Study on Lubrication Performance of Composites
Water-Lubricated Stern Bearing

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Abstract. Stern bearings are the main supporting part of ship stern shafts. Water-lubricated stern bearings have the advantages of compact structure, easy maintenance, no waste and no pollution, and. Water-lubricated stern bearing materials are generally non-metallic materials, which are easy to produce elastic deformation when working. Based on this, fiber resin matrix composite materials are selected as water-lubricated stern bearing materials, and the Fluid-Structure interaction numerical method is used to research the lubrication performance of water-lubricated stern bearings, which is verified by the test with water-lubricated stern bearing rig. The effect of rotating speed on the performance of water-lubricated stern bearing under different loads is studied in this paper. The results provide technical and theoretical basis for the study of water-lubricated stern bearings.

Keywords: Water-lubricated Stern Bearing; Fluid-Structure Interaction; Lubrication Performance; Experimental Verification

1. Introduction
The shaft system is a key component for the propulsion system of ship, and the stern bearing is the key supporting part of the stern shaft. The main advantages of Water-lubricated stern bearing are no pollution, no waste, compact structure and easy maintenance. With the improvement of environmental protection awareness in various countries, water-lubricated stern bearings are more and more widely used [1-8]. In China, the research on water-lubricated bearings is relatively late, and Wuhan University of technology has mainly carried out the research on the lubrication performance, friction and vibration mechanism and life reliability of rubber stern bearings [9-13]. Shanghai Jiaotong University mainly carried out research on water-lubricated bearing materials, structural design of water-lubricated radial and thrust bearings [14-17]. Qingdao University of Science and Technology mainly studies the performance analysis and calculation of water-lubricated bearings with different groove forms and the friction and wear properties of bearing materials [18, 19]. Water-lubricated stern bearing materials generally use non-metallic materials, compared with metallic materials, non-metallic materials are easy to produce elastic deformation under loads. Scholars seldom consider the elastic deformation of the stern bearing when they use the numerical method to study the water-lubricated stern bearings performance, there are some errors between the numerical results and the engineering practice, the needs for the numerical simulation of water-lubricated stern bearings often cannot be met.
According to the lubrication performance and mechanical properties of water-lubricated stern bearings, fiber resin matrix composite materials are selected as the water-lubricated bearing materials. The FSI numerical method is used to research the lubrication performance of water-lubricated stern bearings, which is verified by the test with water-lubricated stern bearing rig. The effect of rotating speed on the water-lubricated stern bearing performance under different loads is studied in this paper. The results provide technical and theoretical basis for study of the water-lubricated stern bearing.

2. Theory and Methodology

2.1. Fluid Governing Equations
The fluid governing equations mainly follows the three laws of fluid mechanics, namely momentum conservation law, mass conservation law and energy conservation law, as shown in equation (1), equation (2) and equation (3).

The mass-conservation equation is

$$\frac{\partial \rho_f}{\partial t} + \nabla (\rho_f \nu) = 0$$

(1)

The momentum conservation equation is

$$\frac{\partial \rho_f}{\partial t} + \nabla (\rho_f \nu \nu - \tau_f) = f_f$$

(2)

The energy conservation equation is

$$\frac{\partial \rho_f E}{\partial t} + \nabla (\rho_f E \nu - \tau_f \nu) + q_f = f_f \nu + q_f$$

(3)

Where \( t \) represents the time, \( f_f \) represents the volume force vector, \( \rho_f \) represents the fluid density, \( \nu \) represents the velocity vector of fluid, \( \tau_f \) represents the shear tensor, \( E \) represents the internal energy per unit mass, \( q_f \) represents the heat loss per unit volume.

2.2. Solid Governing Equations
The solid governing equations are derived from Newton's second law:

$$\rho_s \ddot{d}_s = \nabla \sigma_s + f_s$$

(4)

Where \( \rho_s \) represents the density of solid, \( \ddot{d}_s \) represents the local acceleration vector of the solid region, \( \sigma_s \) represents the Cauchy stress tensor, \( f_s \) represents the volume force vector.

2.3. FSI Equations
The Fluid-Structure Interaction needs to follow the law of basic conservation that is, at the fluid-structure interface, fluid and structure are equal or conserved with respect to stress(\( \tau \)), heat(\( q \)), displacement(\( d \)), temperature(\( T \)) and other variables, satisfying the following four equations:

$$\begin{align*}
\tau_f \cdot n_f &= \tau_s \cdot n_s \\
d_f &= d_s \\
q_f &= q_s \\
T_f &= T_s
\end{align*}$$

(5)

Where \( f \) means fluid and the subscript \( s \) means solid.

3. Numerical Analysis of Water Lubricated Bearings

3.1. Numerical Simulation Model
This paper establishes a water-lubricated stern bearing numerical simulation model, and the bearing FSI model parameters as follows: The length of the model is 420mm, the diameter of the model is
280mm, and the thickness of bush is 20mm, the running clearance is 1‰ D, i.e. 0.28mm. Fiber resin matrix composite materials are selected as water-lubricated stern bearing materials, the compression modulus is 12.5GPa, and the Poisson's ratio is 0.14.

3.2. Solution Parameters
(1) The boundary conditions of the water film are shown in figure 1. The two ends of the model are set as the inlet and outlet respectively. The rotating surface as we can see from figure 1, which is the inner surface, and the Stationary surface of the water film is the Fluid-Structure interface.

![Figure 1. The boundary conditions of water film.](image)

(2) According to the critical Reynolds number:

\[ Re_c = \frac{\rho v h_m}{\mu} \]

Where \( \rho \) is the water density (kg/m\(^3\)), \( \mu \) is the dynamic viscosity of water (Pa \cdot s), \( v \) is the velocity (m/s), \( h_m \) is the average water film thickness. According to the bearing design and experimental conditions, the Reynolds number is less than the critical Reynolds number \( R_{ec} \), thus, laminar flow model is used for calculation.

(3) In the Rayleigh-Plesset cavitation model, the default values of parameters as follows: \( R_{nuc} = 10^{-6} \text{ m}, \ r_{nuc} = 5 \times 10^{-4}, \ F_{vap} = 50, \ F_{con} = 0.01 \).

3.3. Results and Analysis
As shown in figure 2 is the distribution of water film pressure and elastic deformation, where the rotating speed is 200r/min, the specific pressure is 0.2MPa.

![Figure 2. Distribution of the water film pressure and bush deformation.](image)
Figure 2 (a) shows the distribution of water film pressure. There are positive and negative pressure zones in the water film. The water film is generated and supports the external load under the combined effect of positive and negative pressure, and the maximum water film pressure is 0.921MPa.

Figure 2 (b) shows the bearing bush deformation distribution. We can see from the comparison between pressure distributions with the deformation distributions that, the bearing bush deformation distribution is basically consistent with the water film pressure. The axial distribution of water film pressure is characterized by small pressure at both ends, and large in the middle. The bearing bush is "pocket-like" deformation, and the maximum deformation is 1.05μm. Generally speaking, the bearing deformation has a direct relationship with the bearing elastic modulus to a certain extent [20, 21]. Compared with other composites, the fiber resin matrix composite has the slightly influence of deformation on the lubrication performance of water-lubricated bearings because of the high elastic modulus.

The simulation results of lubrication performance with FSI are shown in Figure 3, which shows the dynamic pressure lubrication state of water-lubricated bearings in the rotating speed range of 20~250r/min.

From figures 3(a), 3(b) 3(d) we can be see that the bearing minimum film thickness decreases along with the rotating speed, i.e., the larger the speed, the smaller the minimum film thickness, while the maximum film pressure and elastic deformation are increases with the grow of rotating speed.
According to figure 3 (a), when the rotating speed in the range of 20~50r/min, the water film thickness is within 0.3 μ m. According to Reynolds equation, the vertical bearing loading capacity within the boundary is proportional to the rotating speed, so the thickness of water film is relatively low, and the bearing is in a semi dry friction state. With shaft system speed increasing, establishing bearing water film is easily, at the same time, the lubrication state is improved. With the rise of film thickness, film pressure distribution will be more smooth and steady, the maximum water film pressure will be reduced, and the elastic deformation will become smaller.

Additionally, the minimum film thickness decreases with the specific pressure, i.e., the larger the specific pressure, the smaller the minimum film thickness, while the maximum film pressure and elastic deformation are gradually decrease, which is chiefly because the water film becomes more difficult to be established when the load of bearing increases, consequently, the water film thickness becomes thinner, the lubrication state becomes worse, the distribution of water film pressure rises sharply, the maximum film pressure increases, and the elastic deformation becomes larger.

Figure 3(c) shows that the friction coefficient of bearing increases along with the specific pressure at a certain extent, but with the increase of the rotating speed in the range of 20 ~ 250r/min, the friction coefficient reduces, and the reduction tends to be stable when the rotating speed reaches 100r/min. The water film has become stable with the rotating speed reaches 100r/min, therefore, the friction mode tends to smooth and stable. Compared with the classical Strubeck-Curve, water lubricated bearing is in the condition of mixed lubrication state in the rotating speed range of 20~250r/min.

4. Experimental Research on the Friction Properties of Water Lubricated Bearings

4.1. Experimental Design
In the subsequent follows, related experiments are conducted systematically to obtain experimental results in order to study the friction performance and verify the correctness of the numerical simulation method.

The test rig is mainly consists of driving part, bearing device, loading part and testing part. The loading mode is mainly hydraulic cylinder loading, which is arranged at the fore and aft end of the stern bearing in order to ensure the stern bearing uniform loads. The test rig of water-lubricated bearings can measure the friction coefficient through the torque sensors, as shown in figure 4(a).

Fiber resin matrix composite materials are selected as the water-lubricated stern bearing materials. The linear thermal expansion coefficient of the material is 87.5×10^{-6}·k^{-1}, and the water expansion rate is 0.49%. As shown in figure 4 (b).

![Test rig](image1)
![Water-lubricated stern bearing](image2)

**Figure 4.** Test rig and test bearing.
4.2. Results Analysis

The friction coefficient can be calculated as follows

\[ f = \frac{F_f}{F} = \frac{T_f}{F} \] (7)

Where \( f \) represents friction coefficient, \( F_f \) represents friction, \( F \) represents radial load, \( T_f \) represents friction torque.

The comparison between the friction coefficient of experimental results and simulation results under the different specific pressure is shown in figure 5, we can see that the curves shaper of the simulation results is similar to that of the experimental results, and the friction coefficient of water-lubricated stern bearing decreases gradually with the rise of rotating speed. When the rotating speed reaches 100r/min, the reduction of friction coefficient trends to be stable.

The friction coefficient reduces sharply with the rotating speed in the range of 20~100r/min, which is due to the unstable water film between the bearing surface and journal when the shaft system is rotating at a low rotating speed. Further analysis, the journal and bearing surface are in the state of semi-dry friction or boundary lubrication, and the lubrication conditions are relatively poor, therefore, the friction coefficient is relatively larger. It is beneficial to generate water film with the rise of the rotating speed, as a result, the lubrication condition of bearings is improved and the friction coefficient is reduced gradually until stable.

![Figure 5](image_url)

**Figure 5.** Comparison of experimental results and numerical results at different specific pressure.

According to the results of experimental and numerical calculation, the deviations are shown in table 1.
According to figure 5 and table 1, there is a slight deviation between the results of experimental and numerical simulation, and the deviation is mostly within 10%. With consideration of systematic error and temperature changes, there is a visibly deviation between the results of experimental and numerical simulation, with the maximum deviation is about 11%. In general, the numerical simulation results are consistent with the experimental, with a small deviation between them, which almost can be neglected, consistency proves the correctness of the numerical simulation method.

5. Conclusions
Based on the numerical simulation of ANSYS CFX platform, the water-lubricated stern bearings performance are studied by Fluid-Structure interface method, the related experiments are conducted to obtain experimental results. The conclusion is as follows:

(1) According to the simulation results of Fluid-Structure interface, the water film pressure distribution characteristics of water-lubricated stern bearings are small at both ends and large in the middle, and the deformation characteristics of the bearing bush are similar to water film pressure distribution characteristics, which are “pocket-like” deformation characteristics.

(2) For the water-lubricated stern bearing of fiber resin matrix composite materials, the minimum film thickness increases along with the speed in the range of 20~250r/min, while the friction coefficient, the maximum film pressure and elastic deformation are gradually decrease, and the reduction tends to be stable. In addition, the minimum water film thickness decreases with the specific pressure in the range of 0.1MPa~0.4MPa, while the friction coefficient, maximum water film pressure and elastic deformation are gradually decrease.

(3) Results of the comparison between the test results and numerical simulation show that the bearing friction coefficient rises along with the specific pressure, and which decreases with the increase of rotational speed to a certain extent, but the reduction of friction coefficient gradually tends to be stable. What’s more, the numerical simulation results nearly are consistent with the experimental results, and consistency proves the correctness of the numerical simulation method.

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