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A comprehensive error analysis method for the geometric error of multi-axis machine tool

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ABSTRACT

In this paper, a comprehensive error analysis method is proposed to discover how the geometric error propagation through every motion axis, and to find out which error parameters have greater impact on the tool posture error at the end of the kinematic chain. As the geometric error of a motion axis can be regarded as the differential movement, an error model for a four-axis machine tool is established to calculate the tool posture error with all the geometric error parameters. Then a cumulative process of the differential movements of every axis is proposed to describe the error propagation process when moving the tool to the given position. Moreover, the workspace of the machine tool is discretized into an amount of points with a uniform sampling method on the measured positions of the geometric error. Then, a Spearman rank correlation method is presented to find out how closely linked between a single error parameter and the tool posture error all over the sampling workspace. Hence, the ten key error parameters are selected according to the analysis results in the three-axis and four-axis sampling workspace. Finally, an experiment is conducted on the four-axis machine tool with a three-axis controlled trajectory to verify the effectiveness and correctness of the proposed method using a double ballbar.
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1. Introduction

The geometric errors are one of the major factors to cause the inaccuracy of a machine tool, since they have a significant influence on the quality of the machining operations [1]. It is becoming a key issue to reduce or eliminate the geometric error when manufacturing and assembling a multi-axis machine tool in the design period, or even in daily operation and maintenance [2], for relatively high precision is one of the basic requirements in modern manufacturing. Due to economic consideration, not all geometric errors can be controlled or compensated, but only part of them can be chosen to make the accuracy improvement procedure more efficient and cost-effective. Hence, it is a critical problem that how to evaluate the importance of a single error impacting on the accuracy of a machine tool, so as to find out which are the vital errors needed to be focused on.

The motion axes drive the tool along with the programed path on the workpiece to form the designed surface. As the geometric is inevitable, a mathematical model with all the error parameters should be established to estimate tool posture error, including the cutter location error and the angular error of the tool axis. There have been numerous intensive research works on error modeling for the machine tools over the past decades. Generally, an error model is established to describe the error of cutter location and tool orientation using HTM [3,4], D-H [5], MD-H [6] or MBS [7] theory. With the error model containing both the tool posture error and all the error parameters, a sensitivity analysis method [8] is usually applied to evaluate the relationship between the error of a machine tool and the error components. It computes the partial differentiation with respect to the formula of forward kinematic equation at the given position [9,10]. This is really a hard work and sometimes is infeasible when the measured geometric error is finite and discrete. Furthermore, it is called local sensitivity analysis method [11,12] which just concerns on a few points or tool paths. Obviously, it is not sufficient to estimate overall relationship of the geometric errors in the workspace. Hence, the global sensitivity analysis method is introduced to reflect the average influence of error components in the overall workspace. Zhang et al. [13] presented system reliability and global sensitivity analyses of a machine tool with the multiplicative dimensional reduction method (M-DRM). The variance-based global sensitivity analysis was preformed to screen significant error components of the system kinematic error model. Cheng et al. [14] proposed a method based on the product of exponential (POE) screw theory and Morris approach for volumetric machining accuracy global

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sensitivity analysis of a machine tool. A modified Morris method was used to perform global sensitivity analysis and identify the key error terms that have a greater influence on the volumetric machining error. Li et al. [15] introduced the general local sensitivity indices, general global sensitivity indices and general global sensitivity fluctuation indices to reveal the contributions of error components in a definite cutting tool posture, the average contributions of error components in the given workspace, and the fluctuation of error components in the given workspace, respectively.

Besides, it is also important to observe how geometric errors give influence and how deviations of the tool posture in the workspace accumulate, for it is beneficial for sensitive error control and optimal configuration selection in design part [16]. An error propagation method is normally performed to analyze the geometric accuracy subjected to the influence of a variety of errors. Liu et al. [17] presented an integrated error propagation analysis method to estimate the measurement uncertainty using MonteCarlo method for an H-drive stage with air bearing during high acceleration. Zhu et al. [18] proposed a method for the extraction of machine tool component errors by B-spline fitting method from a statistical point of view, and numerical error compensation experiments were conducted on the XY-plane of a high precision machine tool by using a cross-grid scale system. Tang et al. [19] introduced a new geometric error modeling approach for multi axes system (MAS) based on stream of variation (SOV) theory, especially for multi-axis precision stage. It could be adapted to clearly observe how geometric errors give influence and how deviations accumulate.

However, the above-mentioned approaches in the sensitivity and error propagation analysis generally based on the assumption that all the error parameters have the same data distribution, and basically have the same order of magnitude. Actually, for the different machining accuracy of the components of a machine tool, and the degree of wear in daily operation, the error parameters are widely differences from each other, both in distribution and magnitude. Meanwhile, even in the global sensitivity analysis method as proposed in the previous research, only a few points or target trajectories of the tool cutter are selected as the global sampling set in the workspace to evaluate the influence of a single error parameter on the accuracy of a machine tool. In addition, the norms of the tool cutter location error are chosen as the overall or global error of a machine tool when implementing the sensitivity analysis, and usually the position errors of the cutter location are just taken into consideration as well. Nevertheless, in the practical application, more attention should be paid on every error parameter in the error vector of the tool posture. The norm of the error vector is just a comprehensive conception. It is not sufficient to handle variable machining conditions, such as two-axis and three-axis controlled trajectory, especially the multi-axis machining with a rotation axis, when the tool axis errors should not be ignored in this case.

In this paper, the geometric error of a machine axis is equivalent to the differential movement based on its ideal position, and an error modeling method using differential transformation theory is proposed. An analysis method of error propagation is presented with a cumulative process of the differential movements of every axis at the given tool position. Moreover, a Spearman rank correlation method is introduced to find out the relationship between a single error parameter and the tool posture error all over the sampling workspace. Then, the ten key error parameters with larger absolute correlation coefficients are chosen according to the analysis results in the three-axis and four-axis cases. Finally, an experiment is conducted on a four-axis machine tool with a three-axis controlled test path using a double ballbar. The effectiveness and correctness of the proposed method are verified by comparing the predicted results using the selected errors with the actually measured results by the ballbar.

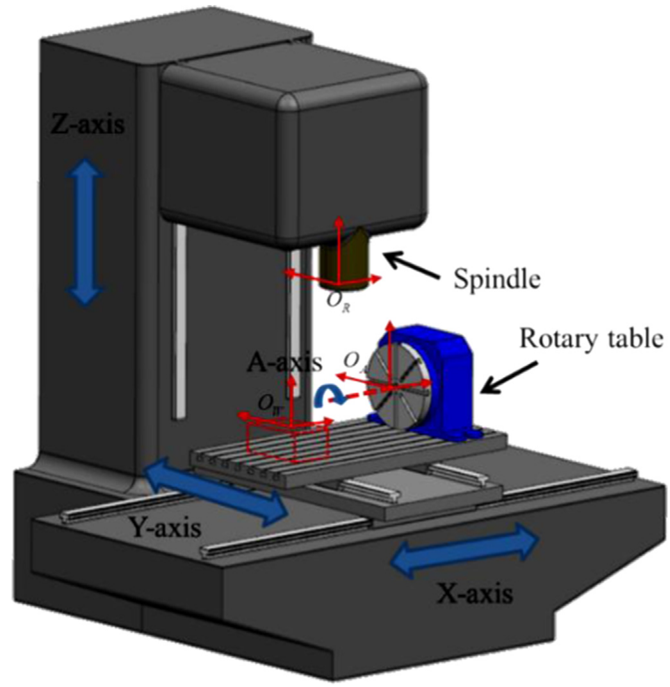

Fig. 1. Four-axis machining center involving a rotary table.

2. Geometric error modeling

A commonly used four-axis machining center (as shown in Fig. 1) is taken as an example to describe the proposed method. There are four movement axes, including three translational axes (*X*-axis, *Y*-axis and *Z*-axis) and one rotary table installed on the workbench. The rotary table rotates around *A*-axis to change the orientation of the workpiece. In order to analyze the kinematic chain of the machine tool, the intersection point O_A of *A*-axis and the end surface of the rotary table is selected as the origin of *A*-axis coordinate system, while the reference point O_R of the machine tool is selected as the origin of *X*-axis, *Y*-axis, and *Z*-axis.

Subsequently, a mathematical model should be established to evaluate the error distribution of the machine tool. The differential transformation theory is introduced in this paper, to express the error propagation process at the certain point in the workspace of the machine tool.

2.1. Differential transformation

There exist six geometric error parameters, including three linear errors and three angular errors, when a component moves along an axis [20]. Taking *A*-axis as an example, it deviates from its ideal position with an error vector $[\delta_{xa}, \delta_{ya}, \delta_{za}, \varepsilon_{xa}, \varepsilon_{ya}, \varepsilon_{za}]$. According to the differential transformation theory [21], they can be equivalent to differential movement from its ideal position since the geometric errors are small. The real transformation matrix ${}^{W}T_a{}'$ of *A*-axis can be defined by Eq. (1).

$$ {}^{W}T_a^{'} = {}^{W}T_a + d{}^{W}T_a = {}^{W}T_a + {}^{W}T_a{}^{W}\Delta_a \quad (1)$$

where ${}^{W}T_a$ is the ideal transformation matrix and the operator ${}^{W}\Delta_a$ represents the differential movement of *A*-axis.

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