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Machining accuracy improvement of non-orthogonal five-axis machine tools by a new iterative compensation methodology based on the relative motion constraint equation

Changjun Wu [a,b], Jinwei Fan [a,*], Qiaohua Wang [b], Dongju Chen [a]

[a] *College of Mechanical Engineering & Applied Electronics Technology, Beijing University of Technology, Beijing, 100124, PR China*
[b] *School of Mechanical and Electrical Engineering, Zhengzhou University of Light Industry, Zhengzhou, 450002, PR China*

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ABSTRACT

This paper proposes a new iterative compensation methodology of geometric errors to improve the machining accuracy of a non-orthogonal five-axis machine tool (NOFAMT). Firstly, based on homogeneous transform matrix (HTM) and multi-body system (MBS) theory, the relative motion constraint equations (TRMCEs) of the tool tip position and tool orientation vector related to a NOFAMT with a nutating rotary *B* axis are established. Then, by utilizing TRMCEs, the mapping relationships between tool path and the numerical control (NC) command without and with considering the geometric errors are constructed respectively. In order to truly reproduce tool motion trajectory of the machine tool driven by the given NC command, the mapping relationship between the NC command and tool cutting trajectory is also established. Meanwhile, procedures of iterative compensation are described by using the aforementioned mapping relationships without the traditional inverse calculation, and the actual NC code is generated in self-developed compensation software. It is not difficult to find that the new approach takes the difference between tool path and tool cutting trajectory as the control objective and can directly obtain the actual NC code controlling the machine tool to achieve the desired machining accuracy. Finally, a cutting test is carried out on the DMU60P NOFAMT. Experimental results show the developed iterative compensation methodology is precise and effective for NOFAMTs. Therefore, compared with the existing methods, the new method is more direct and accurate. And its basic idea can be applied to other type of machine tools.

1. Introduction

With the increasing requirements for higher quality machined complex parts, the importance of improving machine tools' machining accuracy is well recognized in the manufacturing community [1]. Compared with three-axis machine tools, multi-axis machine tools with one or more rotary axes have many advantages, such as higher metal-removal rate, lower cutting time, higher production rate, fewer set-ups [2,3,7–9], better versatility and flexibility, higher machining efficiency [4]. However, due to the additional rotary axes, multi-axis machine tools are introduced more error sources, thus bringing about lots of barriers and difficulties in machining accuracy improvement. Among them, geometric errors are a basic factor resulting in poor machining accuracy [5,6]. Fortunately, the geometric errors can be reduced by error compensation, which has been proven as an economical and effective way [5].

At present, considerable research work for error compensation of multi-axis machine tools is devoted almost entirely to the orthogonal series machine tools [2–7,9,12–18,23,25], whose three linear axes are orthogonal each other and rotary axis center line is parallel to the direction of the linear axis [10]. However, to the best of our knowledge, less attention is paid to error compensation of non-orthogonal multi-axis machine tools, whose rotational axis is in an inclined plane [11].

Unlike the orthogonal multi-axis machine tool, a non-orthogonal multi-axis machine tool with a nutating head or a nutating table can adjust the position and orientation of the cutting tool with respect to the workpiece toward any angle within the workspace. In addition, it also can travel continuously between the horizontal and vertical positions on the same machine [10,11]. Hence, the research on error compensation of non-orthogonal multi-axis machine tools is an important topic.

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* Corresponding author. College of Mechanical Engineering & Applied Electronics Technology, Beijing University of Technology, Ping Leyuan 100#, Chaoyang district, Beijing, 100124, PR China.

E-mail addresses: piaoyanggh2003@163.com (C. Wu), jwfan@bjut.edu.cn (J. Fan).

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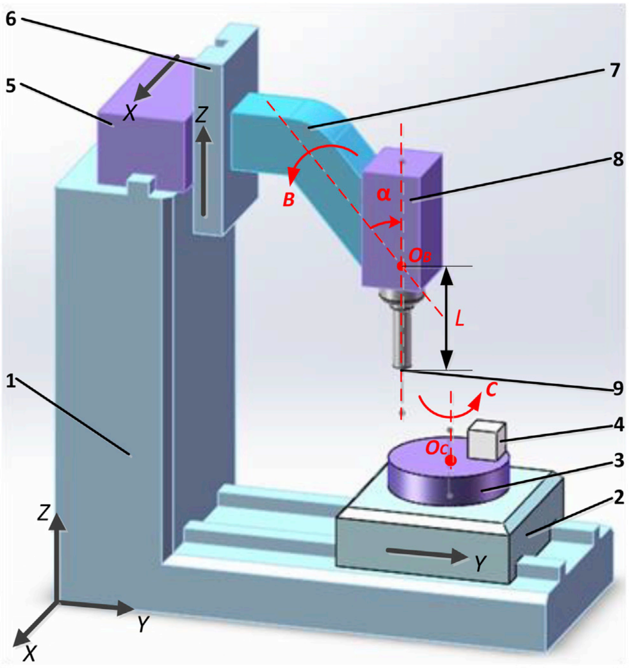
According to the Refs. [12] and [13], error compensation is divided into hardware compensation and software compensation. It is well-known that hardware compensation has economical limitations as machining costs rise exponentially with the level of machining accuracy involved [13], whereas software compensation is easier to carry out at lower costs since only a computer software is needed to compensate errors by correcting numerical control(NC) instructions before executing compensation instructions [12]. Therefore, many literatures have reported that most researchers used software compensation to improve machining accuracy. Khan et al. [14] presented a recursive method to eliminate machine errors from the actual tool path, and then converted the corrected tool paths into practical compensated NC codes. Zhu et al. [15] developed a prototype software compensation system to improve the machining accuracy of a five axis machine tool. The basic compensation idea is to modify the original NC codes to make the actual tool tip poses reach the desired ones. Cui et al. [12] investigated a software system to realize error compensation via NC programs reconstructing according to the predicted errors during virtual machining. Chen et al. [16] used a software error compensation method to generate NC programs based on the summation of differential transformation matrix caused by the geometric errors of each motion axis. Fu et al. [3] described a strategy to obtain the compensated NC codes through calculating differential motion matrix of each axis relative to tool and constructing Jacobian matrix. Ding et al. [17] proposed a compensation principle to calculate the corrected NC codes obtained through algebraic operation. Zhou et al. [18] proposed a new compensation method based on the topology relation between each axis in kinematic chain of machine tools to calculate compensated position command of each axis. Table 1 shows the contributions of software compensation methods based on the published studies in the literature.

As can be observed in the above-mentioned studies, these software compensation methods only focused on how to calculate the modified code of tool path attaching the machine error information without considering tool cutting trajectory of the machine tool driven by the modified NC code. However, in practical machining process, the relative motion trajectory of the cutting tool with respect to the workpiece, which is known as the form of the machined workpiece, is the most important aspect that people interest in. Therefore, the importance of tool cutting trajectory should be well concerned. In addition, since the mapping relationship between the modified code and the tool cutting trajectory can truly indicate the real response of the machine tool to the modified NC code, unless it is perfectly represented, the machine tool driven by the given NC code cannot achieve the desired machining accuracy. In this scenario, authors of this paper have attempted to develop a new iterative methodology to solve this tricky problem.

In this paper, the relative motion constraint equation (TRMCE) is the theoretical basis and the crux of software compensation. To establish TRMCE, a systematic and suitable modeling method appears to be very necessary [19]. Over the past decades, many published articles have researched the modeling methods and have made noteworthy achievements. Eman et al. [20] utilized homogeneous transform matrix (HTM) to develop a generalized error model of a multi-axis machine with arbitrary configuration based on the assumption of rigid body motions. Jha et al. [21] used Denavit-Hartenberg (D-H) method to build a universal error model to improve the quality of cam profile on a five-axis CNC machine tool. Lin et al. [22] introduced a modified Denavit–Hartenberg (MD–H) method to model a multi-axis machine tool. Based on the multi-body system (MBS), Fan et al. [23] proposed a generalized kinematics error modeling method to improve the machining accuracy of NC machine tools by error compensation. Yang et al. [24] presented a new method to identify and correct position independent geometric errors (PIGEs) related to five-axis machine tools based on screw theory. Among these methods, MBS can describe the motion relationship among the components of machine tools simply and conveniently [25,26]. Therefore, in this research, HTM and MBS theory were utilized to establish TRMCE.

Table 1
The contributions of software compensation methods in machine tools.

References	Method	Contributions
[5,12–15,18]	Iterative method	(1) To calculate the additional codes attaching the machine error information; (2) To modify the ideal NC codes of tool path using the result of step (1).
[3,16]	Differential method	(1) To generate NC codes considering the geometric errors of each motion axis; (2) To modify the ideal NC codes of tool path based on the result of step (1).
[17]	Algebraic method	To directly calculate the corrected NC code of tool path considering the machine error information.



1-machine bed, 2-*Y*-axis slide carriage, 3-C-axis rotary table,4- workpiece, 5- *X*-axis slide carriage, 6-*Z*-axis slide carriage, 7-*B*-axis nutating head, 8-spindle, 9-cutting tool.

Fig. 1. The structure of a NOFAMT.

The rest of this paper is arranged as follows. TRMCEs of the tool center position and orientation related to one type non-orthogonal five-axis machine tool(NOFAMT) considering geometric error are established based on HTM and MBS theory in Section 2. In order to develop geometric error compensation, a new iterative compensation methodology based on Section 2 is presented in Section 3. In Section 4, experimental study is carried out to demonstrate the effectiveness of the proposed method, and finally some conclusions are drawn in Section 5.

2. Establishment of TRMCE considering geometric error based on HTM and MBS theory

2.1. Structure of the multi-axis machine tool

In this study, a NOFAMT with a nutating head is chosen as the research object, as shown in Fig. 1. The machine tool consists of machine bed (body 1), *Y*-axis slide carriage (body 2), *C*-axis rotary table (body 3), workpiece (body 4), *X*-axis slide carriage (body 5), *Z*-axis slide carriage (body 6), *B*-axis nutating head (body 7), spindle (body 8) and cutting tool (body 9). There is an angle between the nutating rotary *B*-axis and the axis of cutting tool, which is expressed as α. Note that our method can be