ANALYSIS ON VIBRATION CHARACTERISTICS OF THE SPENT FUEL POOL INSTRUMENT UNDER THE INTERACTION OF SEISMIC LOAD AND FLUID FORCE

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ABSTRACT
In an earthquake, the loads acting on the spent fuel pool instrument are very complicated, which are mainly comprised with seismic loads and fluid forces. The reliability of the spent fuel pool instrument is very important for the security of nuclear power plant under the interaction of seismic loads and fluid forces. Using the principle of force superposition, the mechanical property of the spent fuel pool instrument was analyzed considering both seismic loads and fluid forces in this paper. Firstly, the natural frequencies of the spent fuel pool instrument were calculated with finite element method both in air and water, especially in water, the added mass of the instrument was calculated. And based on the finite element model, the max stress of the instrument under the seismic loads was calculated. Secondly, the hydrodynamic pressures of the spent fuel pool instrument under the earthquake conditions were calculated by the potential fluid theory. Lastly, in order to obtain the flow-induced vibration of the instrument, the coupling vibration equation of the measuring guide tube was presented in this paper to calculate the stress of the tube.

NOMENCLATURE
Flow-induced vibration, Spent fuel pool instrument.

INTRODUCTION
The spent fuel pools, which sit at the reactor buildings and are meant to keep spent fuel submerged in water, are very important to the security of the nuclear reactor. During an earthquake, the mechanical characteristics of the spent fuel pools instrument would be more complicated under seismic loads and fluid forces. For the new designed spent fuel pool instrument, it is necessary to analyze the seismic responses of the elastic tube of the spent fuel pool instrument. Lots of structural seismic analysis was performed in recent years. Jibson and Keefer[1] developed an approach for judging if a landslide or group of landslides of unknown origin was more likely to have formed as a results of earthquake shaking or in a seismic conditions. Sadek and Isam[2] presented a thorough study of the behavior of inclined micro-piles under seismic loading. Their studies provided valuable information about the influence of micro-piles inclined on dynamic amplification and on the seismic-induced internal forces in micro-piles. A new simplified pushover analysis procedure was proposed by Jan and Wang[3], which could estimate the seismic demands of high-rise buildings. Guan and Chen[4] used ANSYS to complete the analysis of the behaviors of structures with and without wind generator, under El-Centro earthquake wave and Taft earthquake wave. By comparing the results of those two
models, the feasibility of the wind energy and building integration was verified. Penna and Lagomarsino[5] presented a macro-element model specifically developed for simulating the cyclic in-plane response of masonry wall, with possible applications in nonlinear static and dynamic analysis of masonry structures.

The spent fuel pool instrument consists of a long elastic tube named measuring guide tube, which subjected to the action of fluid in the earthquake condition. So, the vibration characteristics of the spent fuel pool instrument are very complicated. It is required to demonstrate that the spent fuel pool instrument is adequately designed at the earthquake condition for the design life.

As shown in Fig.1, the measuring guide tube was fixed on the installation base, which can be regarded as the cantilever beam. The length of the measuring guide tube is 9 m, the outside diameter is 21.3 mm, the inside diameter is 17.3 mm, the main material is stainless steel, the modulus of elasticity $E$ is 210 GPa. Based on the assumption that there are little influences between the seismic loads and fluid forces, the seismic analysis and the analysis of turbulent fluid were presented respectively, and the detail analysis method and results were provided in this paper.

![Figure 1: Spent Fuel Pool Instrument](image)

**FIGURE 1: SPENT FUEL POOL INSTRUMENT**

**SEISMIC ANALYSIS**

The seismic analysis model (Finite Element Model) of the spent fuel pool instrument is shown in Fig.2. The material properties of the spent fuel pool instrument are shown in Tab.1. It contains the installation base and the long elastic tube (the measuring guide tube). The installation base was fixed at the floor by eight bolts. Seismic load spectrums, including OBE and SSE, are shown in Fig.3. The first three natural frequencies of the spent fuel pool instrument in air and water were obtained through modal analysis shown in Tab.2. It is obvious that the natural frequencies of the instrument are much lower than the frequency of the seismic load, which would not lead to the resonance. The analysis of the spent fuel pool instrument under seismic load was accomplished by combining spectral analysis with residual mass method. The maximum stresses of the spent fuel pool instrument were calculated when the water depth of the pool was 12 m both at OBE and SSE conditions. And the calculation results were shown at Fig.4~5 and Tab.3.

![Figure 2: The Seismic Analysis Model of the Spent Fuel Pool Instrument](image)

**FIGURE 2: THE SEISMIC ANALYSIS MODEL OF THE SPENT FUEL POOL INSTRUMENT**

**TABLE 1: THE MATERIAL PROPERTIES OF THE SPENT FUEL INSTRUMENT**

<table>
<thead>
<tr>
<th>Material</th>
<th>Elasticity modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Tensile strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Allowable stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>$2.04 \times 10^5$</td>
<td>0.3</td>
<td>520</td>
<td>206</td>
<td>130</td>
</tr>
<tr>
<td>316L</td>
<td>$2.04 \times 10^5$</td>
<td>0.3</td>
<td>480</td>
<td>175</td>
<td>120</td>
</tr>
<tr>
<td>A4-70</td>
<td>$1.98 \times 10^5$</td>
<td>0.3</td>
<td>800</td>
<td>600</td>
<td>130/78</td>
</tr>
</tbody>
</table>

![Figure 3: The Seismic Load Spectrums of OBE and SSE](image)

**FIGURE 3: THE SEISMIC LOAD SPECTRUMS OF OBE AND SSE**
TABLE 2: THE NATURAL FREQUENCIES OF THE SPENT FUEL POOL INSTRUMENT

<table>
<thead>
<tr>
<th></th>
<th>In air</th>
<th>In water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st frequency</td>
<td>1.073</td>
<td>1.013</td>
</tr>
<tr>
<td>2nd frequency</td>
<td>3.005</td>
<td>2.839</td>
</tr>
<tr>
<td>3rd frequency</td>
<td>5.887</td>
<td>5.564</td>
</tr>
</tbody>
</table>

FIGURE 4: COLORED STRESS PATTERNS OF OBE: (A) MEMBRANE STRESS; (B) MEMBRANE STRESS AND BENDING STRESS

TABLE 3: THE CALCULATION RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Membrane stress(MPa)</th>
<th>The limit stress(MPa)</th>
<th>Membrane stress and bending stress(MPa)</th>
<th>The limit stress(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBE</td>
<td>22.7</td>
<td>S=120</td>
<td>26.2</td>
<td>1.5S=175.5</td>
</tr>
<tr>
<td>SSE</td>
<td>50.3</td>
<td>S=120</td>
<td>57.9</td>
<td>1.5S=175.5</td>
</tr>
</tbody>
</table>

FIGURE 5: COLORED STRESS PATTERNS OF SSE: (A) MEMBRANE STRESS; (B) MEMBRANE STRESS AND BENDING STRESS

ANALYSIS ON THE VIBRATION UNDER FLUID FORCE

The equation of motion of the measuring guide tube is expressed as:

\[
EI \dddot{u} + \frac{\rho A}{g} \dddot{z} \left( u + u_g \right) - P = 0
\]  

(1)

Where \( E \) is the modulus of elasticity; \( I \) is the inertia moment of the tube; \( \rho \) is the density of the tube; \( A \) is the cross area of the tube; \( u \) is the elastic displacement; \( u_g \) is the horizontal displacement of the floor; \( P \) is the water pressure.

According to the boundary conditions of the measuring guide tube and the potential fluid theory, the dynamic water pressure can be divided into rigid dynamic water pressure and elastic dynamic water pressure. The rigid dynamic water pressure can be calculated as:

\[
P = P_{r=a_1} + P_{r=a_2}
\]

(2)

Where,
Based on the potential fluid theory, the elastic dynamic water pressure can be calculated by:

\[
P_{r=a_1} = \frac{8h\gamma_0 a_2}{\pi g} u_n \sum_{s=1,3,5}^{\infty} \left( \frac{(-1)^{s-1}}{s^2} \left( \frac{K_{ls}(r_1)}{K'_{ls}(r_1)} \right) \right) \cos \frac{\pi s}{2h} z
\]

\[
P_{r=a_2} = \frac{8h\gamma_0 a_2}{\pi g} u_n \sum_{s=1,3,5}^{\infty} \left( \frac{(-1)^{s-1}}{s^2} \left( \frac{I_{ls}(r_1)}{I'_{ls}(r_1)} \right) \right) \cos \frac{\pi s}{2h} z
\]

Based on the potential fluid theory, the elastic dynamic water pressure pressure can be calculated by:

\[
P = -\frac{4\gamma_0 a_2}{g} \sum_{s=1,3,5}^{\infty} \sum_{n=1}^{\infty} \left( \frac{I_{ls}(r_1)}{I'_{ls}(r_1)} \right) \left( \frac{K_{ls}(r_1)}{K'_{ls}(r_1)} \right) \cos \frac{\pi s}{2h} z \int_0^h X_n \cos \frac{\pi s}{2h} \xi d\xi
\]

Where, \( I \) and \( K \) are the Bessel function of the first and second kind; \( h \) is the length of the tube; \( a_1 \) and \( a_2 \) are the inner and outer diameter, respectively.

By substituting the rigid and elastic water pressures to the motion equation, the stress and the displacement of the tube can be calculated. The calculation results were shown at Tab.3.

**TABLE 3: THE CALCULATION RESULTS**

<table>
<thead>
<tr>
<th></th>
<th>The maximum stress(MPa)</th>
<th>The limit stress(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBE</td>
<td>14.5</td>
<td>S=120</td>
</tr>
<tr>
<td>SSE</td>
<td>34.1</td>
<td>S=120</td>
</tr>
</tbody>
</table>

**RESULTS**

Based on the force superposition principle, the mechanical property of the spent fuel pool instrument was analyzed considered both seismic load and fluid force, and the maximum stress of the spent fuel pool instrument at OBE condition is 40.7 MPa, the maximum stress of the spent fuel pool instrument at SSE condition is 92.0 MPa. According to RCC-M, the calculation results show that the spent fuel pool instrument is adequately designed at the earthquake condition for the design life.

**ACKNOWLEDGMENTS**

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**REFERENCES**


