Analysis of the Identification Principle of Yaw Error of Five-axis Machine Tool Rotary Table in the Virtue Error Sensitive Direction Based on the Machining Test

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Abstract. The identification principle of the yaw error of five-axis machine tool rotary table in the virtue error sensitive direction by DBB is analysed. According to the measurement principle of DBB, the virtue error sensitive direction was adopted, and a machining test to identify the yaw error of the rotating table is designed and discussed. The function relationship of the yaw error and the machining error in the corresponding sensitive direction was deduced, and the analysis shows that the yaw error can be separated from the machining test.

1. Introduction

Error identification method has been used to identify the kinematic errors in single part of five-axis machine tool. Sensor and information technology has been applied in the area of error identification [1-3]. The existing identification methods of the kinematic error of five-axis machine tool almost adopted the special instruments, such as telescoping double ball bar [4-8], R-test [9,10], and so on. They have the disadvantages of computational complexity, time-consuming of operation, high cost, low universality, and so on.

Double ball bar (DBB) is a one-dimensional displacement measurement sensor, as can be seen from Figure 1. The error measurement method by DBB is shown in Figure 2. There is a high-precision steel ball in each end of DBB. One end of the ball is fixed; the other end of the ball is connected to a high-precision displacement sensor. One end of the ball is adsorbed on the spindle, while the other end of the ball is adsorbed on the table. When the rotary table of the machine tool did the circular interpolation movement relative to the spindle, the displacement change between two balls in the bar direction is transported to the computer. The characteristic of DBB measurement is that the ball bar always measuring the error movement in a certain direction, which can be called the sensitive direction of the ball bar, as can be seen in Figure 3. By designing some measurement patterns which are sensitive to the rotary errors of the machine tool table, DBB was used in the measurement of the tilt errors of five-axis machine tool table A-axis [5].

According to the measuring principle of DBB, this paper proposed the concept of virtue sensitive direction vector, and adopted the sensitive direction vector to design a machining test to identify the yaw error of the rotary table.
**Figure.1** Renishaw QC20 ballbar

**Figure.2** Error measurement method by double ball bar

**Figure.3** Error sensitive direction of DBB

**Figure.4** The tilt model of the rotary table
2. Analysis of the error sensitivity of the machining test

The tilt model of the rotary table is shown in Figure 4. The kinematic errors of C-axis can be separated from similar machining tests when A-axis remains stationary [10]. Therefore, in the kinematic chain, only the translation from the coordinate {C} to {A} should be considered. In Figure 4, the translation vector is coarsely represented. The yaw error is one of the rotary errors in the rotating table.

(1) Location of the workpiece

The initial position of the workpiece is in +Y. The distance of the workpiece from the original point in the direction of +Y is L. Suppose that the value of Z-axis of the machining plane is 0, and the workpiece position can be described as[11]

$$C_W^N = \begin{bmatrix} 0 \\ L \\ 0 \end{bmatrix}$$  \hspace{1cm} (1)

To increase the error sensitivity, the workpiece should be fit on the table as far as possible from the centre point of the table. So the value of L should be as big as possible.

(2) Machining test design and analysis

When $\alpha = 90$ degree, $\gamma = 0$ degree, cut the workpiece on the outer side along +X direction. When $\alpha = 90$ degree, $\gamma = 180$ degree, cut the workpiece on the outer side along +X direction, too. The machining difference between these two positions has the biggest error sensitivity to the kinematic errors in the virtue sensitivity direction.

According to the principle robotic kinematic, the position vector of the workpiece in the coordinate system {F} can be obtained:

$$F_W = F_R^C \left[ A_\delta^C(\alpha) + A_\delta^C(\gamma) + C_W^N \right]$$  \hspace{1cm} (2)

Where

$$F_R = \begin{bmatrix} C\alpha & -S\alpha & 0 \\ S\alpha & C\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$  \hspace{1cm} (3)

$$A_\delta^C(\alpha) = \begin{bmatrix} A_\delta^C_x(\alpha) \\ A_\delta^C_y(\alpha) \\ A_\delta^C_z(\alpha) \end{bmatrix}$$  \hspace{1cm} (4)

$$A_\delta^C(\alpha) = \begin{bmatrix} 1 & -A_{\xi z}^C(\alpha) & A_{\xi y}^C(\alpha) \\ -A_{\xi z}^C(\alpha) & 1 & -A_{\xi x}^C(\alpha) \\ -A_{\xi y}^C(\alpha) & A_{\xi x}^C(\alpha) & 1 \end{bmatrix}$$  \hspace{1cm} (5)

$$A_R^C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\gamma & -S\gamma \\ 0 & S\gamma & C\gamma \end{bmatrix}$$  \hspace{1cm} (6)
\[
\begin{bmatrix}
1 & 0 & c_\xi_1 (\gamma) \\
0 & 1 & -c_\xi_1 (\gamma) \\
-c_\xi_1 (\gamma) & c_\xi_1 (\gamma) & 1
\end{bmatrix}
\]
\( (7) \)

\[
\begin{bmatrix}
c_\delta_1 (\gamma) \\
c_\delta_2 (\gamma) \\
0
\end{bmatrix}
\]
\( (8) \)

Through matrix calculation, we can obtain:

\[
F \tilde{W} = \left[ \begin{array}{c}
A_\delta_1 (\alpha) + \cos \gamma * c_\delta_1 (\gamma) - \sin (\gamma) * [c_\delta_1 (\gamma) + L] - \\
A_\xi_1 (\alpha) * \{ \sin \gamma * c_\xi_1 (\gamma) + \cos \gamma * [c_\delta_1 (\gamma) + L] \} + A_\xi_1 (\alpha) * c_\xi_1 (\gamma) * L \\
\cos \alpha * \left( \sin \gamma * c_\delta_1 (\gamma) + \cos \gamma \left( c_\delta_1 (\gamma) + L \right) \right) - A_\xi_1 (\alpha) * c_\xi_1 (\gamma) * L - \\
\sin \alpha * \left( \sin \gamma * c_\delta_1 (\gamma) + \cos \gamma \left( c_\delta_1 (\gamma) + L \right) \right) + c_\xi_1 (\gamma) * L \\
\sin \alpha * \left( c_\delta_1 (\gamma) + \sin \gamma \left( c_\delta_1 (\gamma) + L \right) \right) - A_\xi_1 (\alpha) * c_\xi_1 (\gamma) * L + \\
\cos \alpha * \left( \sin \gamma * c_\delta_1 (\gamma) + \cos \gamma \left( c_\delta_1 (\gamma) + L \right) \right) + c_\xi_1 (\gamma) * L \\
\sin \alpha \end{array} \right]
\]
\( (9) \)

Suppose that \( \tilde{r} = [0 \quad -1 \quad 0] \) is the virtue sensitive direction expressed as a unit vector according to the measurement principle of DBB. Adopt the error sensitive vector in formula (9), we can obtain:
Suppose that:

When $\alpha = 90$ degree, $\gamma = 180$ degree, the center position of the workpiece is $Y_2$.

When $\alpha = 90$ degree, $\gamma = 0$ degree, the center position of the workpiece is $Y_1$.

$h = Y_2 - Y_1$, we can obtain:

$$h = -2 \cdot \xi_y^A (\delta_y + L) + 2 \cdot \xi_x^A \cdot C\delta_x$$

(11)

Where, the value of $\xi_y^A \cdot C\delta_x$ is tiny and can be ignored. The value of $C\delta_y$ can be identified by our previous work [12]. So formula (11) only include one kinematic error $\xi_y^A(\alpha)$ of $A$-axis.

The physical meaning of the machining test is analyzed as follows:

Formula (11) is the distance between the centre point of the workpiece when the rotary angle is 0 degree and the centre point of the workpiece when the rotary angle is 180 degree. Therefore, in theory, $\xi_y^A(\alpha)$ can be identified from this machining test. There may be several possible machining tests which are sensitive to one kinematic error in theory. To improve the efficiency and precision of the error identification, further analysis and experiment should be carried out to compare and choose a better machining test pattern.

3. Conclusions

To identify the kinematic error of the yaw error of five-axis machine tool rotary table, a machining test pattern was designed to identify the yaw error of the rotating table in the virtue error sensitive direction. The virtue error sensitive direction was adopted to separate the error, and the separation principle of the yaw error is analysed. The function relationship of the yaw error and the machining error in the corresponding sensitive direction was deduced, and the yaw error can be separated from the machining test in theory. The physical meaning of the identification result was analyzed. It provides a theoretical evidence to design the machining tests for the rotary error identification for five-axis machine tool.
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