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Kinematics and Thermal Analysis in Large-scale Angular Contact Ball Bearings

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Investigation on large industry scale angular contact ball bearing (ACBB) found that not only skidding behavior but also over-skidding behavior can occur on bearing rolling elements. Over-skidding is a new kinematic feature of bearing components which indicates that the cage/rotor speed ratio exceeds the pure kinematically determined value, which is hardly discussed before. For the purpose of analyse the new kinematics feature. A comprehensive model called kinematic-Hertzian-thermo-hydro-dynamic (KH-THD) model that considered the bearing components kinematics, the bearing components Hertzian, the oil film hydro-dynamic lubrication, and the oil film thermal effects is introduced in this paper to simulate the over-skidding and skidding behaviors. The results of several numerical simulations will be shown in the paper to highlight the effect of the load. Due to skidding or over-skidding, the friction between rolling elements and raceways leads to a considerable temperature gradient within the bearing components.

Keywords: *skidding; over-skidding; rolling element bearings; dynamic model; thermal effect*.

1. Introduction

Angular contact rolling bearings (ACBB) are widely used in rotating machines and turbomachinery, such as electric generators and motors, locomotives and aircraft turbo engines. Skidding is a remarkable problem among various rolling element bearing (REB) failures. Skidding is the macro-slipping that occurs between the rolling elements and raceways, consequently causing a smearing damage [1], [2], which finally may induce early bearing failure. REBs operating at high speeds and low loads tend to skid because of lack of a sufficient friction force and the moment able to overcome the lubricant viscosity and inertia forces [3]–[5].

In order to establish an accurate dynamic model for predicting the bearing kinematics behaviours, a comprehensive dynamic model including rolling element-cage contacts, and dynamic loads cannot be neglected. The effects of the friction force, which maintains the rolling element spinning, and the roller orbital motion should also be analysed in detail [6]–[9]. A five degrees of freedom quasi-static analysis based on rolling element and bearing inner ring assembly equilibrium is implemented for analysing the bearing internal load distribution and kinematics [10]–[12].

The effects of the friction force and damping effect are considered. A test for improving the rolling element bearing gross skidding behaviour shows that a certain extent of lubricant starvation can reduce the skidding since the rolling elements drag forces decease at low loads [13], [14]. Fang et al. [15] developed a comprehensive model to simulate the skidding of a ball bearing; the bearing heat generation and the effects of skidding on the bearing temperature rise were analysed, additionally.

The proposed full-degree-of-freedom kinematic-Hertzian contact-thermal-hydro-dynamic (KH-THD) model in this paper explains the occurrence of over-skidding according to the mechanism of skidding. From the tribology point of view, the model shows the thermal effects and temperature rise on the rolling elements, raceways and on the contact area, and explains why the skidding behaviour should be avoided.

2. Model Development

2.1 Model description

A quasi-static analysis, which involves the load distribution, contact angle for both inner and outer raceway is performed first as the basis of KH-THD model. In order to simplify the model, the assumption of fixed outer ring has been set. The relative movement of the inner and outer rings can be characterized by inner ring displacement only.

The thermal hydro-dynamic (THD) part of the KH-THD model is crucial to analyse the components of relative motion inside the ACBB. The model is a 4*Nb+1 (rolling element self-rotation, orbital rotation and cage rotation)-DOF system. Rolling elements friction force and moment in the contact patch are determined by quasi-static analysis results. The relative motion between the rolling elements and the raceway caused by rolling elements macro-slipping and spinning generate massive heat, which are characterized by the temperature rises in the bearing components due to shear effects. Due to the lubricant oil viscosity sensitive to the temperature change, the traction forces between the rolling element and raceway vary a lot after taking into account the thermal effect. Previous models [5], [6], [8] that predict the skidding onset used a constant oil supply temperature or inlet oil temperature as an input. Therefore, it is necessary to take into account the lubricant viscosity-temperature effect for a more accurate bearing behavior.

2.2 Model structure

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Based on the quasi-static and hydro-dynamic model in Sections 2.1, Figure 1 shows the flow chart of the KH-THD model. The biggest difference between the available models in the literature and the KH-THD model is that a further analysis of the thermal properties of lubricant oil is added. The model contains three layers of loops until a satisfactory solution is achieved.

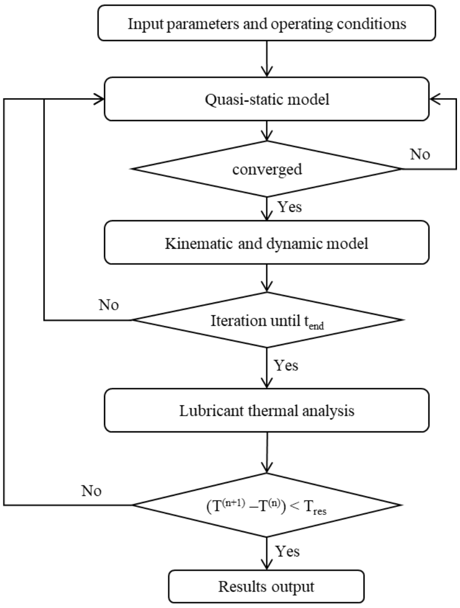

Fig. 1 Flow chart of the KH-THD model.

3. Skidding and Over-skidding Behavior

3.1 Simulation Results

The simulation is based on an industry scale ACBB with a journal diameter around 300 mm. The operating condition of axial load and rotating speed are set according to an industry steam turbine equipped with such bearing. The varying applied axial loads are normalized to the maximum axial load (MAL). The important index for discussing skidding and over-skidding is called cage/rotor speed ratio (CSR). Two kinds of oil supply flow rate are considered in the model to characterize the influence of lubricant supply.

Figure 2 shows a cage orbital rotating speed as a function of the axial load. The CSR shown in Figure 2 is divided into two phases referring to the theoretical cage/speed ratio. Skidding occurs when CSR is smaller than theoretical value, on the contrary, over-skidding occurs when CSR is larger than the theoretical value. Usually, rolling elements’ kinematics behaviors changes from skidding to pure rolling as load increases, without the occurrence of the over-skidding behavior. In Figure 2, rolling elements hardly approach to pure rolling state under ordinary MAL.

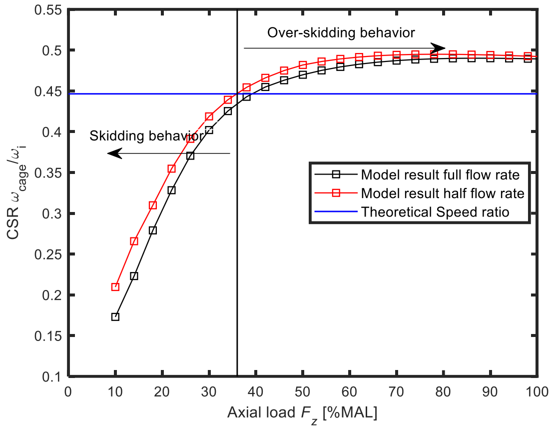

Fig. 2 Skidding and over-skidding behaviour

3.2 The Mechanisms of Skidding and Over-skidding

The three components of the rolling element rotating speed in its local coordinate system are shown in Figure 3. The local coordinate and rolling element rotating orientation angle are illustrated Figure 4. Figure 5 shows the rolling elements spinning orientation angle lift with increasing axial loads.

The load range is divided into three parts according to the rolling elements self-rotation speed. During the 0-400% MAL loading process, the rolling elements rotating speed about the x’ axis, i.e. the circumferential tangent direction, is constantly close to 0. For the 0-80% MAL loading phase 1, the rolling elements hardly rotate about the y’ direction. But they rotate about the z’ direction. By increasing the axial load, the drag resistance is overcame by the increased lubricant traction force. The slipping between balls and raceways substantially decreases. In this way, the kinetic energy provided by traction forces transformed into ball spin motion. For the 80-170% MAL loading phase 2, the rolling elements rotating speed ω nearly keeps constant with the increase in the axial load. For the 170-400% MAL loading phase 3, the self-rotation speed $\omega_{y'}$ grows rapidly and the self-rotation speed $\omega_{z'}$ drops dramatically. This indicates that the rolling elements rotating orientation angle changes from z’ axis to the vertical line of the contact angle; by increasing the axial load, the rolling elements are reaching the pure rolling condition. The process is illustrated in Figure 4

The reasonable explanation is given as follows. Due to raceway structure, rolling elements tend to rotate about the axis which is parallel to the bearing axis z. Under this circumstance, a gyroscopic torque required for changing the angular momentum need enough traction moment. In loading phase 1, there is not enough traction force to balance the gyroscopic torque, therefore, the rolling elements keep their rotating axis along the z’ axis. But the traction force can provide enough energy to overcome drag resistance, thereby the skidding behavior disappears and spin speeds increase, i.e. over-skidding behavior occurs. For large scale bearing, the gyroscopic moment is considerable compared to drag force, thus, it is difficult to satisfy these two forces under lower load. In loading phase 2, the increased axial load is still unable to generate enough traction moment to satisfy those two conditions, but the spinning speed keep increasing, which indicates that the over-skidding behavior still exists. In loading phase 3, enough traction moment can overcome the gyroscopic torque caused by rolling elements that rotates about the line which is vertical to contact angle. The orientation angle increases rapidly until reaching pure rolling condition as shown in Figure 5.

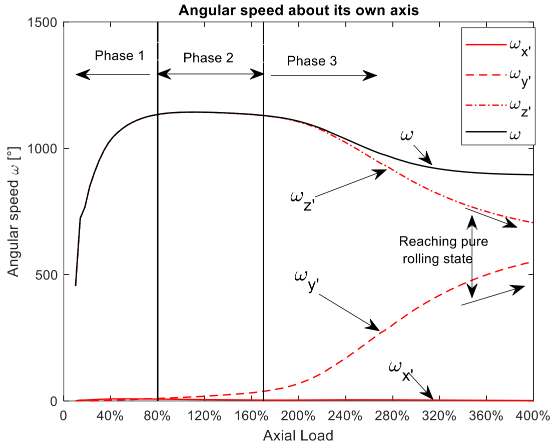

Fig. 3 Rotating speed of the rolling elements about their own axis (x', y', z') with increasing axial loads.

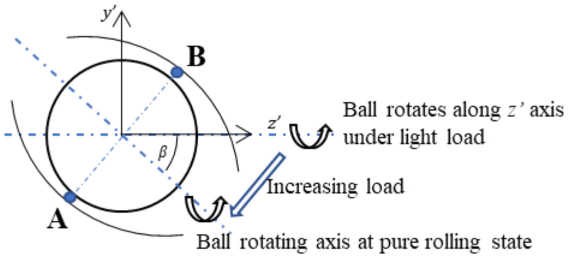

Fig. 4 Schematic diagram of the rolling element spinning orientation angle

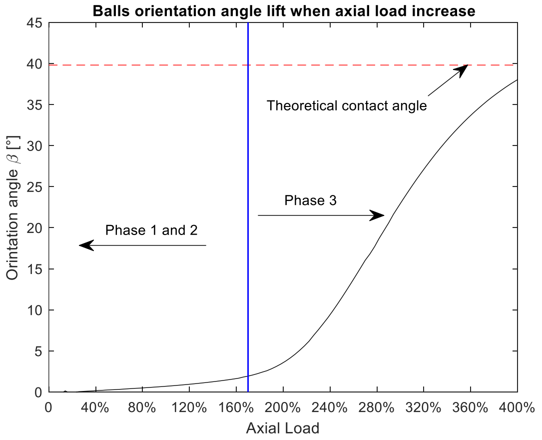

Fig.5 Spinning orientation angle lift of the balls with increasing axial loads.

4. Thermal Analysis on Bearing Components

The steady-state temperature distributions were analysed by taking the rolling element-raceway relative motion and lubricant viscosity-temperature effects into consideration. Using the thermal analysis part of the KH-THD model, the relative motion and viscosity were calculated iteratively according to the algorithm presented in Figure 1. The examples of the calculated inner raceways oil film and inner ring temperature contours are shown in Figure 6 and Figure 7, respectively. The simulation input condition is the nominal rotating speed of the machine and 30% MAL.

In order to simplify the actual situation, the oil-film is flattened to a 2-D plain surface without thickness. From the contours of the temperature distributions presented in Figure 6 and Figure 7, a considerable temperature rise in the oil-film and bearing inner ring can be highlighted. One should note that there are two cooling lubricant supply location on the bearing circumferential direction. In region 2 and 4, where the temperature values show an evident drop. In the highest temperature region of the lubricant films, the temperature rise relative to the inlet temperature of the lubricant reaches nearly 37°C for the inner lubricant film.

Similar temperature sudden change exists on inner rings as shown in Figure 7. In cooled lubricant inlet position, the temperature drops evidently, because a large amount of the heat is removed by cold lubricant. In other regions, the temperature increases gradually along the bearing circumferential direction, and the temperature drops from the contact line position to bearing width edges.

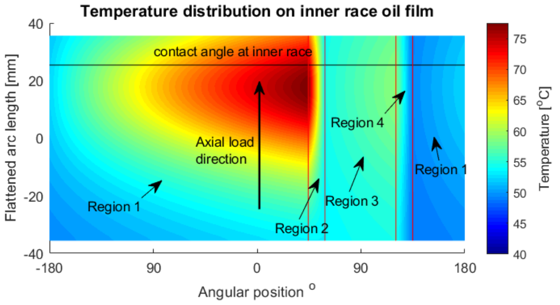

Fig. 6 Temperature distribution of the oil-film on the inner raceway

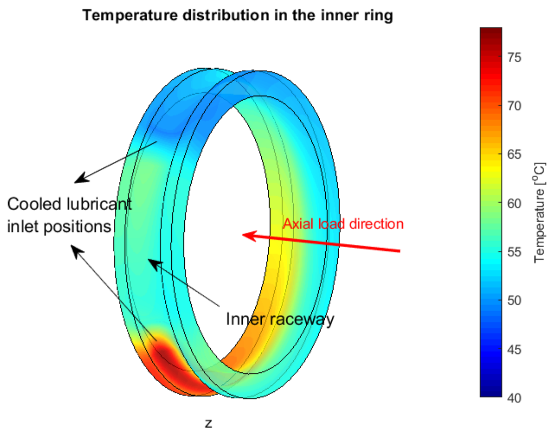

Fig. 7 Temperature distribution in the inner ring

5. Conclusions

The rolling elements kinematic mechanism indicates that large-scale ACBB pure rolling condition requires enough traction force to balance the rolling elements drag effect and gyroscopic torque. In thermal analysis aspect, the relative motion caused by the insufficient traction force between rolling elements and raceways leads to a considerable temperature rise within the bearing components.

References

[1] R. D. Evans, T. A. Barr, L. Houpert, and S. V Boyd, “Prevention of Smearing Damage in Cylindrical Roller Bearings,” Tribol. Trans., Vol. 56, No. 5, pp. 703–716, 2013.

[2] M. Fowell, S. Ioannides, and A. Kadiric, “An Experimental Investigation into the Onset of Smearing Damage in Nonconformal Contacts with Application to Roller Bearings,” Tribol. Trans., Vol. 57, No. 3, pp. 472–488, 2014.

[3] T. A. Harris and M. N. Kotzalas, Advanced concepts of bearing technology: rolling bearing analysis. CRC press, 2006.

[4] P. Pennacchi, P. Borghesani, R. Ricci, and S. Chatterton, “An experimental based assessment of the deviation of the bearing characteristic frequencies,” Proc. 6th Int. Conf. Acoust. Vibratory Surveill. Methods Diagnostic Tech., 2011.

[5] S. Jain, “Skidding and Fault Detection in the Bearings of Wind-Turbine Gearboxes,” no. December, 2012.

[6] Q. Han and F. Chu, “Nonlinear dynamic model for skidding behavior of angular contact ball bearings,” J. Sound Vib., Vol. 354, pp. 219–235, 2015.

[7] Q. Han, X. Li, and F. Chu, “Skidding behavior of cylindrical roller bearings under time-variable load conditions,” Int. J. Mech. Sci., Vol. 135, pp. 203–214, 2018.

[8] Y. Wang, W. Wang, S. Zhang, and Z. Zhao, “Investigation of skidding in angular contact ball bearings under high speed,” Tribol. Int., Vol. 92, pp. 404–417, 2015.

[9] H. Wang, Q. Han, R. Luo, and T. Qing, “Dynamic modeling of moment wheel assemblies with nonlinear rolling bearing supports,” J. Sound Vib., Vol. 406, pp. 124–145, 2017.

[10] S. Jain and H. Hunt, “A dynamic model to predict the occurrence of skidding in wind-turbine bearings,” J. Phys. Conf. Ser., Vol. 305, No. 1, 2011.

[11] J. M. de Mul, J. M. Vree, and D. A. Maas, “Equilibrium and Associated Load Distribution in Ball and Roller Bearings Loaded in Five Degrees of Freedom While Neglecting Friction—Part II: Application to Roller Bearings and Experimental Verification,” J. Tribol., Vol. 111, No. 1, pp. 142-148, 2009.

[12] T. A. Harris, “An Analytical Method to Predict Skidding in Thrust-Loaded, Angular-Contact Ball Bearings,” J. Lubr. Technol., Vol. 93, No. 1, p. 17-23, 2010.

[13] M. Pasdari and C. R. Gentle, “Effect of lubricant starvation on the minimum load condition in a thrust-loaded ball bearing,” ASLE Trans., Vol. 30, No. 3, pp. 355–359, 1987.

[14] C. R. Gentle and M. Pasdari, “Computer simulation of starvation in thrust-loaded ball-bearings,” Wear, Vol. 92, No. 1, pp. 125–134, 1983.

[15] B. Fang, J. Zhang, S. Wan, and J. Hong, “Determination of optimum preload considering the skidding and thermal characteristic of high-speed angular contact ball bearing,” J. Mech. Des. Trans. ASME, Vol. 140, No. 5, pp. 1–11, 2018.