Centrifugal Effect of Thrust Plate of Water-lubricated Thrust Bearing and its Influence Mode

Haonan Zhang¹, Weigang Zheng²⁺, Fuxin Li¹

¹School of Energy and Power Engineering, Wuhan University of Technology, Wuhan, Hubei, 30063, China
²School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan, Hubei, 430070, China
³Engineering Training Center, Wuhan University of Technology, Wuhan, Hubei, 430063, China
⁺Corresponding author’s e-mail: zfeidiao@126.com

Abstract. Water-lubricated thrust bearing with water as the medium, is a mechanical transmission medium with energy saving and environmental protection. The thrust bearing with water medium can reduce the wear of bearing and the friction between gears. At the same time, the shape of the rolling bearing in the state of high-speed operation is bound to undergo a series of changes, and the radial working clearance is also slightly changed due to the centrifugal effect under high-speed operation, which has a certain degree of influence on the thrust disc. The shielded thrust disc avoids the problem of loose sealing, and the tilting thrust bearing has the advantages of obvious centrifugal effect, large rotating inertia of the thrust disc and large bearing size. In view of the characteristics of thrust bearing structure of water medium, this study established the coupling calculation model of the thrust plate after centrifugal denatination based on the finite element analysis method, and explored the design parameters of two key clearances in the assembly structure of the thrust plate. It is found in this paper that the tilting pad bearing under low speed steering will compensate for the deformation of the thrust disc, and when the rotating speed is greater than 3600r/min, the centrifugal deformation of the thrust disc will increase in morphology and even lead to lubrication failure. Therefore, the speed is an important factor that influences the centrifugal effect of the thrust disc and the bearing disc body enlargement.

1. Introduction
The water-lubricated thrust bearing is the core equipment of the fourth generation of passive safety principle bearing technology. The biggest difference between it and the previous bearing technology is that it avoids the problem of dynamic seal of the rotating shaft, which is also a key breakthrough in the field of shaft seal [1]. Technological breakthroughs often bring new research problems, and the design of large-size water-lubricated bearing plates for the main pump is the most significant problem [2]. Under heavy load conditions or in the process of high-speed operation, because the viscosity of water medium is very low, the liquid film thickness of the thrust bearing will be far lower than the actual design value, which results in the frequent occurrence of centrifugal effect of the bearing, and it becomes very urgent to solve the problem of axial deformation [3–4]. How to combine the bearing thrust plate of two-way thrust with the flywheel of the lower part, so as to increase the cycle cycle of
the shielded core main pump and maintain its large rotational inertia is the key and difficult point of the study [5]. The ideal design combination refers to the boundary condition of the film thickness of the thrust bearing as the distribution condition of the thrust liquid film of the axial surface deformation, which is generally true in the state of high-speed operation [6]. In the lubrication of low-viscosity water media, the liquid film thickness of the thrust disc and thrust bearing is usually in the order of 5-10 microns, and the minimum standard of axial denature for combined flywheel design is also in this order [7].

In the research on the thrust bearing structure with water as the medium, foreign researchers seem to be more interested in the bearing support mode and tile surface design principle [8]. In order to understand the positive and negative characteristics of the tile surface in the process of bearing use, foreign researchers often use the center support structure to lubricated the tilting tile bearing, so that the thermal wedge effect can be utilized [9]. In fact, in the actual application, the temperature rise of the thrust disc of the bearing with water medium is not obvious during the work, and even the bearing capacity cannot be generated [10]. When controlling the shape of the tile surface, heat energy and necessary friction force are usually increased by the friction of the surrounding concave and convex surfaces. When the absolute value of the concave and convex is between 0.4 and 0.5, the bearing capacity of the thrust plate is optimal and the centrifugal effect is the most stable [11]. Domestic scholars in this research mainly focused on the thermal elastohydrodynamic lubrication model and thrust bearing thrust plate size calculation of the experimental research, the geometric parameters of tilting tile bearing, medium parameters and working parameters are also done some research, and explains the thrust tile and thrust plate will be caused by the instability of liquid film pressure of bearing system temperature is not uniform, thrust plate of the centrifugal force on the low temperature zone axial shift caused by the centrifugal effect happened [12-13].

Obviously, the existing research on how the centrifugal effect of the bearing system with water media is affected by the temperature region of the thrust disc is not thorough, and the necessary quantitative calculation and analysis are lacking [14]. Based on the existing research results, this paper will use the finite element analysis method to uniformly calculate and analyze the occurrence conditions of centrifugal effect of thrust discs of different sizes under the working state of the bearing system and its influence on the bearing system [15]. The finite element model considering the flywheel combination structure needs to carry out the independent analysis of the deformation of the thrust disc end surface, so the calculated deformation results are substituted into the calculation of multi-field coupling performance, so as to further improve the theoretical model of centrifugal effect of water-lubricated thrust bearing.

2. Methods

2.1 Physical Model of Thrust Bearing Calculation

With water as the medium of shielded nuclear main pump thrust tile bearing USES is center support structure design, in order to satisfy the tilting in the center support bearing capacity demand and tilting tile bearing surface in the process of preparation will set aside a certain height of circular arc form surface bump, and form a symmetrical structure, thrust bearing thrust plate are distributed around. In order to reduce the computational workload of the model and improve the work efficiency, the model can be simplified according to the characteristics of the research object.

The unidirectional modeling analysis of thrust pad is selected in this study. This simplified analysis model is based on the premise that the distribution of the spindle and the tile film is consistent and there is no angular deviation. Therefore, the lubrication performance of thrust bearing can be evaluated by the lubrication performance of one-way tile. The expression equation of the calculated distribution function $h(r, \theta)$ of the entire unidirectional tile film thickness is:

$$h = \sin \gamma \left[r \sin(\theta_p - \theta) - r_m \sin(\theta_p - \theta_m)\right] + h_m + h_c(\theta) + \Delta h$$

(1)
Type, $\theta_p$ for pitch line position Angle, $hc$ for arc convex surface, the film thickness correction of $rm$, $\theta_m$ is not included in the arc respectively convex surface minimum film thickness in the radial coordinate and circumferential coordinate, $hc$ for considering the convex surface and thrust plate deformation after the minimum film thickness, $\Delta h$ for thrust disc axial deformation, the film thickness correction of $\gamma_p$ for tile around the pitch line turning Angle, $h_m$ is not included in the minimum film thickness value when arc convex surface.

In the indoor calculation model of the tilting pad, the temperature field distribution, liquid film flow pattern, coupling effect and flow field distribution between the pad and the pad must be considered. When the calculated pressure value is negative, the liquid film will rupture. At this point, the pressure boundary is:

$$\frac{\partial P}{\partial r} F_r = 0 \quad \frac{\partial P}{\partial \theta} F_\theta = 0$$

(2)

Where, $F_r$ and $F_\theta$ are the radial and circumferential boundary positions of liquid film rupture respectively. However, in order to confirm the axial deformation of the thrust disc under the action of centrifugal force, the centrifugal deformation of the thrust disc needs to be simplified. The specific method is as follows: in the finite element analysis software, the thrust hovers into a solid ring at a certain rotating speed, and then the displacement marker of axial end face by centrifugal force is established. Finally, the corresponding results are obtained based on the calculation of the marker position.

2.2 Finite Element Analysis Method

Reynolds equation is generally derived from hydrodynamics and navistokes equation. From the previous description, we know that in terms of stability, the stability of cylindrical bearing, oil wedge bearing, elliptical bearing and tilting pad bearing is improved in turn. The structure of cylindrical bearing is the simplest, and the bearing capacity is strong, but the stability is poor. In view of the static load of the limited width sliding bearing, we study the pressure of the immeasurable oil film with the Reynolds equation as the research algorithm. The dimensionless form of the Reynolds equation is:

$$\frac{\partial}{\partial r} \left( h^3 \frac{\partial p}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \phi} \left( h^3 \frac{\partial p}{\partial \phi} \right) = 6r \omega \frac{\partial h}{\partial \phi}$$

(3)

Where $\rho$ is the water film pressure, $\mu$ is the dynamic viscosity of water, $h$ is the thickness of water film, $\omega$ is the angular velocity, $R$ and $\phi$ are the polar diameter and angle of any point on the thrust pad surface.

2.3 Boundary Convergence Criteria of Reynolds Equation

According to the finite element analysis model, the water film thickness and the centrifugal deformation of the thrust disk are parameters of one order. Because the complicated assembly parts such as flywheel in the main pump are shielded and calculated, the influence of these assembly relations on the axial surface denaturation is minimal.

In the finite element analysis model, there are mainly three design parameters for the thrust plate and the assembly position, which are the matching relationship between the shield sleeve and the outer ring, the end panel and the outer ring, and the inner wheel hub and the end panel. The finite element analysis model adopts the welding method to deal with these panels.

The boundary conditions applicable to finite element analysis are rather harsh, so pressure load must be applied on the end surface, and the angular velocity of the axis can only be added from the whole, so as to achieve the calculated result closest to the centrifugal force of the end surface in the actual working condition.

3. Experiments

3.1 Experimental Environment Deployment
Water-lubricated thrust bearing liquid film centrifugal test environment requires the following equipment: support with base, and vertically arranged on the base; The driving motor is arranged on the base; The lubricating medium water tank is arranged on the upper part of the drive motor; The rotating shaft, one end of which is connected with the bottom end of the thrust plate under test through the lubricating medium water tank, and the other end is connected with the top of the bracket; The moment arm and set it in the rest axis.

3.2 Experimental Steps

In the first step, in order to ensure the good sealing of the lubricating media water tank, it is necessary to set a non-driven side mechanical seal in the water media box and the static shaft, and the negative is to ensure the support of the whole equipment environment.

The second step is set horizontally after the static shaft, and the motor is started to make the driving shaft start to rotate, releasing the frictional resistance to the liquid film surface of the tilting tile, and exerting a force on the outer end of the moment arm to prevent the rotation of the static shaft.

Third, when the coupling is driven by torque, it is necessary to avoid radial and axial loads on the drive motor and connect it to the speed sensor to analyze the recorded speed parameters.

The fourth step is to multiply the measured force and the moment arm length. For the recorded force value used to test the friction torque of the liquid film of the thrust bearing, the centrifugal force data of the liquid film of the bearing under test can be recorded and analyzed one by one.

4. Discussion and Results

4.1 Centrifugal Deformation Force of Thrust Plate

After simplifying analysis of the centrifugal deformation of the thrust disc, the axial deformation of the thrust disc under the action of centrifugal force can be confirmed. The thrust disk is assumed to be a uniform solid ring, which is rotated at a stable speed in the finite element analysis software.

The centrifugal deformation of thrust plates of different sizes is different under different forces. Since the finite element analysis software is unable to simulate the specific dimensions of the model, centrifugal deformation forces under different working conditions of the thrust plates of different sizes need to be calculated separately. The ideal theoretical and practical values of the model are shown in table 1 below.

Table 1. Theoretical deformation data of centrifugal effect and measured results of centrifugal deformation.

| Parameter                        | Theoretical value | Parameter                        | Measured value |
|----------------------------------|-------------------|----------------------------------|----------------|
| Tile diameter                    | R/mm              | Thrust disc diameter             | D/mm           |
|                                  | 453.2             | Diameter ratio  D/D₀             | 525            |
| Tile wide                        | B/mm              | Flywheel thickness               | 385            |
| Angle                            | °                  |                                  |                |
|                                  | 46                |                                  |                |
| Radial pivot eccentricity        |                  | Speed                           | 600-5000       |
| coefficient                     | 0.53              |                                  |                |
| Weeks to pivot eccentricity      |                  |                                  |                |
| coefficient                     | 0.46              |                                  |                |
| Raised height of tile surface    | h/um              |                                  |                |
|                                  | 24                |                                  |                |
| Speed                            | r/min             |                                  |                |
|                                  | 650-5500          |                                  |                |
| Single tile load                 | W/kN              |                                  |                |
|                                  | 20                |                                  |                |
| Inlet water temperature          | °C                |                                  |                |
|                                  | 63                |                                  |                |
It can be seen from table 1 that axial deformation of the thrust disk caused by centrifugal force is axisymmetric distribution in respect of the rotating shaft, and axial deformation caused by centrifugal force at the inner and outer diameters of the end face is also axisymmetric distribution.

4.2 Analysis of Deformation Independence of Thrust Disc

In the design process of the frontal structure of the thrust plate, the dominant design idea should be to avoid the coupling between the flywheel assembly and the end panel as far as possible, so as to ensure the independence of the thrust plate. Therefore, in the assembly relationship, the independence of the thrust disc should be analyzed separately according to the design clearance.

When the end panel reaches the maximum centrifugal deformation, the thickness of the liquid film also reaches the same magnitude, so the axial deformation caused by centrifugal effect will have an impact on the performance analysis. The specific centrifugal deformation results of the end face of the thrust plate at different rotating speeds are shown in figure 1 below.

![Centrifugal deformation results of thrust disk at different rotating speeds](image)

Figure 1. Centrifugal deformation results of thrust disc end face at different rotating speeds.

As can be seen from the figure, with the increase of the speed of the thrust disc, the shape of the bearing end face also changes, and the influence of centrifugal force on the thrust disc cannot be ignored, and its magnitude can reach the magnitude of the minimum film thickness of the water-lubricated thrust bearing. When the speed of the thrust plate exceeds 3000r/min, the deformation of the thrust plate increases significantly due to centrifugal effect.

4.3 Analysis of Deformation Independence of Thrust Disc

The influence of centrifugal force on the thrust disk was investigated in detail. At high speed, the deformation of the thrust plate is relatively serious, and the friction pressure on the main end of the inference shaft is also greatly increased.

When the load is the same, the minimum film thickness of the bearing system can best reflect the influence of centrifugal effect on the bearing system. The experiment above also shows that the minimum swing Angle of the bearing increases with the increase of rotating speed, and the result after centrifugal deformation of the thrust disc is close to the expected result. The results show that the centrifugal deformation of the thrust disc has little effect on the lubrication performance. However, the risk of internal leakage from the thrust plate of the bearing is significantly increased, which is due to the increased film thickness at the inner diameter due to centrifugal deformation. With the increase of centrifugal deformation force, tile tilting will not compensate for the centrifugal deformation. At this point, the swing Angle will increase rapidly and the minimum film thickness will decrease quickly,
which will affect the bearing performance. Therefore, try to avoid running the thrust plate at speeds greater than 3000r/min.

5. Conclusions
Based on the finite element analysis method, the centrifugal effect of thrust disc on the bearing system is analyzed and prospected. It is found in this paper that with the increase of the speed of the thrust disc, the axial deformation degree of the bearing system with water medium will increase significantly, which will directly affect the lubrication performance of the tilting bearing. At low speed, the bearing system can compensate the deformation of the thrust plate by tilting the tile and keep the relatively stable shape of the thrust plate. Although the research in this paper does not include all the factors, the selected analysis method is more in line with the research theme of this paper, more reliable, can provide some practical guidance for the research on the best working environment of bearing.

Acknowledgments
Project Fund: Undergraduate Program of Independent Innovation Research Fund of Wuhan University of Technology (2019-ND-B1-17).

References
[1] Huang, T. Y., Weng, S. J., Hsu, S. Y. (2017). Effect of Variation of Gap Thickness of the Thrust Bearing on Gap Pressure and Stiffness of the Aerostatic Spindle in Vertical Milling. J. Key Engineering Materials, 739(436):1-6.
[2] Lai, T. W., Guo, Y., Wang, W. (2017). Elasto-hydrodynamic lubrication model of multi-decked foil thrust bearing with copper wire support. J. Journal of Mechanical Science & Technology, 31(9):4371-4379.
[3] Xu, C., Zhang, G.H., Sun, Y. (2019). Performance analysis of air foil thrust bearings with different top foil taper heights. J. Hangkong DongliXuebao/journal of Aerospace Power, 31(12):3064-3072.
[4] Gao, Z., Wang, L., Yang, L. (2017). Effect of wear-ring clearance on performance and flow characteristics of centrifugal pump. J. Journal of Drainage & Irrigation Machinery Engineering, 35(1):13-17.
[5] Zhai, L. M., Luo, Y. Y., Wang, Z. W. (2018). 3D Two-way Coupled TEHD Analysis on the Lubricating Characteristics of Thrust Bearings in Pump-turbine Units by Combining CFD and FEA. J. Chinese Journal of Mechanical Engineering, 29(1):112-123.
[6] Danielsen, K., Gutiérrez Guzmán, F., Dahl, K.V. (2018). Multiscale characterization of White Etching Cracks (WEC) in a 100Cr6 bearing from a thrust bearing test rig. J. Wear, 370:73-82.
[7] Klokchov, S., Egorov, U.P., Carlo Mapelli. (2018). Tin and Nickel Influence on the Structure and Properties of the Leaded Bronze Obtained by Means of the Centrifugal Casting. J. Materials Science Forum, 870:248-252.
[8] Gao, B., Yang, L., Zhang N. (2018). Effects of tongue tip radius on performance and hydrodynamic load characteristics in centrifugal pump. J. Journal of Drainage & Irrigation Machinery Engineering, 74(326):63-82.
[9] Wang, P., Jin, X., Zhou, W.J. (2018). Analysis of Plate Non-parallelism Error of Capacitance Displacement Sensor in Thrust Measurement of Space-borne Micro-thruster[J]. ActaArmamentarii, 39(4):816-824.
[10] X. Zhang, S. Yuan, J. Zhang. Effects of spiral volute type on performance of high specific speed centrifugal pump[J]. Journal of Drainage & Irrigation Machinery Engineering, 2017, 35(1):25-31.
[11] Mou, J., Dai, D., Gu, Y. (2017). Influences of impeller ring structure on performance and flow field of centrifugal pump[J]. Journal of Central South University, 48(6):1522-1529.
[12] Hashemi, A. R., Pishevar, A. R., Valipouri, A. (2018). Numerical and experimental study on the
steady cone-jet mode of electro-centrifugal spinning. J. Physics of Fluids, 30(1):117-123.

[13] Delano, J. E., Amos, C. B., Loveless, J. P. (2017). Influence of the megathrust earthquake cycle on upper-plate deformation in the Cascadia forearc of Washington State, USA. J. Geology, 45(11):45-62.

[14] Chaves, E. J., Duboeuf, L., Schwartz, S. Y. (2017). Aftershocks of the 2016 M w 7.6 Nicoya, Costa Rica, Earthquake and Mechanics of the Plate Interface. J. Bulletin of the Seismological Society of America, 107(3):5-7.

[15] Abbas Babaahmadi, Renate Sliwa, Joan Esterle. (2017). The evolution of a Late Cretaceous–Cenozoic intraplate basin (Duaringa Basin), eastern Australia: evidence for the negative inversion of a pre-existing fold–thrust belt[J]. International Journal of Earth Sciences, 107(5):1895-1910.