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The Analysis and Compensation Experiment of Linear Feed Axis Positioning Error Based on Matrix Operation

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1. Introduction

At present, the numerical control machine tool, which is defined as the national important reserve force, has become an indispensable industrial weapon in the manufacturing industry, and bears an important responsibility in the development of the national manufacturing industry, has become an important symbol of Comprehensive National Power [1-5]. As the main equipment of machine parts production and processing, numerical control machine tool has become one of the hot research topics of domestic and foreign scholars. The actual machining precision of NC machine tool is generally less than that of theoretical design. The reasons are: the positioning precision of the movement axis of NC machine tool is insufficient [6-10], it includes: linear feed axis and rotary feed axis. Therefore, it is an important research direction of NC machine tool to accurately evaluate the positioning accuracy of motion axis and realize accurate compensation. Based on the matrix algorithm, the positioning error of linear feed axis is analyzed, and the positioning error compensation is realized, which improves the positioning accuracy of linear feed axis.

2. The Positioning Error Analysis

The positioning error of NC machine tool is the key parameter to measure the positioning accuracy [11-15]. The positioning error of NC machine tool can be understood as the deviation between the linear feed axis theory and the actual target position after the control instruction is given by the drive system.

As shown in Fig. 1, A is the starting point of the linear feed shaft, B is the driving target. Due to the existence of three-dimensional system error in the actual machine tool space, the starting point A is planned to feed x_i, y_i, z_i and then B_i to the target point. On this basis, the errors Δx, Δy, Δz of three-dimensional system in space are respectively multi-fed to reach the actual target point B_r. The location error is the position deviation between B_r and B_i.

3. The Location Error Analysis Based on Matrix Operation

Vertical linear feed Axis Z axis is the most sensitive motion axis of gantry vertical machining center. Taking the linear feed axis Z axis of gantry vertical machining center as an example, the matrix operation is analyzed, and the research object is shown in Fig. 2.

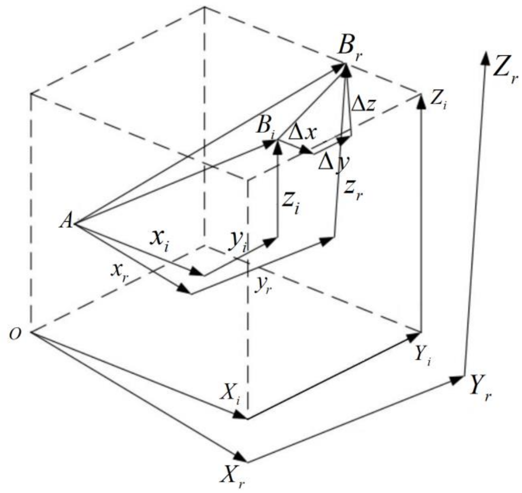

Fig. 1 Three-dimensional space system positioning error analysis diagram

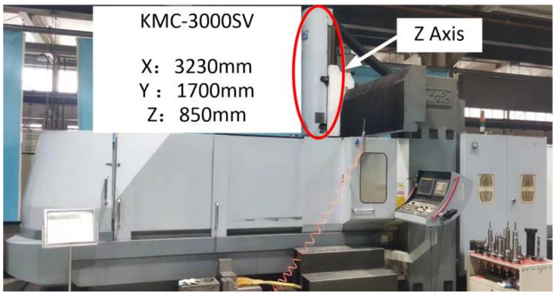

Fig. 2 Gantry vertical machining center

The linear feed axis Z-axis arbitrary step motion will produce six spatial errors, the linear deviations were $\delta_x(z)$, $\delta_y(z)$, $\delta_z(z)$ and the rotation deviations were $\varepsilon_x(z)$, $\varepsilon_y(z)$, $\varepsilon_z(z)$, this is shown in Table 1.

When the Z axis of the linear feed axis is fed along the Z direction at the point (0, 0, z). The Z-axis offset error $\delta_{z1}(z)$ is detected directly by using the linear detection module of dual-frequency laser interferometer, X, Y straightness errors $\Gamma_{x1}(z)$, $\Gamma_{y1}(z)$.

According to the matrix transformation. The points (0, 0, z) can be listed in the coordinate system O_R positions by the matrix expression (1).

Table 1

Feed Axis Z axis spatial error

Num	Name	Symbols
1	X direction offset error	$\delta_x(z)$
2	Y direction offset error	$\delta_y(z)$
3	Z direction offset error	$\delta_z(z)$
4	X direction deflection error	$\varepsilon_x(z)$
5	Y direction deflection error	$\varepsilon_y(z)$
6	Z direction deflection error	$\varepsilon_z(z)$

$$T_{BR}=\begin{bmatrix}1 & -\varepsilon_z(z) & \varepsilon_y(z) & \Gamma_{x1}(z)\\ \varepsilon_z(z) & 1 & -\varepsilon_x(z) & \Gamma_{y1}(z)\\ -\varepsilon_y(z) & \varepsilon_x(z) & 1 & z+\delta_{z1}(z)\\ 0 & 0 & 0 & 1\end{bmatrix}. \quad (1)$$

In order to build a positioning error model. In linear feed Axis Z axis coordinate system O_B select detection point $b_1(x_1, y_1, z_1)$. The initial coincidence of fixed coordinate system O_{B1} and moving coordinate system O_{B2}, O_{B1} and O_{B2} is established. The origin is b_1. The change matrix of the coordinate system O_{B1} and O_{B2} can be established, O_{B1} to R is the matrix formula (2), O_B to O_{B2} is the matrix formula (3):

$$T_{RB_1}=\begin{bmatrix}1 & 0 & 0 & x_1\\ 0 & 1 & 0 & y_1\\ 0 & 0 & 1 & z_1\\ 0 & 0 & 0 & 1\end{bmatrix}, \quad (2)$$

$$T_{B_2B}=\begin{bmatrix}1 & 0 & 0 & -x_1\\ 0 & 1 & 0 & -y_1\\ 0 & 0 & 1 & -z_1\\ 0 & 0 & 0 & 1\end{bmatrix}. \quad (3)$$

When the check point $b_1(x_1, y_1, z_1)$ is feeding along the X direction. Due to the existence of Z Axis straightness error $\delta_{x1}(z)$, $\delta_{y1}(z)$ and migration error $\delta_{z1}(z)$. Thus, the transformation from the coordinate system O_{B2} to O_{B1} can be solved by the matrix formula (4):

$$T_{B_1B_2}=\begin{bmatrix}1 & -\varepsilon_z(z) & \varepsilon_y(z) & \delta_{x1}(z)\\ \varepsilon_z(z) & 1 & -\varepsilon_x(z) & \delta_{y1}(z)\\ -\varepsilon_y(z) & \varepsilon_x(z) & 1 & z+\delta_{z1}(z)\\ 0 & 0 & 0 & 1\end{bmatrix}. \quad (4)$$

To perform matrix operations according to matrix expressions (1), (2), (3), (4):

$$T_{RB}=T_{RB_1}\cdot T_{B_1B_2}\cdot T_{B_2B}=\begin{bmatrix}1 & -\varepsilon_z(z) & \varepsilon_y(z) & \Gamma_{x1}(z)\\ \varepsilon_z(z) & 1 & -\varepsilon_x(z) & \Gamma_{y1}(z)\\ -\varepsilon_y(z) & \varepsilon_x(z) & 1 & z+\delta_{z1}(z)\\ 0 & 0 & 0 & 1\end{bmatrix}=$$

$$=\begin{bmatrix}1 & 0 & 0 & x_1\\ 0 & 1 & 0 & y_1\\ 0 & 0 & 1 & z_1\\ 0 & 0 & 0 & 1\end{bmatrix}\cdot\begin{bmatrix}1 & -\varepsilon_z(z) & \varepsilon_y(z) & \delta_{x1}(z)\\ \varepsilon_z(z) & 1 & -\varepsilon_x(z) & \delta_{y1}(z)\\ -\varepsilon_y(z) & \varepsilon_x(z) & 1 & z+\delta_{z1}(z)\\ 0 & 0 & 0 & 1\end{bmatrix}\cdot\begin{bmatrix}1 & 0 & 0 & -x_1\\ 0 & 1 & 0 & -y_1\\ 0 & 0 & 1 & -z_1\\ 0 & 0 & 0 & 1\end{bmatrix}. \quad (5)$$

Expand the results of the matrix operation (5). Make the matrix equality equal, equations can be constructed (6):

$$\begin{cases}\delta_{z1}(z)=\delta_z(z)-\varepsilon_y(z)\cdot x_1+\varepsilon_x(z)\cdot y_1\\ \Gamma_{x1}(z)=\delta_x(z)-\varepsilon_z(z)\cdot y_1+\varepsilon_y(z)\cdot z_1\\ \Gamma_{y1}(z)=\delta_y(z)-\varepsilon_x(z)\cdot z_1+\varepsilon_z(z)\cdot x_1\end{cases}. \quad (6)$$

Suppose, if three detection lines 1, 2 and 3 are set in the linear feed Axis Z-axis O_B, the detection points $A_1(x_1,y_1,z_1)$, $A_2(x_2,y_2,z_2)$, $A_3(x_3,y_3,z_3)$ are selected, the detection errors are: $\delta_{z1}(z)$, $\delta_{z2}(z)$, $\delta_{z3}(z)$, the A_1 linearity errors in X and Y directions, $\Gamma_{x1}(z)$, $\Gamma_{y1}(z)$, were detected simultaneously, the deviation error of A_2 and the linearity error of Y direction $\Gamma_{x2}(z)$ were detected. A system of Eqs. (7) can be established.

$$\begin{cases}\delta_{z1}(z)=\delta_z(z)-\varepsilon_y(z)\cdot x_1+\varepsilon_x(z)\cdot y_1\\ \Gamma_{x1}(z)=\delta_x(z)-\varepsilon_z(z)\cdot y_1+\varepsilon_y(z)\cdot z_1\\ \Gamma_{y1}(z)=\delta_y(z)-\varepsilon_x(z)\cdot z_1+\varepsilon_z(z)\cdot x_1\\ \delta_{z2}(z)=\delta_z(z)-\varepsilon_y(z)\cdot x_2+\varepsilon_x(z)\cdot y_2\\ \Gamma_{x2}(z)=\delta_x(z)-\varepsilon_z(z)\cdot y_2+\varepsilon_y(z)\cdot z_2\\ \delta_{z3}(z)=\delta_z(z)-\varepsilon_y(z)\cdot x_3+\varepsilon_x(z)\cdot y_3\end{cases}. \quad (7)$$

The system of Eqs. (7) is expressed in a matrix:0

$$\begin{bmatrix}\delta_{z1}(z)\\ \Gamma_{x1}(z)\\ \Gamma_{y1}(z)\\ \delta_{z2}(z)\\ \Gamma_{x2}(z)\\ \delta_{z3}(z)\end{bmatrix}=\begin{bmatrix}1 & 0 & 0 & 0 & y_1 & -x_1\\ 0 & 1 & 0 & -y_1 & 0 & z_1\\ 0 & 0 & 1 & x_1 & z_1 & 0\\ 1 & 0 & 0 & 0 & y_2 & -x_2\\ 0 & 1 & 0 & -y_2 & 0 & z_2\\ 1 & 0 & 0 & 0 & x_3 & -x_3\end{bmatrix}\begin{bmatrix}\delta_z(z)\\ \delta_x(z)\\ \delta_y(z)\\ \varepsilon_z(z)\\ \varepsilon_x(z)\\ \varepsilon_y(z)\end{bmatrix}. \quad (8)$$

Order:

$$\xi_z(z)=\left[\delta_{z1}(z)\cdot\Gamma_{x1}(z)\cdot\Gamma_{y1}(z)\cdot\delta_{z2}(z)\cdot\Gamma_{x2}(z)\cdot\delta_{z3}(z)\right]^T, \quad (9)$$

$$\lambda_z = \begin{bmatrix} 1 & 0 & 0 & 0 & y_1 & -x_1 \\ 0 & 1 & 0 & -y_1 & 0 & z_1 \\ 0 & 0 & 1 & x_1 & z_1 & 0 \\ 1 & 0 & 0 & 0 & y_2 & -x_2 \\ 0 & 1 & 0 & -y_2 & 0 & z_2 \\ 1 & 0 & 0 & 0 & x_3 & -x_3 \end{bmatrix}, \quad (10)$$

$$\varDelta_z(z) = \\ = \left[\delta_z(z)\cdot\delta_x(z)\cdot\delta_y(z)\cdot\varepsilon_z(z)\cdot\varepsilon_x(z)\cdot\varepsilon_y(z)\right]^T. \quad (11)$$

Then the matrix formula (8) can be simplified to a nonhomogeneous linear Eq. (12):

$$\xi_z(z) = \lambda_z \cdot \Delta_z(z)\ \xi_z(z) = \lambda_z \cdot \varDelta_z(z). \quad (12)$$

For non-homogeneous Eq. (12). When the matrix λ_z has full rank, λ_z is invertible, $\delta_z(z)$ has unique solution, the size of $\delta_z(z)$, $\delta_x(z)$, $\delta_y(z)$, $\varepsilon_z(z)$, $\varepsilon_x(z)$, $\varepsilon_y(z)$ can be identified.

If the position relation of detection point A_1, A_2, A_3 exists as follows: $z_2 = z_3$, $z_1 = x_1 = y_2 = x_3 = y_3 = 0$. The Eq. (7) can be simplified, Into Eqs. (13):

$$\begin{cases} \varDelta_{z1}(z) = \delta_z(z) + \varepsilon_x(z)\cdot y_1 \\ \varGamma_{x1}(z) = \delta_x(z) - \varepsilon_z(z)\cdot y_1 \\ \varGamma_{y1}(z) = \delta_y(z) \\ \varDelta_{z2}(z) = \delta_z(z) - \varepsilon_y(z)\cdot x_2 \\ \varGamma_{x2}(z) = \delta_x(z) + \varepsilon_y(z)\cdot z_2 \\ \varDelta_{z3}(z) = \delta_z(z) \end{cases}. \quad (13)$$

The system of Eqs. (13) is expressed as a matrix:

$$\begin{bmatrix} \varDelta_{z1}(z) \\ \varGamma_{x1}(z) \\ \varGamma_{y1}(z) \\ \varDelta_{z2}(z) \\ \varGamma_{x2}(z) \\ \varDelta_{z3}(z) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & z_1 & 0 \\ 0 & 1 & 0 & -y_1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & -x_2 \\ 0 & 1 & 0 & 0 & 0 & z_2 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_z(z) \\ \delta_x(z) \\ \delta_y(z) \\ \varepsilon_z(z) \\ \varepsilon_x(z) \\ \varepsilon_y(z) \end{bmatrix}. \quad (14)$$

Solving matrix formula (14) the rank of the matrix to the right of the equal sign is full rank 6.

Set check points A_1, A_2, A_3 at current position, and $y_1 \neq 0$, $x_2 \neq 0$, The analytic solutions of $\delta_z(z)$, $\delta_x(z)$, $\delta_y(z)$, $\varepsilon_z(z)$, $\varepsilon_x(z)$, $\varepsilon_y(z)$ are unique. Therefore, the solution of the system of Eqs. (12) is obtained as follows:

$$\begin{cases} \delta_z(z) = \delta_{z3}(z) \\ \delta_x(z) = \varGamma_{x2}(z) - x\dfrac{z_2}{y_2}\left[\delta_{z3}(z) - \delta_{z2}(z)\right] \\ \delta_y(z) = \varGamma_{y1}(z) \\ \varepsilon_z(z) = \dfrac{\varGamma_{x2}(z) - \varGamma_{x1}(z)}{y_1} - \\ \quad - \dfrac{z_2}{y_1\cdot x_2}\left[\delta_{z3}(z) - \delta_{z2}(z)\right] \\ \varepsilon_x(z) = \dfrac{\delta_{z1}(z) - \delta_{z3}(z)}{z_1} \\ \varepsilon_y(z) = \dfrac{\delta_{z3}(z) - \delta_{z2}(z)}{x_2} \end{cases}. \quad (15)$$

4. Linear Feed Axis Error Detection

Using the double-frequency Laser Interferometer Linear Detection Module to detect the positioning error of linear feed axis [16-18], taking the vertical linear feed axis Z axis of gantry vertical machining center as the research object, set 10 mm detection compensation. The measurements were repeated three times. Each Detection Point Reserve 5 s time for data acquisition. The aggregate test data is shown in Table 2.

Analysis: The Linear feed axis *Z* axis from absolute position -40 mm to 100 mm. The positioning error keeps increasing all the time. Only the step length (30 mm, 40 mm) decreased slightly by 0.336 µm, the Maximum increment at (40 mm, 50 mm), the maximum increment was 6.342 µm.

Table 2

Test data

Num	Node location, mm	Positioning error, µm	Incremental value, µm
1	-40	-13.946	0
2	-30	-11.976	1.97
3	-20	-8.127	3.849
4	-10	-4.013	4.114
5	0	0	4.013
6	10	5.423	5.423
7	20	8.512	3.089
8	30	12.331	3.819
9	40	11.995	-0.336
10	50	18.337	6.342
11	60	20.329	1.992
12	70	24.631	4.302
13	80	27.923	3.292
14	90	30.317	2.394
15	100	34.189	3.872

5. Compensation Modeling

Taking the vertical linear feed axis *Z* axis of gantry vertical machining center as an example, the error data storage and modeling compensation are carried out.

The node positioning error is detected by the equal step length λ, and the data is saved, as shown in Table 3.

The key to realize the compensation is to establish the correct compensation digital module. The model input is the absolute position P_a and the driving instruction L, and the model output is the relative error ε'. The nodal approximation of the error data in Table 3 is carried out, and the linear equations between the nodes are established, and the formula (16) is obtained.

$$y = \frac{\varepsilon_{i+1} - \varepsilon_i}{P_{i+1} - P_i}\cdot x + \frac{\varepsilon_i \cdot P_{i+1} - \varepsilon_{i+1}\cdot P_i}{P_{i+1} - P_i}. \quad (16)$$

Hypothetically, P_a and P_b are the initial and target positions of the Z axis of the linear feed axis, respectively, $P_a \in (P_i,\ P_{i+1})$, $P_b \in (P_j,\ P_{j+1})$, $0 \le i,\ j \le n$, the expressions (17) and (18) can be obtained analytically by using the expression (16).

$$\varepsilon_a = \frac{\varepsilon_{i+1} \cdot \left(P_a - P\right)_i - \varepsilon_i \cdot \left(P_{i+1} - P_a\right)}{P_{i+1} - P_i}, \tag{17}$$

$$\varepsilon_b = \frac{\varepsilon_{j+1} \cdot \left(P_b - P_j\right) - \varepsilon_j \cdot \left(P_{j+1} - P_b\right)}{P_{j+1} - P_j}. \tag{18}$$

The error between the initial position P_a and the target position P_b is shown as an Eq. (19).

$$\varepsilon' = \varepsilon_b - \varepsilon_a = \frac{\varepsilon_{j+1} \cdot \left(P_b - P_j\right) - \varepsilon_j \cdot \left(P_{j+1} - P_b\right)}{P_{j+1} - P_j} - \frac{\varepsilon_{i+1} \cdot \left(P_a - P_i\right) - \varepsilon_i \cdot \left(P_{i+1} - P_a\right)}{P_{i+1} - P_i}. \tag{19}$$

The corresponding error between the initial position P_a and the target position P_b obtained by the expression (19) is compensated, and the driving instruction L' after compensation is obtained, as shown by the expression (20).

$$L' = L + \varepsilon'. \tag{20}$$

Table 3

Error storage data

Num	Node location	Node step size	Node error
1	P_n	$n\lambda$	ε_n
2	⋮	⋮	⋮
3	P_1	λ	ε_1
4	P_0	0	0
5	P_{-1}	$-\lambda$	ε_{-1}
6	⋮	⋮	⋮
7	P_{-n}	$-n\lambda$	ε_{-n}

6. Compensation Implementation

The model running parameter is set to equal step length of 10 mm, and the error of vertical linear feed axis Z axis of gantry vertical machining center is detected, and the compensation model is established. The 13 mm step size is selected as the compensation evaluation node, as shown in Table 4.

Analysis of residual data in Table 4:

1. Longmen vertical machining center error value from absolute position -40 mm to 80 mm error has obvious accumulation.

Table 4

Node error comparison

Num	Check Point, mm	Compensation before, µm	After compensation, µm
1	-40	-14.330	0.963
2	-27	-11.723	-1.678
3	-14	-5.199	-0.849
4	-11	-4.651	0.347
5	2	2.126	-0.075
6	15	7.267	1.642
7	28	10.965	0.896
8	41	12.318	-1.637
9	54	20.067	-1.102
10	67	20.560	1.276
11	80	28.149	-2.007

2. After compensation, the error of the detection point decreases significantly and fluctuates near the zero line.

3. After compensation, the variance has reached 1.2501, which meets the precision machining requirement.

4. If the detection point step distance is set smaller, the modeling is more accurate and the error compensation effect will be higher.

7. Conclusions

1. The main reason affecting the machining accuracy is the lack of positioning accuracy of the axis of motion of the NC machine tool. The specific process of position error of NC machine tool is represented by mathematical method, which lays a foundation for the compensation of position error of NC machine tool.

2. Taking gantry vertical machining center as the research object, the space positioning error of its core axis Z-axis is synthetically analyzed, and the space positioning error of its linear axis Z-axis is analyzed by matrix operation, in this paper, the characteristics of the parameter solution of location error are discussed, and the analytical model of location error is established.

3. The Z-axis of gantry vertical machining center is measured on-line with the help of dual-frequency laser interferometer, the characteristic relationship of the data of positioning error is analyzed, and the concrete method of positioning error compensation is put forward, the mathematical model of error compensation is established.

4. The experiments on the Z-axis positioning error compensation of gantry vertical machining center are carried out. The results show that the analytical method and compensation for the positioning error of linear feed axis based on matrix operation can meet the actual machining requirements. After compensation, the residual error of positioning accuracy has been reduced to 1.2501, and the numerical control accuracy has been effectively improved.

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B. Yu, X.-P. Chang, Y. Zheng, L. Zhang

THE ANALYSIS AND COMPENSATION EXPERIMENT OF LINEAR FEED AXIS POSITIONING ERROR BASED ON MATRIX OPERATION

S u m m a r y

The positioning accuracy of the linear feed axis is a key factor affecting the machining accuracy of CNC machine tools. The generation process of the positioning error of the linear feed axis is expounded. The Z axis of the vertical linear feed axis of the machining center is the research object, the positioning error analytical matrix is established, and the positioning error calculation of the Z axis of the vertical linear feed axis is completed based on the principle of solving the inhomogeneous linear equation. The positioning error detection of the vertical linear feed axis Z axis of the CNC machining center is carried out. Based on the characteristics of the error detection data, an error compensation model is constructed. , the variance of the positioning error detection point after compensation is reduced to 1.562, which meets the needs of precision machining.

Keywords: gantry vertical machining center, positioning error, matrix operation, linear feed axis, laser interferometer, error compensation.

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