Research on the force of radial bearing of a nuclear main pump rotor system by database method

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Abstract. This paper discusses the method of solving the radial sliding bearing force of a nuclear main pump rotor system using the pre-built database. For a sliding bearing with a certain size, the Reynolds equation can be decomposed and be equivalent of the problem of solving the liquid film pressure in both pure rotation and pure extrusion states. A database for solving the bearing force is established by pre-calculating the liquid film pressure of the radial sliding bearing under these two states with different eccentricities. By comparing with three analytical models, the bearing forces obtained by this method are closer to the results obtained by the finite difference method. And compared with the finite difference method, the method is much faster.

1. Introduction

The main pump rotor system is a high speed and large span flexible rotor system. It is subjected to a variety of nonlinear excitations during operation and is a complex nonlinear dynamic system [1]. When studying the nonlinear dynamics of the main pump rotor system, the linear bearing force model is no longer applicable [2].

To study the nonlinear dynamics of the rotor-bearing system, an important task is to establish an accurate and effective nonlinear bearing force model [3]. At present, the research on the force of nonlinear bearing mainly includes three types, one is solved by finite element method or finite difference method [4]; the second type is solved by simplification model [5–6]; the third type is database method [7]. Although the numerical solution directly adopts high precision, the calculation speed is relatively slow, and it is rarely used in actual engineering calculations, especially transient analysis [8]. The second method is the most widely used in practical engineering because of its superior analytical form, but it lacks precision due to its simplification of boundary conditions [9]. The database method is limited due to too many uncertain parameters and a large amount of data required in the unsteady state of the bearing [10].

In this paper, the database no longer directly stores the final result value of the nonlinear bearing force, but the liquid film pressure distribution of the rotor bearing system is in pure rotation state and pure extrusion state. Thus, the uncertain parameters required to establish the database are reduced from three (journal eccentricity $\varepsilon$, motion parameters of the journal center $\frac{de}{dt}$, $\frac{d\delta}{dt}$) to one (journal eccentricity $\varepsilon$). Moreover, this method avoids the journal center motion parameters, which are difficult to determine in the range of values, and greatly reduces the amount of data required. When the bearing force is actually needed, the liquid film pressure distribution in the pure rotation state and the pure extrusion...
state in the database is searched according to the eccentricity of the current situation. Finally, according to the journal center motion parameters, the required bearing force is obtained.

2. Establishment and call of the liquid film force database

The bearing force is calculated by solving the Reynolds equation. The dimensionless and simplified form of the Reynolds equation is as follows [11]:

\[
P = \frac{PC^2}{6 \eta \omega^* R_b^2}
\]

\[
p = P_1 + q P_2
\]

\[
\frac{\partial}{\partial \theta} \left( H^3 \frac{\partial P_1}{\partial \theta} \right) + \alpha \frac{\partial}{\partial Y} \left( H^3 \frac{\partial P_1}{\partial Y} \right) = -\varepsilon \sin \theta
\]

\[
\frac{\partial}{\partial \theta} \left( H^3 \frac{\partial P_2}{\partial \theta} \right) + \alpha \frac{\partial}{\partial Y} \left( H^3 \frac{\partial P_2}{\partial Y} \right) = \cos \theta
\]

When \( \omega^* \neq 0 \),

\[
P = \frac{PC^2}{12 \eta R_b^2 \frac{de}{dt}}
\]

\[
\frac{\partial}{\partial \theta} \left( H^3 \frac{\partial P_2}{\partial \theta} \right) + \alpha \frac{\partial}{\partial Y} \left( H^3 \frac{\partial P_2}{\partial Y} \right) = \cos \theta
\]

With the following substitutions:

\[
\theta = \frac{x}{R_b}; H = \frac{h}{c} = 1 + \varepsilon \cos \theta; Y = \frac{y}{b}; \alpha = \left( \frac{R_b}{b} \right)^2; \omega^* = \omega - 2 \frac{d\delta}{dt}; q = \frac{2}{\omega^*} \frac{de}{dt}
\]

Where \( R_b \) is the bearing radius; \( c \) is the radius gap between the bearing and the journal; \( \varepsilon \) is the eccentricity; \( b \) is the bearing length; \( \omega \) is the angular velocity; \( \frac{d\delta}{dt} \) is the angular velocity of the journal center in the direction vertical to the eccentric line; \( \frac{de}{dt} \) is the velocity of the journal center in the direction of the eccentric line; \( \eta \) is the viscosity of the lubricating fluid. \( P_1 \) is the dimensionless liquid film pressure distribution when the bearing is in a purely rotating state; \( P_2 \) is the dimensionless liquid film pressure distribution when the bearing is in a purely extruded state; \( P \) is the actually obtained dimensionless liquid film pressure distribution.

It can be observed that the coefficients of the two differential equations in equations (1) and (2) do not include \( \frac{d\delta}{dt} \) and \( \frac{de}{dt} \), and solving these two differential equations almost occupies all calculation time for solving the nonlinear bearing force directly by the numerical solution. Therefore, the values of \( P_1 \) and \( P_2 \) in the case of different eccentricities can be calculated in advance, and store them as a database.

In the nonlinear dynamic analysis of the rotor-bearing system, the closest eccentricity recorded in the database is retrieved according to the current eccentricity value. After reading \( P_1 \) and \( P_2 \), combined with the journal center motion parameters, the actual liquid film pressure distribution is calculated. Finally, the liquid film rupture zone is judged, that is, the pressure value of the region where the liquid film pressure is negative is set to 0, and the nonlinear bearing force solution can be obtained.

The specific operation flow chart is shown in figure 1.
3. Numerical calculation and result analysis

The design parameters of the main pump rotor radial bearing are $R_b = 163\text{mm}$, $c = 40\mu\text{m}$, $b = 104\text{mm}$, and the lubricating fluid is water. Taking the design speed of $\omega = 2250\text{r/min}$ as an example, the nonlinear bearing force is solved.

In order to illustrate that the database established in this paper can effectively solve the bearing force, the bearing force is solved by using this method and infinitely long bearing model, infinitely short bearing model and Capone’s model respectively. Then compare them to the results calculated using the finite difference method. The range of $\varepsilon$ used to establish the database is from 0 to 0.99, and the step size is 0.01.

Example 1: Steady state:

Because in the actual calculation, it is not always possible to find exactly the same $\varepsilon$ in the database, so take $\varepsilon = 0, 0.005, 0.015, 0.025 \ldots 0.995$ in the calculation. The results are given in figures 2 and 3.

![Figure 2. Bearing force in eccentric direction (steady state)](image1)

![Figure 3. Bearing force in vertical eccentric direction (steady state)](image2)

It can be seen from figure 2 and figure 3 that the calculation of the infinitely long bearing model has larger error than the other methods. And the bearing force in both directions is too large. The bearing force of the infinitely short bearing model has a smaller result in the vertical eccentric direction. The results of the Capone model are closer to the finite difference method, but still slightly smaller than the CFD solution. The results obtained by the database method used in this paper are the closest to the finite difference method.

Example 2: Different motion states with the same eccentricity:

Some values of $\frac{de}{dt}$ and $\frac{d\delta}{dt}$ may cause q in equation (1) to take a larger value. In this case, the bearing force will be changed from mainly affected by the rotation effect to mainly affected by the extrusion effect. Now compare the differences in bearing force results for several solutions when converting the dominant factors of bearing forces.
The setting parameters are \( \frac{dx}{dt} = 0.1, 120 \geq \frac{d\delta}{dt} \geq 116 \), and the remaining parameters are the same as in Example 1. The results are given in figures 4 and 5.

![Figure 4. Bearing force in eccentric direction (motion state)](image1)

![Figure 5. Bearing force in vertical eccentric direction (motion state)](image2)

As can be seen from figures 4 and 5, the infinitely long bearing model and the infinitely short bearing model cannot simulate the extrusion effect of the liquid film. This is because the Reynolds equation is simplified when solving their analytical formulas. However, the database model used in this paper has a similar result to the finite difference method in this special case because the data information \( P_2 \) indicating the liquid film squeezing effect is retained. Therefore, the database model has its superiority in the special case where the bearing force is dominated by the liquid film extrusion effect.

4. Conclusions

Based on the Reynolds equation, this paper proposes an improved bearing force database method to solve the force of the main pump radial bearing. The database method in this paper adopts the method of preserving the liquid film rotation effect distribution \( P_1 \) and the liquid film extrusion effect distribution \( P_2 \), which reduces the number of uncertain parameters required to establish the database.

Through numerical calculation, it is verified that the database method is an accurate and efficient method for solving the bearing force of the main pump radial bearing. When the journal is in a stable condition, the bearing force results obtained by the database method are more accurate than those obtained by several nonlinear analytical formulas. Moreover, when the liquid film extrusion effect dominates, the database method can accurately simulate the bearing force. This paper has certain reference significance for the nonlinear dynamic analysis of the main pump rotor system.

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