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Integrated post-processor for 5-axis machine tools with geometric errors compensation

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ABSTRACT

Geometric errors of 5-axis machine tools introduce great deviation in real workpiece manufacture and on-machine measurement like touch-trigger probe measurement. Compensation of those errors by toolpath modification is an effective and distinguished method considering the machine calibration costs and productivity. Development of kinematic transformation model is involved in this paper to clarify the negative influences caused by those errors at first. The deviation of the designed toolpath and the real implemented toolpath in workpiece coordinate system is calculated by this model. An iterative compensation algorithm is then developed through NC code modification. The differential relationship between the NC code and the corresponding real toolpath can be expressed by Jacobi matrix. The optimal linear approximation of the compensated NC code is calculated by utilizing the Newton method. Iteratively applying this approximation progress until the deviation between the nominal and real toolpath satisfies the given tolerance. The variations of the geometric errors at different positions are also taken into account. To this end, the nominal toolpath and the geometric errors of the specific 5-axis machine tool are considered as the input. The new compensated NC code is generated as the output. The methodology can be directly utilized as the post-processor. Experimental results demonstrate the sensibility and effectiveness of the compensation method established in this study.

1. Introduction

With an increasing need for machined components with geometric complexity in a high efficiency, 5-axis machine tools are extensively used in various manufacturing applications requiring higher machining accuracy [1]. The accuracies of workpiece machining, as well as the touch-trigger based on-machine measurement [2], significantly depend on the performance of the machine tools. Among the factors that affect the machining accuracy, the geometric error of machine tool components and structures is one of the biggest sources of inaccuracy [3].

Hence, there has been developed a variety of specific instruments as well as measurement methodologies for geometric error identification. Laser interferometer [4,5] is commonly used for geometric error measurement of 3-axis machine tool. The double ball bar [6,7] and R-test [8–10] are both valid to identify some geometric errors of rotary axis of 5-axis machine tool. Tough-trigger probe is a promising automatic instrument for error measurement, for both errors of linear axis [11] and rotary axis [1,12]. Vendors like Renishaw provide methodologies to identify the geometric errors of rotary axis using a touch-trigger probe. Other instruments like Doppler laser instrument [13] and cross grid encoder [14] are also used for error measurement and identification.

After identifying the geometric errors, the application of full error compensation is emerged. Higher accuracy demands and the intention to decrease the costs of mechanical accuracy promote this development [15]. Error compensation for machining accuracy enhancement based on toolpath modification is an active research at present. Habibi et al. [16,17] developed a revised version of kinematic modeling method for geometrical error compensation. Their method was developed for 3-axis machine tools but not suitable for 5-axis machine tools, which made it less perfect. Ref. [4,18,19] also compensated the geometric errors of 3-axis machine tools by using the error vector equations. Lee et al. [20] used recursive error compensation technique to acquire the right position of the 3-axis machine tools. Those compensation strategies can fully compensate the geometric errors of the 3-axis machine tools to acquire a precision tool tip position, but unsuitable for the tool axis orientation correction. The error compensation of 5-axis machine tools is much more complicated. Hsu and Wang [21] used the decouple method to calculate the compensated toolpath. The compensation of rotary axis was first determined and then the compensated linear axis was decided. Zhu et al. [22] presented an

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integrated geometric error modeling, identification and compensation method. The variation of geometric errors between the nominal tool position and modified tool position are not considered. Chen et al. [2] proposed a modeling method based on differential transform theory for geometric error compensation of 5-axis CNC machine tools. However, variations of the geometric errors at different axis positions are not concerned.

Considering that geometric errors are one of the most significant components for machine accuracy improvement and that numerous technologies for error measurement and identification have been developed, this paper demonstrates a full error compensation model for 5-axis machine tools by correcting corresponding NC codes. The remaining part of this paper is organized as follows. In Section 2, the kinematic model with and without considering the geometric errors is developed. And an iterative compensation algorithm based on Jacobi approximation is invented in Section 3. To validate the effectiveness of the mew method, in Section 4, a particular test piece machining experiment with and without geometric error compensation is conducted. Finally, the contributions of the proposed method are summarized in Section 5.

2. Kinematic model with geometric error constraint

2.1. Ideal kinematic model in post-process

As shown in Fig. 1, a 5-axis machine tool consists of three linear axes and two rotary axes. The relationship between the tool location in workpiece coordinate system and the NC code in machine coordinate system is determined by structure of the given 5-axis machine tool. In this paper, a ZXFYAC type machine tool with double head structure is considered as an example.

To obtain the relationship between tool location in workpiece coordinate system and the NC code in machine coordinate system, kinematic transformation model is established by using Homogeneous Transformation Matrix (HTM) based on rigid body assumption. The tool location in workpiece coordinate system is represented by tool tip position $[x\ \ y\ z]^T$ and tool axis vector $[i\ j\ k]^T$. The corresponding NC code in machine coordinate system is represented by $[X\ \ Y\ Z\ A\ C]^T$. The vector from the intersection of the A-axis and the C-axis to the origin of workpiece coordinate system is $[m_x\ m_y\ m_z\ ]^T$.

According to the topological structure of the machine tool, the workpiece coordinate system with respect to the foundation coordinate system can be modeled as

$$ {}^{W}T_F = {}^{W}T_C R_z(-C)\, {}^{C}T_A R_x(-A)\, {}^{A}T_Y\, {}^{Y}T_F \tag{1} $$

Similarly, the tool coordinate system with respect to the foundation coordinate system can be written as

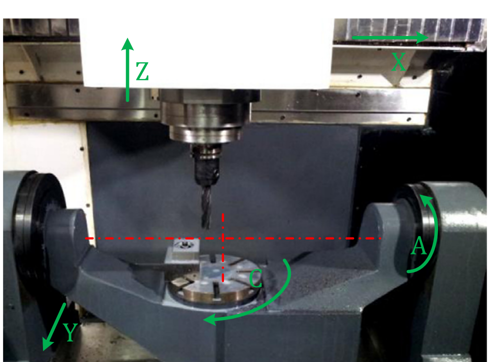

Fig. 1. Structure of the 5-axis machine tool.

$$ {}^{F}T_T = {}^{F}T_X\, {}^{X}T_Z\, {}^{Z}T_T \tag{2} $$

where the detailed modeling is presented in Appendix A. Furthermore, the workpiece coordinate system with respect to the tool coordinate system is

$$ {}^{W}T_T = {}^{W}T_F\, {}^{F}T_T \tag{3} $$

Consequently, equations of the tool location in workpiece coordinate system represented by NC code in machine tool coordinate system are

$$ \begin{aligned} &[i\ j\ k\ 0]^T = {}^{W}T_T [0\ 0\ 1\ 0]^T \\ &[x\ y\ z\ 1]^T = {}^{W}T_T [0\ 0\ 0\ 1]^T \end{aligned} \tag{4} $$

By transforming Eq. (4) from matrix form into algebraic form, we can get the pre-process formula as follows:

$$ \begin{cases} \Psi = f_\Psi (A, C)\ \Psi = i, j, k \\ \Psi = f_\Psi (X, Y, Z, A, C) \Psi = x, y, z \end{cases} \tag{5} $$

where the corresponding algebraic equations are shown in Appendix B. From Eq. (5), we can observe that the tool axis vector $[i\ \ j\ k]^T$ is determined by values A and C while the tool tip position $[x\ y\ z]^T$ is determined by values X, Y, Z, A and C. By calculating the inverse function of Eq. (5), the NC code can be represented by tool location as follows, whose details are presented in Appendix B. This process is called post-process.

$$ \begin{cases} \Gamma = f_\Gamma{}'(i, j, k)\ \Gamma = A, C \\ \Gamma = f_\Gamma{}'(x, y, z, i, j, k)\ \Gamma = X, Y, Z \end{cases} \tag{6} $$

So far, the relationship between the NC code and the tool location can be represented by Eqs. (5) and (6). It is important to note that the post-process is much more complicated compared with this pre-process. From the details of Eq. (6) in Appendix B, multiple solutions exist in determining A and C with the introduction of parameters k_A and k_C. So a multiple selection algorithm should be developed which increases the computation complexity.

2.2. Influence of geometric errors

2.2.1. Error components of motion axis

For a 3-axis machine tool, there are 21 error components [18,19], including 6 errors for each linear axis and 3 squareness errors. For the error components of rotary axis, there are several views. For example, in Refs. [6,13], there are 6 displacement errors and 6 angular errors caused by two rotation axes. In Refs. [23,24], 4 squareness errors are introduced in addition. Meanwhile, some papers suggest that less error components is sufficient to reflect the kinematic characteristics, e.g., Refs. [25,26] point out that 2 displacement errors and 2 angular errors for each rotary axis are enough to definite the geometric errors. In this paper, the error components are defined according to Ref. [13]. There are 33 error components for a 5-axis machine tool, as summarized in Table 1.

Table 1
Error components of motion axis.

Motion axis	X	Y	Z	A	C
Displacement error	$\delta_{xx}, \delta_{yx}, \delta_{zx}$	$\delta_{xy}, \delta_{yy}, \delta_{zy}$	$\delta_{xz}, \delta_{yz}, \delta_{zz}$	$\delta_{xa}, \delta_{ya}, \delta_{za}$	$\delta_{xc}, \delta_{yc}, \delta_{zc}$
Angular error	$\varepsilon_{xx}, \varepsilon_{yx}, \varepsilon_{zx}$	$\varepsilon_{xy}, \varepsilon_{yy}, \varepsilon_{zy}$	$\varepsilon_{xz}, \varepsilon_{yz}, \varepsilon_{zz}$	$\varepsilon_{xa}, \varepsilon_{ya}, \varepsilon_{za}$	$\varepsilon_{xc}, \varepsilon_{yc}, \varepsilon_{zc}$
Squareness error		S_{xy}	S_{xz}, S_{yz}		