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A simulation analysis of the lubrication characteristics of the planetary cylindrical roller bearing in power coupling mechanism

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Abstract. The appropriate lubrication characteristics of the rotating components in the power coupling mechanism are crucial for ensuring its operational stability. In this paper, a computational fluid dynamics (CFD) numerical model of the cylindrical roller bearing considering the revolution of the planetary gear train is established. The global motion relationships of planetary cylindrical roller bearing (PCRB) are characterized through multiple reference frame (MRF) method. The volume of fluid (VOF) model is adopted to simulate the complex oil-air two-phase flow in the bearing cavity. The results indicate that the field distributions of the velocity vector, pressure and lubricating oil in PCRB are significantly migrated due to the centrifugal effect driven by the revolution of the planetary gear train. The outer side of the bearing cavity relative to the revolution center has relatively high lubricating oil content, while the inner side has relatively low content. This zonation phenomenon is further is intensified with the increasing rotational speed and temperature, resulting from enhanced centrifugal effect and reduced oil viscosity. This work can provide applicable guidance for the design of lubrication systems for planetary bearings.

1. Introduction

The power coupling mechanism (PCM) is widely utilized in hybrid drive systems, benefiting from the efficient energy management achieved by planetary transmissions [1]. The lubrication system in the PCM is designed to supply suitable lubricating oil to transmission components, ensuring optimal lubrication and heat dissipation aligned with working conditions [2]. In particular, as the critical transmission components in planetary gear train, the lubrication conditions of the rolling bearings directly determine their operational stability and service life [3]. Given that the planetary transmissions generally involve extreme high-speed and heavy-load operating scenarios, and the specific lubricating oil distribution is difficult to experimentally detect, it is necessary to conduct lubrication characteristics analysis of planetary bearings via numerical simulation to guide lubrication system design.

The breakthroughs in computational fluid dynamics (CFD) have provided efficient numerical tools for investigating the lubrication characteristics of rolling bearings. Employing bi-directional fluid–structure coupling methodology, Jiao et al. [4] analyzed the pressure distribution and lubricating oil flow patterns within high-speed angular contact ball bearings. Shan et al. [5] presented a universal CFD modeling approach for ball bearing lubrication incorporating assembly clearance, and explored the oil-air distribution and temperature variations under different lubrication conditions. Liu et al. [6,7] adopted the volume of fluid (VOF) method to investigate the effects of injection flow rate and lubricating oil viscosity on rolling bearing lubrication characteristics, and further proposed a lubrication analysis modeling method considering the bearing dynamic behavior. Wei et al. [8] achieved improvements in the lubrication and heat dissipation performance of rolling bearings through cage structure design. However, current research on rolling bearing lubrication characteristics mainly focuses on their internal, while neglecting external motions. Actually, the rolling bearings in planetary gear trains possess an additional revolution around the transmission shaft, which inevitably affects the oil-air flow in the bearing cavity. Therefore, the lubrication characteristics of the planetary rolling bearing require systematically discussion. In this paper, a CFD model of the planetary rolling bearing is established to investigate the lubrication characteristics considering planetary revolution. The effects of rotational speed and temperature on the pressure and lubricating oil distributions in the bearing cavity are discussed parametrically to guide the lubrication system design of planetary transmission mechanisms.

2. Models and methodologies

2.1. Geometric description

The layout of the planetary gear train in the PCM is illustrated in Figure 1. Driven by the meshing engagement, planetary gears revolve around the sun gear while rotating on their own axes. The motion of the planetary gears is achieved by a row of NJ205 double-row planetary cylindrical roller bearings (PCRBs). The Lubricating oil is delivered through the internally integrated oil channels, and the specific oil supply path has been marked with blue arrows. The PCRBs are lubricated through the oil injection port located at the bottom. The PCRB is composed of twelve cylindrical rollers, a cage, and inner and outer raceways, and the initial bearing parameters are listed in Table 1.

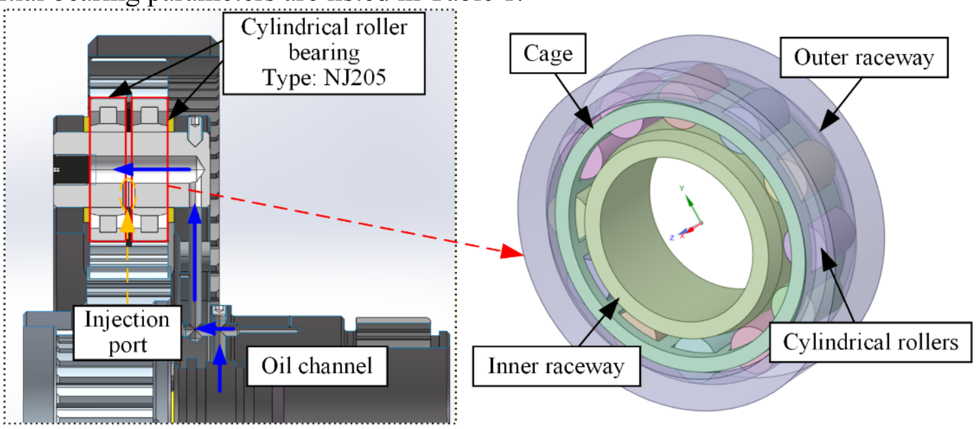


Figure 1. Layout of the planetary gear train in the PCM and composition of the studied PCRB.

Table 1. Initial bearing parameters of the studied PCRB.

Bearing parameters	Value
Inner diameter (mm)	25
Outer diameter (mm)	52
Thicknesses (mm)	14.88
Inner raceway diameter (mm)	31.42
Outer raceway diameter (mm)	46.06
Number of rollers (-)	12
Roller diameter (mm)	7.32
Roller length (mm)	8.78
Cage inner diameter (mm)	36.48
Cage outer diameter (mm)	40.96

2.2. CFD model

To investigate the lubrication characteristics of the PCRB, the simulation fluid domain consisting of the oil inlet and outlet and the bearing cavity is established, as shown in Figure. 2. Considering spatial symmetry, a single-row PCRB is extracted for CFD modeling to reduce computational consumption. The motion relationships of the simulated fluid domain are characterized through the multiple reference frame (MRF) method. Among them, the bearing cavity is first defined to revolve around the transmission shaft in the global coordinate system with revolution speed ω_R, while the oil inlet and outlet remain stationary relative to the bearing cavity. Relative to the global coordinate system, the cage rotates around its own axis at a rotational speed ω_c in the local coordinate system of bearing, while the inner raceway is stationary. The rotational speed ω_c also represents the revolution of the cylindrical rollers around the inner raceway. Finally, the cylindrical rollers are defined to rotate around their own axes relative to the local coordinate system of bearing. The local coordinate systems of each cylindrical roller correspond to their respective spatial positions. The revolution speed ω_R and the revolution radius can be calculated by the meshing engagement between planetary gears and the sun gear as well as the centroid distance. The motion relationships between bearing components can be expressed as

$$\omega_c = \frac{\omega_o(1-\gamma)}{2} \tag{1}$$

$$\omega_r = \frac{d_m \omega_o (1-\gamma^2)}{2D} \tag{2}$$

$$\gamma = \frac{D\cos\alpha}{d_m} \tag{3}$$

where d_m and D denote the bearing pitch diameter and the cylindrical roller diameter, respectively. α denotes roller contact angle. For cylindrical roller bearings, α is defined as 0°.

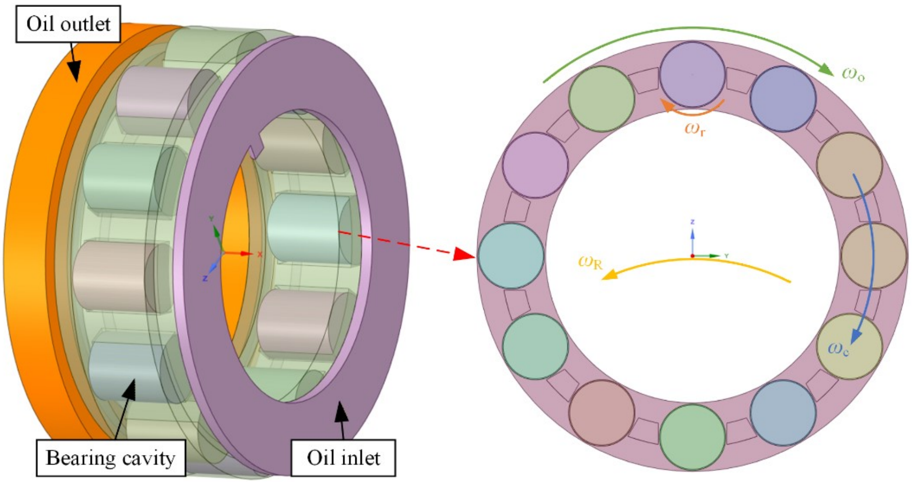


Figure 2. Composition and motion relationships of the lubrication simulation fluid domain.

The established lubrication simulation fluid domain is discretized by tetrahedral and hexahedral mesh elements., as shown in Figure. 3. The VOF multiphase floe and RNG k-ε turbulence models are adopted to capture the complex oil-air two-phase flow in the bearing cavity caused by the high-speed rotation. The symmetry boundary condition is imposed on the geometric symmetry plane. The oil supply port is defined as the velocity inlet, and the flow rate is set to 0.64 L/min. The density and dynamic viscosity of the lubricating oil are 844.5 kg/m^3 and 0.08749 Pa·s, respectively. The lubricating oil outlet is defined as a pressure outlet, and the outlet pressure is set to a standard atmospheric pressure. The oil-air transfer between different fluid domains is achieved through the mesh interfaces. The remaining boundaries of the discrete model are defined as rigid walls.

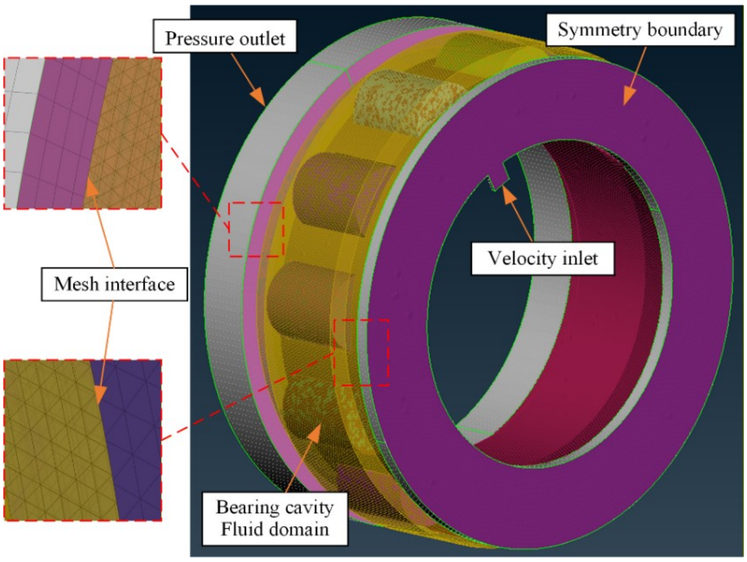


Figure 3. Boundary conditions of the established CFD lubrication simulation model.

3. Results and discussions

3.1. Lubrication flow field characteristics

The internal velocity vector and pressure field distributions of the PCRB considering planetary revolution at a mechanism rotational speed of 3000 rpm are intuitively demonstrated in Figure. 4. The velocity vector distribution on the component surfaces of the PCRB is no longer uniform due to the planetary revolution, and the relative velocity increases with the increasing distance from the transmission shaft. The rotational motion of the cylindrical rollers can also be directly observed through the velocity vector distribution around them. The above phenomena indicate the validity of the motion relationships of the PCRB established based on the MRF method. There exist significant high- and low-pressure regions on both sides of the contact areas between the cylindrical rollers and the inner and outer raceways. This abrupt pressure change is caused by the rapid variation of the slit gap in the contact regions. In addition, the overall pressure level in the bearing cavity exhibits relatively high pressure on its upper half driven by the increased centrifugal acceleration. Therefore, the planetary revolution of the PCRB aggravates the inhomogeneities of its internal velocity vector and pressure distribution.

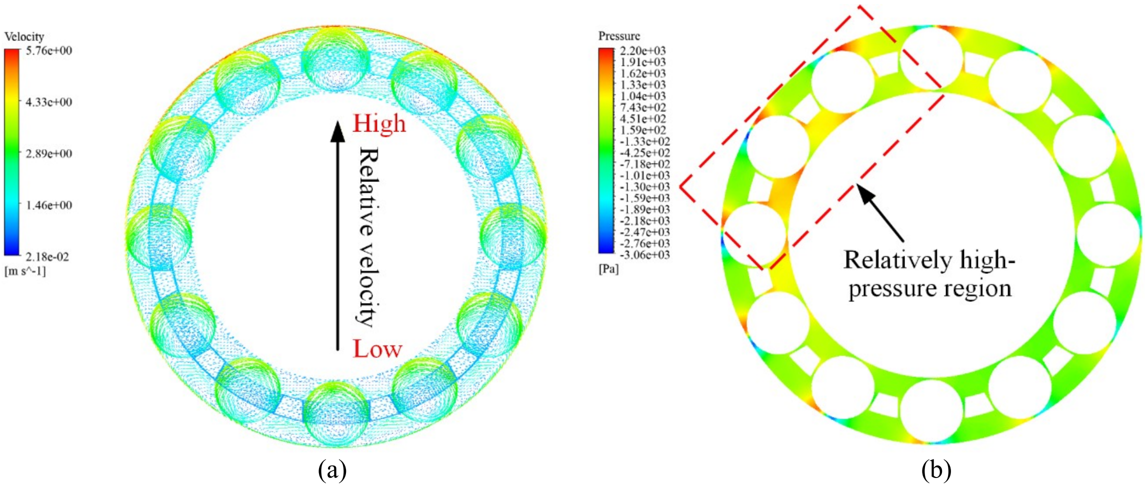


Figure 4. Flow field characteristics of the the PCRB considering planetary revolution. (a) Velocity vector distribution, and (b) pressure distribution.

As presented in Figure. 5, the lubricating oil distribution in the bearing cavity is also highly uneven, manifested as distinct regions with relatively high and low lubricating oil contents. This phenomenon indicates that when the bearing has an external revolutionary motion around a specific rotation center, the lubricating oil in the cavity tends to move toward the far end from the rotation center under the action of centrifugal effect, resulting in constant zonation in the lubricating oil distribution within the cavity. The overall variation trend of lubricating oil distribution on the surfaces of bearing rollers and the cage is basically consistent with that in the cavity. There are significant differences in the lubricant distribution on each bearing roller due to the different lubricant contents in their respective regions.

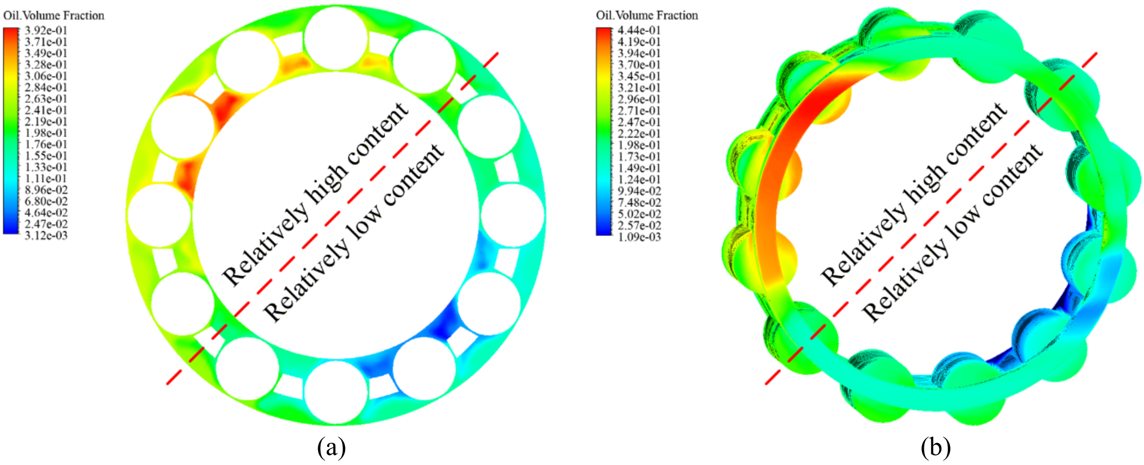


Figure 5. Lubrication distribution of the the PCRB considering planetary revolution. (a) Bearing cavity, and (b) bearing components.

3.2. Effects of rotational speed and oil temperature

Given that the PCM involves variable speed operating conditions and generates temperature rise, the lubrication characteristics of the PCRB under different mechanism rotational speeds and oil temperatures are investigated, as shown in Figures 6 and 7. The overall lubricating oil content in the bearing cavity decreases and the relatively high content region migrates as mechanism rotational speed increases, due to the disturbance to oil-air flow caused by the high-speed vortices generated by the high-speed rotation of cylindrical rollers. Under high rotational speed operating conditions, the difference in lubricating oil content between regions of the bearing cavity becomes increasingly prominent, and the regions with low lubricating oil content expand. As oil increases, the dynamic viscosity of the lubricating oil decreases. With the increment of oil temperature, the lubricating oil distribution in the bearing cavity exhibits significant migration and its content slightly decreases, which are caused by the weakened adhesion capacity of the lubricating oil due to the reduced dynamic viscosity. Therefore, the lubricating oil distribution and content of the PCRB considering planetary revolution are both sensitive to mechanism rotational speed and oil temperature.

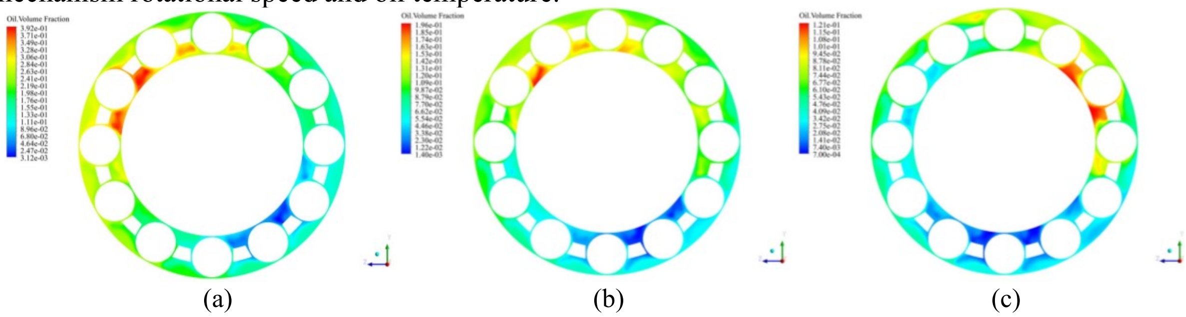
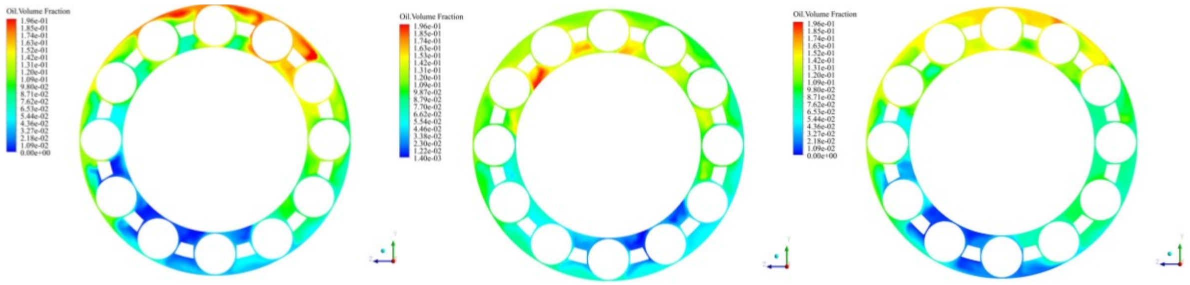


Figure 6. Lubrication distribution of the the PCRB under different mechanism rotational speeds. (a) 3000 rpm, (b) 6000 rpm, and (c) 9000rpm.



(a) (b) (c)

Figure 7. Lubrication distribution of the the PCRB under different oil temperatures. (a) 40℃, (b) 60℃, and (c) 80℃.

4. Conclusion

Based on the above results and discussions, the main conclusions are summarized as below:

(1) The velocity vector and pressure distribution in the bearing cavity are directly affected by the introduced planetary revolution. The non-uniform distributions of velocity vector and pressure are sensitive to rotational center distance. abrupt pressure change in the contact regions between cylindrical rollers and raceways are caused by the rapid transition of the slit gap.

(2) The lubricating oil distribution in the bearing cavity is highly uneven, manifested as distinct regions with relatively high and low lubricating oil contents due to the centrifugal effect driven by planetary revolution.

(3) The overall lubricating oil content in the bearing cavity decreases and the zonation phenomenon intensifies with increasing mechanism rotational speed due to the enhanced centrifugal effect. As the oil temperature increases, the decreased dynamic viscosity of the lubricating oil further leads to a reduction in the lubricating oil content in the bearing cavity.

Acknowledgments

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