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Error calibration of controlled rotary pairs in five-axis machining centers based on the mechanism model and kinematic invariants

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ABSTRACT

The mechanism model of ball bar testing for a two-axis rotary table of 5-axis machining center is discussed, and a new ball bar method to measure the three-dimensional motions of the rotary pairs in multi-axis machining center is developed based on the mechanism model. Then, the fixed axes and moving axes of the rotary pairs are identified by using spherical image circle fitting and striction circle fitting, according to the kinematic invariants of nominal rotation and the measured motions. The structure errors and kinematic pair errors of the rotary pairs are defined and identified by using the fixed and moving axes, and the kinematic model of the two-axis rotary table is deduced with those errors. The simultaneous two-axis motions of the rotary table are measured to verify the proposed calibration method. The experimental results show good agreements with the predicted results calculated by the calibrated kinematic model. Furthermore, the accuracy of the simultaneous multi-axis motions of the machining center is improved when the identified errors are corrected.

1. Introduction

A 5-axis machining center contains two additional perpendicular rotary pairs in comparing with a 3-axis machining center composed of three orthogonal translational pairs; these provide great convenience for machining work-pieces with complicated surfaces. However, the two additional rotary pairs introduce more structure errors and kinematic pair errors [1]. The structure errors correspond to the positional and directional errors of the axis average line of a rotary pair, while the kinematic pair errors correspond to the error motion of the rotary component in relative to the axis average line. It is necessary to calibrate these errors and reduce their influences to improve the accuracy of a 5-axis machining center.

In order to calibrate the errors of the rotary pairs in multi-axis machining centers, some efficient methods, based on the 3D probe-ball [2,3], 4D probe-ball [4,5], ball bar [6–9] or some other ingenious devices [10,11], are presented. In these researches, the positional and directional offsets of the rotary pairs are calibrated by the simultaneous multi-axis motions. These calibrated offsets are regarded as the structure errors, which are unrelated to the rotary angles of the rotary pairs. However, the rotary pairs also have kinematic pair errors, which are changing as the rotary angle varies. Sometimes, the ranges of the kinematic pair errors are nearly to those of the structure errors. Hence, it is beneficial to consider these two errors simultaneously during error calibration.

Generally, the structure errors and kinematic pair errors will be calibrated absolutely, if the three-dimensional motion of the rotary component is measured. In most cases, the three-dimensional motion can be described by the radial run-outs, axial run-outs and tilts of a precise artifact mounted on the rotary component, and then measured by some displacement indicators [12–16]. Unfortunately, for the controlled rotary pairs in 5-axis machining centers, such as the two-axis rotary table, it is difficult to mount the artifact to a suitable place because of space limitation; moreover, the directional offsets and positional offsets between the rotary pairs can't be measured by these methods. Some other precise instruments, such as the laser tracker, autocollimator, polygon, etc. [12,17,18], are also used to measure the motions of the rotary pairs. Nevertheless, these methods may time-consuming or incomplete for three-dimensional motion measurements.

As the ball bar is easy installation and efficient for error measurement of machining centers, in recently researches, the ball bar methods are used to calibrate the errors of the rotary pairs based on the three-dimensional motion measurement. In these methods, the errors of the rotary pairs are defined and calibrated by using the transformation matrixes, and the mounting position errors of the ball bar are corrected before error measurement or identified from the measured results [19–21]. However, the identified results of these methods may be different if the ball bar is mounted to different positions although the mounting

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position errors are eliminated, as the error motions of different points of the rotary component are different, and the transformation matrixes are related to the nominal installation parameters of the ball bar. Thus, is there a ball bar method independent of the mounting positions and their errors absolutely? How to identify the structure errors and kinematic pair errors of the controlled rotary pairs without considering the installation parameters? Solving these problems will improve the efficiency and accuracy of error calibration.

In this paper, the error calibration of rotary pairs is divided into two steps. Firstly, a mechanism model is presented to calculate the three-dimensional motions of the rotary pairs, based on the discrete data measured by the ball bar. This model is independent of the mounting position errors of the ball bar. Then, the structure errors and kinematic pair errors of the rotary pairs are identified by using the kinematic invariants of rotary error motions, in order to eliminate the influences of the installation parameters. The kinematic model of the two-axis rotary table is presented by using the identified structure errors and kinematic pair errors, and the errors of the simultaneous two-axis motions are calculated and corrected with the calibrated kinematic model. This provides a new method for error calibration of the rotary pairs in multi-axis machining centers.

2. The mechanism model for ball bar to test rotary table

A ball bar contains two spherical pairs and one translational pair. During ball bar testing, one spherical pair is mounted on the spindle and the other is mounted on the rotary table. The kinematic chains of the machining center and the ball bar constitute a spatial mechanism, and the displacements measured by the ball bar can be regarded as the output motion of the mechanism. Thus, the three-dimensional motion of the rotary table can be calculated by the displacement equation of the mechanism.

2.1. The three-dimensional motion of the rotary table

The controlled rotary pairs of multi-axis machining center have many different configurations, as the rotary pairs can distribute in different positions and directions of the machining center. For universality, a two-axis rotary table of 5-axis machining center is discussed, as the single rotary pair can be regarded as a special case of the two-axis table, with one of the rotary pairs locked. The ball bar testing devices of the two-axis rotary table are shown in Fig. 1(a).

In order to describe the three-dimensional motion of the rotary table, a fixed frame $\{O_f;\ \boldsymbol{i}_f, \boldsymbol{j}_f, \boldsymbol{k}_f\}$ is employed as the coordinate system of the machining center; meanwhile, a moving frame $\{O_m;\ \boldsymbol{i}_m, \boldsymbol{j}_m, \boldsymbol{k}_m\}$ is employed and attached to the rotary table, shown in Fig. 1(b). Thus, the three-dimensional motion of the rotary table is described by three translations (x_{Omf}, y_{Omf}, z_{Omf}) and three rotations (α, β, γ) of the moving frame in relative to the fixed one. The spherical pair S_D moves with the rotary table, and the trajectory Γ_D of the sphere-center D in the fixed frame is written as

$$\Gamma_D\text{: } \mathbf{r}_{OD} = \mathbf{r}_{Omf} + [\mathbf{R}(\alpha, \beta, \gamma)]\mathbf{r}_{Dm} \tag{1}$$

where, $\boldsymbol{r}_{Omf}$ =[x_{Omf}, y_{Omf}, $z_{Omf}]^T$ is the position vector of the origin point O_m in the fixed frame; $\boldsymbol{r}_{Dm}$ denotes the position vector of point D in the moving frame; $\mathbf{R}(\alpha, \beta, \gamma)$ denotes the rotational matrix, whose value is

$$\mathbf{R}(\alpha, \beta, \gamma) = \begin{bmatrix} c\alpha & -s\alpha & 0 \\ s\alpha & c\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{bmatrix} \tag{2}$$

The letters s and c denote sine and cosine for short.

Generally, the six kinematic parameters (x_{Omf}, y_{Omf}, z_{Omf}, α, β, γ) of the rotary table can be calculated by using Eqs. (1) and (2), if the position vectors $\mathbf{r}_{Dm}^{(j)}$ of three non-collinear points $D^{(j)}$ (j=1, 2, 3) of the rotary table in the moving frame and the corresponding position vectors $\mathbf{r}_{OD}^{(j)}$ in the fixed frame are given. This can be regarded as the forward solution of Eq. (1) with given the position and direction of the moving frame on the rotary table. However, mounting position errors will appear during fixing the ball bar to the table, this means the values of the position vectors $\mathbf{r}_{Dm}^{(j)}$ in the moving frame have errors. In order to avoid the influences of these errors, the position and direction of the moving frame, as well as the six kinematic parameters, are inversely solved with given the position vectors $\mathbf{r}_{OD}^{(j)}$ (j=1, 2, 3) in the fixed frame, as the moving frame can be arbitrary chosen to describe the spatial rigid motion. The origin point O_m and the coordinate axes of the moving frame $\{O_m;\ \boldsymbol{i}_m, \boldsymbol{j}_m, \boldsymbol{k}_m\}$ in the fixed frame can be determined by

$$\begin{cases} \mathbf{r}_{Omf} = \dfrac{\mathbf{r}_{OD}^{(1)} + \mathbf{r}_{OD}^{(2)}}{2} \\ \mathbf{i}_m = \dfrac{\mathbf{r}_{OD}^{(2)} - \mathbf{r}_{OD}^{(1)}}{|\mathbf{r}_{OD}^{(2)} - \mathbf{r}_{OD}^{(1)}|};\ \mathbf{k}_m = \dfrac{(\mathbf{r}_{OD}^{(2)} - \mathbf{r}_{OD}^{(1)}) \times (\mathbf{r}_{OD}^{(3)} - \mathbf{r}_{OD}^{(1)})}{|(\mathbf{r}_{OD}^{(2)} - \mathbf{r}_{OD}^{(1)}) \times (\mathbf{r}_{OD}^{(3)} - \mathbf{r}_{OD}^{(1)})|};\ \mathbf{j}_m = \mathbf{k}_m \times \mathbf{i}_m \end{cases} \tag{3}$$

The vector $\boldsymbol{r}_{Omf}$ corresponds to the three translations (x_{Omf}, y_{Omf}, z_{Omf}) of the rotary table. The three rotations (α, β, γ) of the rotary table can be identified by using the coordinate axes, and the equations are

$$\alpha = \arctan(\frac{i_{m2}}{i_{m1}});\ \beta = \arctan[\frac{-i_{m3}}{\sqrt{(i_{m1})^2 + (i_{m2})^2}}];\quad \gamma = \arctan[\frac{j_{m3}}{k_{m3}}] \tag{4}$$

where, i_{mt}, j_{mt} and k_{mt} denote the t-th elements of vectors $\boldsymbol{i}_m$, $\boldsymbol{j}_m$ and $\boldsymbol{k}_m$.

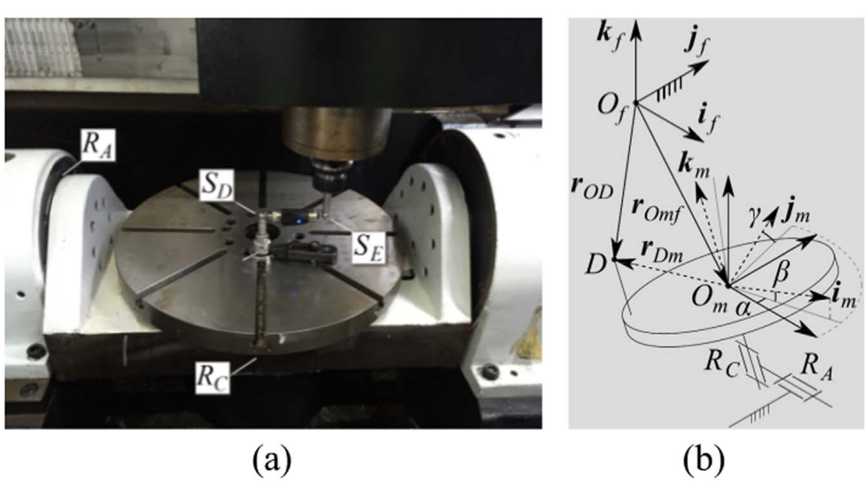

Fig. 1. The devices of ball bar testing.