International Journal of Machine Tools & Manufacture 89 (2015) 142–150

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

Position geometric error modeling, identification and compensation for large 5-axis machining center prototype

Gaoyan Zhong [a,*], Chaoqun Wang [a], Shoufeng Yang [b], Enlai Zheng [a], Yanyan Ge [a]

[a] *College of Engineering, Nanjing Agricultural University, Nanjing 210031, China*
[b] *Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, UK*

ARTICLE INFO

Article history:
Received 7 July 2014
Received in revised form
22 October 2014
Accepted 27 October 2014
Available online 5 November 2014

Keywords:
Position geometric error
Modeling
Compensation
Large
Machining center prototype
Virtual rigid-body

ABSTRACT

This paper presents a position geometric error modeling, identification and compensation method for large 5-axis machining center prototype. First, regarding the prototype as a rigid multi-body system, a geometric error model has been established, which supports the identification of position geometric error associated with a translational axis by using laser interferometer, and a rotational axis by using laser tracker. Second, based on this model, an improved identification approach named as virtual rigid-body is put forward for calculating positioning error of each large translational axis. Detailed derivation of a generalized matrix equation is given. Third, analytical models based on the least-squares theory were adopted to compute error values at an arbitrary position for error compensation. Finally, the identified position geometric errors were compensated by using recursive software-based error compensation method. The results show that the position accuracy of large machining center prototype has been improved with compensation and up to the design requirements.

1. Introduction

Along with large free-form surface parts growing demands, such as impeller, propeller vane, automotive models, yacht hull and so on, large high speed machining center is growing very rapidly in automotive, aerospace, die making and many other industries [1]. In manufacturing process, there are many factors, for instance, geometric errors, cutting force induced errors, kinematics errors, thermal errors, servo errors and tool wear, affecting the manufacturing accuracy. Among these affecting factors, the geometric error of machine tool components and structures is the most important because they affect positioning accuracy during all of the running time [2].

Over the last few decades, the tactics to reduce the geometric errors were divided into two categories [3]: (1) design and build precision machine tools and (2) software-based error compensation techniques. The first one increased the machine building cost exponentially. Also, even if a machine tool was very precise, the built-in accuracy would begin to erode as it ages [4]. The second one were highly cost-effective to improve geometric accuracy of machine tools [5,6], which can be divided into three steps [7]: (1) using a measuring device to measure errors, (2) developing an error model for machine tools and (3) conducting error compensation using the error model.

In the past, many researchers have paid attention to research the error compensation techniques for CNC machine tools and a great deal of research results has been presented. Leete [8] first proposed a model providing for continuous compensation of inherent errors in the machine tool by using the triangular geometry method. Later, the geometric errors on the accuracy of multi-axis machine tools have been widely studied. MOU [9] presented a systematic approach to advance the accuracy and functionality of multi-axis machines for precision manufacturing. Hsu and Wang [7] proposed a decouple method for geometry errors of five-axis machine tools, which calculates the error compensations for rotation axes and linear axes separately. Lee et al. [4] proposed a recursive compensation method to achieve error compensation efficiently.

In measuring device, recently, the most common and effective measuring device for geometric errors of three-axis machine tools has been 6D measurement system [10,11], which can simultaneously measure six degrees of freedom in a linear motion axis. In addition, the double ball bar (DBB) measurement device has often been used in evaluating dynamic errors of linear motion axes [12] and position-independent geometric errors [2], a 3D probe-ball measurement device has been developed to get three-dimensional overall errors of a five-axis machine tool [13], a ball-bar was used to identify the eight deviations inherent to a 5-axis machine center [14], a capacitance-sensor measurement system for measuring

---

[*] Correspondence to: Department of Mechanical Engineering, College of Engineering, Nanjing Agricultural University, No. 40, Dianjiangtai Road, Pukou District, Nanjing 210031, PR China. Fax: + 86 25 58606580.
E-mail address: gyzhong@njau.edu.cn (G. Zhong).

http://dx.doi.org/10.1016/j.ijmachtools.2014.10.009
0890-6955/© 2014 Elsevier Ltd. All rights reserved.

geometric errors of a miniaturized machine tool [4], and laser interferometer, laser tracker system are also used for geometric error calibration of CNC multi-axis machines [15,16,33,34].

As a general modeling method, homogeneous transfer matrix (HTM) [17] has been widely utilized for error models of CNC machine tools [18–20]. In addition, regarding a machine tool as a multi-body system (MBS) composed of a series of rigid bodies, Fan et al. [21] developed a universal kinematics modeling of a CNC machine tool based on MBS. The results of studies were later used for geometric error modeling of machine tools [22–24].

However, for large machining center, angle error would have influence on positioning error due to large translational axis. Convenient measuring devices, effective identification and compensation approaches are required. This paper extends our previous structures research [25,26] to the position geometric error modeling, identification and compensation for large 5-axis machining center prototype. Its goal is to enable the position accuracy of prototype up to design requirements by using the software-based error compensation method.

This paper is organized as follows: In Section 2, the prototype structure and its error definition was described. In Section 3, the geometric error model of the prototype is established based on MBS. In Section 4, an improved identification approach named as virtual rigid-body is put forward for calculating positioning error of each large translational axis and the position errors identification of 40 m × 6 m × 4 m prototype have been done by using laser interferometer for translational axes and using laser tracker for rotational axes. Finally, in Section 5, the identified position geometric errors were compensated by using recursive software-based error compensation method and the results are given before conclusions are drawn in Section 6.

2. Prototype structure and error definition

2.1. Prototype structure

The schematic diagram of 5-axis machining center prototype was shown in Fig. 1, which had 40 m × 6 m × 4 m translational axes, swing angle of the *B*-axis was ± 110°, turning angle of the *C*-axis was ± 360°. It is a TTTRR type [27] machine tool and suitable for large composite material free-form surface parts processing. The positioning accuracies of the machine were designed as 0.15–0.45 mm in the whole schedule.

2.2. Error parameter definition

It is well known that, in a translational axis, the six error components are one positioning error, two straightness errors, and three angular errors called pitch, yaw and roll. Also, in a rotational axis, its three linear error components are one axial error and two radial errors, and three angular error components are one angular position error and two tilt errors [3]. The error parameter definition of prototype was shown in Table 1. In this paper, position geometric errors are positioning error Δx_x, Δy_y, Δz_z for translational axis, and angular position error $\Delta\beta_b$, $\Delta\gamma_c$ for rotational axis, respectively. Other errors parameter compensation will be discussed in later research.

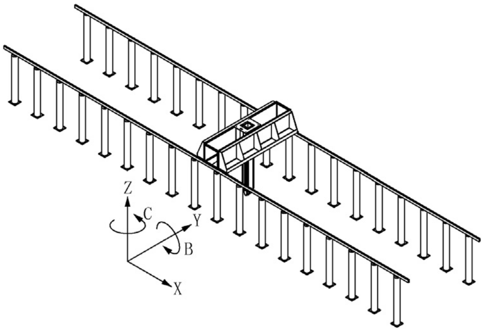

Fig. 1. Prototype structure of the 5-axis machining center.

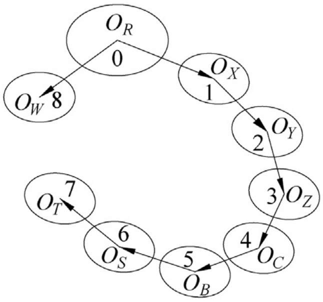

Fig. 2. Topological construction of the 5-axis machining center.

Table 1
Error parameter definition and expression of 5-axis machining center prototype.

Geometric definition		Expression	No.	Geometric definition		Expression	No.
X-linear axis	Positioning error	Δx_x	1	*B*-swing axis	Radial error to *X*	Δx_b	19
	Straightness error to *Y*	Δy_x	2		Axial error	Δy_b	20
	Straightness error to *Z*	Δz_x	3		Radial error to Z	Δz_b	21
	roll error	$\Delta\alpha_x$	4		Tilt error to X	$\Delta\alpha_b$	22
	Pitch error	$\Delta\beta_x$	5		Angular position error	$\Delta\beta_b$	23
	Yaw error	$\Delta\gamma_x$	6		Tilt error to Z	$\Delta\gamma_b$	24
Y-linear axis	Straightness error to *X*	Δx_y	7	*C*-rotation axis	Radial error to X	Δx_c	25
	Positioning error	Δy_y	8		radial error to Y	Δy_c	26
	Straightness error to *Z*	Δz_y	9		Axial error	Δz_c	27
	Yaw error	$\Delta\alpha_y$	10		Tilt error to X	$\Delta\alpha_c$	28
	Roll error	$\Delta\beta_y$	11		Tilt error to Y	$\Delta\beta_c$	29
	Pitch error	$\Delta\gamma_y$	12		Angular position error	$\Delta\gamma_c$	30
Z-linear axis	Straightness error to *X*	Δx_z	13	Perpendicularity errors	Perpendicularity error between *X* and *Y*	$\Delta\varphi_{xy}$	31
	Straightness error to *Y*	Δy_z	14				
	Positioning error	Δz_z	15		Perpendicularity error between *X* and *Z*	$\Delta\varphi_{xz}$	32
	Pitch error	$\Delta\alpha_z$	16				
	Yaw error	$\Delta\beta_z$	17		Perpendicularity error between *Y* and *Z*	$\Delta\varphi_{yz}$	33
	Roll error	$\Delta\gamma_z$	18				