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A new error measurement method to identify all six error parameters of a rotational axis of a machine tool

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ABSTRACT

This paper presents a new error measurement method, a Dual Optical Path Measurement Method (DOPMM), to identify error parameters of the rotational axis of a machine tool along its error sensitive directions. The method development was carried out on a motorized rotary stage equipped with a Doppler laser instrument. An error measurement experiment and a machining experiment were conducted on a five-axis machining center with a titling rotary table. It was found that the DOPMM can identify all of the six volumetric error parameters with the simple algebraic operations. Compared with the existing ball bar tests, which need a mathematical error modeling of machine tools to separate the error parameters, the identified process of DOPMM is more simple and easier to understand. And the operation of machine tools during the measurement is much easier than that of the existing ball bar tests. The experimental results showed that the part precision can have a significant improvement of 68% when the identified error parameters are used for error compensation. Hence, the measurement method established in this study is sensible and efficient, and could be used for the error compensation on a wide range of machine tools to improve their machining precision.

1. Introduction

The rapid development of modern manufacturing technologies requires that the machining operations associated with the manufacturing processes are of ultra-precision. Error compensation has therefore become an inevitable and cost-effective way to improve the accuracy and performance of machine tools, in which error modeling and error identification play a fundamental role. As such, extensive investigations have been carried out to establish efficient volumetric error modeling, measurement and identification methods [1,2]. Among the existing modeling techniques, a widely adopted approach, and probably also a most appropriate approach, is to assume that a machine tool can be treated as a multi-body system (MBS) composed of a few rigid bodies with a kinematic chain and a homogenous transfer matrix (HTM) [3–5]. For a 3-axis machine tool, there are 21 volumetric error parameters, and the measurement methods for translation axis errors have been available recently as specified in ISO230. Some relevant identification methods have also been presented, such as the 9-line method, 12-line method and the laser diagonal method [6,7].

With the rapid development of more sophisticated machine tools, e.g., the five-axis machine tools, machine configurations and machining error compensation processes have become increasingly complex [8,9]. For example, in addition to the translation axis errors it is critical to consider the influence of the errors caused by the movement of rotational axes. In the earliest researches, the position accuracy of multi-axis machine tools was measured for error compensation. Wang and Ehmann [10] developed a single socket method (SSM) to directly measure the positioning errors of a multi-axis machine. However, it was found that the inaccurate coordinates of reference points and the inaccuracy of a ball bar in a measurement would affect the measurement precision. Lei and Hsu [11] developed a 3D probe-ball device to measure the overall positioning errors of a five-axis CNC machine. With this method, several particular test paths need to be designed and the corresponding identification algorithms based on the closed kinematic chain of machine tools are rather complicated.

In the recent decade, the error measurement researches have been refined into the error parameters of the movement axis, which makes it possible to calculate the volumetric error of any position and posture point among the workspace of machine tools. And ball bar is commonly used to measure the volumetric errors of

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the machine tools in order to identify the error parameters. Tsutsumi and Saito [12,13] simplified the machine link errors of a five-axis machining center to thirteen deviations, and used a telescoping ball bar to measure and identify the eight deviations relating to two rotary axes in the five-axis machining center. Zargarbashi and Mayer [14] assessed the motion errors of a trunnion-type A-axis using the double ball bar. The method consisted of five tests using double ball bar with a single setup. However, the identification model was established based on the HTMs and the calculation was relatively complex. Moreover, the method cannot obtain the *A*-axis angular position error. Later on, they developed a 3D Capball sensor to estimate the eight link errors on a fly measurement [15]. Ibaraki [16] presented a machining test to identify the kinematic errors of a five-axis machine tool, which was mostly performed by driving only one linear axis during cutting to minimize the influence of the dynamic error. The calculation formulas were not so complex if compared with the ball bar measurement technique. This method was used for measuring kinematic errors; but it is unclear how the dynamic error was measured.

To date, the error measurement and identification for multi-axis machine tools have not yet been sufficiently investigated. Many of the methods available cannot identify all six error parameters of each rotation axis. Some others may have such a capacity, but usually involve a complicated measurement process and require complex mathematical formulations to identify the error parameters.

Considering that five-axis machine tools are one of the most widely used multi-axis machine systems in today's manufacturing industry, this paper will focus on the identification technology of volumetric error parameters for CNC machine tool rotational axis. To this end, Section 2 of the paper will establish a volumetric error model for a five-axis machine tool based on the multi-body system theory. Section 3 will develop a new error measurement method, a Dual Optical Path Measurement Method (DOPMM), to identify error parameters of the rotational axis of a machine tool, along the error sensitive directions. Section 4 will then verify the feasibility of the DOPMM on a five machining center with a titling rotary table. To examine the effectiveness of the new method, the machining precisions will be compared between the parts with and without the compensation of the error parameters identified by the DOPMM.

2. Volumetric error modeling

Most five-axis machine tools are composed of three translational axes (T) and two rotational axes (R). According to such configuration, three major types of five-axis machine tools have been widely used in industry: RRTTT type, TTTRR type and RTTTR type. Fig. 1 illustrates the schematic structural diagram of a vertical machine tool of type RRTTT. Compared to a three-axis machine, the errors caused by the two rotation axes of a five-axis machine, in addition to the three translation axes, should be taken into consideration when modeling the five-axis volumetric errors.

2.1. Errors parameters

(1) Errors caused by translation axes. For a three-axis machine tool, there are 21 error parameters, including 3 linear displacement errors, 6 straightness errors, 9 angular errors and 3 squareness errors [17].
(2) Errors caused by rotation axes. There are 6 error parameters which are inherent to each of the rotation axes, including 3 angle errors and 3 linear errors. For the *C*-axis rotary axis, these are $\varepsilon_{\alpha c}$, $\varepsilon_{\beta c}$, $\varepsilon_{\gamma c}$, δ_{xc}, δ_{yc} and δ_{zc} as defined in Tables 1 and 2.

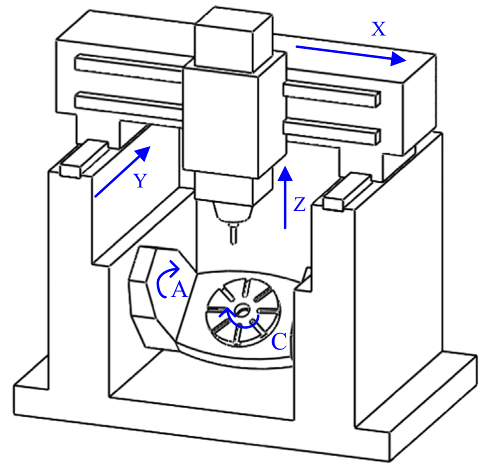

Fig. 1. The schematic structural diagram of a vertical machine tool of type RRTTT.

Table 1
Volumetric errors parameters caused by the 3 translation axes of a five-axis machine tool.

Translation axis	*X*	*Y*	*Z*
Linear displacement error	δ_{xx}	δ_{yy}	δ_{zz}
Straightness errors	$\delta_{yx}\delta_{zx}$	$\delta_{zy}\delta_{xy}$	$\delta_{xz}\delta_{yz}$
Roll, pitch and yaw angular error	$\varepsilon_{xx}\varepsilon_{yx}\varepsilon_{zx}$	$\varepsilon_{yy}\varepsilon_{zy}\varepsilon_{xy}$	$\varepsilon_{zz}\varepsilon_{xz}\varepsilon_{yz}$
Squareness errors	s_{xy}	s_{yz}	s_{xz}

Table 2
Volumetric errors parameters caused by the 2 rotation axes of a five-axis machine tool.

Rotation axis	*A*	*C*
Displacement error	δ_{xa} δ_{ya} δ_{za}	δ_{xc} δ_{yc} δ_{zc}
Angular errors	$\varepsilon_{\alpha a}$ $\varepsilon_{\beta a}$ $\varepsilon_{\gamma a}$	$\varepsilon_{\alpha c}$ $\varepsilon_{\beta c}$ $\varepsilon_{\gamma c}$

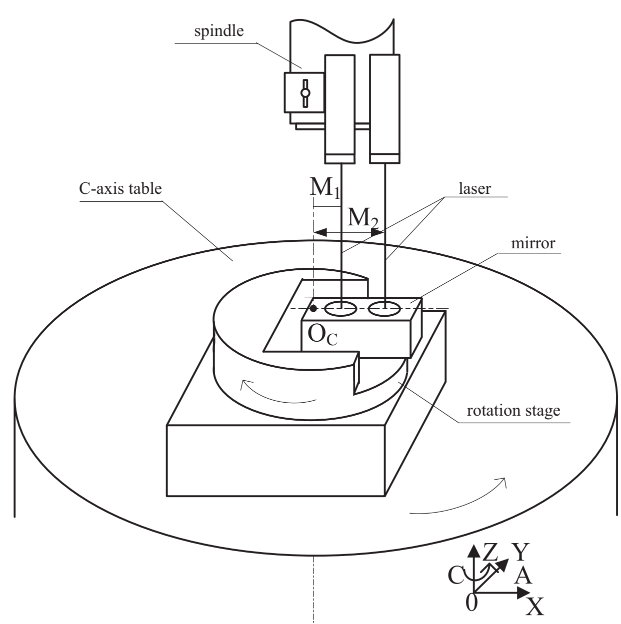

Fig. 2. The schematic of the setup for the measurement of error parameter $\varepsilon_{\beta c}$ and δ_{zc}.

Thus considering the five-axis machine center with a tilting rotary table (the RRTTT type shown in Fig. 1), there are 33 error parameters, as shown in Tables 1 and 2.