ASIATRIB 2002International Conference
JEJU ISLAND, KOREA

Clearance and preload effects on NRRO of miniature ball bearings with waviness

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This paper presents theoretical analysis of the NRRO(the non-repeatable run-out) for a ball bearing with geometric imperfection. This imperfection contains ball size error, ball waviness, outer race waviness and inner race waviness. The 3D dynamic analysis of a ball bearing using the Newton-Raphson method is performed to calculate the displacement of shaft center. The radial and axial NRRO are simulated, and preload and clearance effects are investigated. Preload and clearance have significant effects on radial and axial NRRO of for miniature ball bearings.

Keywords : Ball Bearing, NRRO, 3D model, Preload, Clearance

1. INTRODUCTION

The dominant source of tracking errors in magnetic disk drive is NRRO(non-repeatable run-out) caused by waviness of spindle ball bearings. It is impossible to produce a perfect surface even with the best machine tool. This manufacturing imperfection contains ball size error, ball waviness, outer race waviness and inner race waviness.

There have been some previous researches on NRRO. Ono et al.[1] investigated theoretical 2D radial NRRO of a rigid shaft supported by a ball bearing with small sinusoidal waviness using the Newton-Raphson method. Aktürk[2] investigated 3D radial and the axial vibrations using the Runge-Kutta method.

This paper presents the 3D analysis of the NRRO for a ball bearing with geometric imperfection using the Newton-Raphson method. The radial and axial NRRO are simulated, and preload and clearance effects are investigated.

2. 3D ANALYTICAL MODEL

The Hertzian contact force and deflection relationship in the k-th ball may be written by [1]:

$$P_k = C_k \delta_k^{3/2} \tag{1}$$

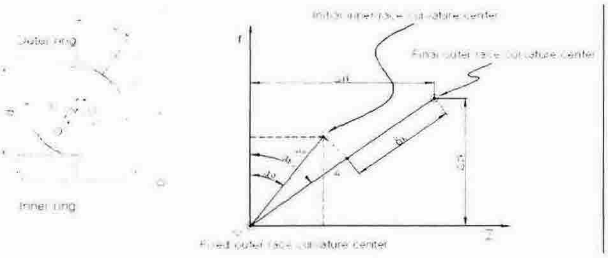
where, the load deflection factor C_k is :

$$C_k = \left[\left(\frac{1}{K_i}\right)^{2/3} + \left(\frac{1}{K_o}\right)^{2/3} \right]^{-3/2} \tag{2}$$

Figure 1 represents contact between ball and races in a ball bearing. Axial deflection and contact angle is given by :

$$\delta_k = A\left(\frac{\cos\alpha_0}{\cos\alpha} - 1\right) \tag{3}$$

where, displacement of the races A is :



(a) Geometry (b)Deflection

Fig. 1 Contact between ball and races in a ball bearing

$$A = r_{go} + r_{gi} - d_b \tag{4}$$

The equilibrium equation in axial direction is given by:

$$F_p = Z P_k \sin\alpha \tag{5}$$

where, F_p is preload and Z is the number of balls. From the equation (1)~(6), initial deflection can be obtained by Newton-Raphson method.

The relative displacement of the races and contact angle due to waviness at each contact points can be obtained from :

$$\delta_k = \sqrt{(z + A_k \sin\alpha_k)^2 + (x\cos\theta_k + y\sin\theta_k + A_k\cos\alpha_k)^2} - A \tag{6}$$

$$\alpha_k = \tan^{-1}\left\{ \frac{z + A_k \sin\alpha_k}{x\cos\theta_k + y\sin\theta_k + A_k\cos\alpha_k} \right\} \tag{7}$$

where, A_k contains the waviness.

$$A_k = r_{go}(\theta_k) + r_{gi}(\theta_k) - d_{bk}(\omega_b t) \tag{8}$$

The equilibrium equation for 3D system can be written as:

$$\begin{aligned} f_x &= \sum_{k=1}^{Z} C_k \delta_k^{3/2} \cos\alpha_k \cos\theta_k = 0 \\ f_y &= \sum_{k=1}^{Z} C_k \delta_k^{3/2} \cos\alpha_k \sin\theta_k = 0 \\ f_z &= \sum_{k=1}^{Z} C_k \delta_k^{3/2} \sin\alpha_k - F_p = 0 \end{aligned} \tag{9}$$

The solution of this equation can be obtained by using the Newton-Raphson iterative method. The time signal of the displacement is transformed to frequency spectrum by FFT.

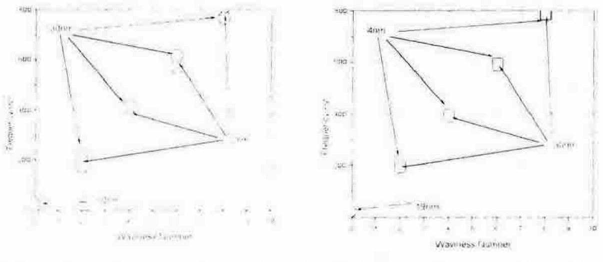
3. NUMERICAL SIMULATION OF 3D MODEL

A numerical simulation of NRRO is carried out for a miniature ball bearing(number of balls:6, ball diameter:3.5mm, PCD:12.5mm, contact angle:10deg). The shaft is assumed to be rotating at 3600rpm.

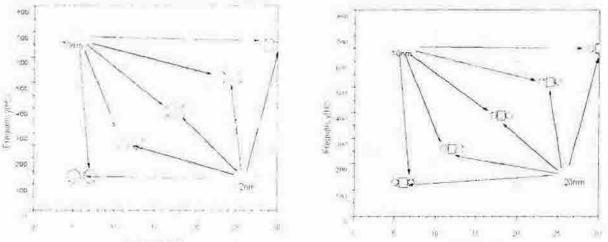
Figure 2 shows the relationship between frequency and amplitude due to one ball waviness. In this figure, the circle indicates amplitude of radial NRRO, and the rectangular indicates that of axial NRRO. It is assumed that only the first ball has 0~10th waviness of 0.1μm. The ball size error generates radial NRRO with cage frequency f_c, and only the even number waviness of ball generates radial NRRO with frequency of $jf_b \pm f_c$ (where, j is even number and f_b is ball passing frequency.). The even number waviness of ball also generates axial NRRO with frequency of jf_b. Figures 2(a) and 2(b) show the example of smaller clearance(1μm) and preload(10N) and the example of greater clearance(5μm) and preload(80N), respectively. In the case of small clearance and preload, NRRO has mainly radial components. However, the larger clearance and preload, the larger axial components and the smaller radial components.

Figure 3 shows the relationship between frequency and amplitude due to outer race waviness. It is assumed that the outer race has 1~10th waviness of 0.1μm. The outer race waviness of $jZ \pm 1$th order generates radial NRRO with frequency of jZf_c (where, Z is ball number.) and the waviness of jZth order generates axial NRRO with frequency of jZf_c. Figure 3(a) and 3(b) show the example of smaller clearance(1μm) and preload(10N) and the example of greater clearance(5μm) and preload(80N), respectively. The results also shows that larger clearance and preload, the larger axial components and the smaller radial components.

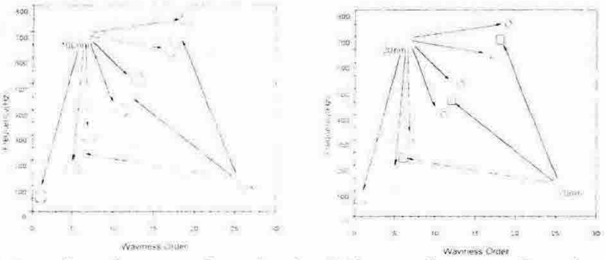
Figure 4 shows the relationship between frequency and amplitude due to inner race waviness. It is assumed that the inner race has 1~10th waviness of 0.1μm. The inner race waviness of 1st order generates radial NRRO with rotating frequency f_r, and the waviness of $jZ \pm 1$th order generate radial NRRO with frequency of $jZ(f_r - f_c) \pm f_c$. The waviness of jZth order generate axial NRRO with frequency of $jZ(f_r - f_c)$. Figure 4(a) and 4(b) show the example of smaller clearance(1μm) and preload(10N) and the example of greater clearance(5μm) and preload(80N), respectively. The results also shows larger clearance and preload, the larger axial components and the smaller radial components.



(a)smaller clearance & preload (b)larger clearance & preload
Fig. 2 Frequency and amplitude due to one ball waviness



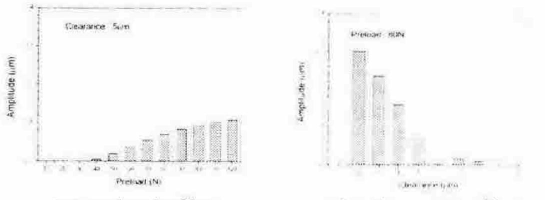
(a)smaller clearance & preload (b)larger clearance & preload
Fig. 3 Frequency and amplitude due to outer race waviness



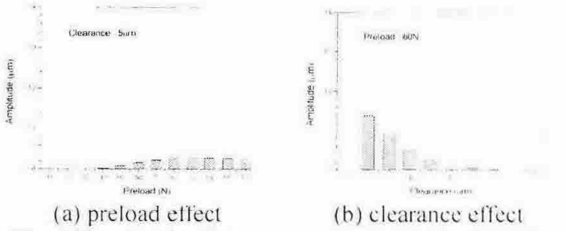
(a)smaller clearance & preload (b)larger clearance & preload
Fig. 4 Frequency and amplitude due to inner race waviness

4. PRELOAD & CLEARANCE EFFECTS

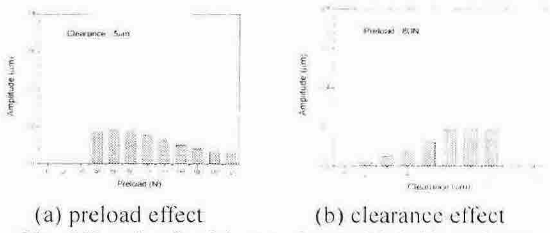
More detailed trends of radial and axial NRRO are investigated in case that only one ball has size error and fourth waviness. Figure 5 shows the trends of radial NRRO with f_c due to one ball size error. Figures 6 and 7 show trends of radial and axial NRRO due to fourth ball waviness. As preload increases, radial NRRO is increased and axial NRRO is decreased. As clearance becomes larger, radial NRRO is decreased and axial NRRO is increased. It is considered that these phenomena are related to the contact angle. It is easily observed that radial and axial NRRO has contrary trends in its magnitude. It is expected that there are optimal design points to minimize both radial and axial NRRO.



(a) preload effect (b) clearance effect
Fig. 5 Trends of radial f_c due to one ball size error



(a) preload effect (b) clearance effect
Fig. 6 Trends of radial $4f_b \pm f_c$ due to 4th ball waviness



(a) preload effect (b) clearance effect
Fig. 7 Trends of axial $4f_b$ due to 4th ball waviness

5. CONCLUSION

The radial and axial NRRO are simulated, and preload and clearance effects are investigated. Preload and clearance have significant effects on radial and axial NRRO of for miniature ball bearings.

6. REFERENCES

[1] Ono, K., Takahasi, K., "Theoretical Analysis of Shaft Vibration Supported by a Ball Bearing with Small Sinusoidal Waviness", IEEE Transaction on Magnetics, Vol.32, No.3, pp. 1709-1714, 1996.

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