A Multi-error Measurement Method for Workpiece of Vertical Machine Tool

Xiaoming Wang¹, Daowen Wan¹, Yongmeng Liu¹, Dawei Wang¹, Zifei Cao¹, Junfeng Wang³, Chuanzhi Sun¹, Dong Zhou³, Xue Chen³ and Hongliang Ma³

1. Center of Ultra-precision Optoelectronic Instrument engineering, Harbin Institute of Technology, Harbin 150080, China
2. Key Lab of Ultra-precision Intelligent Instrumentation Engineering (Harbin Institute of Technology), Ministry of Industry and Information Technology, Harbin 150080, China
3. Qiqihar Heavy CNC Equipment Co., Ltd., Qiqihar 161005, China

Email: wang_xm@hit.edu.cn, lym@hit.edu.cn

Abstract. This paper proposes a method of multi-error separation for online monitoring of machine tool workpieces based on a single sensor with three rotation. Firstly, the multiple error sources what include roundness error, spindle radial rotation error and eccentric error are identified in the measured data of the sensor. Then, a multi-error separation model is established based on error sources. And the accurate separation of each error is realized through theoretical derivation. At the same time, an experimental system is set up to further verify the effectiveness and accuracy of the model.

1. Introduction

As the "worker machine" of the equipment manufacturing industry, the work performance and processing quality of CNC machine tools are one of the main bases for measuring the comprehensive national strength of a country. In order to avoid the machining process of the workpiece due to unqualified precision caused huge economic losses. It is necessary to carry out real-time online monitoring in the processing process to improve the machining accuracy of the workpiece[1]. The spindle radial rotation error is an important index to evaluate the performance of machine tools [2]. Simultaneously, the roundness error of the workpiece surface directly reflects the processing quality[3]. Consequently, it is of great significance to build a reasonable and correct online monitoring mathematical model to achieve accurate measurement and evaluation of various errors.

In the working process of the machine tool, the surface contour signal can be picked up by building a measuring system[4]. However, the spindle radial rotation error, workpiece roundness error and eccentric error are coupled in the signal data. Thus, it can be seen that it is awkward to acquire all errors accurately by direct measurement. Therefore, we must study the error coupling relationship, construct a circle profile measurement model based on multi-error interconnection and solve the precise extraction of workpiece contour information and spindle radial runout[5]. Last but not least, the spindle radial rotation error and roundness error can be evaluated[6].

In terms of rotation error measurement, commonly used methods include one-way method, two-
way method and multi-point method \cite{7,8,9,10}. Among them, the one-way method and the two-way method are difficult to improve the measurement accuracy, so the practical application is subject to certain restrictions. In the multi-point method, the three-point method is favored by many scholars because of its ability to achieve multi-error separation. The traditional three-point method requires the ray directions of the probes of the three sensors to intersect at one point. However, it is difficult to achieve precise alignment in the actual measurement process, and other errors are introduced, resulting in a decrease in measurement accuracy. In this paper, based on the three-point method, a multi-error separation technique based on the non-contact single sensor three-rotation method is proposed by using the laser displacement sensor. This paper is structured as follows: Firstly, the multi-error measurement separation method of single sensor with three transposition method is studied and the mathematical model of multi-error separation is constructed. Secondly, error separation is completed through simulation experiments. Finally, the measurement system is set up for field experiment.

2. Multiple-errors identification and separation

In this paper, the single sensor three rotation method is used to obtain the experimental data and separate the related errors. As shown in Figure 1(a), we set the number of the sensor sampling as $N$. Sampling position 1 is $0^\circ$ position 2 is $\alpha$, and position 3 is $\beta$ respectively. The actual value measured by the sensor is determined by the variation of the workpiece's radial dimension, the average distance between the sensor and the workpiece and the actual position of the workpiece's axis.

![Diagram](image)

**Figure 1.** Measurement principle diagram of single sensor with three rotation method.

**2.1. Separation model of radial variation of workpiece**

As shown in Figure 1 (b), The position vector $OP$ of the workpiece axis is obtained by adding the eccentricity of the workpiece $OO'$ and the radial error vector of the spindle $OO''$. We set $O' (a', a'\prime), OO''(e_x(\theta), e_y(\theta))$. $V(\theta)$ is the roundness error of the spindle. The output signals of sensors in position 1, 2 and 3 can be expressed as:

$$
\begin{bmatrix}
D_1(\theta) \\
D_2(\theta) \\
D_3(\theta)
\end{bmatrix} = 
\begin{bmatrix}
V(\theta) \\
V(\theta + \alpha) \\
V(\theta + \beta)
\end{bmatrix} + 
\begin{bmatrix}
1 & 0 & e(\theta)\cos(\theta) \\
\cos(\alpha) & \sin(\alpha) & \cos(\theta + \alpha) \\
\cos(\beta) & \cos(\beta) & \cos(\theta + \beta)
\end{bmatrix}
\begin{bmatrix}
e(\theta)\cos(\theta) \\
\sin(\theta) \\
e(\theta)\sin(\theta)
\end{bmatrix} \\
\begin{bmatrix}
\cos(\theta + \alpha) & \sin(\theta + \alpha) \\
\cos(\theta + \beta) & \sin(\theta + \beta)
\end{bmatrix}
\begin{bmatrix}
a_1' \\
a_2' \\
a_3'
\end{bmatrix}
$$

(1)

We multiply $D_i(\theta), D_j(\theta)$ and $D_k(\theta)$ by the weight coefficient $1, \lambda$ and $\mu$ to perform unequal weight combination. The combined signal $C(\theta)$ is obtained after the addition.

$$
C(\theta) = D_1(\theta) + \lambda D_2(\theta) + \mu D_3(\theta)
$$

$$
= [V(\theta) + \lambda V(\theta + \alpha) + \mu V(\theta + \beta)] + (1 + \lambda \cos\alpha + \mu \cos\beta) \cdot [e_x(\theta) + a' \cos(\theta) + a' \sin(\theta)]
$$

$$
+ (\lambda \cos\alpha + \mu \sin\beta) \cdot [e_y(\theta) + a' \cos(\theta) + a' \sin(\theta)]
$$

(2)

In order to separate $V(\theta)$ from $C(\theta)$, equation (2) should satisfy the following conditions, we substitute equation (3) into equation (2) and obtain equation (4) respectively.
The sampling signal is discretized. We set \( N = 2^n \) and \( \Delta \theta = \frac{2\pi}{N} \). The angles of position 2, position 3 are \( \alpha = 2p\pi / N = p \cdot \Delta \theta \) and \( \beta = 2q\pi / N = q \cdot \Delta \theta \) respectively, where \( p \) and \( q \) should be integers. According to the characteristics of DFT, we can obtain as:

\[
C(\theta) = V(\theta) + \lambda V(\theta + \alpha) + \mu V(\theta + \beta)
\]

The value of radial dimension variation of workpiece in time domain can be obtained as:

\[
V(n) = IDFT[F_r(k)] = IDFT\left[\frac{F_c(k)}{W(k)}\right]
\]

2.2. Separation model of eccentric error and rotation error

In this sub-section, we build a separate model of eccentric error and rotation error. The radial dimension variation of the workpiece obtained by separation is removed from the sensor measurement signal and then:

\[
D_x(i) - V(i) = e(i)\cos(i \cdot \frac{2\pi}{N}) + a'_x,\cos(i \cdot \frac{2\pi}{N}) + a'_y,\sin(i \cdot \frac{2\pi}{N})
\]

\[
D_y(i) - V(i) = e(i)\cos(i \cdot \frac{2\pi}{N})\cos(p \cdot \frac{2\pi}{N}) + e(i)\sin(i \cdot \frac{2\pi}{N})\sin(p \cdot \frac{2\pi}{N})
\]

\[
+ a'_x,\cos\left\{(i + p) \cdot \frac{2\pi}{N}\right\} + a'_y,\sin\left\{(i + p) \cdot \frac{2\pi}{N}\right\}
\]

We set \( h_1(i) \) and \( h_2(i) \) as equation (9). After theoretical derivation, We can get \( a'_x \) and \( a'_y \) as equation (10).

\[
h_1(i) = D_x(i) - V(i) + p
\]

\[
h_2(i) = \left\{D_x(i) - V(i + p)\right\} - \left\{D_x(i) - V(i)\right\} \cdot \cos(p \cdot \frac{2\pi}{N}) / \sin(p \cdot \frac{2\pi}{N})
\]

\[
a'_x = \frac{2}{N} \sum_{i=0}^{N-1} h_1(i)\sin(i \cdot \frac{2\pi}{N}) - h_1(i)\cos(i \cdot \frac{2\pi}{N}) \cdot \sin(4\pi / N)
\]

\[
a'_y = -\frac{2}{N} \sum_{i=0}^{N-1} h_1(i)\sin(i \cdot \frac{2\pi}{N}) - h_1(i)\cos(i \cdot \frac{2\pi}{N}) \cdot \cos(4\pi / N)
\]

According to equations (10), the initial coordinate of the workpiece's mounting eccentricity can be obtained, and the mounting eccentricity of the workpiece can be further calculated:

\[
a' = \sqrt{(a'_x)^2 + (a'_y)^2}
\]

Further based on the above, the spindle rotation error can be seen as:

\[
e(i) = h_1(i)\cos(i \cdot \frac{2\pi}{N}) + h_2(i)\sin(i \cdot \frac{2\pi}{N}) - \left\{a'_x,\cos(i \cdot \frac{4\pi}{N}) + a'_y,\sin(i \cdot \frac{4\pi}{N})\right\}
\]

3. Experiment

In order to verify the validity of the multi-errors measurement and separation model proposed in the paper. An experiment system with high precision is built as shown in Figure 2.
Firstly, the roundness error is naturally obtained. The schematic diagram is shown in Figure 3 (a), which shows that the roundness error of the workpiece is $R_e=0.0510$ mm. We then remove the eccentricity of the workpiece installation after separating the roundness error of the workpiece, which are $a_x'=-0.0047$ mm and $a_y'=0.0054$ mm. Finally, we carry out the separation and evaluation of the rotation error of the machine tool spindle, and the results are shown in Figure 3 (b). The rotation error of the machine tool spindle is $E_e=0.0530$ mm.

Figure 3. Experimental results of roundness error of workpiece and rotation error.

4. Conclusion
In this paper, a workpiece profile measurement model with multi-error is proposed, which takes into account three kinds of errors: workpiece eccentricity, workpiece roundness and spindle rotation error. Compared with the traditional three-point separation model, the combined effect of the systematic error on the measurement results by the proposed model is analyzed. The error separation of the measurement data was completed through experiments, which verified the practicability and accuracy of the method.

5. Acknowledgments
This research is supported by Scientific and technological cooperation project of Heilongjiang Provincial Academy of Sciences (grant number YS19A15) and the National Natural Science Foundation of China (grant number 91960109) and the Major science and technology projects of Heilongjiang Province (grant number 2020ZX03A02).

6. References
[1] Liu WW, Fan KC, Hu PH and Hu Yi 2018 A parallel error separation method for theonline measurement and reconstruction of cylindrical profiles Precision Engineering. 51 1-9
[2] Denis S A and Samuel G L 2012 Harmonic–analysis–based method for separation of form error during evaluation of high–speed spindle radial errors The International Journal of Advanced Manufacturing Technology. 59 (5) 445-461
[3] Lee J C, Yuki S Y, Gao W, Oh J and Park CH 2014 Precision evaluation of surface form error of a large-scale roll workpiece on a drum roll lathe Precision Engineering. 38 839–848

[4] Jywe W and Che C J 2007 A new 2D error separation technique for performance tests of CNC machine tools Precision Engineering. 31 369–375

[5] Fujimaki K, Sase H and Mitsui K 2008 Effects of sensor noise in digital signal processing of the three-point method Measurement Science and Technology. 19(1) 957-233

[6] Castro HFF 2008 A method for evaluating spindle rotation errors of machine tools using a laser interferometer Measurement. 41(8) 526-537

[7] Zhou FF, Lu HZ, Yuan JL and Li F 2013 Review on multi-Point method for roundness Error Separation Advanced Materials Research. 797 555-560

[8] Ahou M, Sebaa F and Cheikh A 2017 Study and Modeling of Machining Errors on the NC Machine Tool International Journal of Mechanical Engineering and Robotics Research. 6(1) 54-57

[9] Sun SW, Yang JW, Huang J and Cao SQ 2019 Research on the Machining Error Analysis Method of Globoidal Indexing Cam Profile International Journal of Mechanical Engineering and Robotics Research. 8(2) 189 -195

[10] Syh-Shiuh Y 2019 Feed Rate Determination Method for Tool Path Interpolation Considering Piecewise-Continued Machining Segments with Cornering Errors and Kinematic Constraints International Journal of Mechanical Engineering and Robotics Research. 8(3) 354-360