A novel method for bearing lubrication enhancement via the inner ring groove structure

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Abstract: As the bearing rotation speed increases, the efficiency of the jet lubrication is drastically reduced due to the air curtain effect inside bearing cavity. Regarding this, by adding groove structures to the non-contact area of bearing inner ring surface, a novel method which can guide more oil flowing into the bearing raceway was proposed. By numerical simulation, the flow behavior of oil on the bearing inner ring surface was investigated. The results indicate that, compared with the traditional structure, the axial oil flow on grooved inner ring surface was enhanced, and more oil accumulated in the key lubrication area inside bearing cavity. Finally, by lubrication performance experiments, it was proved that the bearing lubrication performance had been improved by adding groove structures on its inner ring surface.

1. Introduction
As a key supporting component, the working performance of rolling bearings determines the stability and dynamic characteristics of mechanical rotation system. Good lubrication can restrain temperature rising and improve the working performance of the bearing[1]. Jet lubrication is currently widely used on high-speed ball bearings owing to its good lubrication performance[2]. For jet lubrication, the lubricating oil is injected from the nozzle, and then flows along the inner ring surface into the bearing cavity to achieve lubrication, as shown in Fig. 1(a). However, when bearing rotates at a high speed, the air curtain, which is a high-pressure and high-speed vortex, occurs around the bearing contact area and prevents oil flowing into the contact area, thus reducing the bearing lubrication efficiency and working performance[3]. Therefore, it is very important to improve the bearing lubrication performance.

Many researchers have carried out researches on bearing lubrication enhancement. Jiang[4] measured the bearing temperature to find out the influence of lubrication parameters on the bearing working performance, such as oil supply, oil viscosity and rotation speed. Guo[5] added guiding fibers on the traditional hole-type nozzle, which improved the utilization of lubricating oil. Chen[6] designed a new fan-type nozzle, which showed good lubrication performance in experiments. By installing the lubricating nozzle on the bearing outer ring, Kosugi[7] proposed an outer ring oil supply method. Moreover, the under-race lubrication, which supplies oil from the inner ring, is also widely applied in aeroengine bearings[8]. These methods can improve bearing lubrication efficiency effectively, but the complex structures also bring more restrictions on the applications of bearings.
The surface structure, such as the groove structure, can change or even control the flow behavior of the fluid, which is widely used in the microfluidic system. When adding groove structures on the surface, the fluid can be controlled to flow along the channel. Based on this, a novel method for bearing lubrication enhancement was proposed in this paper. As shown in Fig. 1, the axial groove structures are added to the non-contact area of the bearing inner ring surface. The purpose is to guide more oil to flow into the raceway, which gives the possibility to improve bearing lubrication efficiency. In this paper, the semicircle groove structures were added on the inner ring surface of H7006C angular contact ball bearing. First the oil flow behavior on bearing inner ring surface and the oil distribution in bearing cavity were numerically studied. After that, the experiments were carried out and the working temperature of these bearings were monitored, and the effect of the groove structures in bearing lubrication enhancement was finally evaluated.

2. Simulation study

2.1 Geometry model
The geometry model of the H7006C angular contact ball bearing is shown in Fig. 2(a). Fig. 2(b) shows the bearing lubrication structure, the nozzle was installed in the position toward the inner ring surface, and the nozzle diameter was 0.5mm. The flow area in the bearing cavity is extracted as the calculation region, which was divided with unstructured mesh method, and the total number of grid cells was about 1.3 million.

2.2 Boundary conditions
Considering the bearing motion characteristics, the bearing inner ring, the cage and the ball were set as rotating wall, the nozzle and the outer ring were set as stationary wall. The inlet at the nozzle was set as velocity-inlet boundary, and the other boundaries were set as pressure boundary[9].

The VOF (Volume of Fluid) model and the standard $k$-$\varepsilon$ turbulent model were employed for the solution of the complex oil-air two phase flow in bearing cavity. During the simulation, the 46# turbine oil was chosen as the lubricating oil with density 876 kg/m$^3$ and viscosity 0.058 kg/(m·s).

2.3 Groove structure
The groove structures were added axially to the area between the nozzle and the raceway on the inner
ring surface, as shown in Fig. 2(c). The purpose is to guide more oil flowing along the axial direction, thus improving the lubrication performance. The cross-sectional shape of the groove structure was semi-elliptical, and the length of the major semi-axis is 0.5mm. A deeper groove may cause damage to the bearing, so the length of the minor semi-axis is a smaller 0.3mm. Besides, in order to improve analysis accuracy of the model, the mesh in the groove area was refined.

3. Oil flow and lubrication analysis

3.1 Oil flow analysis on the bearing inner ring surface
The lubrication state of the contact area between the ball and the raceway determines the lubrication performance of the bearing[10]. A poor lubrication state occurs when the oil flowing into the raceway is insufficient, which leads to the increase of friction heat and causes massive temperature rising. Therefore, it is necessary to analyze the oil flow behavior on bearing inner ring surface.

Fig. 3 shows the phase map of oil volume fraction on bearing inner ring surface at different rotation speeds (in condition that the injection angle is 20°, the oil injection velocity is 20m/s). It can be found that most lubricating oil can flow directly into the raceway when the inner ring rotates at a lower speed of 1.0×10^4 r/min. However, when bearing rotation speed increases to 2.0×10^4 r/min, only a small part of the oil can flow into the raceway, while most of the oil is thrown out due to the centrifugal force. Meanwhile, in the grooved inner ring surface, the axial flow distance of oil increases, resulting in more oil accumulated in the grooved bearing raceway. For intuitive comparison, the amount of oil accumulates in these two inner ring raceways at different rotation speeds were obtained, as shown in Fig. 4. The results also indicate that there is more oil accumulates in the raceway of the grooved inner ring. Based on the above analysis, it can be found that, with the guiding effect of the groove structure, the axial oil flow is enhanced, which is beneficial to improve bearing lubrication efficiency.

3.2 Oil flow and distribution in complete bearing cavity
The lubrication state of the bearing can be evaluated through the oil flow and distribution. Therefore, the oil-air two phase flow simulation in the cavity of the complete bearing was carried out in this section. By comparison, the influence of groove structures on lubrication was further discussed.
Fig. 5. The streamline distribution of lubricating oil flow field in the bearing cavity. The rotation speed is 10000r/min, the injection angle is 20° and the oil injection velocity is 30m/s. Meanwhile, for easy observation and analysis, the radial center section inside bearing cavity is selected to show the oil phase streamline distribution along the axial direction. The simulation results are shown in Fig. 5(b), the axial flow distance of lubricating oil is shorter in the smooth bearing cavity, and the oil can only reach middle of the raceway. While in the grooved bearing cavity, with the guiding effect of the groove structures, the axial flow distance of the oil increases, and the oil can completely pass through the raceway. For further analysis, the oil volume fraction phase maps of the key lubrication area, such as ball and raceway, are extracted to evaluate bearing lubrication performance, as shown in Fig. 5(c). It is easy to find that more lubricating oil accumulates on the surface of the ball and raceway, which is beneficial for the formation of oil film, thus reducing bearing friction and temperature rising. These analyses show that under the guiding effect of the groove structures, more lubricating oil can flow into the key lubrication area in the bearing cavity, which can improve the bearing lubrication performance.

3.3 Bearing lubrication performance experiment

3.3.1 Experiment scheme
Experiments were carried out to verify the effect of groove structures in lubrication enhancement. In the experiment, the inner ring of one test bearing was replaced with the grooved inner ring, as shown in Fig. 6(a), and a traditional smooth bearing without groove structures was taken as the comparison test bearing.

Fig. 6(b) shows the bearing lubrication performance experiment rig, and the mechanical spindle was used as the experimental spindle. In the experiment, the front bearing of the mechanical spindle was replaced by test bearings in turn. And the temperature measuring system was used to obtain the temperature of bearing outer ring, which is an important index to reflect the lubrication performance of bearings.

Fig. 6. The bearing lubrication performance experiment rig.
The temperature measuring system mainly includes the PT100 temperature sensors and MX100 data acquisition system. As shown in Fig. 6(c), a temperature sensor was installed on the experimental platform to obtain the ambient temperature. Through radial through-holes on the bearing block, three sensors were contacted with the outer ring in order to obtain the temperature of the outer rings.

### 3.3.2 Results and discussion

With the oil supply at 0.5ml/h, temperature rising of the two test bearings were experimentally studied. For each given rotation speed, when the temperature rising of the outer ring was less than 0.5°C in an hour, the bearing was regarded to be thermal stable.

![Fig. 7. Outer ring temperature rising of two bearings.](image)

Fig. 7 shows the outer ring temperature rising of these two test bearings. It can be seen that, for each rotation speed, the temperature rising of the grooved bearing is lower than the smooth bearing, and the temperature difference increases with the increase of rotation speed. When the rotation speed reaches 7000r/min, the temperature rising of grooved bearing is 2.5°C lower than that of the smooth bearing. This shows that the lubrication performance of the grooved bearing is improved under the action of groove structures, which indicates the effectiveness of the groove structure in bearing lubrication enhancement.

### 4. Conclusion

By adding groove structure to the bearing inner ring surface, a new method for bearing lubrication enhancement was proposed in this paper. And the effect of groove structure on oil flow and bearing lubrication were analyzed by simulation and experiment. The conclusions are as follows:

1. By simulating the flow behavior of lubricating oil on the bearing inner ring surface, it is found that the groove structure can guide more oil to flow into the raceway along the axial direction.
2. With the guiding effect of the groove structure, more lubricating oil accumulates in the key lubrication area of the bearing, which is beneficial for the formation of lubrication oil film.
3. The temperature rising of the grooved bearing is lower than that of the traditional smooth bearing, and the lubrication performance of the bearing is improved by the groove structure.

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