Research on Reliability of Positioning Error Measurement for NC Milling Machine

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Abstract: Laser interferometer is the common tool to measure the positioning error of CNC machine, and its measurement process will be affected by external factors. Therefore, it is very important to ensure the error accuracy which measured by laser interferometer for compensating the error of CNC machine tools. The positioning error of MVC850B CNC milling machine was measured by Renishaw laser interferometer. Firstly, the positioning error of it was measured in standard and actual environmental parameters, and measured results were comparatively shown in factors of temperature, air pressure and humidity. Secondly, the influence degree that in three conditions of feeding speed, interval distance and processing time was analyzed by the errors of reverse clearance and screw pitch cumulative. Finally, with the statistics of positioning errors measured in a certain period of time, this paper analyzed the reliability of positioning errors measured by laser interferometer and analyzed the variation of milling machine motion axis errors. Meantime, the possible location of machine errors can be predicted, and the positioning accuracy of CNC milling machine would be promoted.

1. Introduction

In modern mechanical manufacturing, precision and ultra-precision CNC machining technology has become the most important component and research direction, and the positioning accuracy of CNC machine tools is an important indicator of machine tool acceptance and testing. At the same time, with the use of machine tools, positioning accuracy will gradually decrease. Therefore, it is particularly important to study the positioning error of CNC machine tools, and many scholars had done some research [1-4]. Kwintarini W [5,6] summarized the influencing factors of positioning accuracy of NC milling machine and the limitations of existing processing technology. Soori M [7] proposed a virtual machining system, which can generate modified codes of actual workpiece in virtual environment. The results show that the processing accuracy can be improved by inputting the actual codes into CNC machine tools. Xiao Li [8] proposed a contour error detection method based on monocular vision. In the conditions of wide working range and high feed rate, it can accurately measure the two-dimensional errors of any trajectory of machine tools. JY Chen [9] analyzed the factors affecting the machining accuracy of NC machine tools by using the method of combining the ball bar instrument with laser interferometer and compensated the errors, which improved the positioning accuracy. Chen [10] putted forward a scheme of automatic measurement of machine tool positioning accuracy based on the combination of 3D side head and macro program, which could effectively improve machine tool positioning accuracy without adding expensive equipment. It can be seen that a large number of studies are only based on theoretical analysis or mathematical modeling, and lack of analysis in the actual measurement process.
The content of this paper is based on a large number of experiments. Through comparative experiments, the influence of environmental factors on positioning error measurement is analyzed. At the same time, the variation of errors under the influence of single factors such as feeding speed, measuring distance and processing time is analyzed. Finally, the reliability of positioning errors and the reasons affecting positioning accuracy are analyzed by measuring positioning errors several times in a certain period of time and drawing probability distribution curves.

2. Experimental preparation

2.1 Introduction of experimental device

The experimental research equipment is a three-axis NC milling machine whose model is MVC850B, and its 3-axis travel length (x-y-z) of the machine is 800mm-500mm-550mm. The measuring instrument is LaserXL-30 laser interferometer produced in Renishaw, Germany, with supporting measuring software. Fig 1 is a device for measuring positioning error of NC milling machine. Before each measurement, it is necessary to start the machine tool running empty for 1-2 hours, so that the machine tool would reach a relative equilibrium state. Meanwhile, the laser should preheat for about 20 minutes, so that the laser frequency could reach a stable state. The last but not least, minimizing the vibration and interference sources of the surrounding environment during the experiment.

![Fig 1. Positioning Error Measuring Device for NC Milling Machine](image)

2.2 Principle of Error Measurement

Laser interferometer is used to measure the positioning error of NC milling machine. First, The laser device emits laser beam ① which is divided into reflected beam ② and emitted beam ③ by spectroscope. The two beams of light would be reflected to the same position of the spectroscopthrough the speculum. After being modulated by the spectroscope, the beam ④ is transmitted to the laser device, so that the interference fringes of the two beams are produced in the laser device. Finally, it is transmitted to a computer with a measuring software for recording and obtaining error data [13].

3. Analysis of Contrast Test of Environmental Parameters

Laser interferometer is sensitive to working environment because it uses photoelectric effect to measure positioning error of machine tools. In order to ensure the high accuracy of laser measurement, there are strict requirements for the actual working environment. The main indicators of environmental control are air temperature, relative humidity and atmospheric pressure. The comprehensive results of the above indexes will cause the change of refractive index of air, which will lead to the change of wavelength and eventually lead to measurement error [14,15].

The positioning errors of X-axis and Y-axis are measured in standard environment state and actual environment state modified by environmental parameters, as shown in Fig 2 and Fig 3. The actual environmental parameters and standard parameters are shown in Table 1.
According to Edlen's empirical formula, the measurement error $\delta$ caused by environment can be expressed as follows:

$$\delta = -0.929 \times 10^{-6} \Delta t - 0.042 \times 10^{-4} \Delta f + 0.269 \times 10^{-8} \Delta p$$

In the formula, $\Delta t$, $\Delta f$ and $\Delta p$ are the changes of temperature, humidity and air pressure relative to the standard state.

Because of the short time interval between the two measurements before and after the correction of environmental parameters, the influence of machine tool temperature variation is neglected here. Through calculation, it can be concluded that the measurement errors of X-axis and Y-axis caused by environment are -7.6$\mu$m and -6.6$\mu$m. According to Fig 2 and Fig 3, the actual measurement errors caused by environment measured directly are -9.8$\mu$m and -5.3$\mu$m. The measured data are not much different from those calculated by theoretical empirical formulas, which shows that more accurate positioning errors of machine tools can be obtained by modifying environmental parameters. It is of great significance to eliminate the measurement errors caused by the environment when the machine tool errors are compensated in the actual processing in the future. At the same time, it can be concluded that the influence of temperature on measurement error is greater, followed by the influence of air pressure, and the influence of humidity is smaller, which can be ignored.

4. Single factor analysis of positioning error

On the basis of a large number of experimental studies, the effects of feed speed, interval distance and processing time on measurement positioning error are summarized. Feed speed, interval distance and processing time are taken as variables, and reverse clearance error and pitch cumulative error are taken as response outputs. The feed speed ranges from 50mm/min to 4000mm/min. The interval distance is measured respectively by 1mm, 5mm, 10mm, 20mm, 50mm and 100mm. The processing time is from 1h to 13h. By controlling the two factors unchanged and changing one of them, the positioning error of the machine tool is measured. The range value between the response output reverse clearance and the accumulated pitch error in the range of each factor is obtained by statistical calculation, as shown in Table 2.
Table 2. Range value of response results of different factors

|                         | Range value of reverse clearance(μm) | Range value of accumulated pitch error(μm) |
|-------------------------|--------------------------------------|-------------------------------------------|
|                         | X-axis  | Y-axis  | X-axis  | Y-axis  |
| Feed speed              | 3.5     | 4.8     | 5.7     | 7.3     |
| interval distance       | 4.1     | 6.6     | 3.4     | 7.3     |
| processing time         | 1.4     | 2       | 24.9    | 18.7    |

According to Table 2, it can be clearly compared that the feed speed and interval distance have greater impact on the reverse clearance than the processing time, while the processing time has greater impact on the accumulated pitch error than the feed speed and interval distance. In order to understand more intuitively the influence trend of feed speed and distance measurement on the reverse clearance and the influence trend of processing time on the accumulated pitch error, the trend change charts as shown in Fig 4, Fig 5, Fig 6 and Fig 7 (the points 1-6 of the transverse axis in Fig 5 represent ranging of 1 mm, 5 mm, 10 mm, 20 mm, 50 mm and 100 mm).

As can be seen from Fig 4, the reverse clearance decreases gradually with the increase of feed speed, and the fluctuation is small after 2000 mm/min. The feed speed of Y-axis 800mm/min, 1200mm/min and 1800mm/min were taken to verify the validity of the validation and the reverse clearance of Y-axis was respectively 13.6μm, 12.9μm and 12.7μm. Fig 5 shows that the reverse clearance decreases with the increase of interval distance. After the increase of interval distance is 20 mm, the change of the reverse clearance fluctuates slightly. Interval distance reflects the continuity of machine tool motion. The Y-axis interval distance is 25 mm, and the reverse clearance of the Y-axis is 12.9μm, which is validated. From Fig 6 and Fig 7, it can be seen that the accumulative pitch errors of X-axis and Y-axis of NC milling machine gradually increase with the increase of processing time.
With the increase of processing time, the temperature would increase, which lead to the linear expansion of transmission and finally influence on positioning errors. Therefore, when compiling the program for workpiece processing, we should choose the appropriate feed speed to ensure the continuity of processing as far as possible, and timely heat dissipation to the machine tool.

5. Analysis of Positioning Error Distribution

5.1 Reliability Analysis of Reverse Gap

Because there are tolerances in the manufacture and assembly of machine tools and other factors, the positioning errors of machine tools will also appear randomness. The reliability analysis of the positioning errors of machine tools can judge the accuracy retention of machine tools and predict the possible errors. The positioning error of machine tools is measured in one day, and each measurement is independent, that means each measurement is under the same conditions. Recording 100 random measurements as a whole of machine tool reverse clearance in a certain period of time, we can get that the intervals of X-axis and Y-axis reverse clearance are respectively (7.4-10.1)μm and (10.5-13.9)μm. Taking the above sections as intervals of 0.2μm, the quantity and frequency of each interval are counted, the histogram is drawn, then the Gauss fitting is carried out, and the results are shown in Fig 8 and Fig 9.

![Fig 8. X-axis Reverse Clearance Statistical Map](image1)

![Fig 9. Y-axis Reverse Clearance Statistical Map](image2)

N (μ, σ²) is used to represent the normal distribution of random variable θ obeying a mathematical expectation μ and variance σ². From Fig 8 and Fig 9, it can be seen that the X-axis reverse clearance basically obeys the normal distribution of NX (8.4, 0.4265), and the Y-axis reverse clearance basically obeys the normal distribution of NY (12.4717, 1.004). It can be concluded that the reverse clearance of X-axis is smaller and more stable than that of Y-axis, and the wear of Y-axis transmission mechanism is more serious.

In order to test the reliability of the above normal distribution, selected randomly 10 times of X-axis and Y-axis backlash measurements on the same conditions, and calculated their average and variance, as shown in Table 3.

|                | X-axis | Y-axis |
|----------------|--------|--------|
| Average(μm)    | 8.521  | 12.353 |
| Variance       | 0.363696 | 0.506153 |

The deviation between the mathematical expectation of random small sample data and the mathematical expectation of total data is used as the criterion to test the reliability of machine tool error distribution. It is calculated that the reliability of X-axis reverse clearance normal distribution is 98.58%, and that of Y-axis reverse clearance normal distribution is 99.05%. The reliability are all relatively high. It is simpler and more accurate to analyze the current situation of machine tools with...
5.2 Verification and Analysis of Linear Positioning Accuracy

On the same condition, 50 times of positioning error measurement results are selected randomly, and the error distribution curves of each positioning point are drawn with the distance of 100 mm. The distribution curves of X-axis and Y-axis pitch errors are obtained as shown in Fig 10 and Fig 11. (In order to observe more clearly, the distribution curve is enlarged five times and placed in the overall pitch error variation map)

The overall variation trend of pitch errors of X-axis and Y-axis can be obtained intuitively through Fig 10 and Fig 11. By analyzing the error distribution of each measuring point, the reasons affecting the positioning accuracy can be found, and the larger position of the errors can be generated, which is conducive to error compensation. From the pitch error distribution curves of X-axis and Y-axis, it can be seen that the error distribution of each measuring point of X-axis is relatively centralized, and with the increase of feed stroke, the accumulated pitch error does not change in a large range. This shows that the reliability of the pitch error of X-axis is relatively high, and the transmission mechanism of X-axis is relatively in good condition and the accuracy is maintained. The distribution of error points of Y-axis is relatively scattered, and with the increase of feed stroke, the range of accumulated error of pitch varies greatly, which indicates that the reliability of measured pitch error of Y-axis is relatively low, and the Y-axis transmission mechanism is worn seriously.

6. Conclusion

By measuring the positioning error of NC milling machine and analyzing the measurement results on different factors, the following conclusions can be drawn:

(1) External temperature, humidity and atmospheric pressure have impacts on the measurement of positioning error of machine tools, and temperature has the greatest impact, followed by atmospheric pressure, humidity has the smallest impact, which can be ignored.

(2) Feed speed and interval distance have a greater impact on the reverse clearance, while processing time has a greater impact on the accumulated pitch error. Reverse clearance decreases with the increase of feed speed and interval distance, and the accumulated pitch error increases with the increase of processing time.

(3) The reverse clearance of X-axis and Y-axis obeys the normal distribution of $N_X(8.4, 0.4265)$ and $N_Y(12.4717, 1.004)$ respectively, and the reliability is respectively 98.58% and 99.05%, which is all high.

(4) The reliability of Y-axis error detection is lower than that of X-axis error detection, and the stability of pitch error is worse, which indicates that Y-axis is worn more serious that would affects the quality and accuracy stability of processed products.
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