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Accuracy enhancement of five-axis machine tool based on differential motion matrix: Geometric error modeling, identification and compensation

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ABSTRACT

This paper presents the precision enhancement of five-axis machine tools according to differential motion matrix, including geometric error modeling, identification and compensation. Differential motion matrix describes the relationship between transforming differential changes of coordinate frames. Firstly, differential motion matrix of each axis relative to tool is established based on homogenous transformation matrix of tool relative to each axis. Secondly, the influences of errors of each axis on accuracy of tool are calculated with error vector of each axis. The sum of these influences is integration of error components of machine tool in coordinate system of tool. It endows the error modeling clear physical meaning. Moreover, integrated error components are transformed to coordinate frame of working table for integrated error transformation matrix of machine tools. Thirdly, constructed Jacobian is established using differential motion matrix of each axis without extra calculation to compensate the integrated error components of tool. It makes compensation easy and convenient with reuse of intermediate. Fourthly, six-circle method of ballbar is developed based on differential motion matrix to identify all ten error components of each rotary axis. Finally, the experiments are carried out on SmartCNC500 five-axis machine tool to testify the effectiveness of proposed accuracy enhancement with differential motion matrix.

1. Introduction

With high metal-removal rate, lower cutting time, high productivity and less workpiece set-up time, five-axis machine tools play an important role in the modern manufacturing industry [1]. The machining accuracy is one of the most important parameters of machine tools, which has great influence on the precision of workpieces. Factors which impact the machining accuracy include geometric errors, thermal errors, cutting force deformation error, servo tracking error and so forth. Among them, geometric errors and thermal errors account for about 60% of the total machining errors [2]. Due to their repeatability, stability, and measurability, prediction and compensation of geometric errors are an effective way to improve the machining accuracy of machine tools.

During the past decades, geometric error modeling and compensation of five-axis machine tools have attracted researchers' attention. The modeling makes use of homogeneous transformation matrices to represent the kinematics of machine tools based on multi-body system [3–5]. Uddin et al. presented a simulator of geometric errors for five-axis machine tools and proposed the compensation of tool position and orientation [1]. Chen et al. established volumetric error modeling with homogeneous transformation matrices and carried out the sensitivity analysis of 37 errors of model for design of five-axis machine tools [6]. Zhu et al. proposed the process of geometric error modeling, identification and compensation for machine tools, and also developed the corresponding software system for compensation by correcting NC codes [7]. Khan and Chen adopted 39 of 52 geometric errors to establish geometric error model based on the rigid body kinematics [8]. Then, they designed one compensation algorithm with the systematic error model using recursive method [9]. Cui et al. represented the geometric error model with multi-body system and developed compensation algorithm for three common movements: rapid positioning, linear interpolation, and circular interpolation [10]. Kong and Cheung adopted the surface generation mechanism of machine tools based on multi-body theory to develop the integrated kinematics error model [11]. They also proposed kinematic error measurement of motion slides for modeling and developed error compensation with ideal tool path

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and integrated error mapping. Chen et al. developed geometric error modeling with differential transform theory [12]. They regarded basic geometric errors of axes as a differential operator in the form of matrix, and computed Jacobian matrix for compensation. Lin and Shen proposed matrix summation approach for geometric error modeling [13]. They divided the errors into six components with clear meaning. Mir et al. proposed tool path prediction with geometric errors to improve the accuracy of workpiece [14]. They identified the geometric errors with sensitivity Jacobian matrix and predicted tool paths to compare with nominal path for assessment. Fu et al. developed integrated geometric error model with product of exponential (POE) formulas according to the clear physical properties [15]. They established twists and POE model for each axis and organized all twists and POE models with typological structure of machine tools to develop integrated POE error model.

The great majority of geometric errors modeling approaches are on the basis of multi-body theory. These geometric error models are established with the complex multiplication of homogeneous transformation matrices. The error calculation may be tedious and fallible due to numerous matrices including ideal and error matrices of each part. What's worse, these models cannot reflect the influences of geometric errors of each axis on integrated errors of machine tools, so error models play the very small role in design and manufacture of machine tools. As a result, one geometric error model which reflects the physical meaning of geometric errors should be developed in a different approach instead of complex matrices multiplication.

Some other studies focus on the effective and novel error compensation to enhance the precision of machine tools [16]. Lei and Hsu calculated Jacobian matrix based on the nominal forward transformation of machine tools in order for compensation [17]. They dealt with the problems of the zero denominators through extra compensation of special cases, which are singular problems of Jacobian essentially. Lei and Sung generated the compensated NURBS path through approximate error compensation function with the basis functions of setting NURBS path [18]. The compensation can be realized by simply calculating the errors of control points, and it can achieve high accuracy by inserting new knots systematically. However, the compensation of whole surface maybe not realized with approximation error compensation function with NURBS path because the tool path are common lines rather than NURBS path, such as straight lines and circle arcs. In addition, the geometric errors closely relate to the movement of each axis, which may lead the approximation of compensation to failure. Peng et al. proposed geometric error compensation with total differential methods, which improved the calculation speed and avoided the inverse kinematics solution [19]. They proposed the universal post processing algorithm with iteration to ensure the accuracy of compensation. While the differential computing causes huge and complex calculation. The differential also has singularity problems.

The most compensation used the iterative technology to ensure the compensation accuracy by reversing the calculated geometric errors of tool or using differential method. The iterative may greatly increase the amount of calculation. As a result, the approach reduces the compensation computation speed with uncertain multiple iterations. Jacobian matrix based on homogeneous transform matrix is another approach for compensation. However, Jacobian matrix is hard to calculate with partial differential. Moreover, the singularity problem is another difficulty of Jacobian matrix based on homogeneous matrix. The desired compensation will be easy, precision and have high computational efficiency.

Error identification of rotary axis is essential for error modeling of five-axis machine tools. It has attracted a lot of attention from research scholars for many years. Tsutumi and Saito proposed simultaneous multi-axis motion with ballbar to identify eight errors of two rotary axes [20,21]. Yang et al. established parametric model of errors for identification of rotary axis, and they designed some special measurement paths to increase the sensitivity [22]. Tsutumi et al. calibrated geometric errors of rotary axis by measuring the actual trajectories with two settings of ballbar. Measurements with different coordinate frames were compared and analyzed for identification precision [23]. Lei and Yang used two measurement paths of each rotary axis to identify position-independent errors by single motion of rotary axis. They also calculated the standard uncertainties of measurement for confidence intervals [24]. Xiang et al. proposed three measuring patterns to identify the eight position-independent errors of rotary axes. These patterns only needed two rotary axes moving to obtain a circular trajectory [25]. Lei et al. presented a particular circular test path for motion errors of two rotary axes, in which the circular path is caused by two rotary axes moving simultaneously without three linear axes [26]. However, all errors of two rotary axes including offset errors and squareness errors cannot be identified quickly and efficiently by these methods.

Transforming differential changes between coordinate frames has been widely used in the error modeling of robots. It helps calculate the contribution of errors of each joint to the accuracy of end-effector. The calibration and error compensation of robots can be achieved to improve the accuracy of robots with the error model. In addition, transforming differential changes between coordinate frames can be used to establish Jacobian matrix of robots. So it plays a great role in the kinematics and dynamics of robots. And it also can give a great help for design and motion control of robots. While in the field of machine tools, transforming differential changes between coordinate frames has not been spread.

This paper focuses on applying transforming differential changes between coordinate frames into accuracy improvement of machine tools. Firstly, the effect of geometric error components occurring in each axis to the tool will be calculated with differential motion matrix, namely, transforming differential changes between coordinate frames. Differential motion matrix of each axis to tool will be developed with the help of topological structure of machine tools. Secondly, the integrated geometric error components in tool coordinate frame will be obtained with simple summation, which can reflect the contribution of geometric errors of each axis to the machine tools. Thirdly, geometric error model of machine tools in working table coordinate system will be established including position and orientation errors of tool with the help of the forward kinematics. Fourthly, Jacobian matrix of machine tools will be obtained according to differential motion matrix of each axis to compensate integrated geometric error components in tool coordinate frame. Jacobian can be calculated during geometric error modeling without extra calculation, which makes the compensation easy and efficient. Finally, error identification of rotary axis with ballbar will be presented based on differential motion matrix.

The rest of the paper is arranged as follows: Section 2 establishes the integrated geometric error model of machine tools with differential motion matrix. First, the transforming differential change between coordinate frames is briefly reviewed. Second, the forward kinematics of machine tools is developed. Third, the geometric error components of each axis are translated into tool coordinate system with differential motion matrix. The summation of geometric error components are transformed for integrated error model in working table coordinate system. In Section 3, constructed Jacobian matrix is obtained with differential motion matrix. Section 4 establishes six-circle method to identify 10 errors of each rotary axis. In Section 5, experiments are carried out on five-axis machine tools to testify the accuracy of proposed error modeling, identification and compensation.