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A novel spindle inclination error identification and compensation method in ultra-precision raster milling

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ABSTRACT

In the ultra-precision raster milling (UPRM) process, the existence of spindle inclination error can directly affect the dimensional accuracy of machined components. This study developed a novel spindle inclination error identification and compensation method based on the groove cutting in UPRM. In this method, the tilt angle of the intersection curve of two toruses (ICTT) generated from two neighboring rotary cuts in UPRM was measured to identify the spindle inclination error. A mathematical model was developed to simulate the ICTT profile and present the relationship between the tilt angle of ICTTs and the spindle inclination error by solving the differential of the ICTT function, by which the spindle inclination error can be solved under the given cutting parameters and the tilt angle of ICTTs. The effects of cutting parameters on the tilt angle of ICTTs were explored. An error compensation procedure was designed and a group of groove cutting experiments was conducted to identify and compensate the spindle inclination error. The theoretical and experimental results show that the proposed method can compensate for the spindle inclination error effectively and accurately.

1. Introduction

In ultra-precision machining, the accuracy of machine tools affects the surface quality of manufactured products. With the increase of functional demand on products and the associated demand on tolerance, cutting accuracy and efficiency in the manufacturing process has become more significant. As errors can directly affect cutting accuracy, the reduction of errors is crucial. For decades, error identification and compensation have drawn the attention of researchers in conventional cutting [1], high speed machining [2], micromilling [3], and ultra-precision diamond turning [4]. Based on the error classification method, errors existing in the cutting process include: geometric errors, thermally induced errors, load induced errors, and other sources of error such as fixing, material instability, instrumentation, and controller errors, all of which contribute to the dimensional accuracy and surface roughness of machined products [5]. Among these sources of machine tool errors, geometric errors [6–8] and thermally induced errors [9–12] are traditionally thought to be the key contributors and so a significant body of research has focused on them.

Geometric errors are usually generated by the inaccuracy, misalignment, and improper assembly of the machine parts. The errors can be reduced by the structural improvement of the machine tool through good design, manufacturing and assembly [13]. However, the method is either time-consuming or very expensive, especially when the accuracy requirements of the machine tool are beyond a certain level. Therefore, error compensation is employed to improve machine tool accuracy. Error compensation is a systematic process, which consist of four steps: modeling, measurement, parameter identification, and compensation [14]. Over the years, many different error compensation methods have been employed to improve the accuracy of machine tools: Lee and Liu (2006) developed a general volumetric error model to synthesize all geometric error components of a three-axis miniaturized machine tool and delivered a recursive compensation method to achieve error compensation [15]; Liang and Li (1997) proposed a comprehensive advanced error compensation system which can be used to compensate for geometric, thermal and force induced errors on a turning center in real-time [16]; Zhu and Ding (2012) presented an integrated geometric error modeling, identification and compensation method for machine tools that includes translational and angular geometric error parameters for identifying errors and correcting them using corresponding NC codes [17]; and, Hsu and Wang (2007) developed a geometric error compensation method for five-axis machine tools that calculates the error compensations for rotation axes and linear axes separately [18]. Many different theories are employed in the above mentioned models, such as incorporating statistical analysis [19], rigid body kinematics [20], and screw theory [21]. However, little research has been focused on error modeling and compensation in UPRM.

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Ultra-precision raster milling is also called ultra-precision fly cutting, because during the cutting process the diamond tool rotates around its spindle circularly with high speed while the workpiece is fixed on the rotary table. The cutting mechanism of UPRM is quite different from micromilling and single point diamond turning. Until now, the comprehensive kinematics model for UPRM was derived by Kong and Cheung (2012) whose integrated kinematics error model can predict the surface generation with error budget [22]. Zhang also conducted some meaningful research related to the effects of spindle vibration on surface generation in UPRM [23–25]. However, there has been no research on spindle inclination error and its compensation method in UPRM.

In the present research, a theoretical and experimental investigation was conducted on the spindle inclination error and its compensation method in ultra-precision raster milling. The intersection curve of two toruses (ICTT) generated from two neighboring rotary cuts in UPRM was measured to identify the spindle inclination error. A mathematical model was established to depict the relationship between the tilt angle of ICTTs and the spindle inclination error. The model can calculate the spindle inclination error accurately based on the measured tilt angle of ICTT and the given cutting parameters. The calculated error can then be used to compensate spindle inclination error to obtain an ideal result. This study provides a useful method for improving the accuracy of spindle inclination.

2. Experiments

In this investigation, all the cutting experiments were performed on a Precitech Freeform 705G (Precitech Inc., USA) CNC ultra-precision raster milling machine which owns 5-axes including three linear axes (*X*, *Y* and *Z* axes) and two optional rotary axes (*B* and *C* axes), as is indicated in Fig. 1(a). In the machining system, the workpiece is mounted on the *B* axis rotatable table, while the diamond tool is installed on the aerostatic gas bearing spindle holder rotating around the spindle circularly, the experimental setup is shown in Fig. 1(b). The pose of the aerostatic gas spindle can be adjusted by the rotatable *C* axis, so that multisurface structures can be machined using this type of machine.

In this research, the experiments were performed by a series of designed groove cuttings on a brass bulk, as is shown in Fig. 2(a). In the groove cutting, the cross-section profile of the groove should be the profile of cutting edge of the cutting tool due to no feed in the step direction. To protect the cutting tool, each groove was generated by several layers of groove cutting in the cutting depth direction (see Fig. 2(b)).

In this experiment, two diamond tools with tool nose radii of 0.256 mm and 0.631 mm were employed to machine grooves and identify the spindle inclination error. The tilt angle of each ICTT from both machined grooves was measured. The measured tilt angles of ICTTs were then used to calculate the spindle inclination error, and the spindle inclination error was compensated by adjusting the *C* axis. To explore the effects of diamond tool geometric parameters and cutting parameters on the tilt angle of the ICTT, different cutting depths and feed rates were used to machine the grooves. The specific tool geometric parameters and cutting parameters used in this experiment are shown in Table 1.

After compensation, the cutting machine was operated to repeat cutting the same numbers of grooves with the same cutting parameters listed in Table 1. The tilt angle of ICTTs after

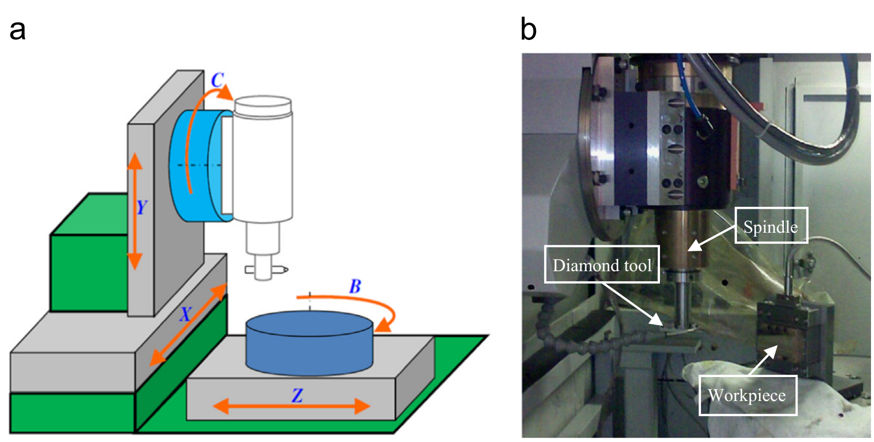

Fig. 1. Schematic diagram of freeform 705G machine (a) and the experimental setup for groove cutting (b).

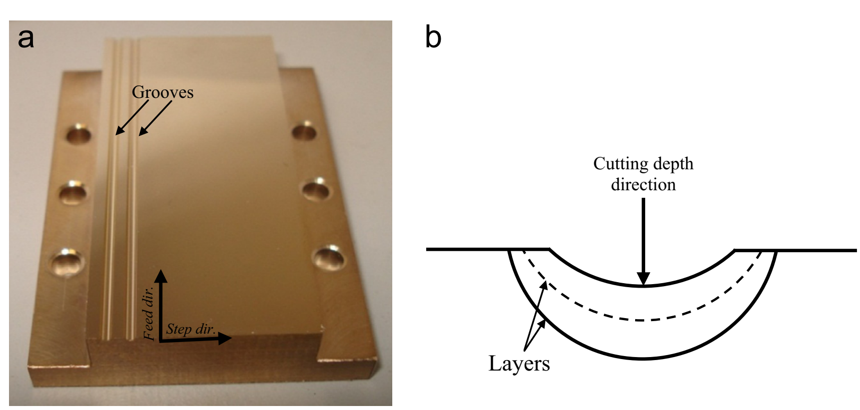

Fig. 2. The workpiece used in the experiment (a) and the cutting strategy of grooves (b).