International Journal of Machine Tools & Manufacture 101 (2016) 65–78

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Modeling and compensation of volumetric errors for five-axis machine tools

Sitong Xiang [a], Yusuf Altintas [b,*]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Road, Shanghai 200240, PR China
[b] Manufacturing Automation Laboratory, Department of Mechanical Engineering, The University of British Columbia, Vancouver, BC, Canada, V6T 1Z4

ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form
4 November 2015
Accepted 11 November 2015
Available online 1 December 2015

Keywords:
Five-axis machine tool
Volumetric error
Error measuring
Error compensation
Screw theory

ABSTRACT

This article proposes a method to measure, model and compensate both geometrically dependent and independent volumetric errors of five-axis, serial CNC machine tools. The forward and inverse kinematics of the machine tool are modeled using the screw theory, and the 41 errors of all 5 axes are represented by error motion twists. The component errors of translational drives have been measured with a laser interferometer, and the errors of two rotary drives have been identified with ballbar measurements. The complete volumetric error model of a five-axis machine has been modeled in the machine's coordinate system and proven experimentally. The volumetric errors are mapped to the part coordinates along the tool path, and compensated using the kinematic model of the machine. The compensation strategy has been demonstrated on a five-axis machine tool controlled by an industrial CNC with a limited freedom, as well as by a Virtual CNC which allows the incorporation of compensating all 41 errors.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

There are 21 known geometric errors in three-axis machine tools [1], and 41 errors exist for five-axis serial machine tools. The errors have integrated effects in determining the orientation and position errors of the tool tip relative to the workpiece in five axis machine tools. The modeling and compensation of these volumetric errors are needed to improve the accuracy of the machine in the five-axis machining of parts [2].

The volumetric error compensation of multi-axis machine tools has 3 engineering steps: the kinematic modeling, measurement and modeling of axis errors, and their compensation during the positioning of the machine along the tool path. The kinematics of the machine have been modeled by applying the homogeneous transformation matrix (HTM) [1], by using the screw theory [3,4], by the product of exponential model [5], or by the differentiable manifold-based method [6]. This paper adopts the screw theory-based, generalized modular kinematic model of the five-axis machines reported previously [3].

The geometric errors of machine axes are measured by direct and indirect methods as reviewed by Schwenke [7] and Ibaraki [8]. The laser interferometer is mostly used in measuring the geometric errors of translational axes directly, and the geometric errors of rotary axes are identified indirectly by measurements with a ballbar [9], *R*-test [10,11], touch trigger probe [12,13], machining tests [14] and tracking interferometer [15,16]. Once the geometric errors of the axes are measured and modeled as a function of position in the Machine Coordinate System (MCS), they are translated to the tool orientation and tool tip position using a forward kinematic model of the machine in the Part Coordinate System (PCS). The errors are compensated by transforming the tool position and orientation errors to drive components via the inverse kinematic model of the machine in PCS. Lei and Hsu [17] presented a compensation algorithm for five-axis machine tools and analyzed the singularity problems. They [18] compensated the tool axis orientation errors first, followed by the compensation of the translational errors. Zhu [19] presented an identification approach for recognizing 6 error parameters of rotary axes via the ballbar test and verified the compensation of a five-axis machine tool on a “*S*” shape tool path. Huang [20] merged an iterative compensation method into the post-processor and generated a new, error-compensated NC program.

Commercial CNC systems have look-up tables which can be filled with axis errors at each position of the machine within its operating volume. However, they allow for the compensation of only translational errors, but not the deviations of tool orientations needed in five-axis machining applications [7].

This paper presents a detailed modeling, measurement and compensation method for the volumetric errors of five-axis machine tools as outlined in the flow chart given in Fig. 1. Yang et al. [21] used the screw theory to identify and compensate the 11

---

* Corresponding author.
E-mail addresses: stone.xiangst@gmail.com, xiangst@sjtu.edu.cn (S. Xiang), altintas@mech.ubc.ca (Y. Altintas).

http://dx.doi.org/10.1016/j.ijmachtools.2015.11.006
0890-6955/© 2015 Elsevier Ltd. All rights reserved.

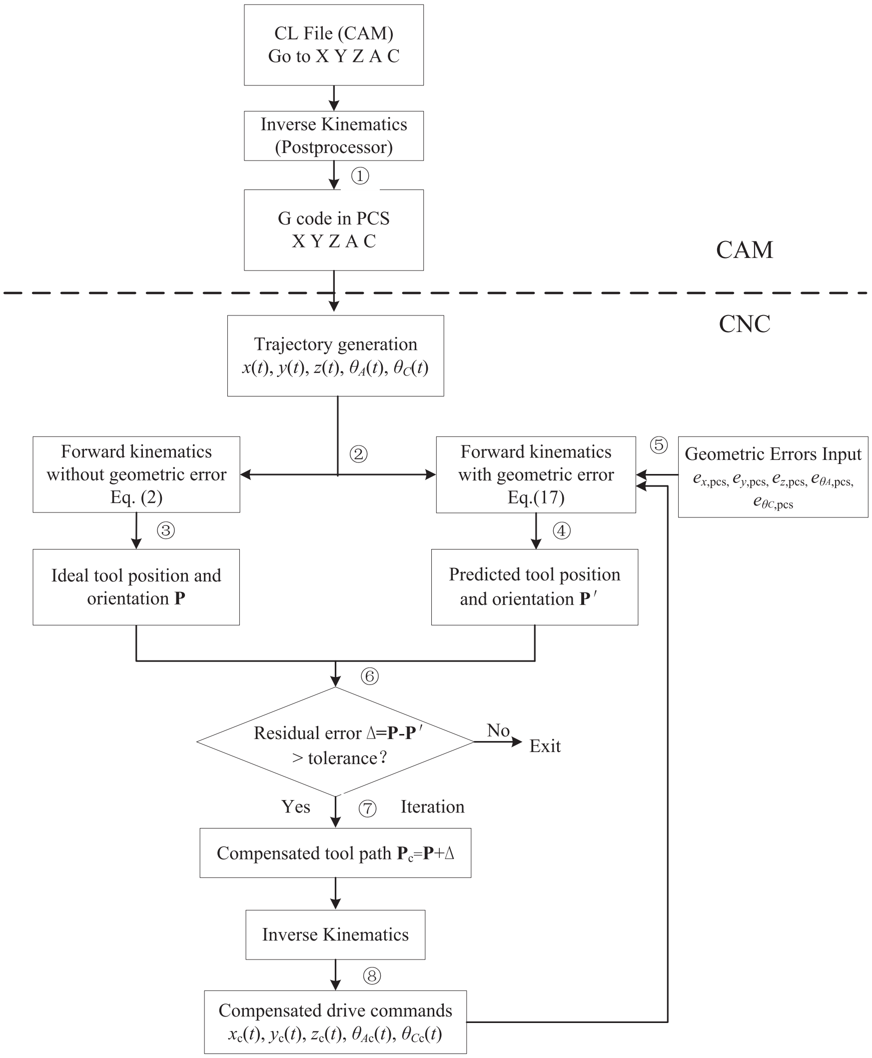

Fig. 1. Flowchart of compensation strategy.

position-independent geometric errors (PIGEs), i.e., the squareness of 3 translational axes and 4 linear offsets and 4 angular tilts of two rotary axes. This article extends Yang's method [21] by including both position-dependent and position-independent 41 geometric errors with a proposed, unified compensation method with the introduction of error twists.

Henceforth, the paper is organized to present the measurement, modeling and compensation algorithms used in Fig. 1. The kinematic model of a sample five-axis machine tool is modeled with the screw theory in Section 2. The concept of error twists is introduced to build a 3D volumetric error map of the machine in Section 3. Section 4 presents a methodology to identify all the errors of rotary axes, and Section 5 demonstrates the compensation strategy of volumetric errors. The paper is concluded in Section 6 by summarizing the effectiveness of the method and its practical application in CNC systems.

2. Kinematic model of five-axis machine tools

Although any serial, five-axis kinematic configuration can be modeled with the generalized kinematic model developed in our Virtual CNC [3], a machine tool with 3 translational and a trunnion with 2 rotary drives is used to illustrate the proposed modeling of volumetric errors and their compensation (Fig. 2). The MCS is

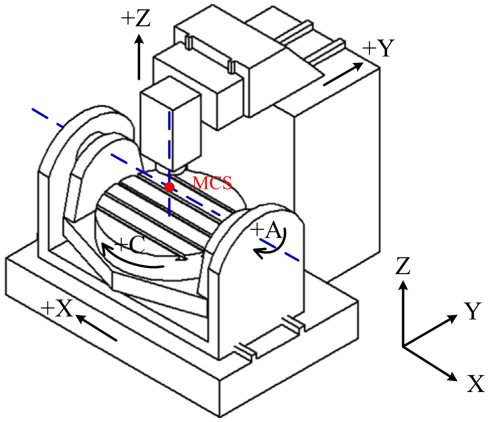

Fig. 2. Configuration of the five-axis machine tool.

defined at the intersection of the centerlines of the two rotary axes. The objective is to predict the relative error between the tool tip and workpiece clamped on the table as the drives move within the workspace of the machine. The kinematics of the machine is modeled using screw theory as presented in [3] and summarized for the particular five-axis machine used here.

The motion commands to the five drives (x, y, z, θ_A, θ_C) are used to predict the position and orientation of the tool tip relative to the

Download English Version:

https://daneshyari.com/en/article/780463

Download Persian Version:

https://daneshyari.com/article/780463

Daneshyari.com