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Geometric error measurement and identification for rotary table of multi-axis machine tool using double ballbar

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ABSTRACT

In this paper, comprehensive geometric errors, including linkage errors and volumetric errors, of a rotary table are measured totally by employing a double ballbar and obtained by a two-step identification procedure. The derivations of the center of the ball installed on the table are measured in the error sensitive directions with newly developed serial of two axes controlled circular paths. Hence, there are nine results measured from three mounting positions of the ball at the same rotation angle. These results are used to form the identification model based on the homogeneous transformation. Moreover, a sensitivity analysis method is applied to select the optimum installation parameters of the ballbar to diminish the influence of the inaccuracy of the measurement parameters. As the mounting position errors of the socket on the table are inevitable during the installation of the balls, a new correction procedure is developed as well. Finally, an experiment is conducted on the four-axis machining center. The comparison results between the predicted errors and the measured results are shown to verify the proposed method.

1. Introduction

Multi-axis CNC machines are one of the most important components in modern manufacturing facilities, which are required to reach increasing high-performance machining. As long as the geometric errors are systematic or repeatable and measurable, error compensation is an effective way to achieve high machining accuracy with low cost [1]. A rotary table is often used on multi-axis machine tools to orient and position the workpiece and the tool. Its accuracy is crucial for part manufacturing with multi-axis machine tools [2]. If there is an effective method to improve or compensate for those deviations, the machining performance of multi-axis machines will be improved drastically.

In the past decades, some researches have been taken to measure and identify the errors that are inherent to a rotary axis of a multi-axis machine tool. Tsutsumi and Saito [3,4] proposed a calibration method using the simultaneous four-axis control technique for five-axis machining centers with a tilting rotary table. The eight deviations were estimated by the observation equations from the ballbar measured results. Dassanayake et al. [5] developed the method to identify the ten inherent deviations to double pivot heat type five-axis machines based on simultaneous five-axis control motions using ballbar as well. Zargarbashi and Mayer [6] presented a method consisting of five double ballbar tests to evaluate five trunnion axis motion errors including axial, radial and tilt errors.

Some new instruments also have been developed as well. Lei and Hsu [7–9] measured the deviations of the tool paths on a spherical test surface using probe–ballbar which consists of a 3D probe. The overall positioning errors of the relative motion were measured by the 3D probe and were used to justify the volumetric accuracy of the five-axis machine. Bringmann, Knapp and Weikert [12–14] developed a Calibration method for five-axis machining center using newly developed 4D probe and a ball artifact. There were 14 errors, including the link errors and some positioning errors, could be identified by the presented procedure. Mayer and Zargarbashi [15] presented a non-contact measuring instrument for on the fly Cartesian volumetric error measurement of five-axis machine tools using a programmed end point constraint procedure. Four link error parameters were estimated following the identification procedure.

However, the aforementioned approaches concerned about the linkage errors that were constant during rotary axis movement. Actually, each rotary axis also brings six volumetric geometric error parameters when rotates around its axis. These error parameters change with the rotation angle accordingly. For high-accuracy machining, they should not be ignored. Suh et al. [16] presented a comprehensive procedure for the calibration the volumetric errors of the rotary table using autocollimator, polygon and LVDTs. Lee et al. [10] used a double ballbar to measure some of

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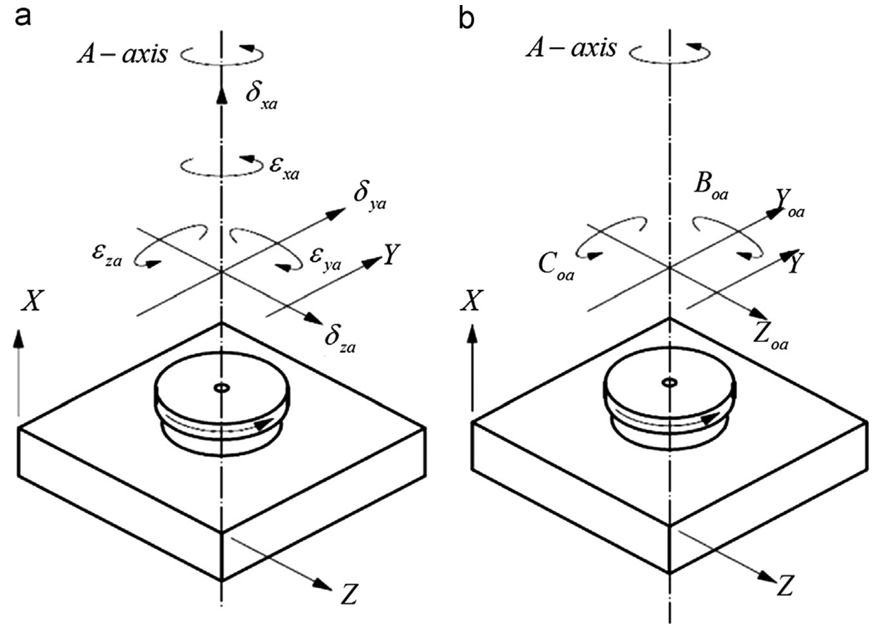

Fig. 1. The geometric errors of rotary axis A. (a) Error motions of axis of rotation and (b) location errors of an axis average line.

the position dependent and independent errors of a rotary axis through reverse kinematic approaches. Zhu et al. [11] proposed a new identification method to recognize 6 angular geometric error parameters for each rotation axis based on a ballbar. Other commercial instruments were also available, such as electronic levels and laser interferometers with rotary indexers [17]. They can measure a part of errors of a rotary axis. Nevertheless, these instruments were greatly expensive, and the measurement processes were time-consuming with even highly skilled technical people.

However, the present researches concerned only some of the geometric error parameters. The multi-axis controlled motions are needed and the installation parameters of the ballbar are selected relying on the empirical during measurement. These drawbacks further limit the accuracy of error identification of the rotary table, especially in high accuracy machining occasion. This paper develops a measurement procedure to obtain the derivations of the center of the ball installed on the rotary table by a double ballbar with serial of circular paths. The geometric errors model and both the linkage and volumetric error parameters to be estimated from the measured data are presented together with the identification procedure. During the measurement, a sensitivity analysis method is applied to select the optimum installation parameters. Moreover, a new correction method for adjusting the mounting position of the socket on the table is presented as well. Then, a two-step error identification procedure is proposed to compute linkage errors and volumetric errors from the measured results. Finally, an experiment is conducted on a four-axis machine center to test and verify the proposed method.

2. The principle of the ballbar measurement method

According to the standard of ISO230-7 [18], there are two major error sources of a rotary axis: the error motions of axis of rotation and the location errors of the axis average line. The former is called the volumetric error, and the latter is commonly named linkage errors.

The existence of the geometric error vector $[\delta_{xa}, \delta_{ya}, \delta_{za}, \varepsilon_{xa}, \varepsilon_{ya}, \varepsilon_{za}]^T$ (as shown in Fig. 1a) during the movement of the rotary table can be represented by three translation errors and three angular errors. They change with the rotation position. Meanwhile, there are four linkage errors $[Y_{oa}, Z_{oa}, B_{oa}, C_{oa}]^T$ (as shown in Fig. 1b) that are caused by the inaccuracy of the parts manufacturing and assembling. In contrast, they keep constant during the table rotation.

The double ballbar is a precision instrument that is commonly used to measure relative displacements between the spindle and the workbench. As shown in Fig. 2, in a typical double ballbar application, there are two sockets in the ballbar measurement system. One is clamped by the tool holder on the spindle, and the other is set on the workbench. The double ballbar is installed on the ball bowls of the sockets.

The spindle is moved by three linear axes, X, Y, and Z, to drive the ballbar rotating around the center point of the ball bawl of the socket installed on the workbench. Because the geometric errors of the machine tool are unavoidable, the sockets on the workbench and spindle deviate from their ideal position, and hence the position of the center points P_b and P_s are changed accordingly. It contributes to the change of the distance between the two center points. If the ideal length of the double ballbar is R, the variation distance dR between the real center points P'_s and P'_b measured by the ballbar can be represented by

$$(R+dR)^2 = \|P'_s - P'_b\|_2 \quad (1)$$

For the errors of linear axes are rather smaller than the rotary axes, and they can be carefully calibrated before measurement, the errors of the center point P_b can be eliminated. If the deviations of the center point P_s in the axis directions are $[dx_s, dy_s, dz_s]$, the real position of P_b and P_s are $[x_b, y_b, z_b]$ and $[x_s+dx_s, y_s+dy_s, z_s+dz_s]$, respectively. The relationship between dR and the deviations of the center point P_s can be represented by the first-order equation.

$$RdR = -(x_s-x_b)dx_s - (y_s-y_b)dy_s - (y_s-y_b)dz_s$$

Moving the ballbar by the spindle to X-axis direction, the position of P_b is moved to $[x_s+R, y_s, z_s]$. Then, the variation distance dR read from the ballbar test software is equal to $-dx_s$. Similarly, the same results of dy_s and dz_s can be obtained. Theoretically speaking, the derivations of the socket caused by the geometric errors of the rotary table can be measured by ballbar step by step in the error sensitive directions.