Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 09, September - 2017

Calculation Method of Dynamic Load Bearing Curve of Double-row Four-point Contact Ball Bearing

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***Abstract*—On the basis of the static analysis of double-row four-point contact ball bearings, the relationship between the basic rated life of bearings and the dynamic loads of bearings were deduced. According to the definition of dynamic load bearing curve of bearing, the dynamic bearing curve of double-row four-point contact ball bearing was plotted. The calculation case and application case of dynamic bearing curves of double-row four-point contact ball bearings were also given.**

Key words*— *Double-Row Four-Point Contact Ball Bearing; Dynamic Load; Bearing Curve

I. INTRODUCTION

Wind energy as a renewable clean energy has been paid attention all over the world, and the wind power generation technology developed rapidly. Yaw bearings and variable pitch bearings are the key components of wind turbines, and the structure is mostly double-row four-point contact ball bearings with inner ring or outer ring with teeth. The wind turbines in the work are usually subjected to combined loads (axial force, radial force and overturning moment) and impact loads, which requires that the yaw bearings and the variable pitch bearings have sufficient carrying capacity. The dynamic bearing curve of the bearing shows the maximum dynamic load bearing can bear under the premise of the given life, which is of great significance for the selection of the bearing and the load .

At present, the research of bearing load curve mainly focuses on the static load bearing curve[1-9]. In 2012, Wang Hong and others gave the theoretical calculation formula of bearing capacity and life estimation of multi row roller slewing bearing, and introduced simplified drawing method of bearing dynamic and static bearing capacity curve based on Hertz contact theory, Lundberg-Palmgren fatigue life theory and the special geometric structure characteristics and working conditions of multi row roller slewing bearing[10]. This method is generally used to quickly test whether the load is available, but the calculation results are not accurate enough.

Abroad, Göncz P presented calculation model of dynamic and static bearing capacity of three row roller bearing and analyzed the static bearing capacity of large double-row four-point contact ball bearing[11-13]. Kania L et al analyzed the bearing capacity of cross roller slewing bearings, and gave the bearing curves of bearings under different cross angles [14,15].

In this paper, we deduced the mathematical relation between the basic rated life and the dynamic load of double-row four-point contact ball bearing on the basis of static analysis, introduce the drawing method of dynamic load curve, and give the calculation and application case.

II. EXACT SOLUTION OF CONTACT FORCE

The structure of the double-row four-point contact ball bearing is shown in Figure 1:

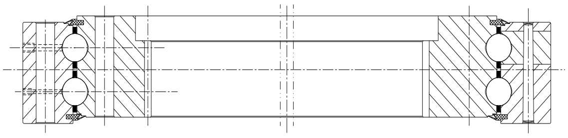

Fig.1 Stucture of double-row four-point contact ball bearing

Build the bearing coordinate system as shown in Figure 2. x axis along the bearing axis direction, r is the inner diameter direction, each ball position angle φ_j can be expressed as: $\varphi_j=2\pi\ (j-1)/(z/2)$ (j=1,2,3... Z/2) where Z is the number of steel balls in double row bearings.

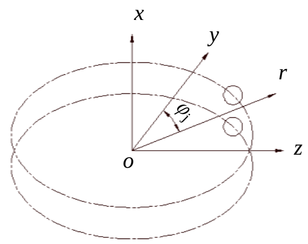

Fig.2 Coordinated system of the bearing

The contact pairs mainly subjected to axial force symmetry for contact 1 (upper), contact 3 (below), the other two contact pairs, respectively called contact 2, contact 4.

Before being subjected to an external load, when take axial clearance u_a into account, the center of curvature of the inner and outer groove of any pair of steel ball contacts A can be obtained by the following formula:

$$A=\left(f_i+f_e-1\right)D_W-\frac{1}{2}u_a\cos\alpha_0 \qquad (1)$$

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Where f_i is the radius coefficient of the inner raceway curvature; f_e is the curvature radius factor of the outer raceway; D_w is the diameter of the steel ball; α_0 is the contact angle of initial position.

When the axial clearance u_a =0, the curvature center distance of the inner and outer groove A_0 can be obtained by the following formula:

$$A_0 = (f_i + f_e - 1)D_W \qquad (2)$$

Suppose the outer ring is fixed and the inner race rotates, the outer load acted on the inner ring is shown in Figure 3. Where F_a is the axial dynamic load, F_r is the radial load, M is the the overturning moment dynamic

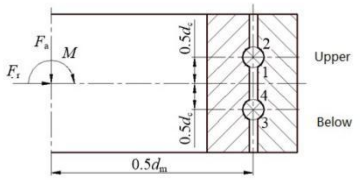

Fig.3 External applied loads on bearing

load, d_m is the pitch circle diameter of the bearing. d_c is the center distance between the two rows of ball bearings of double-row four-point contact ball bearing.

When the double-row four-point contact ball bearing is subjected to an external load, the inner ring is displaced, and the center of curvature of the groove of all pairs of contacts has changed. The center of curvature between the inner and outer groove of the contact pairs k (k=1,2,3,4) at the position angle φ_j is $A_{k\varphi j}$:

$$\begin{aligned}
A_{1\varphi_j} &= \left[\left(A\sin\alpha_0 + \delta_a + R_i\theta\cos\varphi_j\right)^2 + \left(\begin{matrix} A\cos\alpha_0 + \delta_r\cos\varphi_j \\ + 0.5d_c\theta\cos\varphi_j \end{matrix}\right)^2 \right]^{\frac{1}{2}} \\
A_{2\varphi_j} &= \left[\left(A\sin\alpha_0 - \delta_a - R_i\theta\cos\varphi_j\right)^2 + \left(\begin{matrix} A\cos\alpha_0 + \delta_r\cos\varphi_j \\ + 0.5d_c\theta\cos\varphi_j \end{matrix}\right)^2 \right]^{\frac{1}{2}} \\
A_{3\varphi_j} &= \left[\left(A\sin\alpha_0 + \delta_a + R_i\theta\cos\varphi_j\right)^2 + \left(\begin{matrix} A\cos\alpha_0 + \delta_r\cos\varphi_j \\ - 0.5d_c\theta\cos\varphi_j \end{matrix}\right)^2 \right]^{\frac{1}{2}} \\
A_{4\varphi_j} &= \left[\left(A\sin\alpha_0 - \delta_a - R_i\theta\cos\varphi_j\right)^2 + \left(\begin{matrix} A\cos\alpha_0 + \delta_r\cos\varphi_j \\ - 0.5d_c\theta\cos\varphi_j \end{matrix}\right)^2 \right]^{\frac{1}{2}}
\end{aligned} \qquad (3)$$

Where δ_a, δ_r and θ respectively are the axial displacement, the radial displacement and the inclination angle of the inner ring when the inner ring bears the axial dynamic load F_a, the radial load F_r and the overturning moment dynamic load M; the radius of curvature of the raceway R_i = 1/2 d_m+(f_i−0.5) $D_w\cos\alpha_0$−1/4$u_a(\cos\alpha_0)^2$;

Where d_m is the diameter of the bearing pitch circle; φ_j is the position angle of steel ball.

After the displacement of the inner ring, the contact angle $\alpha_{k\varphi j}$ of contact pairs k (k=1,2,3,4) at position φ_j is:

$$\alpha_{k\varphi_j} = \arcsin\left(\frac{A\sin\alpha_0 + \delta_a + R_i\theta\cos\varphi_j}{A_{k\varphi_j}}\right) \qquad (4)$$

The inner ring is in equilibrium under the action of external load and normal contact load $Q_{k\varphi j}$, and the forces acting on the inner ring are shown in Figure 4

Fig.4 Forces acting on inner raceway

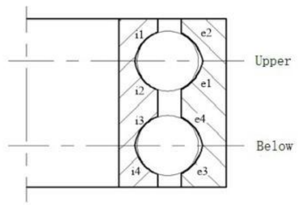

Fig.5 the diagram of raceway groove of bearing

According to mechanical equilibrium equation:

$$\begin{cases}
\sum_{\varphi_j=0}^{2\pi}\left(\begin{matrix} Q_{1\varphi_j}\sin\alpha_{1\varphi_j} - Q_{2\varphi_j}\sin\alpha_{2\varphi_j} + \\ Q_{3\varphi_j}\sin\alpha_{3\varphi_j} - Q_{4\varphi_j}\sin\alpha_{4\varphi_j} \end{matrix}\right) - F_a = 0 \\
\sum_{\varphi_j=0}^{2\pi}\left(\begin{matrix} Q_{1\varphi_j}\cos\alpha_{1\varphi_j} - Q_{2\varphi_j}\cos\alpha_{2\varphi_j} + \\ Q_{3\varphi_j}\cos\alpha_{3\varphi_j} - Q_{4\varphi_j}\cos\alpha_{4\varphi_j} \end{matrix}\right)\cos\varphi_j - F_r = 0 \\
\frac{1}{2}d_m\sum_{\varphi_j=0}^{2\pi}\left(\begin{matrix} Q_{1\varphi_j}\sin\alpha_{1\varphi_j} - Q_{2\varphi_j}\sin\alpha_{2\varphi_j} + \\ Q_{3\varphi_j}\sin\alpha_{3\varphi_j} - Q_{4\varphi_j}\sin\alpha_{4\varphi_j} \end{matrix}\right)\cos\varphi_j + \\
\frac{1}{2}d_c\sum_{\varphi_j=0}^{2\pi}\left(\begin{matrix} Q_{1\varphi_j}\cos\alpha_{1\varphi_j} - Q_{2\varphi_j}\cos\alpha_{2\varphi_j} + \\ Q_{3\varphi_j}\cos\alpha_{3\varphi_j} - Q_{4\varphi_j}\cos\alpha_{4\varphi_j} \end{matrix}\right)\cos\varphi_j - M = 0
\end{cases} \qquad (5)$$

Where $Q_{k\varphi j}$ is the normal contact load of contact pairs k at position φ_j; d_c is the center distance between the two rows of ball bearings of double-row four-point contact ball bearing.

$Q_{k\varphi j}$ can be get according to the Hertz contact theory:

$$Q_{k\varphi_j} = \begin{cases} K_n \delta_{k\varphi_j}^{1.5}, \forall \delta_{k\varphi_j} \geq 0 \\ 0, \forall \delta_{k\varphi_j} < 0 \end{cases} \quad (6)$$

Where, K_n is the total load deformation constant of the rolling body and the inner and outer rings; $\delta_{k\varphi j}$ is the total elastic contact deformation between the steel ball and the inner and outer raceway, along the direction of contact pairs k, at position φ_j:

$$\delta_{k\varphi_j} = A_{k\varphi_j} - A_0 \quad (7)$$

According to the given geometric parameters of the bearing and an initial value of inner ring displacement (δ_a, δ_r, θ), A, A_0 and $A_{k\varphi j}$ can be calculated through formula 1~3. Put the values of A, A_0 and $A_{k\varphi j}$ into the formula 7 to obtain $\delta_{k\varphi j}$, Then, $Q_{k\varphi j}$ and $\alpha_{k\varphi j}$ are calculated by formula 6 and 4, respectively. Put $Q_{k\varphi j}$ and $\alpha_{k\varphi j}$ into the formula 5, while making F_r=0, F_a and M for continuous values, according to formula 5, using the Newton-Raphson method, to obtain the final value of bearing inner ring displacement's (δ_a, δ_r, θ) under each working conditions (F_a, M, F_r). By formula 6, the normal contact load $Q_{k\varphi j}$ of each position angle of the bearing is obtained.

III. CALCULATE THE BASIC RATED LIFE OF THE BERARING

The raceway of double-row four-point contact ball bearings is a typical peach shaped groove. The steel ball has four contact points with the inner and outer raceway, which correspond to four channels. Name the four channels as channel 1, 2, 3, 4, as shown in Figure 5.

A. Basic Dynamic Load of Bearing.

For double-row four-point contact ball bearings, the rated dynamic load of the rings $Q_{ci(e)}$ is:

$$Q_{ci(e)} = 98.1\lambda\eta\left(\frac{2f_{i(e)}}{2f_{i(e)}-1}\right)^{0.41} \times \frac{(1\mp\gamma)^{1.39}}{(1\pm\gamma)^{1/3}} \times \left(\frac{D_W}{d_m}\right)^{0.3} \times (Z)^{-1/3} 3.624 D_W^{1.4} \quad (8)$$

In the formula, the symbol i stands for the inner ring, and the symbol e stands for the outer ring; λ and η are correction factors for double-row four-point contact ball bearings.

B. Basic Equivalent Dynamic Load of Bearing.

As the outer ring is fixed and the inner race rotates, the equivalent rolling load on the raceway k of the inner race is:

$$Q_{e\mu k} = \left(\frac{1}{Z}\sum_{\varphi_j=0}^{2\pi} Q_{k\varphi_j}^3\right)^{1/3} \quad (9)$$

The equivalent rolling load on the outer raceway k is:

$$Q_{evk} = \left(\frac{1}{Z}\sum_{\varphi_j=0}^{2\pi} Q_{k\varphi_j}^{10/3}\right)^{0.3} \quad (10)$$

Where $Q_{k\varphi j}$ is the contact load of steel ball.

C. Rated Life Calculation of Inner Ring.

The rated life of each raceway on the inner ring is:

$$L_{10ik} = (Q_{ci} / Q_{e\mu k})^3 \quad (11)$$

Rated life of inner ring is:

$$L_{10i} = \left(\sum_{k=1}^{4} L_{10ik}^{-10/9}\right)^{-0.9} \quad (12)$$

D. Rated Life Calculation of Outer Ring.

The rated life of each raceway on the outer ring is:

$$L_{10ek} = (Q_{ce} / Q_{evk})^3 \quad (13)$$

Rated life of outer ring is:

$$L_{10e} = (\sum_{k=1}^{4} L_{10ek}^{-10/9}) - 0.9 \quad (14)$$

The rated life of double-row four-point contact ball bearings L_{10} can be obtained by fitting the rated life of the inner ring and the rated life of the outer ring:

$$L_{10} = \left(L_{10i}^{-10/9} + L_{10e}^{-10/9}\right) \times 10^6 \quad (15)$$

IV. APPLICATION CASE

The structural parameters and material parameters of a certain type double-row four-point contact ball bearing are shown in Tab 1:

TABLE.1 Parameters of a Double-row Four-point Contact Ball Bearing

parameter	values
Pitch diameter of ball set d_m [mm]	2215
Ball diameter D_W [mm]	44.45
The center distance of double row steel ball d_c [mm]	69
The radius of curvature of inner channel r_i [mm]	23.34
The radius of curvature of outer channel r_e [mm]	23.34

The number of balls Z	128×2
Poisson ratio of ball and ferrule v	0.3
Axial play u_a [mm]	-0.01
Elastic modulus of ball and bearing rings E [Gpa]	207

The bearing's structural parameters, material parameters and an initial value (0, 0, 0) of the displacement of the inner ring are substituted into above calculation method to obtain the rated life of the bearing L_{10}. The axial dynamic load F_a and overturning moment dynamic load M which conform to the L_{10}-30000< ε are extracted as the points on the coordinate system. This example takes ε=0.01 and obtains a series of points, as shown in Figure 6.

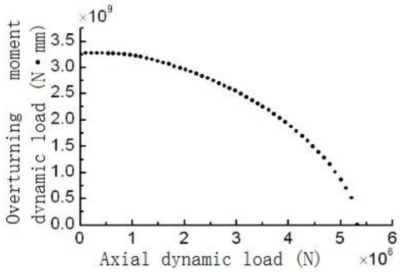

Fig.6 Force combination position points of double-row four-point contact ball bearings

Connected above points, the dynamic load bearing curves of the double-row four-point contact ball bearings are obtained, as shown in Figure 7.

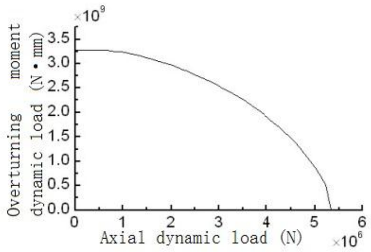

Fig.7 Dynamic load bearing diagram of double row four point contact ball bearing

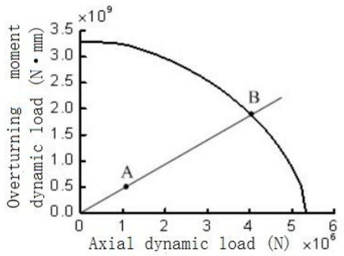

Fig.8 Schematic diagram of "A" and "B" points

The method of using the dynamic load bearing curve to determine whether the bearing selected meets the life requirement under given load are as follows:

1. Users provide the axial dynamic load F_{aA}, overturning moment M_A and rated life L_A of the double-row four-point contact ball bearings. In this example, the double-row four-point contact ball bearing has a rotational speed of 0.1r/min, and the required service life is 175200 hours. That is to say L_A=1051200 r. The axial dynamic load and overturning moment respectively are: F_{aA}=1100kN and M_A=500kN·m.

2. In the dynamic load bearing curve, find the coordinate point corresponding to the given load F_{aA} and M_A, and use the point "A" to indicate. In this example, the coordinates of point "A" are (F_{aA} , M_A), in which F_{aA}=1100kN and M_A=500kN·m.

3. Connect the coordinate system origin and point "A", extend above line and crossed the dynamic load bearing curve to point "B". As shown in Figure 8, find the coordinate value of "B" point. In this example, the coordinates of the point "B" are (F_{aB} , M_B), where F_{aB}=4000kN and M_B=1800kN·m.

4. Calculate load factor f_L. In this example, the load factor $f_L=F_{aA}/F_{aB}$=4000/1100=3.636.

5. Calculate the life of the selected double-row four-point contact ball bearings at a given F_{aA} and M conditions: $L=30000\times f_L^3$. In this case, $L=30000\times f_L^3$=1442524.4 r.

6.Determine whether the condition $L\geq L_A$ is established, if it is established, the designed bearings can meet the life requirements under the given load F_{aA} and M_A, otherwise, the designed bearings can't meet the life requirements. In this example, L=1442524.4>L_A=1051200, so the double-row four-point contact ball bearing selected can meet the requirements of life under the given load F_{aA}=1100kN and M=500kN·m.

V. CONCLUSION

This paper deduced the relationship between the basic rated life and the dynamic load of bearing based on the static model of double-row four-point contact ball bearing. The bearing curve of bearing dynamic load is drawn, axial dynamic load F_a as the abscissa, overturning moment dynamic load M as the ordinate, according to the definition of dynamic load bearing curve of rolling bearing. The point on the curve can be understood as the dynamic load that the bearing can bear when the bearing life is given value. The calculation of dynamic carrying curve of double-row four-point contact ball bearing provides a basis for the selection and application of such bearings.

ACKNOWLEDGMENT

This research is supported by the National Science Foundation of China(No. 51475143) and Tianjin Natural Science Foundation (No.16JCYBJC18900).

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