Test Analysis of Friction Moment between Ball and Cage of Miniature Bearing at Very Low Speed

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Abstract. In some applications, especially for the attitude control of navigation system, the friction moment of instrument ball bearings is one of the much more important factors. Its magnitude and fluctuation affect not only the energy transfer but also the accuracy of signal transfer even though the bearings work at very low speed. Experimental analysis showed that the cage rotated with a minor fluctuation along its orbital axis and even this minor fluctuation could also make a great contribution to the moment for the ball bearing. A simplified model of deformation within the contact of ball and cage was built to deduce the contact time. Combined with the experimental results, the angular acceleration were obtained by the model of contact, then the value of moment due to sliding, which induced the fluctuation of cage, between ball and ribbon cage pockets of miniature bearing were obtained.

Introduction

Since the 90’s of twenty century, Lovell M.R.[1,2] predicted the hysteresis behavior in both pre-rolling and steady region by ball-plate experiments under different loads (81.6N, 133.5N, 185.4N), different lubricants and different oscillating speeds. Houpert L.[3] numerically calculated the location of pure rolling lines on the contact ellipse based on the quasi-static to predict the moment due to pivoting on contact ellipse and the contact race curvature respectively. Since Walters C.T.[4], Gupta P.K.[5], etc. developed the dynamics methods of bearing, the dynamic analysis of cage at high speed have been made a deeper understand. A lot of researches demonstrated that the cage would rotate in unsteady state once its speed exceeded some critical value, which seriously affected the performance of bearing, but when it worked at lower this critical speed, the cage were in steady motion. So the moment due to sliding between cage and ball or inner/outer race were usually neglected for a low speed.

Generally the ribbon cage is designed as ball-guide when it works at low speed. The cage may or not be in contact with ball at a given time, depending on the relative position of the bodies in question. The normal and friction forces at the ball-cage contact may push or resist the motion of cage. For this reason, the experiments were conducted to analysis the contribution of the cage fluctuation to the moment for the applications of critical requirements on moment at very low speed.

Experimental Procedure

The apparatus mainly consists of the YZC-II friction moment tester and the non-contact laser displacement sensor of Japanese LK-G35 series, as shown in Fig. 1. The outer race of axial load matches up with the grating rotor, which connects to the photoelectric system so as to monitor and control the motion state of testing bearing. Based on the theory of electromagnetic induction, the magnitude of the electromagnetic moment produced by the induced current has a strict functional relationship with the current by a special sensor, so the moment of bearing becomes its only load. YZC-II friction moment tester can measure both the staring moment and the dynamic moment.
Fig. 2 represents the ribbon cage. When the testing bearing works, the axial displacement (referring to Y direction in Fig. 1) of some circular points on the cage can be measured by the laser displacement sensor and the shape of test data will also be wave-like. Because of the size of testing bearing is so small, which limits test means, the only one laser probe can be used.

The same type of bearing was measured at the speed of 5r/min and 10r/min respectively. Table 1 shows its structure parameters.

In order to display the test results clearly, drawing of partial enlargement of testing data by laser at different speeds are depicted in Fig. 3 (a) and (b).

**Data Analysis**

**The Axial Motion of Cage along Y Axis.** Because of the limitation of test error and test precision, abnormal data or outrage data are different at different speeds. Fig. 3 shows that, the testing data is much more similar to the wave-like geometry size of ribbon cage at lower speed and the maximum dots displacement can be tested directly, as shown in Fig. 4. Oppositely, at the higher speed there are much more contour curve distortions (see Fig.3(b)), so the positions of maximum dots of pockets are assumed at the center of some same data segments of peaks.

**Table 1 Structure parameters of ball bearing**

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ball diameter, D</td>
<td>2.381 mm</td>
</tr>
<tr>
<td>number of balls, z</td>
<td>8</td>
</tr>
<tr>
<td>pitch diameter, d_0</td>
<td>10.5 mm</td>
</tr>
<tr>
<td>inner diameter of inner race, d</td>
<td>6 mm</td>
</tr>
<tr>
<td>outer diameter of outer race, D</td>
<td>15 mm</td>
</tr>
<tr>
<td>static contact angle</td>
<td>0°</td>
</tr>
<tr>
<td>inner race conformity, f_i</td>
<td>0.55</td>
</tr>
<tr>
<td>outer race conformity, f_o</td>
<td>0.55</td>
</tr>
<tr>
<td>depth of the ribbon cage pockets</td>
<td>1.22 mm</td>
</tr>
<tr>
<td>clearance between ball and pockets</td>
<td>0.035mm</td>
</tr>
</tbody>
</table>
In order to eliminate the geometry error, the axial displacements of the same maximal dots of the pockets with different periods from No.1 to No.8 are shown in Fig. 5. The axial displacement of dots should be the total displacement of axial translation and swing about Y axis at the same maximal dots. Obviously, all the value of the total displacement seem too small, about in the range of 0.008mm, except No.5, which may be caused by the measurement errors.

![Fig. 5(a) The axial displacement of the same maximum dots with different periods at 5r/min](image)

![Fig. 5(b) The axial displacement of the same maximum dots with different periods at 10r/min](image)

**The Circular Fluctuation of Cage about Y Axis.** Once the positions of maximum dots of the pockets are determined, according to the sampling time between the two maximum dots, the average angular velocity of cage during the 45 degree angle \((360/z)\) can be computed. As shown in Fig.6 (a) and (b), the point-line with the *represents the angular velocity of cage, and the dashed line represents the theoretical velocity of ball-cage, about 0.321rad/s at speed 5r/min and about 0.642rad/s at speed10r/min, which suppose there is no gross slip at the raceway contact. The value of the angular velocity of cage, as shown in Fig. 6 (a), is mainly in the range of 0.31~0.34 rad/s and 0.62~0.66 rad/s in Fig.6 (b). Obviously, the cage motion is fluctuant along the theory value. That is because the normal and friction forces within the contact push or resist the motion of cage. At the same time, the contact forces also resist or push the motion of ball. Because of the lighter quality of cage, the fluctuation range of the cage was larger than the ball. Suppose the cage contact with the ball at the average velocity \(V_c\) during the 45 degree angle, since it is not measured in real-time. Then the average velocity of ball \(V_b\) can be calculated by the momentum theorem. Also suppose the both are at the same rotation \(V_o\) after contact. Hence:

\[
\frac{m_c}{z}V_c + m_bV_o = \left(\frac{m_c}{z} + m_b\right)V_o, \\
w_b = \frac{\left(\frac{m_c}{z} + m_b\right)w_o - \frac{m_c}{z}w_c}{m_b}. 
\]

Where \(m_c, m_b\) are the mass of cage, ball respectively. \(w_c, w_b\) are the average angular velocity of cage, ball, as the solid-line shown in Fig. 6. \(w_o\) is the same angular velocity after contact, which can be replaced by the theory value referred above.

![Fig. 6(a) The average angular velocity of ball and cage during the 45 degree angle at 5r/min](image)

![Fig. 6(b) The average angular velocity of ball and cage during the 45 degree angle at 10r/min](image)
Model of Moment. Because the relative contact and sliding speeds of ball and cage versus time are different, the different normal and friction forces may lead to the dynamic moment. If the angular acceleration $\varepsilon$ is determined, the moment $M_C$ due to sliding between ball and cage can be computed. Thus,

$$J \varepsilon = M_C,$$

where $J$ is the cage principal moments of inertia about $Y$ axis and $\varepsilon$ is calculated by the following differentiation expression:

$$\varepsilon = \frac{dw_c}{dt}.$$

Here we think $w_c$ as the pre-and post velocity of contact. So the $dw_c$ can be obtained by the difference of $w_c$ and $dt$ is considered to be the contact time. In order to estimate the value of it, a simplified model of contact-deformation is built as shown in Fig.7, which describes that the contact time is due to the difference of velocity of ball and cage. Thus:

$$| (V_c - V_o) t - (V_b - V_o)t | = \delta,$$

$$t = \frac{\delta}{2 | (w_c - w_b) |},$$

where $d_m$ is the pitch diameter of bearing, and $\delta$ can be replaced by the normal contact deformation between ball and inner race based on the quasi-static method [6], about 0.0003 mm. Fig. 8 (a) and (b) show the angular acceleration of cage and the moment due to its fluctuation at speeds 5r/min and 10r/min respectively.

Both the geometry and test error caused inevitably larger value, as shown in Fig. 8, which can be excluded by dealing with the experimental data. The main fluctuation range value of $M_C$ at 5 r/min is about -3~3µN·m and the ratio of it is 86.4%. The main fluctuation range value of $M_C$ at 10 r/min is about -4~4µN·m and the ratio of it is 87.3%. Comparing the theoretical with testing result in Table 2, we can deduce that the fluctuation motion of cage even at very low speed can make a great contribution to the moment of bearing.

Conclusions

(1) When the bearing works at very low speed, the axial motion of cage along $Y$ axis is very light, but the circular fluctuation of cage about $Y$ axis is relatively obvious. Because of the lighter quality of cage, the fluctuation range of it is larger than the ball.
A simplified model of deformation within the contact of ball and cage was built to deduce the contact time. Then the angular acceleration and moment due to sliding between ball and cage were obtained. The results showed that for the applications of critical requirements on moment, the fluctuation motion of cage even at very low speed can make a great contribution to the moment of bearing.

<table>
<thead>
<tr>
<th>Test result</th>
<th>MC</th>
<th>Theoretical calculation</th>
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<tbody>
<tr>
<td>$M_S$</td>
<td>$M_D$</td>
<td>$M_C$</td>
</tr>
<tr>
<td>8-13</td>
<td>5r/min</td>
<td>2-6</td>
</tr>
<tr>
<td>10r/min</td>
<td>3-6</td>
<td>-4-4</td>
</tr>
</tbody>
</table>

$M_S$: the starting moment  
$M_D$: the dynamic moment  
$M_C$: moment due to sliding between ball and cage  
$M_E$: elastic rolling resistance moment  
$M_S$: moment due to pivoting on contact ellipse  
$M_K$: moment due to the contact race curvature  
$M$: $M_E + M_S + M_K$

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References


