Experimental analysis on three-axis vibration of angular contact ball bearing in gyro motor

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Abstract. The practical application shows that it is not enough to evaluate and monitor the vibration state of bearings only from a single radial or axial vibration, so it is significant to study the vibration in three directions. In this paper, the necessity of three-axis vibration monitoring is validated through the correlation of three-axis vibration for bearings and the experimental analysis on gyro motor bearing running at a high speed of 15000rpm. The test process for gyro motor bearing is introduced by means of three-axis vibration monitoring technique, the experimental data is analysed through both the time and frequency domain, the potential flaws during bearing running is quickly recognized. The abnormal motion state is presented and the actual collision wear pictures are given by using the VHX-900 digital microscope. The result illustrates that it is especially effective to monitor the vibration condition of a bearing cage with the displacement data from the circumferential vibration which is namely torsional vibration.

1. Introduction

Gyro motor bearing is a double angular contact ball bearing. The existing test for vibration level and monitoring of angular contact ball bearings are all carried out based on the radial information [1], which pick up vibration signals in a single direction by using piezoelectric acceleration sensor or Doppler laser sensor for quality evaluation and signal analysis corresponding to a specific bearing model. The method above is suitable for those whose vibration value is obviously large in a single direction. In fact, the angular contact ball bearing has not only radial vibration when in operation, but also the axial and torsional vibration, only a single directional vibration assessment for the bearing vibration is not comprehensive enough.

The cited references make use of the equipment, three-axis vibration acceleration sensor combined with some hardware and software technology of the computer like the virtual instrument technology to put forward both the method of measuring three-axis vibration acceleration and evaluation for bearing vibration level from the perspective of the principal vibration of bearing [2]. In this paper, the necessity of three-axis vibration monitoring is validated through investigation on the vibration correlation of angular contact bearings. To monitor the vibration level in three directions on gyro motor bearing running at a speed of 1500rpm, an experimental method based on three-axis vibration monitoring is proposed, vibration signals in three directions are further analysed and compared. Flaws
on the bearing are quickly found out combined with motion state analysis of bearing cage. It validates the effectiveness of three-axis vibration measurement for bearings.

2. Correlation of three-axis vibration of bearings

The correlation of three-axis vibration signals is mainly seen as an parametric concept to study the correlation degree of radial, axial and circumferential vibration value from bearing outer ring when it is in operation, which can be expressed with the following mathematical formula:

$$\rho_{XY} = \frac{\text{cov}(X,Y)}{\sqrt{D(X)}\sqrt{D(Y)}} = \frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}}$$

(1)

When $\rho_{XY}$ is obtained within the range $|\rho_{XY}| \geq 0.8$, it can be regarded as a high correlation, when $0.5 \leq |\rho_{XY}| < 0.8$, it can be regarded as a moderate correlation, when $0.3 \leq |\rho_{XY}| < 0.5$, it can be regarded as a low correlation and when $|\rho_{XY}| < 0.5$, it indicates that the correlation between the two vibrational time series is weak. In order to give a further explanation on the correlation degree of discrete three-axis vibration signals of bearings, 5 precision angular contact ball bearings, B7003C, are randomly selected, and the three-axis vibration measurement is carried out on Andrew B-TEST1010 bearing tester, the test conditions specified are in accordance with the national standard GB/T24610-2009 rolling bearing vibration measurement method. Then the correlation coefficient of the vibration signals are calculated and the results are shown in table 1.

| Sequence number | The radial and axial | The radial and circumferential | The axial and circumferential | Correlation degree |
|-----------------|---------------------|-------------------------------|-----------------------------|--------------------|
| 1               | 0.068               | -0.039                        | 0.037                       | weak               |
| 2               | 0.071               | -0.20                         | -0.015                      | weak               |
| 3               | 0.019               | -0.13                         | 0.031                       | weak               |
| 4               | 0.11                | -0.15                         | 0.17                        | weak               |
| 5               | 0.27                | -0.14                         | 0.056                       | weak               |

From the table it can be seen that for the radial, axial and circumferential vibration signals of the bearing, the absolute value of correlation coefficient between any two ones does not exceed 0.3, indicating that the bearing has weak correlation between any two vibration signals, that is, there exists strong independence on three-axis vibration value. Therefore, it is necessary to monitor the angular contact ball bearings in three directions in order to comprehensively evaluate the bearing vibration quality.

3. Experimental application example

3.1. Test process

In order to obtain the relevant dynamic parameters of gyro motor bearing in real time, the schematic drawing of the monitoring system is shown in figure1, which mainly comprises a driving module (signal generator, drive circuit), gyro motor, acquisition module (vibration acceleration sensor, acoustic sensor, current sensor, data acquisition card and computer processing module). In the process of monitoring, the first step is to adjust the signal generator to output the square wave with a certain frequency, and then input it to the gyro motor after the frequency division of the driving circuit to make it run as required. The three-axis vibration acceleration sensor, acoustic sensor, and current sensor completes the acquisition task on the three-axis vibration acceleration, sound pressure and the current signals respectively. Signal processing and real-time monitoring are carried out on Labview. Experimental data analysis including acceleration spectrum analysis, cepstrum analysis, displacement spectrum analysis and characteristic parameter analysis are further conducted in Matlab.
3.2. Experimental data analysis

3.2.1. Acceleration spectrum analysis. Due to the fact that the vibration of gyro motor is mainly from angular contact ball bearing in the axial, radial and circumferential direction, and that there is also some vibration on the rotor, the flexible head and the system itself. Then a three-axis vibration sensor is installed on the gyro shell connected to the bearing seat, measuring the vibration value in three directions.

By using the method of three-axis vibration test for bearing, the vibration of a dynamic tuned gyro motor bearing is studied and analysed when running for 200 hours at a speed of 15000 rpm. Figure 2 is the time-domain waveform of the vibration acceleration in three directions acquired from the bearing seat, from which, it can be concluded that the amplitude of the radial vibration acceleration is obvious, and that the circumferential vibration acceleration is smaller than other two ones. Figure 3 is the corresponding spectrum. It is clear to see that there exists big shock in the radial direction. In the spectrum, the response frequency is 8950 Hz with many sidebands around it. Therefore, it is necessary to perform cepstrum analysis for determining the modulation frequency corresponding to the sidebands.

![Figure 1: Schematic diagram of the gyro motor bearing dynamic test system.](image)

**Figure 1.** Schematic diagram of the gyro motor bearing dynamic test system.

![Figure 2: Time history of gyro motor bearing.](image)

**Figure 2.** Time history of gyro motor bearing.

![Figure 3: Corresponding acceleration spectrum.](image)

**Figure 3.** Corresponding acceleration spectrum.
3.2.2. Cepstrum analysis. Some high frequency peaks occur in part of the radial vibration acceleration spectrum of the bearing. 8000~10000Hz band above is filtered to carry on cepstrum analysis [3], as shown in figure 4, the highest amplitude appears at 0.011 seconds, converted to frequency units, it is close to the characteristic frequency of the bearing cage, 93Hz. It indicates that the high frequency vibration part of the bearing is modulated by the abnormal vibration of the bearing cage. The abnormal vibration of the cage has a great influence on the running stability of the bearing. It is necessary to analyse the displacement spectrum of the abnormal vibration of the cage to determine the specific vibration condition in three directions.

![Figure 4. Acceleration cepstrum of radial vibration.](image)

3.2.3. Displacement spectrum analysis. For the gyro vibration, the low-frequency vibration displacement has a more direct impact on the performance of the gyro [4]. For this reason, the spectrum of the three-axis vibration displacement is shown in figure 5 after secondary integration for the vibration acceleration value [5]. It can be seen from the vibration displacement spectrum in three directions that the radial and axial displacement of the bearing is smaller than the circumferential vibration displacement, of which the main frequency component is 94Hz, the characteristic frequency of the bearing cage. As a result, it is demonstrated that the torsional vibration displacement of the cage is most suitable for evaluating the vibration stability of the gyro motor bearing.

![Figure 5. Spectrum of three-axis vibration displacement.](image)
3.3. Time domain characteristic parameters analysis
In order to give a further analysis of gyro motor bearing and compare with each other in three directions during a long period of time, a 200-hour run-in test was performed and the state parameters were automatically recorded once per hour in the measurement system. Various average value of time domain characteristic parameters within 200 hours are listed in table 2. For the magnitude of torsional vibration, it can be ignored in the view of measurement of the vibration acceleration, in which the vibration value in radial and axial direction is obviously larger. However, the vibration displacement value becomes the largest one after secondary integration. The result is consistent with the one in the spectrum analysis above.

| Table 2. Characteristic parameters of gyro motor bearing for 200 hours. |
|---------------------------------------------------------------|
| Direction | State parameters | Reference value |
| radial     | Acceleration RMS (m/s^2) | 8.46 |
|            | Acceleration kurtosis value | 2.95 |
|            | Acceleration crest factor | 3.97 |
|            | Displacement RMS (μm) | 0.23 |
| axial      | Acceleration RMS (m/s^2) | 2.73 |
|            | Acceleration kurtosis value | 2.76 |
|            | Acceleration crest factor | 3.77 |
|            | Displacement RMS (μm) | 0.52 |
| circumferential | Acceleration RMS (m/s^2) | 1.29 |
|            | Acceleration kurtosis value | 2.85 |
|            | Acceleration crest factor | 3.80 |
|            | Displacement RMS (μm) | 1.45 |

3.4. Motion analysis of bearing cage
The characteristic frequency of bearing cage can be clearly found out in the cepstrum and the displacement spectrum, however, its comparison with the theoretical characteristic frequency is not enough. To figure out what detective failures exist on the cage, abnormal motion of angular contact ball bearings during high speed operation is analyzed in figure 6 to figure 11, the VHX-900 digital microscope comes into use to magnify cage failure 100 times larger than it was.

3.4.1. Interaction between cage and steel ball. When angular contact ball bearings are running at high speed, the rotational speed of the rolling elements and the cage do not always coincide. Figure 6 shows the case where the rolling elements lag the cage and the cage advances the rolling elements when the speed of the two ones are not the same. At this time, the cage is subjected to the impact force from the rolling elements which acts on the crossbeam between the pockets of the cage. The direction of action is mainly circumferential, resulting in the maximum amplitude of the characteristic frequency of the cage in the circumferential displacement spectrum in figure 5. The red circle part in figure 7 is the collision wear diagram taken by VHX-900 digital microscope.
3.4.2. *Interaction between cage and outer ring.* Figure 8 is the structure of cage in normal condition, the connecting portion between the pockets of the cage is called a lintel, and the bulging portion of the end surface of the cage is called a side lintel. The cage of the gyro motor angular contact ball bearing studied in this paper is guided by the outer ring. During high-speed rotation, the lubricating oil enters and fills the gap to generate the hydrodynamic pressure force. In this case, the guiding effect of the outer ring on the cage can be considered as dynamic pressure lubrication, Due to the bias of the cage, there is a small gap between it and the outer ring, as shown in figure 9.

![Figure 8. Cage in normal condition.](image1)

![Figure 9. Outer ring vs cage.](image2)

When lubricant is sufficient, no contact between the two occurs. Considering that in high-speed condition, bearing cage can be regarded as flexible body [6], the lintel is easily deformable, partial surface of lintel is higher than the side lintel as figure 10, and finally collides with the outer ring and wears. The red circle part in figure 11 is the collision wear diagram taken by digital microscope.

![Figure 10. Deformed cage in high-speed condition.](image3)

![Figure 11. Cage lintel wear marks.](image4)

4. Conclusions

It has the prominent advantage of multi information fusion and sensitive diagnosis in vibration screening for the angular contact ball bearing in gyro motor through the three-axis vibration measurement technique combined with signal processing. The main points can be summarized as follows: first of all, from the perspective of weak correlation, it is necessary to carry out the test and analysis on the angular contact ball bearings in three directions. Then, through experimental examples, it is demonstrated that the torsional vibration displacement of the cage is most suitable for evaluating the vibration stability of the gyro motor bearing. Then, by analysing the time-domain characteristic parameters of vibration signals, it is shown that the torsional vibration displacement is the largest. Finally, through the motion analysis of the interaction between the bearing cage and the balls and the outer ring, the cage wear can be explained and the wear reasons agree well with real wear. The study shows a successful example to apply the three-axis vibration technique for the diagnosis of health condition of bearing cage.
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