the mass matrix, \( \{T\} \) is the rigid body displacement caused by excitation.

In the ABS modal combination method, the peak response is estimated as follow:

\[ u_k = \sum \| \phi \| \psi \| X \| \]

(3)

In the CQC modal combination method, the peak response is estimated as follow:

\[ u_k = \sqrt{\sum \sum \lambda \rho \psi \psi} \]

(4)

Where, \( \psi_m \) is the modal response associated with mode m, and \( \rho_{mn} \) is the cross mode coefficient.

3. Seismic wave selection
Floor response spectrum is an important basis for vibration input of equipment on floor and plays an important role in the structural dynamic analysis of nuclear power plants, Floor response spectrum of nuclear power plant is affected by many factors such as SSI analysis, ground motion input, structure and site characteristics. This paper refers to the horizontal and vertical floor response spectra of the building of the nuclear fuel cycle science and technology demonstration project.

According to the requirements of Code for Seismic Design of Nuclear Power Plants (GB 50267-97), in this paper, the floor response spectra of the operating reference earthquake (SL-1) and the safety
shutdown earthquake (SL-2) are calculated respectively. According to "RG.1.61 Seismic Design Damping Value of Nuclear Power Plant" standard requirements, The damping ratio under SL-1 seismic load is 2%, as shown in Figure 1, and 3% under SL-2 seismic load, as shown in Figure 2.

![Figure 1. The damping ratio under SL-1 seismic load](image1.png)

![Figure 2. The damping ratio under SL-2 seismic load](image2.png)

4. Test
The manipulator is mainly composed of the active forearm, the active upper arm, the wall pipe, the driven upper arm, the driven forearm, the handle and the clamp. Each part is transmitted through the wire rope and chain.

The natural frequency of the manipulator is measured by the natural frequency measuring system of hammering method[3]. Realize the excitation (percussion) and response on the computer real-time display hammer frequency response curve, calculate the transfer function and other spectrum analysis. Portable USB interface data collector is used in this experiment.

The configuration and installation of experimental equipment are shown in Figure 3.
Figure 3. The configuration and installation of experimental equipment

5. Response spectrum analysis

5.1. Finite element modeling
In this paper, Altair HyperMesh software is used to simplify the structure, divide the mesh, select the element, set the material and set the boundary conditions. The overall structure of the manipulator is simulated by shell-plate element (SHELL181) and tetrahedral element (SOLID187), rigid units are used for welding, beam unit (BEAM188) are used for bolting, the weight block was simulated by mass21 unit. The analysis model is shown in Figure 4.

Figure 4. The analysis model

5.2. Material definition
The main material physical parameters of this analysis are shown in Table 1 below.
Table 1. The main material physical parameters

| Material Type | Type | Y yield strength | Modulus of elasticity (GPa) | Density (g/cm³) | Yield strength (MPa) | Tensile strength (MPa) |
|---------------|------|-----------------|----------------------------|----------------|---------------------|-----------------------|
| 14Cr17Ni2     | 0.3  | 206             | 7.9                        | 540            | 1080                |                       |
| 06Cr19Ni10    | 0.3  | 206             | 7.93                       | 210            | 520                 |                       |

5.3. Loading and solving
The embedded wall pipe is simulated by tetrahedron element, and the translational freedom of the external surface of the embedded wall pipe is constrained in X, Y and Z directions. The solution was solved by ANSYS software[4].

6. Results analysis

6.1. Comparison of modal test results with experimental results
The vibration shapes of the driving arm and the driven arm of the equipment measured by hammering test are shown in Figure 5. The modal modes of the driving arm and the driven arm are calculated by modal analysis, as shown in Figure 6. The frequency comparison between the two is shown in Table 2.

![Figure 5](image1.png)
![Figure 6](image2.png)

Figure 5. The vibration shapes of the driving arm and the driven arm of the equipment measured by hammering test

Figure 6. The modal modes of the driving arm and the driven arm are calculated by modal analysis

| Left-right direction | Test mode (Hz) | Simulation analysis mode (Hz) | Otherness (%) |
|----------------------|----------------|-------------------------------|---------------|
| Driving arm          | 4.347          | 4.746                         | 9             |
| Driven arm           | 4.200          | 4.359                         | 4             |

By comparing the test modes and simulation analysis modes of the driving arm and the driven arm, the difference between them is 9% and 4%, far less than the general requirement for modal analysis (20%).
the accuracy of the calculation model is verified, can be used for subsequent static analysis and response spectrum analysis [5].

6.2. Static analysis and response spectrum analysis results
The displacement and stress nephograms of the structure under the combined working conditions of static analysis and SL-1 response spectrum analysis are shown in Figure 7. The displacement and stress nephograms of the structure under the combined working conditions of static analysis and SL-2 response spectrum analysis are shown in Figure 8.

![Figure 7](image1)
![Figure 8](image2)

Figure 7. The displacement and stress nephograms of the structure under the combined working conditions of static analysis and SL-1 response spectrum analysis

Figure 8. The displacement and stress nephograms of the structure under the combined working conditions of static analysis and SL-2 response spectrum analysis

7. Conclusion
(1) In this paper, the hammering method is used to test the modal, and the hammering method is used to test the natural frequency of the engineering structure. It is simple and easy to do, and can completely obtain the test results that meet the engineering requirements.

(2) Compared with the measured natural frequency and the simulation frequency, the difference between the two is less than 10%, and the simulation analysis results can accurately reflect the force situation of the manipulator.

(3) In this paper, the finite element model of manipulator is established, which takes into account the connection relationship and interaction between various parts of manipulator, and the analysis results are accurate and reliable. This modeling method can be extended to the response spectrum analysis of similar structures.

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