An experiment study on deterioration of dynamic rotational accuracy of motorized spindle

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Abstract. High-speed precision spindle is one of the core functional components of CNC machine tools, and its life is the key bottleneck factor restricting the reliability of CNC equipment made in China. So far, the research on the life of motorized spindle is still in the initial stage, and lacks a systematic and complete theoretical support. Motorized spindle is a typical product with high reliability and long life, and it is difficult to have faults or obvious performance degradation in the limited test time, so the traditional reliability evaluation method based on statistical theory is not effective. Therefore, it is of great significance for the reasonable evaluation of the reliability level of motorized spindle to carry out the test technology research on the impact force and life of motorized spindle. In this paper, the spindle alternating load test device is developed. The relationship between alternating impact load and spindle precision retention is studied experimentally. Taking spindle rotation accuracy as the main assessment factor, the mapping relationship between alternating impact load and spindle system life was established.

1. Introduction

The most important factor of motorized spindle is dynamic rotational accuracy, which is mainly affected by bearing wear, system heating, vibration and noise. Masiji’s [1] research shows that about 30% ~ 70% of the roundness error of the precision turning parts is caused by the rotation error of the spindle, and the higher the accuracy of the machine tool, the greater the proportion of it. The radial rotation error shows the radial runout of motorized spindle. As the output of the whole motorized spindle system, the axis track is the integration of bearing wear, thermal deformation of the system, vibration and noise information, which can comprehensively reflect the performance state of the motorized spindle. Zhang Shibing [2], carried out studies on the accuracy and retention of angular contact ball bearings, the static model and pseudo-dynamic model of angular contact ball bearings were established, the influence of bearing parameters on bearing wear, accuracy and retention, and the bearing accuracy life model were explored. Gao [3] conducted FMECA and FTA analysis on the spindle system, the spindle radial runout considering the dynamic wear of the bearing, the time-varying clearance model of the spindle bearing and the time-varying radial runout model of the spindle shaft end were analyzed. A dynamic loading device that could simulate the load on the motorized spindle were designed by Wang Kai [4]. The mechanism and dynamometer are used as the reliability test scheme of the motorized spindle loading device, and the reliability test platform of the motorized spindle is built, which can simulate the actual working conditions to carry out the loading test of the motorized spindle. Li Yang [5], conducted a systematic study on the compilation method of the loading spectrum of the loading test program of
motorized spindle, which provided a set of feasible technical solutions for the compilation of the loading spectrum of the loading test program of motorized spindle, and provided theoretical basis and technical support for carrying out the loading test of the motorized spindle under simulated real working conditions. At present, the related research on the retention of rotation accuracy of motorized spindle is still in the initial stage, but it has been achieved. In this paper, the spindle alternating load test device is developed. The relationship between alternating impact load and spindle precision retention is studied experimentally. Taking spindle rotation accuracy as the main assessment factor, the mapping relationship between alternating impact load and spindle system life was established.

2. Development of test equipment

The principle of the test device for life prediction of motorized spindle under alternating impact load are shown in Fig. 2.

![Fig.1 The principle of the test device](image)

The main working principle of the system is: using the high-speed cylinder loading device to exert the alternating impact load of different frequencies on the motorized spindle. The control system is used to simulate the processing status of motorized spindle under different working conditions. Finally, various signals including vibration and displacement are collected through the monitoring system, and the signal analog quantity is transformed into digital quantity which can be used for life analysis. Input software to complete the recording and analysis of data functions. As shown in Fig. 2.

The high-speed cylinder loading device is used to load alternating impact loads in the radial direction of the spindle. The loaded radial force can be applied to the force bar through the loading spring. The force bar loads the alternating impact load onto the spindle check bar through the force bearing. The frequency of the alternating load is changed by changing the time of the solenoid valve of the cylinder.

In order to prevent the separation of the force rod and the force bearing under the high frequency action,
an initial preload force is set up during the initial installation of the cylinder. In order to test the influence of alternating impact load on the performance of the spindle, two high precision capacitive displacement sensors with orthogonal arrangement are used to measure the dynamic rotation accuracy of the spindle. The parameters of the spring, cylinder and capacitive displacement sensor are shown in Table 1, 2 and 3.

### Table 1  Parameters of spring components

| Stiffness  | Maximum compression | Outer diameter | Length |
|------------|---------------------|----------------|--------|
| 40N/mm     | 30mm                | 20mm           | 120mm  |

### Table 2  Parameters of cylinder components

| Stroke     | Diameter | Maximum force | Maximum frequency |
|------------|----------|---------------|-------------------|
| 25mm       | 100mm    | 4500N         | 10Hz              |

### Table 3  Parameters of high precision displacement sensor

| Item                     | Parameter          | Item                     | Parameter          |
|--------------------------|--------------------|--------------------------|--------------------|
| Inductive area radius    | 2 mm               | Linearity                | 0.1%               |
| measurement range        | 250 μm             | Temp. Range              | 4-50°C             |
| Output voltage range     | ±10 V              | Output sensitivity /     | 0.08 V/μm          |
| Connection Type          | Differential       | Ambient temperature      | 20±1℃              |

3. Test method and measurement system

3.1. Test method of the rotational accuracy

Conventional measurement methods of spindle rotating accuracy include static method, single-direction method, and two-direction method [6]. In this article, rotation is in the sensitive direction of the rotor, so two-direction method is utilized. The schematic of two direction measurement method is shown in Fig. 3. Two orthogonal capacitive displacement sensors are applied to inspect the radial error motion.

Fig.3  Schematic of two-direction measurement method
The displacement signals acquired by the capacitive displacement sensor \( X \) and \( Y \), are \( \Delta X(\theta) \) and \( \Delta Y(\theta) \), respectively,

\[
\begin{align*}
\Delta X(\theta) &= \delta_X + \Delta e_X + \Delta R_X \\
\Delta Y(\theta) &= \delta_Y + \Delta e_Y + \Delta R_Y
\end{align*}
\]

where \( \delta_X \) and \( \delta_Y \) are the rotor error motion in \( X \) and \( Y \) direction, \( \Delta e_X \) and \( \Delta e_Y \) are installation eccentricity error in \( X \) and \( Y \) direction, and \( \Delta R_X \) and \( \Delta R_Y \) are cylinder error of the rotor. The installation eccentricity error can be eliminated by filtering first harmonic component. In order to facilitate the analysis, cylinder error of the rotor can be omitted due to its high precision.

The vector diagram of rotational accuracy for sensitive direction is shown in Fig. 4.

![Vector diagram](image)

Fig.4  The vector diagram of rotational accuracy for sensitive direction

According to the geometric relationship of the vector diagram, the following equations can be obtained apparently.

\[
\begin{align*}
\overrightarrow{ab} &= \Delta X(\theta) \cdot \cos(\theta) \\
\overrightarrow{ac} &= \Delta Y(\theta) \cdot \sin(\theta) = \overrightarrow{ef} \\
\overrightarrow{ad} &= \overrightarrow{ab} + \overrightarrow{ef} = \Delta X(\theta) \cdot \cos(\theta) + \Delta Y(\theta) \cdot \sin(\theta)
\end{align*}
\]

The radial error motion at angular position \( u \) can be calculated by the equation 6

\[
r(\theta) = r_i + \Delta X(\theta) \cdot \cos(\theta) + \Delta Y(\theta) \cdot \sin(\theta)
\]

where \( r_i \) is the value of the basic circle radius set by alignment of the displacement sensors and the rotor. By adjusting the value of \( r_i \), the plot of the error motion would be easy to identify, without affecting error motion value.

3.2. Measurement system of rotational performance

Fig.5 shows the monolithic Shock vibration system and radial error measurement system used for measuring the rotational accuracy of the test rig. The system consists of NI DAQ Card (USB-6356) and capacitive displacement sensors (C8-2.0 Lion, Inc.) including the amplifier. All the devices are placed on a vibration-isolated table. Table 2 shows the test conditions in this experiment.
4. Experimental analysis

In accordance with ANSI/ASME standard or ISO standard [7], total error motion polar plots can be plotted by using the data of displacement sensors as shown in Fig. 6. Least square circle (LSC) evaluation method is used to assess the synchronous radial error of the rotor. Actually, the calculation of synchronous error motion value is a process of nonlinear least square fitting. The alternating load with excitation frequency of 6 Hz and Max. excitation force of 1000N. Since the time for the excitation force to increase from 0N to 1000N is very small, it is simplified as alternating impact load in this test.

Table 4  Test condition

| Time          | Speed of the Spindle | Exciting Frequency | Max Exciting force |
|---------------|----------------------|--------------------|--------------------|
| 10 Hours per day | 6000rpm              | 6 Hz               | 1000 N             |

According to the test plan in Table 4, the synchronous error value and asynchronous error value of the spindle under the specified working conditions were tested respectively. The test results are shown in Figure 7, when the spindle speed is 6000rpm, the excitation frequency is 6 Hz, and the maximum
excitation force is 1000N, the synchronous and asynchronous errors of the spindle have no obvious change with time in the 20(200 hours) days before the test. When the test time is more than 20 days, both synchronous and asynchronous errors of the spindle increase with time, and the rate of increase increases with the time.

![Dynamic rotary accuracy of spindle under alternating impact load](image)

**Fig.7** Dynamic rotary accuracy of spindle under alternating impact load

5. Conclusion
The deterioration of dynamic rotational accuracy of motorized spindle is the main determinant of the life of motorized spindle. The life of high-speed motorized spindles depends on the life of high-speed bearings, and the life of high-speed motorized spindle bearings generally refers to the accuracy life, that is, the retention time of bearing accuracy. After the use of precision bearings for a period of time, due to the wear between the rolling body, the ring raceway and the cage, the accuracy of the bearings is reduced. At this time, the bearings may not appear fatigue damage, but it can not meet the requirements of accuracy. Fatigue pitting of spindle bearing can not be directly measured after spindle assembly is completed, and the causes and manifestations of wear are very complex. There is no direct empirical formula for bearing accuracy retention. By testing the dynamic rotation accuracy of the spindle, we can predict the life reduction of the spindle caused by fatigue pitting and wear of bearings. Further study on the deterioration of dynamic rotational accuracy of motorized spindle should be carried out as soon as possible.

Acknowledgments
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