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Abstract: In this study, two-row tapered roller bearings (TBR) with different rib structures were tested under the condition of loss of lubrication. It was found that the double-row TBR with outer ring rib structure worked normally after 40 min of the test, but the inner ring bearing of the side structure has failed. In order to explain this phenomenon, computational fluid dynamics (CFD) numerical simulation models of two structural bearings were established, and the flow characteristics of the oil in the bearing cavity under the conditions of full lubrication and loss of lubrication were studied by the method of discrete inlet oil volume. The research results show that, in the fully lubricated state, the oil volume fraction of the double-row TBR outer ring wall of the outer ring rib structure is 11.296 times higher than that of the inner ring rib structure. Moreover, the volume fraction of oil on the roller surface is 2.07 times higher in the outer ring rib structure than the inner ring rib structure. The volume fraction of lubricating oil in the bearing cavity decreases as the speed increases; however, the double-row TBR with the outer ring rib structure still shows a better lubrication effect than the inner ring rib structure. In the final stage of the loss of lubrication, the volume fraction of the bearing flow field of the outer ring rib structure is twice that of the inner ring rib structure, making the outer ring rib structure double-row tapered roller bearing (TBR) more dry Operational ability.

Keywords: double-row tapered roller bearing (TBR); loss of lubrication; oil volume distribution; computational fluid dynamics (CFD)

1. Introduction

Double-row tapered roller bearings (TBR) can withstand large radial and axial loads. These attributes have facilitated their wide application in helicopter transmission systems and other important fields. However, during the bearing operation process, failures may occur owing to excessive load and poor lubricating oil quality, which could lead to severe safety accidents. The distribution of lubricating oil flow fields in the bearing cavity of double-row TBRs is directly related to their service life. Therefore, it is necessary to conduct an in-depth study on their distribution in the cavity of double-row TBRs.

The law of movement of oil and gas two-phase flow is relatively complicated. At present, advanced experimental methods are generally used to obtain the law of two-phase flow. Yan K et al. [1] used PIV technology to measure the flow field distribution in the bearing and found that there are exit eddy currents on both sides of the steel ball; as the bearing speed increases, the vortex size increases. Wu W et al. [2–4] used a high-speed camera to study the distribution of oil inside the bearing under oil injection lubrication. The study found that most of the oil was distributed near the outer ring; the oil volume...
fraction inside the bearing increased with the increase in inlet flow. Ran Z [5] also uses a high-speed camera to study the flow field distribution of the ball bearing under oil injection lubrication.

With the advancement of computer technology, the computational fluid dynamics (CFD) method has been widely adopted in the analysis and research of flow fields in rotating machinery [6], like bearings and gears. Raju KS et al. [7] simulated the movement of a needle roller bearing using the moving reference frame method. By comparing the distributions of the oil volume fractions at two different inlet positions for lubricating oil, they obtained the best position for setting the lubricating oil inlet. Crouchez-Pillot et al. [8] used the volume of fluid (VOF) multiphase flow modeling method and the mesh adaptive technology to track the two phases of oil and gas in the bearing cavity of a certain engine and obtained the distribution law of the lubricating oil in the bearing cavity. They obtained the distributions of the flow, pressure, and velocity fields of the lubricating oil in the bearing cavity under the uniform gas-liquid two-phase condition. Hu et al. [10] established a 3D transient simulation model of the oil-gas two-phase flow in high-speed angular contact ball bearings based on the VOF method and sliding mesh technique. They studied the characteristics of the flow field in the bearing cavity and obtained the distribution law of lubricating oil—such that the average volume fraction of the lubricating oil decreases with the increase of rotational speed but increases with the increase of oil flow. Zhai et al. [11] used the rotating reference frame method and the VOF model to analyze the gas flow of roller bearings under different rotational speeds and cage structure parameters. They determined the influence laws of the bearing revolution, steel ball spin, cage structure, and other parameters on the bearing lubrication performance. With the angular contact ball bearing as the research object, Fu et al. [12] analyzed the influence of the lubrication and working condition parameters on the bearing lubrication performance. Their study showed that the lubricating oil is mainly distributed on the surface of the inner and outer ring raceways and the ball surface of the bearing, and is slightly distributed near the cage. Gao et al. [13] tracked the oil and gas two-phase flow in the roller bearing under ring lubrication using the CLSVOF multiphase flow analysis method and analyzed the influence of factors, such as the rotational speed on the distribution of the lubricating oil. They found that the volume fraction of the lubricating oil exhibited a convex variation trend owing to the relative movement between the inner ring and the cage; furthermore, the volume fraction of the lubricating oil changed linearly with the linear change of the inner ring rotational speed. Wang et al. [14] used the multiple reference frame (MRF) method to analyze the pressure distribution in the bearing cavity, the gas-liquid two-phase flow, and other change laws under different cage guidance modes. Their research shows that under high rotational speeds, the pressure difference in the bearing cavity increases rapidly, and the flow velocity in the bearing cavity is the greatest when employing the outer ring guidance mode. Liu et al. [15] used the VOF method and MRF model to perform numerical calculations on the flow characteristics of lubricating oil in the cavity of high-speed angular contact ball bearings. Zhang [16] established a CFD calculation model for tapered roller bearings and found that the oil volume fraction of the bearing fluid area first increased and then decreased with the increase of the bearing inner ring speed, while the oil volume fraction increased with the increase of the fuel injection volume and the number of nozzles. Linfeng Ge et al. [17] use the CFD method to optimize the bearing model, by adding groove structures to the non-contact area of the bearing inner ring surface, a guiding method for lubrication enhancement was proposed. Their study shows that the oil volume fraction in the cavity decreases with the increase of the bearing rotational speed and increases with the increase of the inlet oil volume; however, the relationships are nonlinear.

Under special working conditions of loss of lubrication, Roy M [18] found the bearing failed due to lack of lubrication causing overheating and deformation of rollers by metal-to-metal contact, which resulted in the formation of untampered martensite.
Under special working conditions of loss of lubrication, Roy M [18] found the bearing failure. For the bearing with the inner ring rib structure, the cage turned black, a crack appeared at the spacer beam of the large roller cage, and the small roller cage fractured, as shown in Figure 2. The double-row TBR with the outer ring rib structure exhibits better oil retaining capacity than that with the inner ring rib structure, and its dry running ability is also stronger in the oil loss state. These observations are consistent with the simulation analysis results of this study.

In order to explore the influence of the rib structure on the lubrication of bearings in the process of oil loss, the CFD method is used to analyze the distribution of lubricant in the two structural bearing cavities in these processes. Figure 3 illustrates the analysis process of the bearing lubrication situation and the comparison of the oil distribution of the bearing structure based on CFD.
Under special working conditions of loss of lubrication, Roy M [18] based on computational fluid dynamics (CFD) simulations, presents a method to calculate the onset of starvation in oil-lubricated point contacts. In summary, lubricating oil distributions in roller bearings under different working conditions can be effectively predicted through CFD numerical simulations. However, currently available research is mainly focused on ball bearings; mainly to study the bearing characteristics of lubricating oil in double-row tapered roller bearings (TBR) mainly to study the bearing basins during this process are compared. Guide the selection of double-row tapered roller bearings with special structures were tested under certain reducer as the test rig. The test speed is 5000 r/min, and the power is $P = 100$ kW, \( \text{Apl. Sci. 2021, 11, x FOR PEER REVIEW 4 of 17} \)

3. CFD Theory

3.1. Governing Equation

The fluid flow pattern in the double-row TBR is relatively complicated; however, it still satisfies the Navier–Stokes governing equation, including the mass conservation equation, momentum conservation equation, and energy conservation equation [20]. In this work, only the fluid flow in the bearing was studied, and the working temperature was predefined. Therefore, the energy equation is not considered here [21].

$$\frac{\partial \rho}{\partial t} + \nabla (\rho u) = 0 \quad (1)$$

$$\frac{\partial (\rho u_i)}{\partial t} + \nabla (\rho u u_i) = \nabla (\mu \cdot \text{grad}(u_i)) - \frac{\partial p}{\partial x_i} + S_i \quad (2)$$

where $\rho$ is the lubricating oil density, kg/m$^3$; $t$ is time, s; $u$ is the velocity vector, m/s, $u = [u_1, u_2, u_3]$; $\mu$ is the dynamic viscosity of the lubricating oil, Pa·s; $p$ is the pressure on the lubricating oil infinitesimal body, Pa; $x_i$ represents the coordinate in all directions, where...
\( i = 1, 2, \text{ and } 3, \) corresponding to the x, y, and z directions, respectively. \( S_i \) is the general source term, \( \text{kg} / (\text{m}^2 \cdot \text{s}^2) \).

### 3.2. VOF Multiphase Flow Model

The internal flow field analysis of double-row TBRs involves the oil-gas two-phase flow. To track the oil-gas two-phase flow, the VOF method is adopted [22]. Since the double-row TBR only involves two phases of oil and gas, this study adopts the VOF model, where the sum of the volume fractions of all phases in each control volume in the model is 1.

\[
\varphi_{\text{oil}} + \varphi_{\text{air}} = 1 \tag{3}
\]

where \( \varphi_{\text{oil}} \) represents the volume fraction of the oil and \( \varphi_{\text{air}} \) represents the volume fraction of the air.

### 3.3. Turbulence Model

Double-row TBRs have complex structures and motion states and involve the two phases of oil and gas. They also operate at high rotational speeds, and the turbulence in the bearing fluid domain is strong. To better simulate the fluid flow on the curved wall, the RNG \( k - \varepsilon \) turbulence model is adopted in this study [23]. The equations for the turbulence kinetic energy \( k \) and the turbulent dissipation rate \( \varepsilon \) are respectively as follows:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \alpha_k \mu_{\text{eff}} \frac{\partial k}{\partial x_j} \right] + G_k + \rho \varepsilon \tag{4}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \alpha_\varepsilon \mu_{\text{eff}} \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{C_1 \varepsilon}{k} G_k - C_2 \rho \varepsilon \frac{k^2}{\varepsilon} \tag{5}
\]

\[
\mu_{\text{eff}} = \mu + \mu_t \tag{6}
\]

where \( \mu_{\text{eff}} \) is the total viscosity of the lubricating oil; \( \mu \) is the dynamic viscosity of the lubricating oil; \( \mu_t \) is the eddy viscosity caused by the local turbulent motion of the lubricating oil; \( G_k \) is the production term of the turbulence kinetic energy \( k \) caused by the average velocity gradient of the lubricating oil; \( \alpha_k \) and \( \alpha_\varepsilon \) are respectively the reciprocals of the effective Prandtl numbers of the turbulence kinetic energy and turbulent dissipation rate, and \( C_1 \varepsilon \) and \( C_2 \varepsilon \) are model constants.

### 3.4. MRF Model

During the use of double-row TBRs, the outer ring is stationary and belongs to the static region, whereas the inner ring, rolling elements, and cage are rotating and belong to the dynamic region. Owing to the presence of the motion region, the established fixed reference coordinate system can change from a steady state to a transient state. Thus, the MRF method is employed to convert the transient flow of the fluid into a steady-state flow for the solution [24,25]. The motion form is described by the rotating coordinate system, as shown in Figure 4 [26].

The bearing rotates at a speed of \( \omega \) relative to the fixed coordinate system, and the motion state of the airflow at any point in the bearing cavity can be determined by the following equations:

\[
\nu = \nu_r + \nu_r
\]

\[
\nu_r = \nu_l + \omega \times r
\]
4. Numerical Computational Model

4.1. Computational Model

According to the parameters of the double-row TBRs listed in Table 1, the 3D models for the two types of bearings with the inner ring and outer ring rib structures are established, as shown in Figure 5.

Table 1. Main parameters of double-row TBRs.

|                          | Outer Ring Rib | Inner Ring Rib |
|--------------------------|----------------|---------------|
| Number of small rollers   | 21             |               |
| Number of large rollers   | 19             |               |
| Outer ring width (mm)    | 53             |               |
| Inner ring width on the small roller side (mm) | 24    |               |
| Inner ring width on the large roller side (mm) | 35    |               |
| Oil filling port         | 6 × φ2 mm (uniform distribution) |               |

When using the CFD method for the simulation, tiny structures—such as the transition circle and chamfered circle of the bearing—that have little effect on the calculation results of the flow field are ignored. Because the inner ring material and rotational speed on both the left and right sides of the double-row TBR are the same, the bearing inner rings on both sides are combined to create an integral structure in the modeling. The rollers as well as the inner and outer rings are lubricated by an oil film, and the gap is very small. Given the requirements of the flow passage extraction and meshing, the tapered roller size is reduced by 0.5 mm [2]. The simplified models for bearings with different ring rib structures are shown in Figure 6.
The internal flow field analysis model of the bearing is extracted using the ANSYS Design Modeler, as shown in Figure 7. Six oil ports are uniformly distributed on the outer ring of the bearing, where two oil ports are used for oil filling, and the other four are pressure outlets. The pressure is atmospheric pressure.

![Figure 7. Internal flow field analysis models of the bearings. (a) Outer ring rib structure; (b) Inner ring rib structure.](image)

4.2. Meshing

The double-row TBR is composed of large/small rollers, an inner ring, an outer ring, a cage, and other components, which give it a relatively complex structure. The hexahedral mesh has high accuracy and a small number of nodes, but for complex models similar to bearings, the tetrahedral mesh has stronger adaptability and can meet the complex structure of any shape. A certain degree of optimization will be carried out during the mesh generation process. The mesh size and node density are also easier to control, so higher quality meshes can be generated, and the mesh quality is often better than that of a hexahedron. Thus, the unstructured tetrahedral meshing elements are used here. To improve the computational accuracy and convergence, the tapered roller contact area is locally refined to ensure that there are at least two layers of meshes for the passage gap at the tapered roller. The passage meshes for the two types of structures are shown in Figure 8.

In order to eliminate the influence of the number of grids on the calculation results, the volume fraction of the oil on the roller wall is used as the monitoring quantity, and the grid independence is verified. The verification result is shown in Figure 9. When the number of grids in the flow field of the outer ring rib structure bearing is 350 W and the number of grids in the inner ring rib structure bearing flow field is 200 W, increasing the number of grids, and the volume fraction of the roller wall oil basically does not change. Thus, the mesh quality parameters are finally determined as shown in Table 2. The maximum skewness is lower than 0.8 to ensure the convergence of the simulation calculation.
The internal flow field analysis model of the bearing is extracted using the ANSYS Fluent software. The calculation model is set to the steady-state. The VOF two-phase flow model is then turned on, and the turbulence equation is selected. The PRESTO! scheme is adopted for the discretization of the pressure term. The phase function residual is set to 10\(^{-5}\) to determine the convergence of the computation [13].

The settings for the double-row TBR working conditions are as follows: inner ring rotational speed \(n = 5000\) r/min, the small roller rotational speed is 2251 r/min, the large roller rotational speed is 2211 r/min, and the maximum flow rate is 0.02 kg/s in the fully lubricated state. The properties of the oil are shown in Table 3. The oil loss process is reflected by the change of the bearing inlet oil volume, and the inlet oil volume is discretized into 15 nodes according to the ratio of the R10 priority coefficient, as presented in Table 4.

### Table 2. Mesh quality parameters.

|                  | Outer Ring Rib | Inner Ring Rib |
|------------------|----------------|---------------|
| Mesh number      | 3,479,889      | 1,977,547     |
| Average skewness | 0.2393         | 0.1236        |
| Maximum skewness | 0.7501         | 0.7816        |

### 4.3. Simulation Settings

The .mesh file is imported into the Fluent software, and the calculation model is set to the steady-state. The VOF two-phase flow model is then turned on, and the turbulence model is set to the RNG \(k-\varepsilon\) model. The first-order upwind scheme discrete phase function equation is selected. The Second-order upwind scheme discrete momentum equation and turbulence equation is selected. The PRESTO! scheme is adopted for the discretization of the pressure term. The phase function residual is set to 10\(^{-5}\) to determine the convergence of the computation [13].

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### Table 3. The properties of oil.

| Density Viscosity Temperature |
|------------------------------|
| 875.15 kg/m³ 0.0251 kg/(m·s) 60 °C |

### Figure 8. Meshing for the bearings of two different structures. (a) Outer ring rib structure; (b) Inner ring rib structure.

### Figure 9. Results of grid independence verification. (a) Outer ring rib structure; (b) Inner ring rib structure.
Table 3. The properties of oil.

| Density    | Viscosity    | Temperature |
|------------|--------------|-------------|
| 875.15 kg/m³ | 0.0251 kg/(m·s) | 60 °C       |

Table 4. Division of discrete nodes of inlet oil volume in the oil loss process.

| No. | Inlet Oil Volume (kg/s) | No. | Inlet Oil Volume (kg/s) | No. | Inlet Oil Volume (kg/s) |
|-----|-------------------------|-----|-------------------------|-----|-------------------------|
| 1   | 0.0200                  | 6   | 0.0063                  | 11  | 0.0020                  |
| 2   | 0.0160                  | 7   | 0.0050                  | 12  | 0.0016                  |
| 3   | 0.0126                  | 8   | 0.0040                  | 13  | 0.00126                 |
| 4   | 0.0100                  | 9   | 0.0032                  | 14  | 0.0010                  |
| 5   | 0.0080                  | 10  | 0.0025                  | 15  | 0.0008                  |

In the calculation process, the continuity, velocity, oil-liquid integral, turbulence kinetic energy (k) and turbulent energy (ε) dissipation rate are detected. When the relative change of the monitoring parameters is less than 1% within 1000 steps, it is considered as convergence.

5. Flow Field Analysis in the Fully Lubricated State

5.1. Comparison of Oil Distribution on the Inner/Outer Ring Wall

The calculated oil distributions on the inner/outer ring wall of the two types of bearings with different rib structures are shown in Figure 10 and Table 5. It can be observed that: (1) for the two types of rib structures, the oil volume fraction on the outer ring wall is greater than that on the inner ring wall. This is because the lubricating oil in the bearing cavity is affected by the inertial force and most of it is attached to the outer ring wall; (2) The volume fraction of the lubricating oil on the outer ring wall of the bearing with the outer ring rib structure is larger than that with the inner ring rib structure, the oil volume fraction of the double-row TBR outer ring wall of the outer ring rib structure is 11.296 times higher than that of the inner ring rib structure. This is because the outer ring rib can effectively prevent the oil from being thrown out of the bearing cavity through the outer ring wall; (3) The volume fraction of lubricating oil on the inner ring wall of the bearing with the inner ring rib structure is larger than that with the outer ring rib structure. This is because the inner ring rib can effectively prevent the lubricating oil attached to the inner ring wall from being thrown out of the bearing cavity.

5.2. Oil Distributions on the Large/Small Roller Walls

The lubricating oil distributions on the rollers of the two types of bearings with different rib structures are shown in Figure 11, and the volume fractions of the lubricating oil on the walls of the large and small rollers are listed in Table 6. It can be observed that: (1) the lubrication conditions of the large and small rollers of the bearing with the outer ring rib structure are better than those with the inner ring rib structure. (2) For the bearing with the inner ring rib structure, the lubrication condition of the large roller wall is better than that of the small roller wall. (3) For the bearing with the outer ring rib structure, the lubrication condition of the small roller wall is better than that of the large roller wall. (4) The oil volume fraction of the roller wall of the outer ring rib structure bearing is twice that of the inner ring rib structure.
The volume fraction of the lubricating oil on the outer ring wall of the bearing with the inner ring rib structure is greater than that with the outer ring rib structure. This is because the lubricating oil in the bearing cavity is affected by the inertial force and most of it is attached to the outer ring wall; (2) the lubricating oil volume fraction on the outer ring wall is twice that of the inner ring rib structure. This is because the outer ring rib can effectively prevent the oil from being thrown out of the bearing cavity through the outer ring wall; (3) for the bearing with the outer ring rib structure, the lubricating oil volume fraction on the walls of the large and small rollers is 11.296% and 4.719%, respectively. This is greater than that on the inner ring rib structure. This is because the outer ring rib can effectively prevent the lubricating oil attached to the inner ring wall from being thrown out of the bearing cavity.

Figure 10. Oil distributions on the inner/outer ring wall of the bearings. (a) Outer ring rib structure; (b) Inner ring rib structure.

Table 5. Average volume fraction of lubricating oil on the inner/outer ring wall (%).

|                | Inner Ring          | Outer Ring          |
|----------------|---------------------|---------------------|
| Outer ring rib | 0.47190             | 5.3308              |
| Inner ring rib | 0.88942             | 2.6373              |

Figure 11. Oil distributions on the large/small roller walls. (a) Outer ring rib structure; (b) Inner ring rib structure.

Table 6. Volume fraction of lubricating oil on the roller wall (%).

|                | Large Roller | Small Roller | Average  |
|----------------|--------------|--------------|----------|
| Inner ring rib | 0.8254       | 0.4248       | 0.00647  |
| Outer ring rib | 1.1613       | 1.5719       | 0.01344  |
The roller directly below the bearing oil inlet is numbered as 1, and the rest of the rollers are numbered along the bearing’s rotation direction (as shown in Figure 12). The volume fraction of the oil on the wall of all the rollers is calculated. The variation of the lubricating oil volume fraction on the walls of the large and small rollers with the change of the roller position is shown in Figure 13. It can be deduced that: (1) the distribution trend of the lubricating oil on the roller walls of bearings with the two types of rib structures is the same. The closer it is to the bearing oil inlet, the higher the lubricating oil volume fraction on the roller wall. Further, the lubricating oil volume fraction on the roller gradually decreases along the bearing rotation direction. (2) For the bearing with the outer ring rib structure, the lubrication condition of the small roller wall is better than that of the large roller wall; however, for the bearing with the inner ring rib structure, the lubrication condition of the large roller wall is better than that of the small roller wall.

5.3. Volume Distribution of Lubricating Oil on the Cage Wall

Figure 14 shows the distribution contours of the lubricating oil on the cage walls of the bearings of two different structures. It can be observed that the oil distribution amount on the cage wall of the bearing with the outer ring rib structure is greater than that with the inner ring rib structure.

5.4. Distribution of Lubricating Oil at the Roller Rib and Roller Center Section

The small roller center section, the large roller center section, the small roller rib, and the large roller rib are selected for the comparative analysis of the two types of bearings with different rib structures. Figure 15 shows the distributions of the lubricating oil at the small roller center sections of the two types of bearings, which can be seen that the distribution of oil on this section is similar to the simulation result of Yan Ke [27]. It can be observed from Figure 14 that: (1) for the two types of bearings with different rib structures, there is sufficient lubricating oil at the small rollers. The area pointed by arrow 1 has sufficient and uniform lubricating oil; the area pointed by arrow 2 is the area in the flow field with the least amount of lubricating oil. This is because this area is relatively far away from the oil filling port, and most of the lubricating oil is thrown out of the bearing along the rotation direction while entering the gap between the roller and inner and outer rings. (2) The oil distribution on the outer ring wall of the bearing with the outer ring rib structure is better than that with the inner ring rib structure. No obvious oil-deficient area is observed on the outer ring wall of the bearing with the outer ring rib structure. (3) The oil distribution on the inner ring wall of the bearing with the outer ring rib structure is inferior to that with the inner ring rib structure. This is because when the rib is on the outer ring, the inner ring of the bearing cannot effectively prevent the oil on the inner ring wall from being thrown out of the bearing cavity along the inner ring wall.

![Oil inlet](image1)

**Figure 12.** Schematic diagram of roller numbers.
Figure 12. Schematic diagram of roller numbers.
(a) 

(b) 

Figure 13. Oil distributions on the walls of large and small rollers. (a) Outer ring rib structure; (b) Inner ring rib structure.

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Figure 14. Lubricating oil distribution contours on cage walls. (a) Outer ring rib structure; (b) Inner ring rib structure.

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Figure 15. Lubricating oil distributions at the center sections of the bearing small rollers. (a) Outer ring rib structure; (b) Inner ring rib structure.

Figure 16 shows the distribution contours of the lubricating oil at the center sections of the large rollers of the two types of bearings. It can be observed that most of the lubricating oil is distributed in the gap between the roller and outer ring wall, and the bearing with the outer ring rib structure has a better lubricating oil distribution at the large roller center section.

Figure 16. Lubricating oil distribution contours on cage walls. (a) Outer ring rib structure; (b) Inner ring rib structure.
5.4. Distribution of Lubricating Oil at the Roller Rib and Roller Center Section

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Figure 15. Lubricating oil distributions at the center sections of the bearing small rollers. (a) Outer ring rib structure; (b) Inner ring rib structure.

Figure 16 shows the distribution contours of the lubricating oil at the center sections of the large rollers of the two types of bearings. It can be observed that most of the lubricating oil is distributed in the gap between the roller and outer ring wall, and the bearing with the outer ring rib structure has a better lubricating oil distribution at the large roller center section.

Figures 17 and 18 show the oil distributions at the small roller rib and the large roller rib of the two types of bearings, respectively. It can be observed from the figures that the bearing with the outer ring rib structure has more sufficient and even oil distribution at the ribs. This is because when most of the lubricating oil is attached to the outer ring wall of the bearing, compared with the bearing with the inner ring rib structure, the bearing with the outer ring rib structure can block the lubricating oil better and prevent it from being thrown out of the bearing cavity along the outer ring wall.

5.5. Simulation Analysis of Bearing Flow Field at Different Rotational Speeds

Five rotational speeds are selected for comparison, namely 4000 r/min, 4500 r/min, 5000 r/min, 5500 r/min, and 6000 r/min, as shown in Figure 19. It can be observed from Figure 15 that with the increase of the rotational speed of the double-row TBRs with different rib structures, the oil distribution amount on the surface of each component in the bearing cavity all decrease and exhibit similar downward trends. At the various rotational speeds, the bearing with the outer ring rib structure always exhibited better lubrication conditions than that with the inner ring rib structure.

5.6. Flow Field Analysis in the Oil Loss State

According to Table 6, CFD simulation is performed on the flow field of the two types of bearings at each oil loss node. The inlet oil volume and oil volume fraction at each discrete oil volume node are extracted for the bearing with the outer ring rib structure. Matlab software is employed to perform numerical fitting, where the linear interpolation, quadratic interpolation, and power methods are applied, respectively. The obtained fitted relationships are presented in Table 7.
Figure 16. Lubricating oil distribution at the center sections of the bearing large rollers. (a) Outer ring rib structure; (b) Inner ring rib structure.

Figure 17. Lubricating oil distributions at the small roller ribs of the bearings. (a) Outer ring rib structure; (b) Inner ring rib structure.

Figure 18. Lubricating oil distribution at the large roller ribs of the bearing. (a) Outer ring rib structure; (b) Inner ring rib structure.
with the increase of the rotational speed of the double-row TBRs with different rib structures, the oil distribution amount on the surface of each component in the bearing cavity all decrease and exhibit similar downward trends. At the various rotational speeds, the bearing with the outer ring rib structure always exhibited better lubrication conditions than that with the inner ring rib structure.

Figure 19. Lubricating oil distributions on various bearing components at different rotational speeds. (a) Outer ring rib structure; (b) Inner ring rib structure.

Table 7. Relationships obtained by numerical fitting.

| Fitting Method       | Fitting Formula                | Root Mean Square (RMS) |
|----------------------|--------------------------------|------------------------|
| Linear interpolation | $y = 0.93x + 0.0032$           | $1.4 \times 10^{-3}$   |
| Quadratic interpolation | $y = -23.55x^2 + 1.368x + 0.0021$ | $2.0 \times 10^{-4}$ |
| Power                | $y = 0.233x^{0.6235}$           | $9.4 \times 10^{-4}$   |

In the table: $x$ is the inlet oil volume; $y$ is the volume fraction of lubricating oil in the fluid domain.

The comparison result shows that the error is the smallest when using the quadratic interpolation method for data fitting, thus, the fitting curve equation is:

$$y = -23.55x^2 + 1.368x + 0.0021$$  \(9\)

Similarly, the volume fractions of lubricating oil in the bearing cavity of the bearing with the inner ring rib structure during the oil loss process are also fitted, and the obtained fitting curve equation is:

$$y = -6.728x^2 + 0.5932x + 0.0012$$  \(10\)

The variation patterns of the lubricating oil volume fraction in the bearing cavity with the inlet flow rate during oil loss for the two types of bearings are shown in Figure 20. It
In the table: \( x \) is the inlet oil volume; \( y \) is the volume fraction of lubricating oil in the bearing cavity. The comparison result shows that the error is the smallest when using the quadratic interpolation method for data fitting, thus, the fitting curve equation is:

\[
y = -6.728x^2 + 1.368x + 0.0021 \quad (9)
\]

can be observed from Figure 19 that: (1) In the oil loss state, the lubricating oil volume fraction in the cavity of the bearing with the outer ring rib structure decreases faster with the decrease of the inlet flow rate, but the lubrication effect of the bearing with the outer ring rib structure is still better than that with the inner ring rib structure; (2) In the final stage of the loss of lubrication, the volume fraction of the bearing flow field of the outer ring rib structure is twice that of the inner ring rib structure.

![Figure 20. Changes in the volume fraction of lubricating oil in the bearing cavity during oil loss.](image)

6. Conclusions

In this study, a comparison verification test of the bearing dry running performance was conducted. CFD numerical simulation models were established for two types of double-row TBRs with different rib structures, and the lubricating oil flow characteristics in the bearing cavity in both fully lubricated and oil loss states were studied. The distribution law of the bearing lubricating oil was explored under different lubricating oil flow rates and rotational speeds. The research results show that:

1. Through a comparative test of the two types of double-row TBRs with different rib structures, it shows that the internal lubrication condition of the double-row TBR with the outer ring rib structure is better than that with the inner ring rib structure.
2. In the fully lubricated state, the double-row TBR with the outer ring rib structure has a better lubrication condition than that with the inner ring rib structure, the oil volume fraction of the double-row TBR outer ring wall of the outer ring rib structure is 11.296 times higher than that of the inner ring rib structure. The rib can effectively prevent the lubricating oil attached to the inner/outer ring wall from being thrown out of the bearing cavity.
3. In the loss of lubrication state, the lubrication effect of the bearing with the outer ring rib structure is still better than that with the inner ring rib structure. In the final stage of the loss of lubrication, the volume fraction of the bearing flow field of the outer ring rib structure is twice that of the inner ring rib structure.

This article uses a discrete method to study the changes in the distribution of oil and gas in the bearing under the condition of loss of lubrication. In the future, it is expected that the dynamic grid or the slip grid can be used to analyze this process of the bearing. The bearing structure optimization can be guided by studying the influence of changes in bearing structure parameters on the distribution of oil and gas in the bearing.
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Nomenclature

TBR Tapered roller bearings
CFD Computational fluid dynamics
MRF Markov Random Field
VOF Volume of Fluid

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