Thermohydrodynamic performance of water-lubricated thrust bearing of mine high speed rescue pump

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Abstract: In order to meet the requirement of axial force balance of mine rescue pump with high speed and big power, the capacity and reliability of water-lubricated thrust bearing of the pump unit should be improved. This paper presented a study on the capacity of water film and bearing bush deformation of water-lubricated thrust bearing based on the change of temperature in the motor chamber, which is under the actual operation condition of mine high speed rescue pump. In this study, the Reynolds equation was solved by MATLAB to get the thickness of water film, and the deformation of bearing bush was obtained through the joint solution of heat-fluid-solid coupling equation by ANSYS. The results show that the temperatures have little effect on the pressure distribution of water film and the deformation distribution of bearing bush. However, the maximum pressure of water film increases with the temperature. The research of the paper could provide theoretical support and technical guidance for the design of water-lubricated thrust bearings under big power and high speed conditions in the future.

1. Introduction

Mine high speed rescue pump has the advantages of small size, high speed and big power, which could meet the requirements of rapid drainage emergency when coal mine flooding accident occurs. In the pump, the residual axial force of the unit is balanced by the water-lubricated thrust bearing in the motor chamber.[1-2]

Many scholars studied the performance of water-lubricated thrust bearings theoretically. Gohara[3] studied the water-lubricated thrust bearings in non-rotating shafts and found that the stiffness of thrust bearings could be greatly improved by using thin film throttle, and the numerical results were in good agreement with the experimental results. Nakao[4] systematically expounded the design process and performance characteristics of water-lubricated thrust bearings in ultra-precision machine tools, and gave the influence of bearing clearance size and water supply pressure on bearing stiffness. Hanawa[5] proposed a new type of porous water-lubricated thrust bearing. Through theoretical research and experimental analysis, the relationship between water film clearance and bearing capacity and stiffness was obtained. Lin[6] found that the effect of inertia on the static characteristics of Water Lubricated Spiral Groove Thrust bearings is greater than that of cavitation at high speed. Zhang[7] proposed the
relevant design reference formulas and obtained the bearing capacity, pressure distribution and friction coefficient of Water-lubricated thrust bearings under different geometric parameters based on the numerical simulation method. Wang[8] analyzed the relationship between fulcrum contact and wear deformation, and the influence of load size on the start-up process of Water-lubricated thrust bearing. Wang[9] proposed a design method of Water-lubricated thrust bearing for vertical shafting used multi-knowledge system. Based on the expansion of Reynolds equation, Wang[10] found that the slip region near the inlet of the flow field has an important influence on the bearing capacity of thrust bearing.

Although domestic and foreign scholars have a wide range of research on water-lubricated thrust bearings, there are few studies on high speed and heavy load conditions. In view of the shortcomings of the present research, this paper takes the thrust bearing of mine high speed rescue pump as the research object, and studies the load-bearing performance and lubrication mechanism at different temperatures for the high speed rescue pump.

2. Theoretical Analysis

2.1. Hydrodynamic Lubrication Mechanism

Figure 1 is a schematic diagram of the work principle of the thrust bearing in the cylindrical coordinate system, in which the thrust disc rotates synchronously with the shaft, and the thrust bearing bush is stationary. Hydrodynamic lubrication is formed when liquid enters wedge gap between thrust disc and thrust bearing bush.

$$\Pi_f : \rho \dot{v}_i - \sigma_{i,j}^s + f_i^s + \psi_i = 0$$
$$\Omega_f : \rho \dot{v}_i - \sigma_{i,j}^s + f_i^s - \psi_i L(\Pi_s) = 0$$

where, $f$ is volume force, $\rho$ is density, $D$ is displacement, $v$ is velocity and $\sigma$ is stress, $\psi$ is a Lagrangian operator on the boundary of fluid-structure interaction.

In the immersion boundary method, a separation function can be used to solve the problem. The separation function can be regarded as an interpolation of forces acting on the interface of fluid-solid
coupling. Therefore, in the calculation process, the shape of the interface can be regarded as a boundary layer with finite thickness.

2.3. Thermosetting Coupling Equation

When the temperature field is coupled with the strain field, it is assumed that the force and the thermal load are applied slowly, so that the transition from one stable state to another stable state is also considered as a balanced state.

In such problems, the temperature field and strain field interact forming a coupling relationship. Coupled thermoelastic problems need to be solved by combining heat conduction equation, displacement equation and equilibrium equation. The heat conduction equation is the Fourier heat conduction equation, which takes into account the deformation of the thermoelastic micro-element.

Heat conduction equation:

\[
\lambda \nabla^2 T = C_e \frac{\partial T}{\partial \tau} + T_0 \beta \frac{\partial e}{\partial \tau}
\]  

[3]

Displacement equation:

\[
\begin{align*}
(\lambda + G) \frac{\partial e}{\partial x} + GV^2 u - \beta \frac{\partial t}{\partial x} + X &= 0 \\
(\lambda + G) \frac{\partial e}{\partial y} + GV^2 v - \beta \frac{\partial t}{\partial y} + Y &= 0 \\
(\lambda + G) \frac{\partial e}{\partial z} + GV^2 w - \beta \frac{\partial t}{\partial z} + Z &= 0
\end{align*}
\]  

[4]

Equilibrium equation:

\[
\begin{align*}
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + X &= 0 \\
\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z} + Y &= 0 \\
\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + Z &= 0
\end{align*}
\]  

[5]

where, \(\nabla^2\) is Laplace operator, \(e\) is the volume change per unit volume, \(\lambda\) is lambda constant, \(G\) is shear modulus of elasticity, \(\beta\) is thermal stress coefficient.

3. Mathematical model

3.1. Solution method

The one-dimensional form of Reynolds equation is expanded and solved by numerical method. When the difference method is used to solve the pressure distribution of liquid film in thrust bearing, the water film corresponding to a single thrust pad is discretized into meshes. The pressure values at each node of the mesh constitute the difference and quotient values of each order, so that the pressure values at each node can be solved. The pressure values at each node are taken as the basis for numerical integration of the performance parameters.

After getting the water film thickness, the value of water film thickness is brought into the three-dimensional model CREO. Then, the mesh is generated by ICEM and the performance is analyzed in
CFX. Finally, the bearing capacity and pressure distribution of the bearing are loaded by water film in ANSYS Workbench, and the Thermal-Fluid-solid coupling calculation is carried out in the platform.

3.2. Geometric Model
According to the calculation of bearing capacity of high speed rescue pump GPQ200-300, the parameters of the thrust bearings are as follows: inner diameter \( D_{1tb} \) is 120 mm, the outer diameter \( D_{2tb} \) is 225 mm, the center angle \( \theta_{tb} \) is 60°, the inclination angle \( \beta_{tb} \) is 0.01°, and the number of thrust bushes \( k_{tb} \) is 6. Besides, the material of the thrust bearing is graphite (No. P10356), the specific parameters are: hardness, 95; compressive strength, 40000 PSI; flexural strength, 14000 PSI; modulus of elasticity, 3.8×10^6 PSI; coefficient of thermal expansion, 3.5uin/in-°F; thermal conductivity, 8 BTU/hr-ft-°F.

3.3. Mesh generation
The thickness of water film is very small, in order to capture the flow characteristics of water film better, the hexahedral structured grid is used to divide the water film and bearing bush because of the better convergence and smaller stage error. The computational domain mesh is shown in Figure 2.

3.4. Boundary conditions
In actual operation, water is injected into the motor chamber to ensure internal circulation which is isolated from the outside chamber. Therefore, in CFX, the inlet and outlet are set as pressure boundaries. The wall of the water film near the bearing bush is stationary, and the wall near the thrust disk is rotating. The rotating speed is 6000r/min. In thermal state, the contact surface between bearing bush and water film is selected, and the temperature field in flow field is applied to calculate the coupled temperature field to obtain the thermal field distribution. In static structure, the contact surface between bearing bush and water film is selected, the fluid pressure field is applied to calculate the coupled pressure field, and the structural temperature field load and fluid pressure load are applied to the bearing bush together. The load conditions are solved on Workbench to obtain the stress-deformation results on the bearing.

4. Simulation results
Figure 3 shows the water film pressure distribution on the thrust bearing surface at different temperatures in the motor chamber under the design flow rate \( (1Q_d) \) when the mine high speed rescue pump runs at 6000r/min speed. From the figure, it can be seen that the increase of temperature has little effect on the distribution trend of the whole water film pressure field. The maximum area in pressure cloud is defined as the pressure center area. At three temperatures, the pressure center area of water film appears near the circumferential inlet of the whole water film. With the increase of temperature, the pressure center area decreases. When the motor chamber is at the limit temperature of 70 °C, the pressure center area near the circumferential inlet of the thrust water film is very small, and
there is another pressure center area near the radial outlet of the water film. The phenomenon may be led by that: the water viscosity decreases with the increase of temperature. Also, the continuity of the water film is destroyed, which may cause the rupture of the whole bearing water film, resulting in the appearance of small-scale vortices in the local area. In addition, with the increase of temperature, the maximum pressure of water film gets greater, and the change of water viscosity will cause the change of the maximum pressure of water film.

Figure 4 shows the deformation cloud of thrust bearing at 6000r/min speed under different temperatures in the motor chamber. At three temperatures, the maximum deformation of the thrust bearing appears at the top corner of the inner diameter edge of the bearing bush which is near the radial outlet of the water film. With the increase of the radius of the bearing, the surface deformation of the bearing decreases gradually. With the increase of temperature, the maximum deformation value on the surface of bearing increases, and the minimum deformation area keeps approaching the outer diameter of bearing. The maximum deformation value of bearing surface is 0.263μm at 30℃ and 1.043μm at 70℃. Considering the thickness of water film required for load-bearing of the unit at the two temperatures, because the area of the largest deformation area accounts for a small proportion of the whole bearing area and at the edge of the inlet, it can be considered that the bearing can work normally at 70℃ without affecting the overall water film distribution and bearing capacity.

5. Conclusion
The influence of temperature, water film pressure distribution and bearing bush deformation of water-lubricated bearing of high speed rescue pump was analyzed by ANSYS Workbench based on fluid-solid-thermal coupling method. The simulation shows that the pressure distribution of water film and
the deformation distribution of bearing bush have no obvious change at different temperatures. But with the increase of temperature, the maximum pressure of water film has a great rise.

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