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Analysis of Slipping Performance of Angular Contact Ball Bearing for Micro Turbine

Guang-chao Wang*, Yu Wang*, Tian-zhen Jiang*, Qing-peng Han**, Rui Zhu***, Hang-yuan Lv****and Tian-qi You*

Keywords: Angular Contact Ball Bearings, Slippage Analysis, Preload, Contact Force.

ABSTRACT

For angular contact ball bearings that rotate at high speed and bear combined load and angular deflection, this paper calculates the microturbine angular contact ball bearing 7000c through quasi-static equations on the basis of Hertzian contact theory, obtains the changes of bearing force and slippage under different axial preload, radial load, inclination angle and speed, and obtains the slip critical curve of ball bearing based on Hirano slip criterion. The results show that angular contact ball bearings running at higher speeds require large axial preload forces in order to prevent ball slippage. When the bearing does not bear the radial load, and the axial preload is lower than 100N, the bearing will slip in the entire speed within the speed of 20000-70000r/min, and when the radial load is 2000N, the bearing will not slip in the entire speed.

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* *Graduate Student, College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 201306, China.*

* *Graduate Student, College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 201306, China.*

* *Graduate Student, College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 201306, China.*

** *Associate Professor, College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 201306, China, email: hanqingpeng@shiep.edu.cn*

*** *Professor, College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 201306, China.*

**** *Associate Professor, School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, China.*

* *Graduate Student, College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai 201306, China.*

INTRODUCTION

Bearings are crucial in rotating machinery. Among them, angular contact ball bearings have been widely used in machine tool systems, gas turbines, engines, generators and other spindles. The main advantages of angular contact ball bearings are their ability to accommodate combined axial and radial loads, operation at high speeds and extreme precision. Among them, slippage is a phenomenon caused by insufficient drag force at the contact point, which frequently occurs in the contact area between the ball and the channel. Slippage of angular contact ball bearings can lead to cage speed instability, increased operating temperatures and early bearing failure. Therefore, in order to provide theoretical analysis principles in the practical design and application of angular contact ball bearings, a lot of research has been carried out on the slippage problem.

Bian et al. (2021) studied the relationship between the linear velocity and cage slip rate of the bearing sphere and the axial load, radial load and speed of the bearing was studied. By analyzing the bearing model, Han and Chu (2017) proposed a spatial three-dimensional nonlinear dynamic model that can predict the slipping behavior of the sphere. Fan et al. (2017) calculated the Hertz contact stiffness of bearings through the study of Hertz contact theory and elastic fluid lubrication theory. Huang et al. (2021) obtained the critical plane of bearing slip based on bearing quasi-static analysis and test slip criterion, established the limit state equation of bearing slip based on whether the bearing slipped as the discriminant condition, and calculated the reliability sensitivity by Kriging method, and evaluated the influence degree of bearing parameters on the slippage phenomenon. Xu et al. (2021) took H7006C angular contact ball bearing as the research object to study the relationship between bearing slip characteristics and inner ring speed, axial load and radial load. Peng et al. (2023) On the basis of the force analysis of the bearing elements, the contact state judgment conditions between the sphere and the left and right half of the inner ring were introduced, and the three-point contact ball bearing was analyzed by kinetic method, and the influence of the design contact angle and operating parameters on the bearing slip rate was analyzed. Hirano (1965) criterion studies the drag slip and gyro slip problems that occur during bearing rotation, and obtains a formula that can accurately judge the bearing slip performance through test and fitting. Hirano formula has high use value, especially in academic research and engineering applications, because of its concise and efficient calculation formula, so it is widely used, which can be applied in medium and high speed, under pure axial load or combined load conditions.

It can be observed from the above literature that most of the literature considers the slippage analysis under normal working conditions of the bearing, and rarely mentions the slipping behavior of the bearing under the action of angular deflection and combined load, this paper analyzes the slip behavior of micro-turbine angular contact ball bearings under combined load and angular deflection at high speed on the basis of Hertzian contact theory, and uses the Hirano criterion to analyze the slippage performance of each ball of angular contact ball bearings. The structure of this paper is as follows: Firstly, from the perspective of the geometric relationship of the bearing, the ball force balance and the overall force balance of the bearing, the quasi-static model of angular contact ball bearing is proposed. Then, based on Hirano slip criteria and the slip behavior of diagonal contact ball bearings under angular deflection, MATLAB calculation and analysis are carried out. Finally, the conclusion of this study on slippage is drawn.

Determination of Angular Contact Ball Bearing Slippage

Analysis of Bearing Geometric Relationships

The relative axial displacement between the inner and outer rings of angular contact ball bearings is expressed as δ_x,Radial relative displacement in the vertical direction is expressed as and radial relative displacement in the horizontal direction is expressed as δ_z,and the vertical relative angular displacement is expressed as θ_y and horizontal relative angular displacement expressed as θ_z.

By applying an axial load to the bearing F_x,Radial loads are applied vertically F_y and apply radial loads horizontally F_z and the application of bending moments in the vertical direction M_y and apply bending moments horizontally M_z,The Cartesian coordinate system shown in Figure1 was established.

Assuming that there are uniformly distributed Z balls inside angular contact ball bearings, the position angle of the j ball is:

$$\psi_j = \psi_1 + 2\pi(j-1)/Z \tag{1}$$

When the bearing is not running, the centerof the bearing ball, the center of curvature of the outer channel and the center of curvature of the inner channel are 3 points collinear. When the bearing is running at high speed, the ball is affected by the gyroscopic moment and centrifugal force, the position of the center of the ball changes relative to the non-running state of the bearing, and the relationship between the inner and outer rings of the bearing and the geometry of the ball is shown in Figure 2.

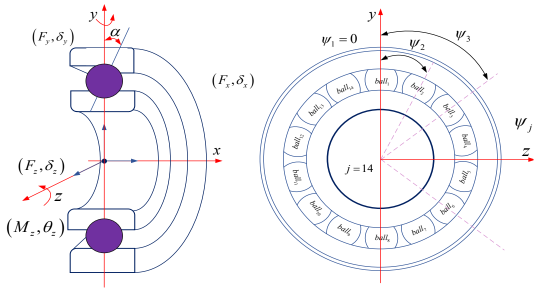


Fig.1. Angular contact ball bearing force and ball position angle distribution diagram

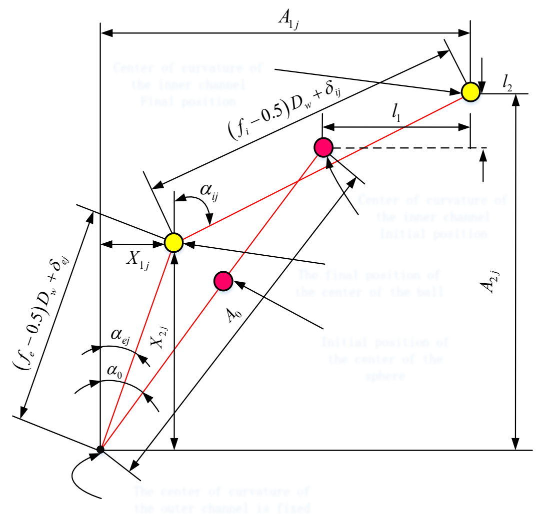


Fig.2. The geometric relationship between the ball and the inner and outer rings of the bearing

When the bearing is not subjected to force, the center distance of curvature of the inner and outer channels is:

$$A_0 = (f_i + f_e - 1)D_w \tag{2}$$

Formula: f_i,f_e represents the radius coefficient of curvature of the inner and outer channels; D_w represents the diameter of the ball,mm.j ball,The axial and radial distances A_{1j} 、F_x of the inner and outer channel curvature centers are respectively:

$$\begin{cases} A_{1j} = A_0 \sin\alpha^0 + l_1 \\ A_{2j} = A_0 \cos\alpha^0 + l_2 \end{cases} \tag{3}$$

$$\begin{cases} l_1 = \delta_x + R_i\theta_z \cos\psi_j - R_i\theta_y \sin\psi_j \\ l_2 = \delta_y \cos\psi_j - \delta_z \sin\psi_j \end{cases} \tag{4}$$

$$R_i = \frac{1}{2}D_{pw} + (f_i - 0.5)D_w \cos\alpha^0 \tag{5}$$

Formula: α^0 represents the initial contact angle at no load ; R_i represents the radius of the center trajectory of the curvature of the inner channel, mm; D_{pw} represents the diameter of the ball set pitch, mm. The angle at which the ball is in contact with the inner ring α_{ij} and the trigonometric expression for the contact angle α_{ej} between the ball and the outer ring is:

$$\begin{cases} \cos\alpha_{ej} = \frac{X_{2j}}{(f_e-0.5)D_w+\delta_{ej}} \\ \sin\alpha_{ej} = \frac{X_{1j}}{(f_e-0.5)D_w+\delta_{ej}} \\ \cos\alpha_{ij} = \frac{A_{2j}-X_{2j}}{(f_i-0.5)D_w+\delta_{ij}} \\ \sin\alpha_{ij} = \frac{A_{2j}-X_{1j}}{(f_i-0.5)D_w+\delta_{ij}} \end{cases} \quad (6)$$

Formula: X_{1j} , X_{2j} represents the axial and radial distances between the center of the j ball and the center of curvature of the outer channel, respectively; X_{1j} , δ_{ej} represents the amount of deformation produced by the j ball through contact with the inner and outer rings, respectively. It is calculated by the Pythagorean theorem:

$$\begin{cases} \left(A_{1j}-X_{1j}\right)^2 + \left(A_{2j}-X_{2j}\right)^2 - \\ \qquad \left[(f_i-0.5)D_w+\delta_{ij}\right]^2 = 0 \\ X_{1j}^2 + X_{2j}^2 - \left[(f_e-0.5)D_w+\delta_{ej}\right]^2 = 0 \end{cases} \quad (7)$$

Force Balance Equation for a Sphere

The bearing sphere is subjected to complex forces and moments under high-speed operating conditions. As shown in Figure 3, the force analysis of the sphere is performed by establishing the force balance equation. in Fig. 3, Parameters λ_{ij} and λ_{ej} are used to represent the control parameters between the inner and outer channels, respectively,Due to the external channel control theory of bearings, angular contact ball bearings only have pure rolling during operation during high-speed operation,So the parameters can be selected $\lambda_{ij}=0$, $\lambda_{ej}=2$; Q_{ij}, Q_{ej} represents the contact load of the ball and the inner and outer rings, respectively, and the formula for calculating the contact load of the ball and the inner and outer rings through Hertz contact theory is:

$$Q_{ij} = K_{ij}\delta_{ij}^{1.5} \text{ , } Q_{ej} = K_{ij}\delta_{ej}^{1.5} \quad (8)$$

Formula, $K_{ij}$and K_{ej} represents the inner ring load and the outer ring load deformation factor, respectively.

The centrifugal force on the ball is F_{cj}, the gyro moment M_{gj} is expressed as:

$$F_{cj} = \frac{1}{12}\pi\rho D_w^3 d_m \omega^2 \left(\frac{\omega_m}{\omega}\right)_j^2 \quad (9)$$

$$M_{gj} = \frac{1}{60}\pi\rho D_w^5 \left(\frac{\omega_R}{\omega}\right)\left(\frac{\omega_m}{\omega}\right)\omega^2 \sin\beta_j \quad (10)$$

Formula: d_m represents the center circle diameter; ω represents the speed of rotating the ferrule ; The angular velocity of the ball and its angular velocity are expressed by ω_m, ω_R respectively; β_j represents the spiral angle of the j ball. The solution method is detailed in the literature.

The force equilibrium relationship of the ball is shown in Fig.3, according to the mechanical equilibrium relationship:

$$Q_{ij}\sin\alpha_{ij} - Q_{ej}\sin\alpha_{ej} - \frac{M_{gj}}{D_w}\left(\lambda_{ij}\cos\alpha_{ij} - \lambda_{ej}\cos\alpha_{ej}\right) = 0 \quad (11)$$

$$Q_{ij}\cos\alpha_{ij} - Q_{ej}\cos\alpha_{ej} - \frac{M_{gj}}{D_w}\left(\lambda_{ij}\sin\alpha_{ij} - \lambda_{ej}\sin\alpha_{ej}\right) + F_{cj} = 0 \quad (12)$$

$$F_{cj} = \frac{1}{2} m d_m \omega^2 \left(\frac{\omega_m}{\omega}\right)_j^2 \quad (13)$$

Formula: F_{cj} represents the centrifugal force on which the sphere is subjected.

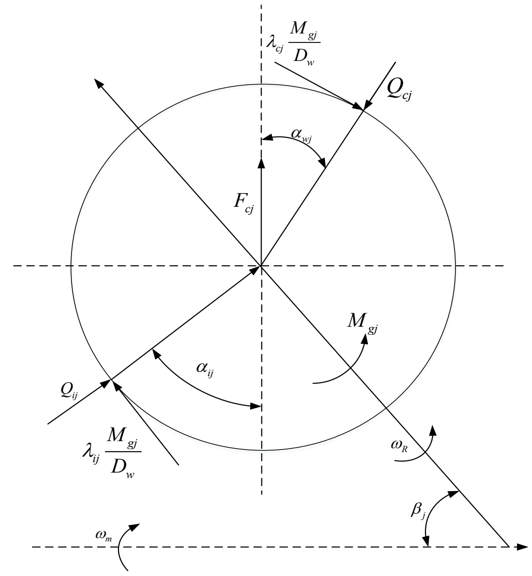


Fig.3. Force analysis of ball

Equation for the Overall Balance of the Bearing Inner Ring

Due to axial loads and radial loads, the bearing inner ring is subjected to the mechanical balance equation as follows:

$$F_x - \sum_{j=1}^{Z} Q_{ij}\sin\alpha_{ij} = 0 \quad (14)$$

$$F_y - \sum_{j=1}^{Z} Q_{ij}\cos\alpha_{ij}\cos\varphi_j = 0 \quad (15)$$

$$M_y - \sum_{j=1}^{Z} Q_{ij}\sin\alpha_{ij} R_i \cos\varphi_j = 0 \quad (16)$$

Formula: $R_i = d_m/2 + f_i - 0.5D_w\cos\alpha_0$, F_x represents axial load; F_y represents radial loads; M_y represents the bending moment of the bearing.

The contact angle of the inner and outer rings of the bearing is α_{ij}, α_{ej}, Dynamic parameters such as contact load Q_{ij}, Q_{ej} can be calculated by solving the nonlinear equations listed above using the *Newton-Raphson* iterative method.

Angular Contact Ball Bearing Slippage Prediction

Slippage is the overall sliding of the ball in the rolling direction relative to the channel, which can have a serious adverse effect on bearing performance, such as wear or excessive heating of parts. There are several analytical formulas for predicting angular contact ball bearing slippage. Hirano (1965) proposes empirical slip guidelines (known as the Hirano Criterion) applicable to angular contact ball bearings. In order to avoid slipping the ball, the conditions that need to be met are:

$$\frac{Q_a}{Fc} > 10 \quad (17)$$

Q_a is the axial component of the normal force Q_i between the ball and the inner channel, determined as:

$$Q_a = Q_i \sin\alpha_i \quad (18)$$

Fc is the centrifugal force acting on the ball:

$$F_c = \frac{1}{2} m d_m w_m^2 \quad (19)$$

Substituting equation (18) into equation (17) yields:

$$SF = \frac{Q_i \sin\alpha_i}{F_c} > 10 \quad (20)$$

Formula: *SF* is the angular contact ball bearing Hirano slip coefficient, which is used to determine whether angular contact ball bearing slippage occurs. The contact force and contact angle between the ball and the inner channel are determined by the quasi-static model of angular contact ball bearings described in the previous section.

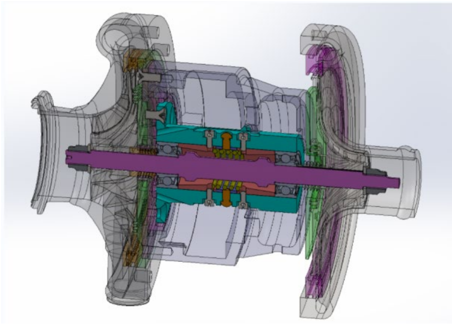
In this study, angular contact ball bearing 7000c is taken as an example, and table 1 is the main structural parameters of this bearing.

Table 1. Structural parameters of 7000C angular contact ball bearings

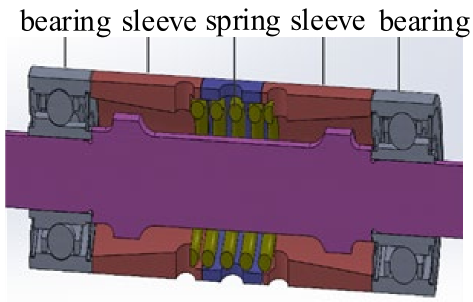
name	numeric value	name	numeric value
Inner diameter (mm)	10	Contact angle (degrees)	15
Outside diameter (mm)	26	Curvature coefficient of the outer ring (mm)	0.5235
Inner ring width (mm)	8	Inner ring curvature coefficient (mm)	0.52
Outer ring width (mm)	11.50	Outer ring shoulder diameter (mm)	21.4
Ball diameter (mm)	4.4850	Inner ring shoulder diameter (mm)	15.74
Pitch diameter (mm)	18	Number of balls	10

Taking the turbine rotor upper angular contact bearing as an example, the material of the bearing parts mainly includes: the ring and steel ball materials are Cr4Mo4V, the material processing performance and high temperature performance are good, and the hardness of long-term working at 316°C is 58HRC. The cage material is tin bronze QSn6.5-0.1, which has high strength, elasticity, wear resistance and anti-magnetic and corrosion resistance. The sealing material is fluoroelastomer (PECK).

The bearing is mounted on the turbine rotor as shown in Figure4.



(a) Schematic diagram of the overall structure of the turbine



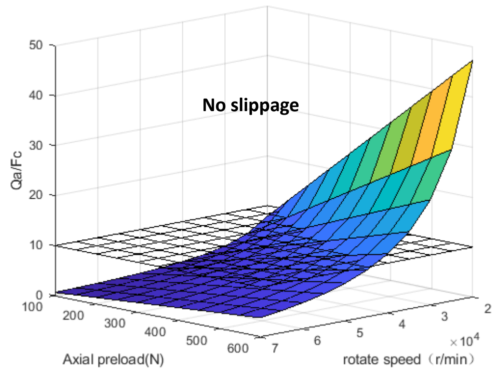
(b) The way the bearings are mounted on the turbine rotor

Fig.4. angular contact bearings how to mount on turbine rotors

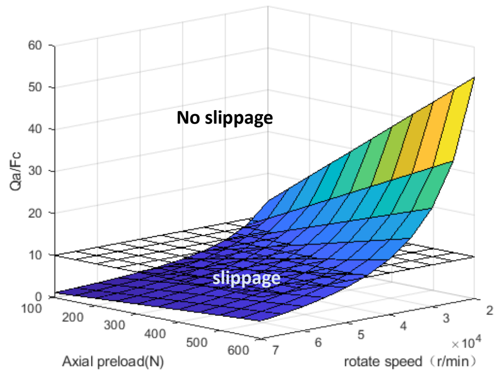
Research of Angular Contact Ball Bearing Slippage

In this section, the numerical analysis results of angular contact ball bearing slippage are presented, and the influence of different working conditions on the slippage behavior is studied. To determine whether a sphere has slipped, the slip coefficient is calculated according to the Hirano criterion, defined as $\frac{Q_a}{F_c}$,As shown in Equation (20).

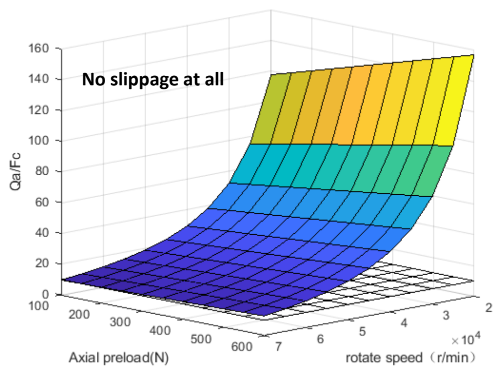
In order to study the influence of speed and axial preload on the slippage of diagonal contact ball bearings, the sliding behavior of the bearing was calculated and analyzed by MATLAB software, and the speed and axial preload of the bearing changed in the range of 20000-70000 r/min and 100-600 N, respectively. All spheres of an axially loaded bearing are subjected to the same contact load, so the slip factor of a typical sphere can be calculated to study bearing slip. The calculation of the slippage coefficient is shown in Figure 5, which clearly shows the slippery and non-slip areas distinguished by the horizontal plane with a threshold of 10.0. The graphic results show that when the radial load is 0, when the axial preload is less than 100 N, slippage will occur throughout the speed; As the radial load increases, the derived axial force of the bearing increases, and the less likely the bearing is to slip (see Fig. 5b). When the radial load reaches 2000 N, the bearing does not slip at all. That is, in order to prevent ball slippage, angular contact ball bearings operating at higher speeds require a large axial preload.



（a） Fr=0N



（b） Fr=100N



（c） Fr=2000N

Fig. 5. Relationship between slip coefficient and axial preload and speed of angular contact ball bearings

As shown in Figure 6, when the radial load on the bearing is 0 and the axial preload is 500 N, the moment load on the bearing is 6×10^4 N·m. As the speed increases, the centrifugal force increases, and the contact force between the roller and the outer channel increases. At the same time, the contact force between the roller and the inner channel will be reduced, which will also lead to increased bearing slippage at high speeds.

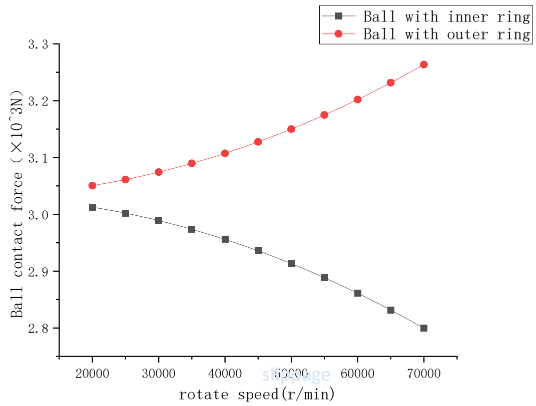


Fig.6. The contact force of the ball when the axial preload is 500N

Figure 7 is the contact load diagram of angular contact ball bearings, when the axial preload of angular contact ball bearings is 0 and the radial load is between 50N-100N, the moment loads borne by the bearings are 1.18×102 N·m, 1.40×102 N·m, 1.62×102 N·m, 1.82×102 N·m, 2.02×102 N·m, 2.20×102 N·m, it can be concluded from the figure that the contact load increases with the increase of radial load. And the sphere located at the angle of 0° directly below the radial load has the most obvious load change amplitude.

In order to study the slippage behavior of a single ball in angular contact ball bearings under radial and axial combined loads, through experiments and consideration of the actual working conditions of the bearing, the bearing speed of 24000 r/min and 40000r/min was selected to determine the critical curve of ball slippage as shown in Figure 8. Each point on the slip critical curve represents the radial load and axial preload applied when the slip coefficient of the ball reaches a critical value of 10.0. Therefore, the load corresponding to the point to the right of the slippage critical curve of the ball avoids the slippage of the specified ball. Due to the intrinsic symmetry of the bearing with respect to the shaft, only the slip critical curve of one hemisphere of the bearing (i.e. sphere 1-5) is drawn. All lines converge to a point at zero radial load, because all balls are subjected to the same load without radial load (i.e. in pure axial preload). In order to prevent slippage, the radial load decreases when the axial preload increases, and the two are inversely proportional to the bottom of the No. 5 sphere. For the remaining 1-4 spheres, the axial preload increases, the radial load also increases, and the axial preload is proportional to the radial load. In summary, the common non-slip area of this bearing is below sphere No. 1.

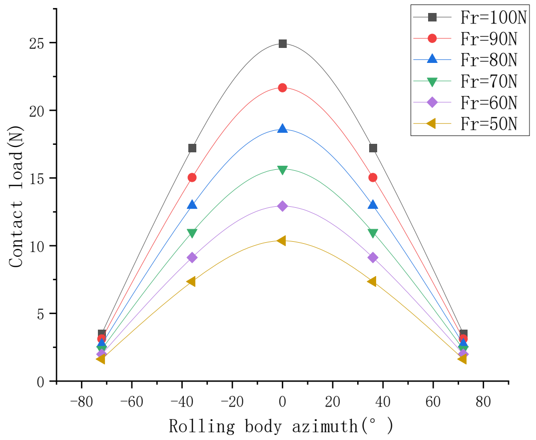
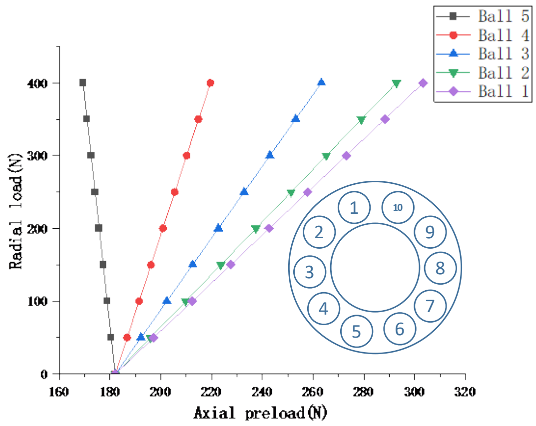
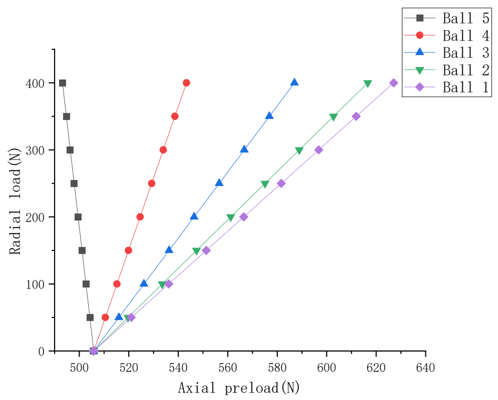


Fig.7. The ball is in contact with the inner raceway under different radial forces



（a） n=24000r/min



（b） n=40000r/min

Fig. 8. Critical curve for slippage for each ball in angular contact ball bearings

The Effect of Angular Deflection on Slippage

Angular deflection is a common problem in rolling bearing applications, and initial mounting errors are one of the common causes of bearing deflection. In fact, despite the correct bearing mounting, the bearing deflection occurs during operation due to the elastic bending of the shaft under load, which affects the mechanical properties of the bearing (such as fatigue life, stiffness and wear). Therefore, it is also important to study bearing slip under angular deflection.

Figure 9 shows the contact stress between the ball and the inner raceway at different deflection angles (the deflection angle from top to bottom is 0.0028 rad, 0.0025 rad, 0.0022 rad, 0.0019 rad, 0.0016 rad, 0.0013 rad) under the working condition of 0 axial preload and 200 N. At this time, the moment loads of the bearings at different deflection angles are 3.28×10^2 N·m, 3.18×10^2 N·m, 3.09×10^2 N·m, 2.89×10^2 N·m, 2.59×10^2 N·m, 2.20×10^2 N·m, respectively, as can be seen from the figure, with the increase of the deflection angle, the rate of stress change increases. In addition, when the radial load is 100N and the axial preload value is 200-600N, the effect of the axial preload on the diagonal deflection is shown in Figure 10; The effect of moment load on angular deflection is shown in Figure 11. As the moment load or axial preload of the bearing increases, the angular deflection of the bearing increases.

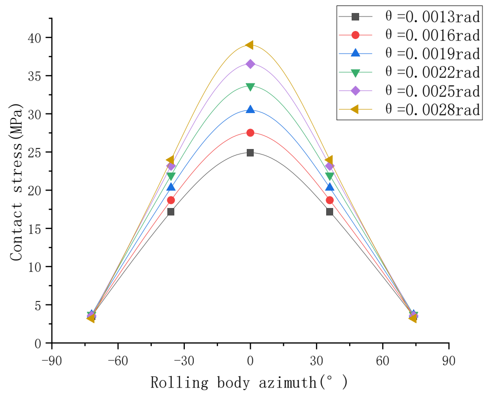
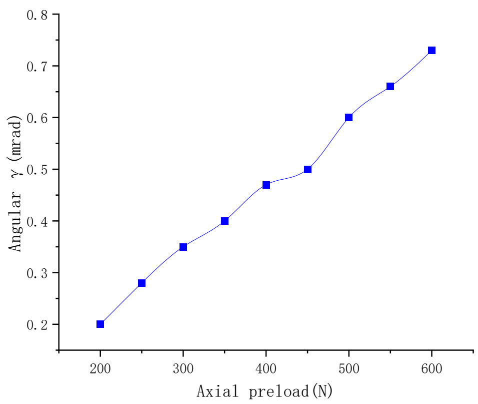
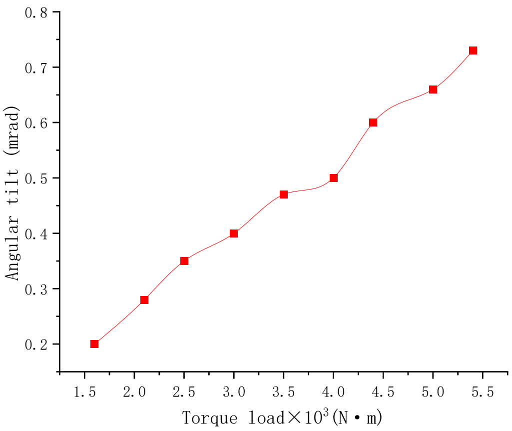


Fig.9. Contact stress between the ball and the inner raceway at different deflection angles



（n=20000r/min）

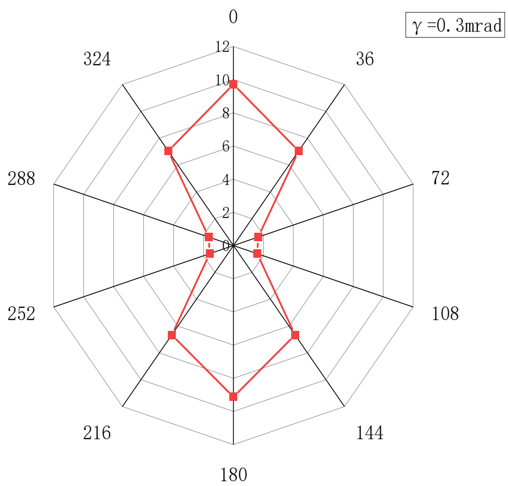
Fig.10. Effect of axial preload on 7000c angular deflection (n=20000r/min).



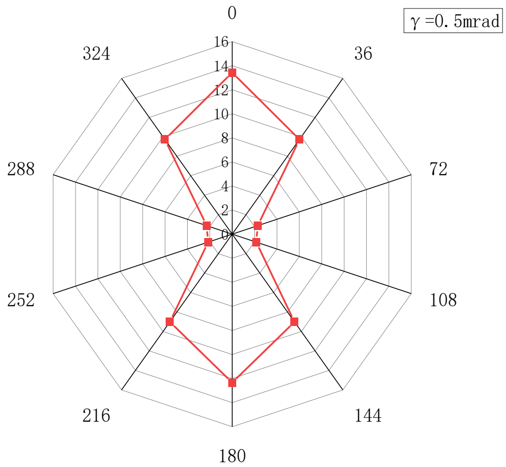
（n=20000r/min）

Fig.11. The effect of moment load on angular deflection 7000c（n=20000r/min）

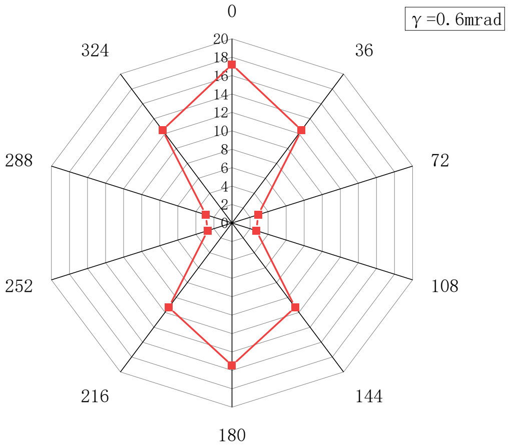
As shown in Figure 12, the slip rate of each ball under different axial preload forces of angular contact ball bearings, considering the actual working conditions of angular contact ball bearings and the selection of radial loads of 100 N by experimental method, the axial preload forces are 300N, 400 N and 500 N, respectively, and the stress moment loads are 2.5×10^3 N·m, 3.4×10^3 N·m, 4.4×10^3 N·m, and the deflection angles are 0.3 mrad, 0.5 mrad, and 0.6 mrad, respectively. Derived the Hirano criterion slip coefficient of each ball of the bearing, it can be seen from the figure that the upper and lower spheres are affected by angular deflection than the middle sphere, so they are subject to greater contact force than the middle sphere, as can be seen from the formula, the Hirano slip coefficient is also relatively large, from Fig. 12a it can be seen that the slip coefficient of each ball is less than 10, so under this working condition, each ball of the bearing slips. Under the condition of constant radial load, with the increase of axial preload and moment load (as shown in Fig. 12b, c), the contact load on the bearing sphere increases, so the Hirano slip coefficient increases, so the less likely the bearing is to slip.



（a） Fr=100N、Fa=300N



（b） Fr=100N、Fa=400N



（c） Fr=100N、Fa=500N

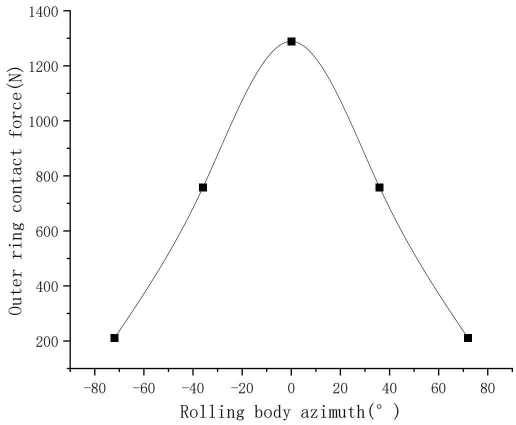
Fig. 12. Slip rate of each ball under different axial preloads

Determination of the Minimum Preload

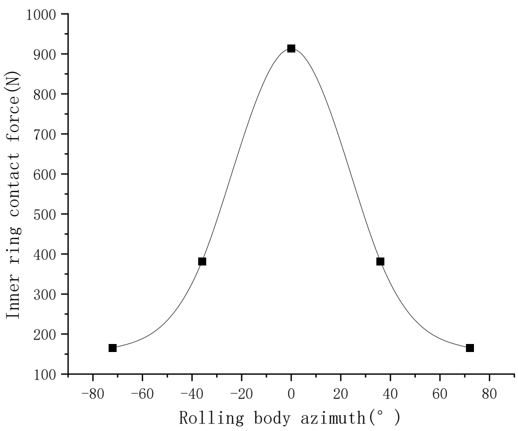
Angular contact ball bearing ball bearing ball body is in the rotation, revolution and gyro slip and other conditions composed of complex running process, each operating state on the bearing stiffness, temperature rise, service life will have an impact, so for different working conditions on the bearing performance needs, the selection of the best preload size for the performance of the bearing is of great significance, this section is mainly for the bearing during operation to reduce the preload required to reduce the preload required for skidding.

Angular Contact Ball Bearing Ball Force Analysis

The quasi-static calculation and experimental verification of 7000C angular contact ball bearing are carried out, and the value is 63000 r/min considering the most stable speed. The load of the bearing is as follows: (1) The radial load Fr of the bearing takes the typical value of 150 N. (2) The axial load of the bearing depends on the sum of the working load of the turbine disc and the axial preload of the bearing. Figure 13 shows the contact stresses between the roller and the inner or the outer rings when the radial load is 150 N. As can be seen from the figure that, due to the centrifugal force outward, the contact force between the ball and the outer channel will increase, and the contact force between the ball and the inner channel will decrease, so the contact force between the sphere and the outer ring is greater than the contact force between the sphere and the inner ring. As shown in Figure 14, the relationship between the slip coefficient of the angular contact ball bearing Hirano and the axial force, it can be seen from the figure that the axial force of the angular contact ball bearing is proportional to the Hirano slip coefficient, and when the axial force reaches 1200N, the Hirano slip coefficient reaches 10, that is, the bearing does not slip at this time. As shown in Figure 15, the slip rate of each sphere is 63000r/min and subjected to 1200N working conditions, and it can be seen from the figure that the Hirano slip coefficient of each sphere is greater than 10, so the bearing does not slip at this time.



(a) The ball is in contact with the outer ring stress



(b) The ball is in contact with the inner ring stress

Fig. 13. The contact stress between the ball and the inner and outer ring at an axial load of 150N

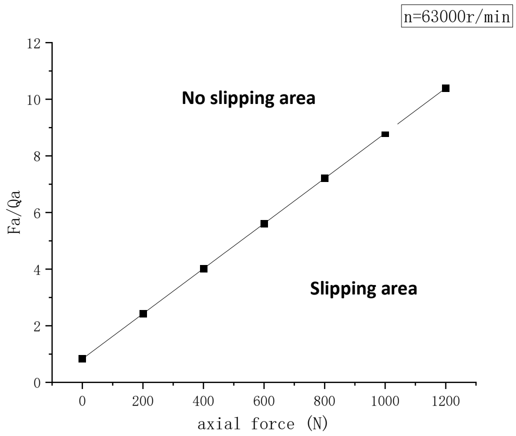


Fig. 14. The effect of axial force on slippage

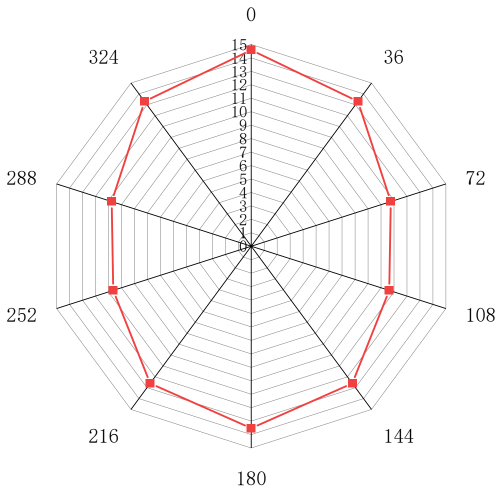


Fig. 15. Slip rate per ball at 63000r/min

MATLAB calculates the minimum preload required for the sphere at different speeds, as shown in Figure 16, from which it can be seen that as the bearing speed increases, the required preload force of the bearing becomes larger and larger, and the slope of the curve increases. Therefore, when the bearing speed increases, it is necessary to provide greater preload.

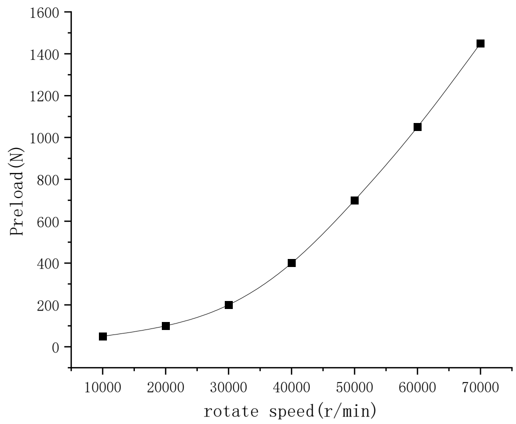


Fig. 16. The relationship between rotational speed and preload

Figure 17 shows the effect of rotational speed and preload on the contact force between the ball and the inner ring. It can be seen from the figure that when the bearing speed remains unchanged, with the increase of axial preload, the contact force between the ball and the inner ring increases, and the increase speed is faster; When the bearing preload is unchanged, with the increase of bearing speed, the contact force between the ball and the inner ring also increases, and when the growth rate is slow, the bearing preload has a greater impact on the contact force between the bearing ball and the raceway. The logic for calculating the minimum preload force to overcome bearing slippage is shown in Figure 18.

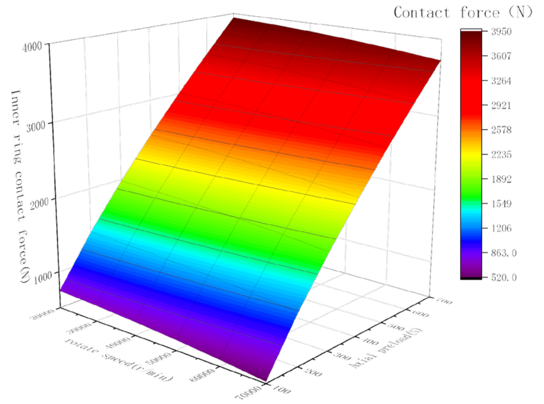


Fig. 17. The effect of rotational speed and preload on the contact force between the ball and the inner ring

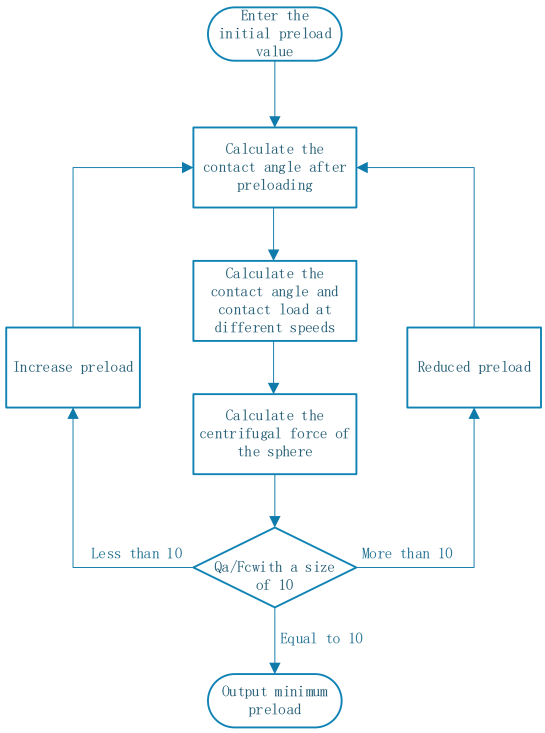


Fig. 18. Calculate the minimum preload logic block diagram

CONCLUSIONS

An analytical method is proposed to predict the slipping of micro-turbine angular contact ball bearings by using Hirano criterion and proposed hydrostatic model. Based on this method, the slipping of angular contact ball bearings is investigated by considering the effects of rotational speed, combined load and angular deflection, and the following conclusions are drawn from the calculations and analysis:

- In order to prevent angular contact ball bearings from slipping, a large axial force is required in the case of angular contact ball bearings operating at higher speeds. Existence of angular deflection, with the increase of axial load, Hirano slippage coefficient located in the bearing upper end roller and lower end roller increases the greater, so the bearing is less likely to slip.
- Due to the outward centrifugal force, the contact force between the ball and the outer groove will increase with the increase of centrifugal force. At the same time, the contact force between the ball and the inner groove decreases, which will also lead to increased slippage of the bearing at high speeds.
- With the increase of the angular deflection, the contact force of the roller and the inner raceway becomes larger, the axial load borne by the roller and its moment load also increases.
- Increasing the radial load or axial load of angular contact ball bearings can improve the Hirano slipping coefficient, so as to reduce the bearing slipping.
- Based on the Hirano test criterion, the critical curve of ball bearing slippage is obtained. Taking the angular contact ball bearing 7000C as an example, the influence of axial preload, radial force and rotational speed on ball bearing slippage is obtained, and the optimal preload required for angular contact ball bearing at different rotational speeds is finally calculated.

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