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Effect of servo and geometric errors of tilting-rotary tables on volumetric errors in five-axis machine tools

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ABSTRACT

The tilting-rotary table becomes a standard accessory for five-axis machine tools. An approach for volumetric errors evaluation taking into account servo and geometric errors of the tilting-rotary table is proposed in this paper. A simple machining model of volumetric circles is used to evaluate volumetric errors due to servo errors of the tilting-rotary table. A kinematic error model is used to predict the volumetric errors resulting from geometric errors associated with the tilting-rotary table. Then effects of the two error sources are added to predict the total volumetric errors. A test part obtained by improving the cone frustum specified in NAS979 is presented to validate this method. Cases studies with cutting experiments are carried out on a commercial five-axis machine tool. The results show that the proposed model is effective to evaluate the effect of servo and geometric errors of the tilting-rotary table on volumetric errors in the five-axis machine tool.

1. Introduction

Five-axis machine tools are widely used to machine complex parts with high accuracy. In industrial application, there are three combinations to yield the five-axis machine tool configuration [1]. The first is a universal head type with two rotary axes, and this type is often applied to the manufacturing of aero parts or dies. The second is a tilting-rotary table type with two rotary axes, which is commonly adopted to machine small and medium precise components. The third is a mixture type with a tilting head and a rotary table. In today's market, the tilting-rotary table becomes a standard accessory for machine tools. High-accuracy tilting-rotary tables have the positioning accuracy less than 0.001°. Consequently, by adding a modular tilting-rotary table, a conventional machining center with three orthogonal linear axes is easy to be converted to a five-axis machine tool. This is one of the reasons that the tilting-rotary table type is the most common five-axis machine tool. However, due to the added errors of the tilting-rotary table, it is more difficult to control volumetric errors of five-axis machine tools.

In recent years, notable efforts have taken place to investigate volumetric errors in multi-axis machine tools [2]. Volumetric errors of multi-axis machine tools are often decomposed into the following error sources: (1) the contouring errors due to the effect of servo errors of the axis drives, (2) the geometric errors of the machine and (3) the dynamic errors resulting from the machine structure deflection under dynamic loads, especially for high-speed machine tools [3]. On one hand, some measuring instruments are proposed to measure these errors. Wang et al. calculated volumetric errors in the work space of a machine tool based on the measurement by three CCD cameras [4]. Mayer et al. presented a 3D proximity sensing head to measure the link errors of a horizontal five-axis machine tool [5]. In addition, touch-trigger probes and laser interferometers were also used to calibrate a five-axis machine tool and assess its volumetric errors [6–8]. On the other hand, some methods are presented to estimate these errors. Tsutsumi et al. presented a method to identify eight geometric errors inherent to a five-axis machine tool by means of simultaneous four-axis control movements [9,10]. Uddin and Khan developed a model to predict geometric errors of five-axis machines by considering kinematic errors, respectively [11,12]. Zhu and Yang established an integrated geometric error model of a CNC machine tool [13,14]. Givi et al. used differential kinematics to estimate volumetric errors of five-axis machines [15].

However, the mentioned errors in the above are mainly about geometric errors. Sencer et al. presented a prediction model of contouring errors based on the five-axis machine kinematics and dynamics [16]. Mei et al. investigated contouring errors of a NC servo table at high speed with the consideration of friction [17]. Schmitz et al. compared the contributions of the geometric, servo and cutting forces errors to inaccuracies on a part manufactured by a three-axis high-speed milling machine [18]. Slamani et al. evaluated the volumetric errors of a five-axis high-speed machine

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tool taking into account geometric and dynamic errors. They developed polynomial functions to represent and predict the geometric errors, and a second-order transfer function model was established to predict dynamic errors [19,20].

While the above work focus on high-speed machine tools, and dynamic errors due to forces and deflections are the hot issue of their research. The objective of this paper is not to elaborate a complete error model of a five-axis machine tool, but to develop a simple approach which can be easily used to evaluate the effect of servo and geometric errors of tilting-rotary tables on volumetric errors of five-axis machine tools. The evaluation can help quantifying the relative impact of the two error sources to the total volumetric errors and selecting a reasonable tilting-rotary table for building a five-axis machine tool.

The structure of this paper is as follows. Error modeling of the tilting-rotary table is described in detail in Section 2. Section 3 proposes an approach to evaluate volumetric errors due to servo and geometric errors in the tilting-rotary table. Experimental validation and results discussion are presented in Section 4. Finally, Section 5 provides the conclusions of this paper.

2. Error modeling of the tilting-rotary table

In this study, a vertical five-axis machine tool equipped with a tilting-rotary table is considered as the target as shown in Fig. 1. As can be seen from Fig. 1, the tilting-rotary table is mounted on the rectangular worktable of the vertical three-axis machine tool. The tilting-rotary table is subject to unavoidable errors between the command and actual positions due to the imperfect mechanical structures and imperfect control systems. Their effects propagate through the machine kinematic chain, and cause volumetric errors between the workpiece and the cutting tool as seen in Fig. 2. Since the programmed feeding rate of rotary axes is not high, the dynamic errors are negligible here.

2.1. Servo error model

High contouring accuracy is required in many precision components and should be provided by servo control systems. It is known that circular tests provide a quick and efficient way to check the accuracy of servo control systems [20]. In order to analyze the effect of servo errors of the tilting-rotary table on

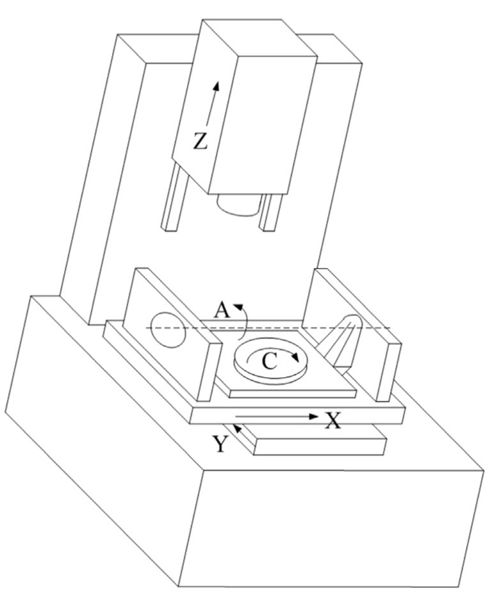

Fig. 1. Configuration of a typical five-axis machine tool with a tilting-rotary table.

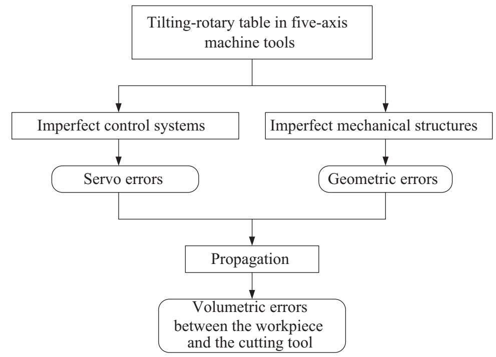

Fig. 2. Propagation of errors in the tilting-rotary table.

volumetric errors, a volumetric circle is taken as a target as illustrated in Fig. 3. X_{Wi}-Y_{Wi}-Z_{Wi} is the workpiece coordinate system, and X_{tj}-Y_{tj}-Z_{tj} is the tool coordinate system. The volumetric circle is obtained through two rotation transforms of a standard circle paralleled Cartesian coordinate system. Firstly, the standard circle rotates by ϕ_x about X_{W0}-axis. Secondly, the circle rotated about X_{W0}-axis rotates by ϕ_y about Y_{W1}-axis again. The simultaneous movements of the tilting-rotary table are demanded while the volumetric circle is machined. Consequently, servo errors of the two rotary axes have a significant effect. In this section, a simple model is developed to evaluate the effect of servo errors for each rotary axis as follows.

As seen from the Fig. 3, the tool coordinate system X_{ti}-Y_{ti}-Z_{ti} is attached in the spindle, and the point P is the cutter tip, where the diameter of the tool is ignored. The effective tool length, L, is determined from the origin point O_{ti} to the cutter tip P. Initially, the workpiece coordinate system X_{W0}-Y_{W0}-Z_{W0} coincides with the tool coordinate system X_{t0}-Y_{t0}-Z_{t0}. Then A-axis rotates by ϕ_x, and at this time the equation of the circle in the coordinate system X_{W1}-Y_{W1}-Z_{W1} can be derived as:

$$\begin{cases} Px^2 + Py^2 = (L \sin \phi_x)^2 \\ Pz = -L \cos \phi_x \end{cases} \tag{1}$$

Assuming that C-axis rotates continuously with the rotation velocity ω, any point of the circle in the coordinate system X_{W1}-Y_{W1}-Z_{W1} can be expressed as:

$$\begin{cases} Px = R \sin \omega t \\ Py = R \cos \omega t \\ Pz = H \end{cases} \tag{2}$$

where, $R = L \sin \phi_x$, $H = -L \cos \phi_x$. Consequently, the unit vector defining the tool axis orientation $[O_i, O_j, O_k]^T$ in the coordinate system X_{W1}-Y_{W1}-Z_{W1} is obtained as:

$$\begin{bmatrix} O_i \\ O_j \\ O_k \end{bmatrix} = \begin{bmatrix} \sin \phi_x \sin \omega t \\ \sin \phi_x \cos \omega t \\ -\cos \phi_x \end{bmatrix} \tag{3}$$

Finally, the volumetric circle is obtained by rotating ϕ_y about Y_{W1}-axis as well as the tool coordinate system X_{t0}-Y_{t0}-Z_{t0}, and this volumetric circle should be machined by simultaneous movements of two rotary axes. The coordinate of the new cutter tip P' in the coordinate system X_{W1}-Y_{W1}-Z_{W1} is calculated by rotation transformation metrics as:

$$\begin{cases} Px' = Px \cos \phi_y + Pz \sin \phi_y \\ Py' = Py \\ Pz' = -Px \sin \phi_y + Pz \cos \phi_y \end{cases} \tag{4}$$