The error's measurement and identification of five-axes CNC MACHINE based on touch-trigger probe

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Abstract. This paper is about the static error measuring strategy of five-axis CNC machine tool basing on the touch-trigger probe, which is the mainly measuring tool to detect the static error of the five-axis machine tool of RTTTR and RRTTT topological structure. According to kinematic chain of the five-axis NC machine, the relationship between NC machine coordinate system and workpiece coordinate system is established and the relationship between NC machine coordinate system and tool coordinate system. Now the measurement and identification of three axis NC machine tool has been studied a lot, which means that the error of straight line can be measure and compensate very well. So in this paper we assume that the error of the translation axis has been compensated and the motion error of the rotation axis is small enough relative to the static error. Then based on the relationship between static error and the actual coordinate values in the model established before, the static error of each rotation axis can be solved.

Introduction

In 1986, the general error model which was suit for any structure multi-axis machine was built by Ehmann et al[1], which was based on multi-body dynamics and the conversion of homogeneous coordinate matrix. In 1989, Elshchnawy and Ham[2] derived the geometric error model of three-axis machine tool by the rigid body kinematic model. The next year, the machine error model based on kinematic was made by Kurtoglu et al[3] applied to the milling machine, which included 18 kinds of motion error in addition to vertical error. In 2000, Okafor[4] built up general error model to vertical milling machine containing geometric errors and thermal errors using the method of the conversion of homogeneous coordinate matrix, and the verification of compensation had been implemented after the measurement of 21 geometric error components. In this year, Ahn[5] designed a model based on backlash and classified it in geometric error. In 1998, Jianguo Yang[6] from Shanghai Jiao Tong University obtained geometric and thermal error in turning processing centers using the conversion of homogeneous coordinate matrix. In 2005, Xiaoli Lee[7] from Huazhong University of Science and Technology proposed a method to general geometric error model in five-axis processing centers using multi-body kinematic. With the measuring tool of ball-bar, Tsutsumi and Saito[8] detected the Static error of five-axis CNC machine tool rotary axes, Khan and Chen[9] measured other 5 errors in addition to rotary axis positioning error by the ball-bar. With the laser Interferometer and the new twelve-line method based on laser interferometer for three linear axes error identification, Youwu Liu and Qing Zhang[10,11] measured all of 21 errors of three-axis CNC machine tools by laser interferometer. Jian Xiao and

Baoan Guo[12] conducted the error measurement and compensation on the rotation axis of C-axis by grinding products from company with the measurement of laser tracker.

Location errors modeling

This paper mainly take five axis CNC machine tools with the topological structure RTTTR as the research platform, which simplified model as shown below. According to the analysis of the structure of five axis machine tools, we can find the rotation axis B is fixed on Z axis, and the turntable-side rotation axis C is mounted on a three-axis CNC machine tools workbench. Starting from the machine tool coordinate system established by machine tool body, after a series of motion axes (a series of coordinate transformation), the workpiece and cutting tool end can be reached. According to the motion transmission of NC machine tool, the relationship can be divided into two parts, the workpiece drive chain and the tool drive chain. The workpiece drive chain is as follows: machine tool R → X-axis → Y-axis → rotation axis C → workpiece W, while the tool drive chain :machine tool R → Z-axis → B-axis → tool T. Then we can build up the two relationships according to the kinematics transformation matrix:

$$T_{RW} = T_{RX} \cdot T_{XY} \cdot T_{YC}^{e} \cdot T_{CW} = T_{RX} \cdot T_{XY} \cdot T_{YC} \cdot E_{YC} \cdot T_{CW} \quad (2\text{-}1)$$

$$T_{RT} = T_{RZ} \cdot T_{ZB}^{e} \cdot T_{BT} = T_{RZ} \cdot T_{ZB} \cdot E_{ZB} \cdot T_{BT} \quad (2\text{-}2)$$

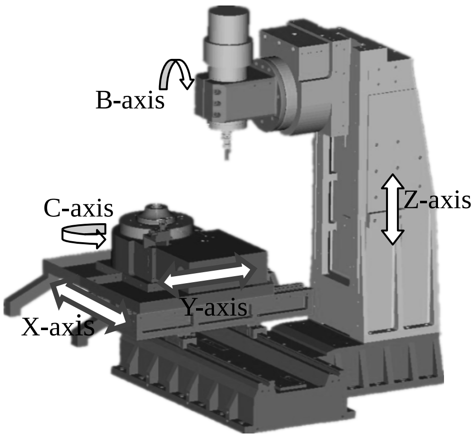

Fig.1 Pendulum head single turntable five axis CNC machine tool

In this paper, we mainly use the workpiece drive chain.

If there is no position error d_{yBZ}, the y coordinates of the measuring probe touching points are equal, and the direction is opposite, that is a1=-a2. If the position error d_{yBZ} exists, and the other position error and angle error is 0, then $a1 = y_{1b}^{2a} - d_{yBZ}$, $a2 = y_{1b}^{2a} - d_{yBZ}$, so because the existence of position error d_{yBZ}, and according to the relationship above, we can get the formulation $-(y_{1b}^{2a} - d_{yBZ}) = y_{2b}^{2a} - d_{yBZ}$. Therefore, we have $y_{1b}^{2a} + y_{2b}^{2a} = 2d_{yBZ}$.

If only the error a_{BZ} exists, because a_{BZ} is a static error, what's more, the static error a_{BZ} is very small, and the approximation of a_{BZ} is equal to 0, then we can be obtained the formulation $\sin a_{BZ} \approx \tan a_{BZ} \approx a_{BZ}$, and according to the geometric relations in the graph we can get $\Delta y = z_b \tan a_{BZ}$. Therefore, we have $\Delta y \approx z_b \tan a_{BZ} \approx z_b a_{BZ}$. According to Fig.2, we can also know $a1 = -a2$, and get the following geometric relation $a1 = y_{1b}^{2a} - z_b a_{BZ}$, and the relation $a2 = y_{2b}^{2a} - z_b a_{BZ}$, then we have $-(y_{1b}^{2a} - z_b a_{BZ}) = y_{2b}^{2a} - z_b a_{BZ}$, and finishing the two formulas, we can get $y_{1b}^{2a}+y_{2b}^{2a}=2z_b a_{BZ}$.

In summary, if position error d_{yBZ} and angle error a_{BZ} exist at the same time, we can get the equation $y_{1b}^{2a}+y_{2b}^{2a}=2d_{yBZ}+2z_b a_{BZ}$.

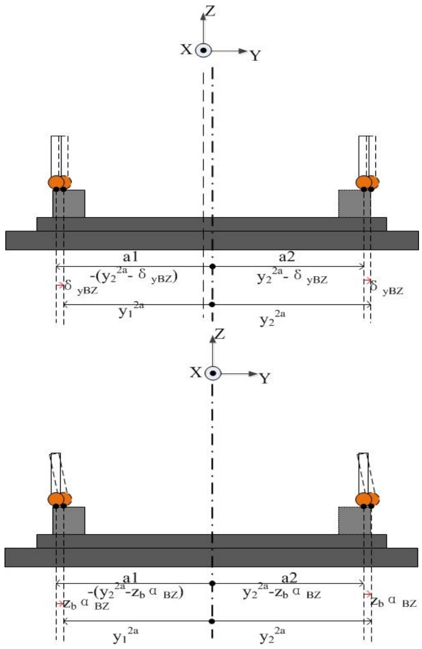

Fig.2 The influence of position error and angle error of pendulum head

According to the analysis of the position error and the angle error on the head side, if position error d_{yCY} and angle error a_{CY} exist at the same time, we can get the equation $y_1^{2a}+y_2^{2a}=2d_{yCY}-2z^{2a}a_{CY}$.

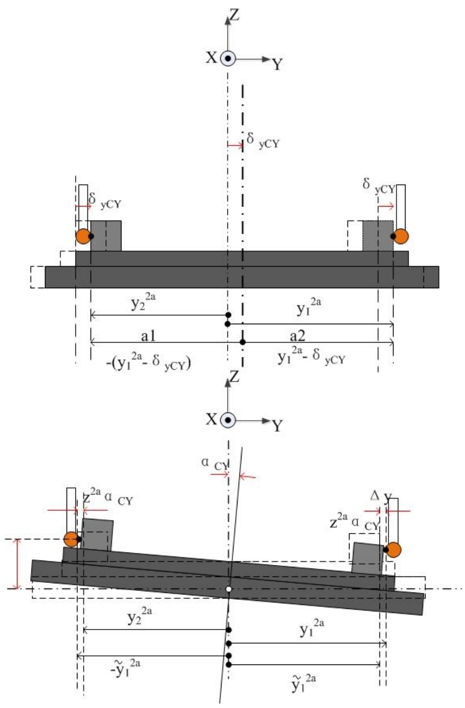

Fig.3 The position error and angle error of turntable

The measurement and identification of static errors

The analysis of static errors

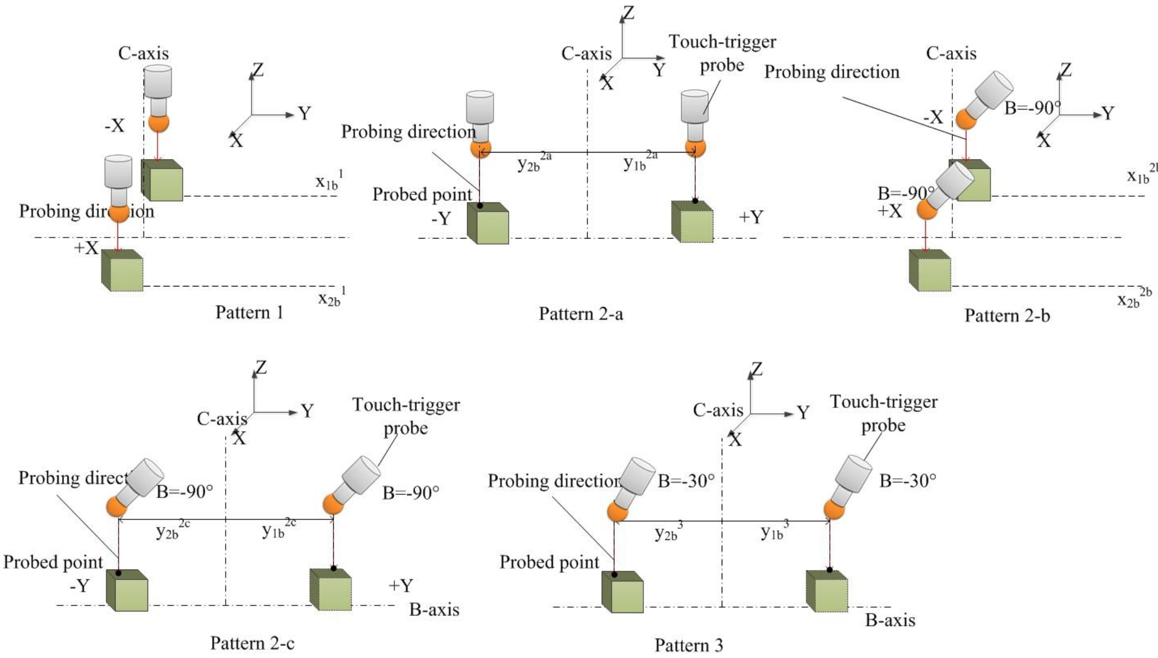

Fig.4 The measurement of static errors of the head

Fig.4 describes the probing patterns in the process of measuring static errors of rotation head, and we carry out the measurement of static error by measuring the geometric error of the measuring blocks. We ignore or compensate the errors of the linear axis in the process of measurement, pendulum head side and the turntable side all have static errors at the same time, so the errors will affect each other in the process of measurement, and then we first measure the static errors of pendulum head side. We can choose four same measuring blocks, putting them on turntable directly, so that turntable's static errors can't have effect to pendulum head's errors. In the measurement process, we set up the relationship between the coordinate values and each static error. Here we are mainly take 2-a as an example to explain how each error and coordinates are linked in detail. Four identical rectangular geometrical standard measuring blocks are placed in the -Y direction, +Y direction, -X direction and +X direction and direction and the -Y direction respectively. When placing these blocks, ensure the mutual symmetry of the -Y direction and the +Y direction and the mutual symmetry of the -X direction and the +X direction. Then, use a standard measurement procedure to measure the target points of Y coordinate from the –Y direction. Express the coordinate values in the machine tool coordinate system, we can know that $y_{2b}^{2a} < 0$ in this place. Then we measure another block in the +Y direction using the same measurement method, we should measure the symmetric target points from +Y direction, we also can know that $y_{1b}^{2a} > 0$ in this place.

Based on the above analysis, we know the influence of the position error and the angle error on the coordinate values, then we can get the equations of the probing patterns:

Pattern 1： $$x_{1b}^{1} + x_{2b}^{1} = 2d_{xBZ} - 2z_b b_{BZ} \quad (3\text{-}1)$$

Pattern 2-a： $$y_{1b}^{2a} + y_{2b}^{2a} = 2d_{yBZ} + 2z_b a_{BZ} \quad (3\text{-}2)$$

Pattern 2-b: $x_{1b}^{2b} + x_{2b}^{2b} = 2d_{xBZ}$ (3-3)

Pattern 2-c: $y_{1b}^{2c} + y_{2b}^{2c} = 2d_{yBZ} + 2z_b g_{BZ}$ (3-4)

Pattern 3: $y_{1b}^{3} + y_{2b}^{3} = 2d_{yBZ} + 2z_b a_{BZ} \cos 30^{\circ} - 2z_b g_{BZ} \sin(-30^{\circ})$ (3-5)

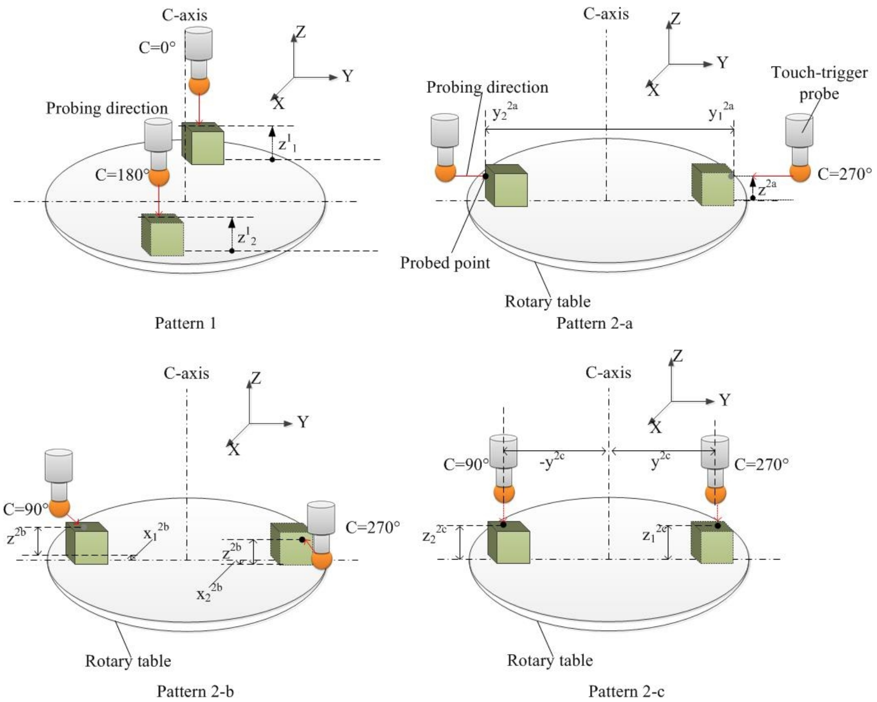

Fig.5 The measurement of turntable-side static errors:

Fig.5 describes the probing patterns in the process of measuring static errors of turntable, similar to the analysis of the head-side static errors， we can get the equations of the probing patterns:

Pattern 1: $z_1^1 - z_2^1 = 2x_1 b_{CY}$ (3-6)

Pattern 2-a: $y_1^{2a} + y_2^{2a} = 2d_{yCY} - 2z^{2a} a_{CY}$ (3-7)

Pattern 2-b: $x_1^{2b} + x_2^{2b} = 2d_{xCY} + 2z^{2b} b_{CY}$ (3-8)

Pattern 2-c: $z_1^{2c} - z_2^{2c} = 2y^{2c} a_{CY}$ (3-9)

Measurement procedure

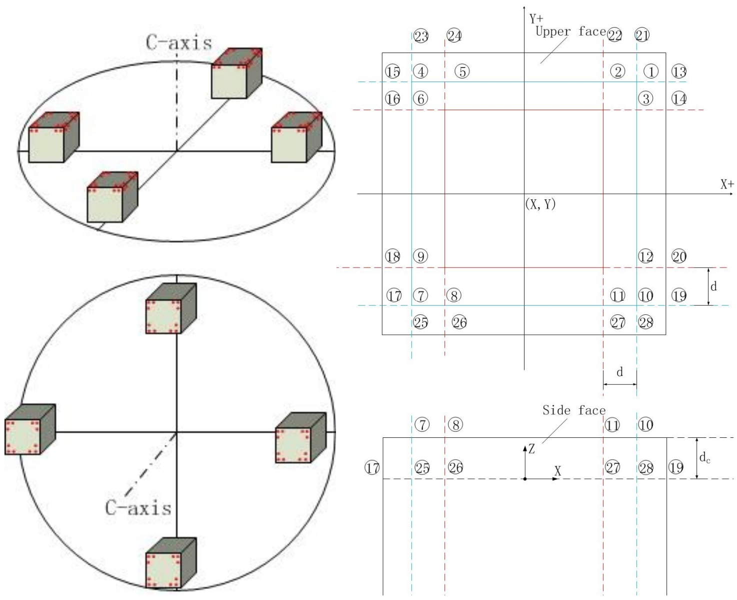

Fig.6 Probed points on the upper side and side face of measuring blocks

In the measurement, the measuring blocks are rectangular, and the size is 10mm*10mm*10mm. To reduce the influence of other factors, we probe multiple points and average them.

When measuring the static errors of the pendulum head side and the turntable side, we first measure the errors of the pendulum head-side B axis, then we put the measuring blocks directly on the linear axes rather than on the turntable. So that the influence of C axis' errors are removed. When we measure the static errors of the B axis, we compensate them. After compensating, we can measure and identify the static errors of C axis.

In the process of measuring head-side static errors, the four standard blocks are placed on the linear axes of the machine tool directly. The coordinates of the center points of the four standard blocks are (X,Y,Z)=(-30,0,-202.684),(30,0,-202.684),(0,-30,-202.684),(0,30, -202.684).

When measuring the coordinates of the pendulum head side, in the position of (X,Y,Z) = (-30,0,-202.684), 12 points on the upper face and 16 points on the side face of the coordinates need to be measured. When measuring the coordinates of the points, the probe must follow the normal direction. And on the positions of ((X,Y,Z) = (30,0,-202.684), (0,-30, -202.684) and (0,30,-202.684), we need to measure the same points.

When B=-30°,we need to measure 48 points in the same measurement sequence are measured in the workpiece coordinate system, as shown in Fig.6. Because the measuring time is short, the actual operation is only about 10 minutes. During the measurement, the standard blocks need to be measured repeatly many times.

After measuring the static error of the of the pendulum head, we compensate it. Then the static error of the turntable is measured and identified.

When measuring the coordinates of the turntable, we need to measure 112 points when B=0°,and 28 points are measured at C=0°,90°,180°,270°respectively. We also need to measure 42 points when B=-90°,and 14 points(six points on upper face and eight points on side face) are measured at C=90°,180°,270°respectively.

A brief introduction to the static error of the rotary axes of five axis CNC machine tool with double head

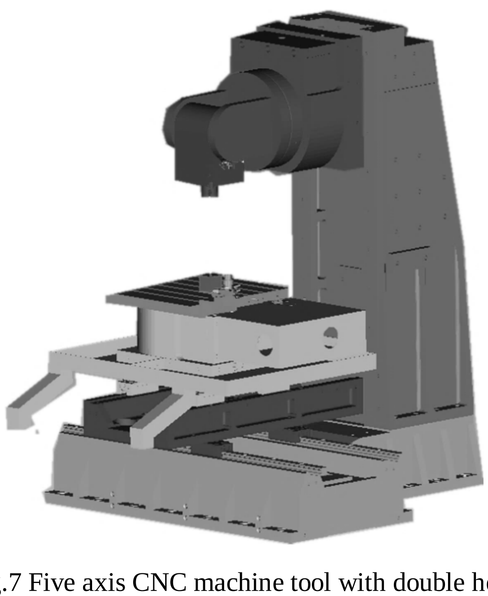

Fig.7 Five axis CNC machine tool with double head

Analyze the influence of the single position error and the single angle error on the coordinate values, we also can establish the relationships between the static errors and the coordinate values of the rotation axes.

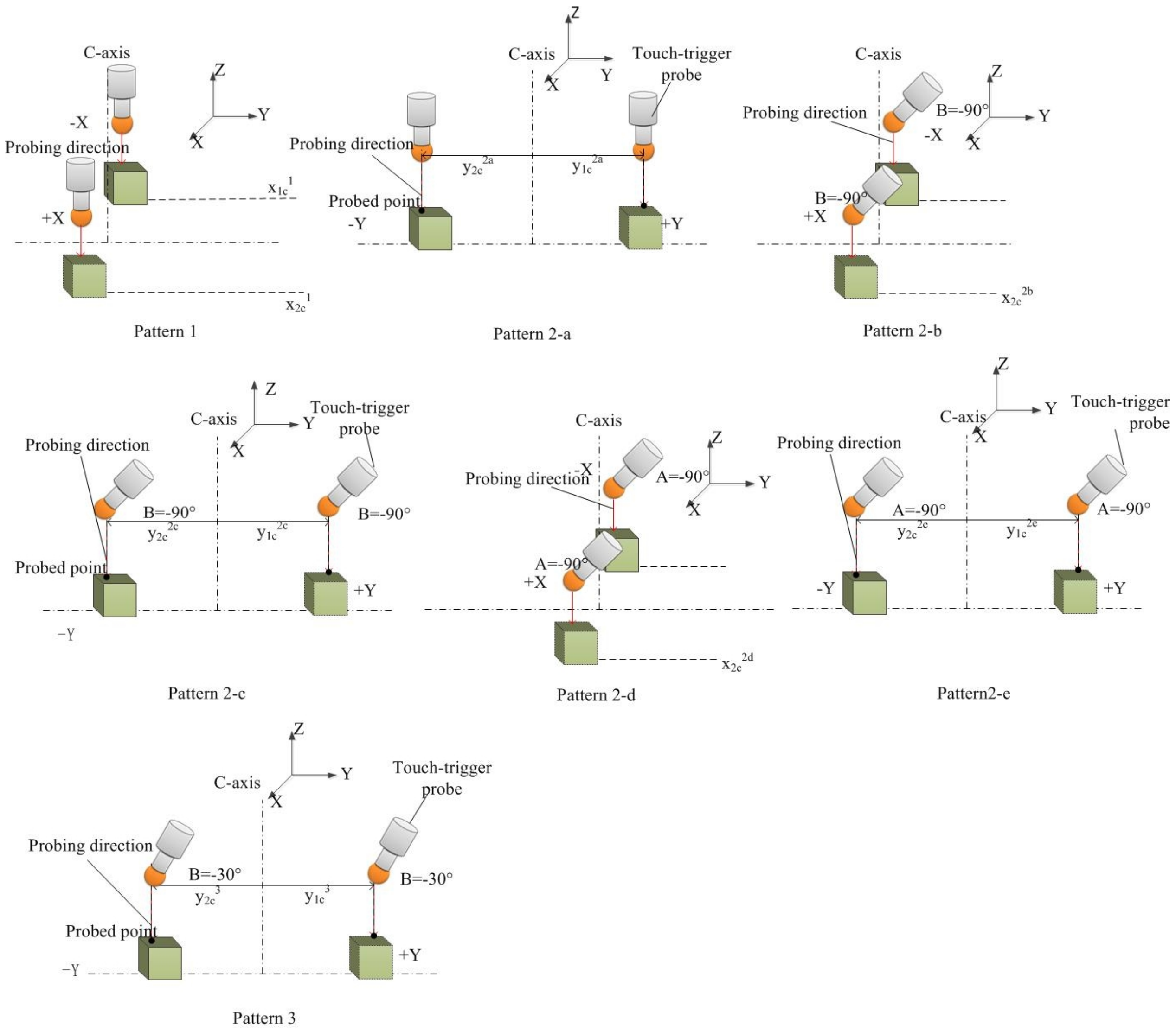

Fig.8 The measurement of static errors of five axis CNC machine tool with double head

According to the above analysis of static error measurement of the five axis CNC machine tool with double head，and the above measuring schematic diagram, we can get the following relations:

Pattern 1：$x_{1c}^{1}+x_{2c}^{1}=2d_{xBZ}-2Rb_{BZ}$ (4-3)

Pattern 2-a：$y_{1c}^{2a}+y_{2c}^{2a}=2d_{yBZ}+2Ra_{BZ}$ (4-4)

Pattern 2-b：$x_{1c}^{2b}+x_{2c}^{2b}=2d_{xBZ}-2d_{zBA}$ (4-5)

Pattern 2-c： $y_{1c}^{2c}+y_{2c}^{2c}=2d_{yBZ}+2Rg_{BZ}$ (4-6)

Pattern 2-d：$x_{1c}^{2d}+x_{2c}^{2d}=2d_{xBZ}+2Rg_{BZ}+2Rg_{BA}$ (4-7)

Pattern 2-e： $y_{1c}^{2e}+y_{2c}^{2e}=2d_{yBZ}$ (4-8)

Pattern 3： $x_{13}+x_{23}=2d_{xBZ}-2d_{zBA}\sin 30^{\circ}-2Rb_{BZ}\cos 30^{\circ}$ (4-9)

Experimental results

The results of pendulum head single turntable five axis CNC machine tool

From the modeling and analysis of the errors of the head side, we can see that the static errors of the B axis of the rotary shaft are connected with the average coordinate values of various measurement modes. And we use the established relations to solve the single static error. In the process of solving the single error, we find that the established relationships and our solution are no problems. There is no problem for the solution of the single side of the head, so if there are problems with multiple static errors, we will verify this problem next.

In the solution of multiple static errors on the head side, the static errors exist. Giving all static errors certain numerical values, then according to the measuring relationships in the measurement modes of rotation axis B axis and the coordinate transformation, find out the values of the static errors.

Table 4-1 Simulation results in setting and identification values of the head-side static errors

	Given values1	Identification values1	Deviation values 1	Given values 2	Identification values 2	Deviation values 2
a_{BZ} (**0**)	0.0150	0.0150	0	0.0250	0.0250	0
b_{BZ} (**0**)	-0.0100	-0.0100	0	0.0340	0.0340	0
g_{BZ} (**0**)	0.0200	0.0200	0	-0.0100	-0.0100	0
d_{xBZ} (mm)	0.0300	0.0300	0	-0.0400	-0.0400	0
d_{yBZ} (mm)	0.0250	0.0250	0	-0.0350	-0.0350	0

Similar to the static error of the head side， we can get table 4-2.

Table 4-2 Simulation results in setting and identification values of the turntable's static errors

	Given values1	Identification values1	Deviation values 1	Given values 2	Identification values 2	Deviation values 2
a_{CY} (**0**)	0.0150	0.0150	0	0.0250	0.0250	0
b_{CY} (**0**)	-0.0100	-0.0100	0	0.0340	0.0340	0
d_{xCY} (mm)	0.0300	0.0300	0	-0.0400	-0.0400	0
d_{yCY} (mm)	0.0250	0.0250	0	-0.0350	-0.0350	0

The results of five axis CNC machine tool with double head

Similar to the static error of the RTTTR， we can get table 4-3.

Table 4-3 Simulation results in setting and identification values

	Given values1	Identification values1	Deviation values 1	Given values 2	Identification values 2	Deviation values 2
a_{BA} (0)	0.0120	0.0120	0	-0.0180	-0.0180	0
d_{xBA} (mm)	0.0100	0.0100	0	0.0230	0.0230	0
a_{BZ} (0)	0.0150	0.0150	0	0.0250	0.0250	0
b_{BZ} (0)	-0.0100	-0.0100	0	0.0340	0.0340	0
g_{BZ} (0)	0.0200	0.0200	0	-0.0100	-0.0100	0
d_{xBZ} (mm)	0.0300	0.0300	0	-0.0400	-0.0400	0
d_{yBZ} (mm)	0.0250	0.0250	0	-0.0350	-0.0350	0
d_{zBZ} (mm)	-0.0100	-0.0100	0	0.0180	0.0180	0

Conclusion

This paper proposes a scheme to measure static errors of rotary axes by on-the-machine measurement of the test piece by using a contact-type touch-trigger probe installed on the machine's spindle. This paper introduces the methods in measuring rotation axes' static errors of RTTTR and TTTRR mainly. We use special angles to measure static errors in order to calculate conveniently.

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