Calculation and Analysis of Stable Operation of Feed water Pumps for Floating Nuclear Power Stations under Marine Conditions

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Abstract. Feed water pumps play an important role in floating nuclear power plant system equipment, and their safe and reliable operation directly affects the safety and reliability of the entire power plant. The movement status of floating nuclear power plants under sea conditions will change, and additional inertial forces are generated on the pipelines of the water supply system, which may cause cavitation of the feed water pump. This paper deduces the additional force on the fluid at the inlet pipe of the feed pump under the marine environment, establishes a mathematical model of the fluid flow at the inlet pipe of the feed pump under the influence of ocean conditions, and calculates the stable operation of the feed pump under the ocean conditions once in a century according to the layout plan. The requirements of effective cavitation allowance and necessary cavitation allowance provide theoretical calculation basis for design and layout optimization of feed pumps for floating nuclear power plants.

1. Introduction
As the key equipment of the secondary loop system of the floating nuclear power plant, its ability to operate safely and stably is related to the overall safety and economics of the secondary loop system and even the nuclear power plant [1]. Preventing cavitation is a basic requirement for the operation of the feed pump. The movement state of floating nuclear power plants changes under marine conditions, and the feedwater system will generate additional inertial forces, which may cause the feedwater pump inlet pressure to be lower than the saturation pressure at the corresponding temperature and cause cavitation, which will affect the thermal and hydraulic characteristics of the entire nuclear power plant on normal working condition.

In order to ensure the stable and safe operation of the feed pump of a floating nuclear power plant, it is necessary to establish a detailed mathematical model of the fluid flow at the inlet pipe of the feed pump affected by ocean conditions. The traditional methods of analyzing the marine conditions are to simplify the marine conditions into independent fluctuations and swings, and to analyze and study the effects of them separately. It is difficult to comprehensively consider the impact of actual marine conditions. However, the flow characteristics of fluids under actual ocean conditions are extremely complicated, with translation in three directions and rotation in three directions. In order to realistically simulate the operating characteristics of feedwater pumps under marine environmental conditions, this paper deduces the additional forces of 6 degrees of freedom on the pipeline fluid at the inlet of the
feedwater pump, which can provide calculation model support for the operational stability analysis of the feedwater pumps of floating nuclear power plants under marine conditions.

2. Mathematical model building

2.1. An analysis of marine conditions once in a century

Based on statistics of wind and wave parameters in a certain sea area for one hundred years, in order to analyze the flow of the fluid when the ship is shaking, a non-inertial coordinate system oxyz fixed on the ship is used for research. The inertial coordinate system oxyz is fixed to the earth. In order to solve the six-degree-of-freedom motion of the hull, the hydrodynamic calculation software AQWA [2] based on the three-dimensional potential flow theory was used to calculate the hydrodynamic response of the hull in the frequency domain, and the RAO curves of the motion of different degrees of freedom were obtained. The three-dimensional potential flow theory is based on the micro-amplitude wave hypothesis and linear principle. The velocity potentials are solved according to the boundary conditions. The pressure distribution in the flow field is obtained from the Lagrange integral equation, and the flow field at each point on the wet surface of the floating body is obtained. The pressure integral determines the fluid force on the float.

2.2. Mechanical analysis of fluid flow under marine conditions

The fluid is segmented according to the pipeline, and translational and rotational forces in three directions are considered for each segment of fluid, and these inertial forces are decomposed into a direction perpendicular to the flow and a direction parallel to the flow. Because the component force perpendicular to the flow direction has no effect on the flow, it is not considered in the calculation; the component force parallel to the flow direction will hinder or drive the fluid.

The pressure drop (regardless of positive or negative) that acts as a hindrance or drive due to the inertial force component is collectively referred to as an additional pressure drop. The additional pressure drop due to ocean conditions is expressed as:

$$\Delta p = \left( \int_{L} (F_1 + F_2) \frac{dL}{dL} \right) / A$$

(1)

Where: $\Delta p$ represents the additional pressure drop caused by ocean conditions, $Pa$, $F_1$ is the additional force on the fluid in the control body due to rotation, $N$, $F_2$ is the additional force on the fluid in the control body due to translation, $N$, $L$ is the control body, $A$ is Cross-sectional area in the direction of flow.

2.2.1. Derivation of additional pressure drop on the rotating fluid. The additional force on the rotating fluid of the pipeline is divided into two parts, normal force and tangential force, which is expressed as [3-4]:

$$F_1 = F_n^r + F_t^r = -dm \left[ \bar{\omega} \times (\bar{\omega} \times \bar{r}) + \bar{\beta} \times \bar{r} \right]$$

(2)

In the formula, $\bar{\omega}$, $\bar{\beta}$ are the rocking angular velocity and the angular acceleration at time $t$, respectively, $F_n^r$ indicating the normal force and $F_t^r$ the tangential force.

As shown in Figure 1, when the hull is swung (rolled) about the x axis:

$$\bar{L} = (x_2 - x_1, y_2 - y_1, z_2 - z_1) \quad \bar{r} = (x, y, z)$$

(3)

$$F_n^r = -dm \left[ \bar{\omega} \times (\bar{\omega} \times \bar{r}) \right] = \bar{\omega} \cdot dm(0, y, z)$$

(4)

$$F_t^r = -dm \cdot (\bar{\beta} \times \bar{r}) = \bar{\beta} \cdot dm(0, z, -y)$$

(5)
Where $P_{nx}$ indicates the additional pressure drop caused by the normal force during rolling, $P_{tx}$ indicates the additional pressure drop caused by the tangential force during rolling, $(x_1, y_1, z_1)$ indicates the starting point coordinates of the fluid in the pipeline, $(x_2, y_2, z_2)$ indicates the coordinates of the end point of the fluid in the pipeline, and $\rho$ indicates the fluid density.

The expression of the additional force when the hull is swaying (pitch) about the y axis is:

$$P_{sy} = \frac{\omega^2 \rho}{2} \left( z_2^2 - z_1^2 + x_2^2 - x_1^2 \right)$$

$$P_{sy} = \beta \rho \cdot (z_2 x_2 - z_1 x_1)$$

Where $P_{sy}$ indicates the additional pressure drop caused by the normal force during pitching and $P_{sy}$ indicates the additional pressure drop caused by the tangential force during pitching.

The expression of the additional force when the hull sways (rotates) around the z axis is:

$$P_{sz} = \frac{\omega^2 \rho}{2} \left( y_2^2 - y_1^2 + x_2^2 - x_1^2 \right)$$

$$P_{sz} = \beta \rho \cdot (y_2 x_2 - y_1 x_1)$$

Where $P_{sz}$ indicates the additional pressure drop caused by the normal force during rotation, and $P_{sz}$ indicates the additional pressure drop caused by the tangential force during rotation.

2.2.2. Derivation of Additional Pressure Drop on Pipeline Translational Fluid. The additional force on the fluid when the pipeline is moving is expressed as:

$$F_z = F_x + F_y + F_z = (a_x + a_y + a_z) \cdot dm$$

In the formula: $F_x$, $F_y$, $F_z$ respectively represent translational forces in three directions of x, y, and z, and $a_x$, $a_y$, $a_z$ respectively represent translational acceleration in three directions of x, y, and z.

The additional translational force when the hull is translated along the x axis is:

$$P_t = \int F_z \cdot dl \int (0, 0, 0) (x_2 - x_1, y_2 - y_1, z_2 - z_1) \cdot a_x \cdot \rho \, dl$$

$$= \alpha_x \rho \cdot (x_2 - x_1)$$

Where $P_t$ represents the additional pressure drop caused by translational forces in the x direction.
The expression of the additional pressure drop when the hull is translated along the y-axis and z-axis is:

\[ P_y = a_y \rho \cdot (y_2 - y_1) \]  

\[ P_z = a_z \rho \cdot (z_2 - z_1) \]  

Where \( P_y \) indicates the additional pressure drop caused by translational force in the y direction; where \( P_z \) indicates the additional pressure drop caused by translational force in the z direction.

2.3. Effective cavitation margin requirements for feedwater pumps under marine conditions

The effective cavitation margin refers to the excess energy of the unit weight of liquid over the vaporization head at the suction port of the pump. When the liquid level of the suction container is higher than the pump axis, the effective cavitation margin of the feed pump under marine conditions can be expressed as:

\[ \Delta NPSH = H_g - h_\omega + \frac{\Delta p}{\rho g} \]  

Where:

- \( H_g \) —geometric installation height or filling head, m;
- \( h_\omega \) —Loss of flow resistance in the suction line, m;

In the floating nuclear power plant, when the main feed pump is selected for flow design, the conventional thermal power drum boiler is used, that is, 10% is selected as the flow margin [5], and the pipeline flow resistance loss is calculated under the 10% flow margin value.

Necessary cavitation margin is the minimum cavitation margin value for a given pump at the specified speed, flow rate and liquid delivery conditions to achieve the specified performance. In order to ensure that cavitation does not occur when the feedwater pump runs under a 10% flow margin, the value of 10% of the rated flow margin should be taken. At this time, [6] should be satisfied:

\[ 1.1 \Delta NPSH \geq 1.1 NPSH_r \]  

3. Introduction to the feedwater pump example

This article selects the water supply system deaerator, feed pump and the pipe section between them as an example for calculation. The schematic diagram of the pipe layout is shown in Figure 2. The coordinates of the relative swing center positions of the pipeline nodes in the picture are: A (18.53, 0.40, -7.49), B (20.63, 0.40, -7.49), C (23.02, 0.40, -7.49), D (23.02, 0.40, -4.35), E (19.57, 0.40, -4.35), F (19.57, 2.87, -4.35), G (19.57, 2.87, -0.75). Calculate the environmental conditions once in a century for the segmented pipeline in the figure, and consider the flow loss margin for the flow loss in the suction pipeline. In order to ensure that the pump does not cause cavitation, the effective cavitation margin at
the lowest point needs to be studied. Due to the large amount of data, the time period with the lowest effective cavitation margin is mainly selected as shown in Figure 3:

![Figure 3. The curve of Effective cavitation allowance](image_url)

As can be seen from the figure, the effective cavitation margin at the lowest point as 4.302m, which can be obtained from equation (17):

\[
NPSH_r \leq \frac{NPSH_{\text{min}}}{1.1} = 3.91m
\]  

(18)

It can be obtained from the above that the required cavitation allowance at the 110% flow condition point in this example is not higher than 3.91m. At this time, it can be satisfied that the cavitation does not occur during the normal operation of the feed pump, and the floating nuclear power plant feed pump can be guaranteed Stable operation.

4. Conclusion
Under marine conditions, the effective cavitation margin of a floating nuclear power plant's feed pump periodically changes with time. The greater the acceleration caused by the inertial force, the smaller the value of the effective cavitation margin at the lowest point of the feed pump. The effective cavitation margin at the lowest point in the feedwater pump example is reduced by 0.9m compared to the static state. When the required cavitation margin does not meet the requirements, the pressure at the inlet of the feedwater pump will be periodically lower than the fluid vaporization pressure Causes cavitation. And this periodic cavitation not only destroys the material of the feed pump, but also appears noise and vibration. Therefore, when designing, checking, and arranging the feed pump, it is necessary to fully consider the impact of ocean conditions on the stable operation of the feed pump.

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