Numerical simulation and structure optimization of control rod drop impact in floating reactor

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Abstract. In order to simulate the impact of control rod assembly on upper grid plate of reactor core after emergency shutdown of offshore floating reactor, the structure size of upper grid plate was optimized. In this study, ADAMS simulation software was used to simulate the impact stress and strain of 50 mm and 100 mm thick upper grid plate with and without spring buffer at 0.5 m / s impact speed. Therefore, the thickness of the buffer plate on the grid can be reduced, and the simulation results show that the buffer plate can be optimized effectively.

1. Introduction

In recent years, as an organic combination of offshore ship platform engineering and nuclear energy engineering [1-2], offshore floating nuclear power station has been highly valued by the state and industry. As an important means of reactor safe shutdown, the rapid rod dropping of control rod drive line is an important research field of reactor. Due to the high cost, long cycle and many limitations of control rod drive line test, theoretical research and simulation analysis are generally conducted in engineering design to provide theoretical basis for the test, and then test verification is carried out. [3].

Yan Dapeng [3] analyzed a continuous impact force model coupled with hydraulic buffer and mechanical buffer structure. Through comprehensive calculation and analysis, it was recommended that the fluid compressible model should be preferred for rod drop impact buffering of control rod drive line. Zhu Zihao's paper [4] is used in LMS Virtual. Lab The virtual ball is set in the motion software to model and solve the rod dropping process of the drive line of floating nuclear power plant, and the dynamic simulation method suitable for the marine condition is obtained. Guo Xiaoming paper [5] analyzed the impact force of CF series fuel assembly in the buffer process, compared and analyzed the rod drop impact results of different guide tube and buffer section structures, providing reference for subsequent improvement. In this paper, Xu Zhen [6] analyzed the force condition of the control rod in each stage of the inclined rod dropping process, and obtained the rod dropping control equation. Ma Chao [7] analyzed the rod drop sensitivity of control rod drop calculation program crac under different loop flow conditions.

At present, a large number of rod drop studies in China only focus on the analysis of rod drop time and rod drop process, and the impact analysis of rod drop after impact with related structural components is less. In this paper, based on the control rod assembly of offshore floating reactor under the action of gravity and acceleration spring, the impact of rod drop on the grid plate of the reactor internals is analyzed and evaluated by using the simulation software, and the reasonable optimization scheme is proposed to reduce the damage of the reactor internals caused by the impact force of rod dropping.
2. Research object
During the emergency shutdown of offshore floating reactor, the control rod will drop rapidly; during the rod dropping process, the control rod drive line will collide with the 50 mm thick upper core plate of the reactor internals at a speed of 0.5 m / s after passing through the rod drop buffer structure, as shown in Figure 1.

In order to reduce the deformation of the upper core plate after rod drop impact, the thickness of the upper core plate can be increased or the buffer spring device can be added at the bottom of the control rod. Simulation analysis method is used to simulate the deformation of the upper core plate after rod drop impact. The analysis provides technical support for selecting reasonable scheme in engineering application.

(1) Scheme of thickening upper core plate
In this scheme, the thickness of the upper core plate is increased, and the control rod impacts the upper core plate with different thicknesses of 50mm and 100mm at the final velocity of 0.5m/s, and the maximum deformation is calculated.

(2) Scheme of adding buffer spring
In this scheme, a spring is installed at the bottom of the control rod, the spring compression is 100 mm, and the spring stiffness is 20 N/mm; through simulation analysis, the maximum deformation is calculated when the 50 mm upper core plate is impacted at the final velocity of 0.5 m/s and 1.1m/s respectively.

Through the simulation analysis of the maximum deformation of the upper core plate under different working conditions, the reasonable design scheme is optimized.

3. Analysis method and process
HyperMesh was used to simplify the geometric model, mesh generation and assembly MSC. Dytran. The software module establishes Euler domain, sets contact and coupling to simulate the falling process of control rod; uses LS-DYNA module to obtain control rod, collision speed, and calculates the collision
between control rod and upper core plate; uses LS Prepost software module to obtain the core Analysis results of impact force, stress and deformation of upper plate.

3.1. Meshing.
Since it is necessary to analyze the stress condition of the upper core plate after collision, and the minimum gap between holes is 2mm, hexahedral solid element is used to mesh the upper core plate, and the minimum size is set as 1mm in the weak part, as shown in Fig. 3:

(a) Grid generation at round hole (b) Grid generation at the edge of core plate

Figure 3. Grid generation of upper core plate

In LS-Dyna, the spring element is a discrete element (DISCRETE), which is represented by a line segment connecting the two ends of the spring. The upper end point of the spring shares a node with the bottom center of the control rod, and the lower end point is connected with the barrel through rigid constraints. Because the spring element also participates in the control of the calculation step length in LS-Dyna, the mass must be added to the two nodes of the spring, so the mass is added to the lower node of the spring Unit of measurement. Therefore, the grid division of control rod and buffer spring is shown in Fig. 4.

Figure 4. Buffer spring model

3.2. Material setting
The upper core plate is made of 321 stainless steel and the control rod assembly is made of 304 stainless steel. The linear elastic material model (MAT) is used in LS-Dyna. Material parameters are shown in Table 1.

| NO. | Parts                        | Material Science | Modulus of elasticity (GPA) | Yield strength (MPA) | Poisson's ratio |
|-----|-------------------------------|------------------|----------------------------|----------------------|----------------|
| 1   | Upper core plate              | 321              | 190                        | 205                  | 0.3            |
| 2   | Control rod assembly          | 304              | 190                        | 205                  | 0.3            |

3.3. Contact settings
The collision between the control rod assembly and the core plate is a contact process, and the contact is a highly nonlinear behavior. In LS-Dyna, we use surface contact based on penalty function method (SURFACE_TO_SURFACE) to complete the contact setting by specifying the contact master surface
and contact slave surface. The output can be set to obtain the curve of contact force changing with time in the process of collision.

3.4. Solution settings
LS-Dyna is an explicit dynamic solver. In order to make the results converge, the time step is limited. (1) In order to avoid contact initial penetration, there is an initial gap of 0.5mm between the cylinder and the upper core plate; (2) The gravity acceleration is set as 9.8m/s²; (3) The initial vertical downward velocity (0.5m/s, 1m/s) was added to the control rod assembly; (4) In order to avoid penetration in the contact process, the time step coefficient is taken as 0.5, and the minimum time step is controlled at a small level.

4. Impact simulation results
According to the simulation analysis and solution of four different working conditions in the two schemes of thickening the upper core plate and adding buffer spring, the following different simulation results can be obtained, as shown in Table 2:

| Condition          | Collision velocity (m/s) | Plate thickness (mm) | Maximum stress (MPa) | Maximum deformation (mm) |
|--------------------|--------------------------|----------------------|----------------------|--------------------------|
| Upset upper core late | 0.5                      | 50                   | 760                  | 4.8                      |
| Upset upper core late | 0.5                      | 100                  | 539                  | 1.60                     |
| Spring device      | 0.5                      | 50                   | 52.55                | 0.398                    |
| Spring device      | 1                        | 50                   | 115.48               | 0.88                     |

4.1. Condition 1
When the control rod impacts the 50 mm thick upper core plate at the final velocity of 0.5 m / s, the maximum stress of 760 MPa occurs at 8 ms, the maximum deformation occurs at 8.4 MS, and the depression deformation is - 4.80 mm; the maximum stress nephogram is shown in Fig. 5(a), the maximum stress time history curve during the collision process is shown in Fig. 5(b), and the maximum deformation curve is shown in Fig. 5(c).
According to the above analysis results, the impact stress has reached the yield limit of the upper core plate material, so it can not meet the requirements of condition I.

4.2. Condition 2

When the control rod impacted the 50mm thick upper core plate at the final velocity of 0.5 m/s, the maximum stress was 593 MPa at 3.36ms, and the maximum deformation occurred at 3.04ms, and the depression deformation was -1.60mm. At this time, the yield limit of the upper core plate material was reached. The maximum stress nephogram is shown in Fig.6(a), the maximum stress time history curve during collision is shown in Fig.6(b), and the maximum deformation curve is shown in FIG. 6(c).
According to the above analysis results, the impact stress has reached the yield limit of the upper core plate material, so it can not meet the requirements of condition II.

4.3. Condition 3
After the buffer spring was set at the bottom of the control rod, the 50mm thick upper core plate was impacted at the speed of 0.5m/s. The maximum stress was 52.55MPa at 83.5 ms and 0.398mm at 83.5ms. The maximum stress nephogram is shown in FIG.7(a), the maximum stress time history curve during collision is shown in FIG. 7(b), and the maximum deformation curve is shown in FIG. 7(c).
According to the above analysis results, the impact stress is less than the yield limit of the upper core plate material, which meets the requirements of condition III.

4.4. Condition 4
After the buffer spring was set at the bottom of the control rod, the 50 mm thick upper core plate was impacted at the speed of 1.1m/s. The maximum stress was 115.48MPa at 83.5ms and 0.88mm at 83.5ms. The maximum stress nephogram is shown in FIG.8(a), the maximum stress time history curve during collision is shown in FIG. 8(b), and the maximum deformation curve is shown in FIG.8(c).
According to the above analysis results, the impact stress is less than the yield limit of the upper core plate material, which meets the requirements of condition IV.

4.5. Result analysis

Through the simulation analysis of the above four kinds of rod drop impact conditions, it is found that in the process of impacting the upper core plate in condition 1 and condition 2, there will be greater stress and deformation when the upper core plate is directly contacted. The stress is far more than the allowable stress of 321 stainless steel, and increasing the thickness of the upper core plate has no obvious effect on reducing the impact stress and deformation of the upper core plate.

After adding the spring buffer device, the stress and deformation of the 50mm thick upper core plate in the impact process are relatively small, which is within the range of material physical properties. Even if the influence of water resistance is ignored, that is, the control rod assembly impacts the upper core plate at 1.1 m/s, the maximum stress of the upper core plate is within the allowable stress of the material.

The calculation and analysis show that the maximum stress and deformation of the grid plate on the core can meet the requirements of the limit when the collision velocity is 0.5 m/s and 1.1 m/s respectively, and the thickness of the grid plate on the core remains unchanged (50mm).

5. Conclusion

Through the simulation analysis, it can be concluded that when the control rod collides with the upper core plate at a certain end velocity, increasing the thickness of the upper core plate has limited contribution to reducing the stress and deformation, while adding the buffer spring can effectively reduce the stress and deformation of the upper core plate. Therefore, the scheme of adding buffer spring
to the control rod can be used to reduce the stress and deformation of the upper core plate for further engineering test verification.

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