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On-machine measurement of location errors on five-axis machine tools by machining tests and a laser displacement sensor

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ABSTRACT

This paper proposes an on-machine measurement (OMM) of all location errors on five-axis machine tools. Five machining patterns are successively performed on a cubic workpiece. The basic idea is to use a set of large rotations of rotary axes to prolong the moving distance of linear axes when squareness errors of linear axes are identified. Then, a set of small rotations of rotary axes are used to decouple the squareness errors of linear and rotary axes. Based on this, the long and deep slots in previous machining tests are improved to be a set of short and shallow ones. These miniaturized slots reduce the material removal and minimize the influence of cutting force and thermal deformation on the measuring results. Then the cutting tool is substituted by a laser displacement sensor (LDS) to measure the mismatch between the finished surfaces of the corresponding slots. All the measured surfaces are located on the bottom of the slots to fit the LDS characteristic of one dimensional measurement. Three gestures of the rotary table and tilting head are used to implement the single-setup OMM and the influence of location errors on the measuring results is compensated. Validation of the identified values is also provided by a set of simple tests using different measuring instruments. The efficiency and accuracy of location errors measurement method on five-axis machine tools are improved.

1. Introduction

1.1. Previous literatures

The geometric error identification of five-axis machine tools has been widely investigated. Many researchers have studied identification methods relying on various kinds of measuring instruments. The double ball bar (DBB) has been widely applied for measurement of geometric errors [1–7]. Another two kinds of continuous measuring method named R-test [8–13] and Non-contact R-test [14, 15] have also been proposed. They both used the instrument called 'Chase-the-Ball'. Compared to the DBB, the 'Chase-the-Ball' is capable of acquiring three dimensional coordinates of the ball at one sampling point. On the other hand, as a discrete on-machine measuring instrument, the touch trigger probe has also been used to design efficient identification methods for geometric errors by Ibaraki et al. [16,17] and Mayer et al. [18,19].

Compared to the unloaded measuring method mentioned above, machine operators are more concerned about location accuracy of machine tools during the actual machining. For the purpose of evaluating the real machining performance, a cone frustum workpiece is provided in standard NAS979 [20]. Ibaraki et al. [21] used this cone frustum to verify the estimation and the compensation of geometric errors of five-axis machine tools. In ISO10791 [22] a workpiece with more complex geometry is machined and probed on a CMM (coordinate measuring machine) for the accuracy check of five-axis machine tools. In 2010, Ibaraki et al. [23] provided a set of machining tests to estimate rotary axes location errors. During these tests, a set of steps are machined on a cubic workpiece at different gestures of motion axes and then the workpiece geometry are checked on a CMM. In 2014, Ibaraki et al. [24] improved the machining tests for measurement of rotary axes error motions by an on-machine measurement (OMM). Recently, Givi et al. [25] performed a set of machining tests and then measure the geometry of finished workpiece by OMM using a touch trigger probe which fixed on the spindle of machine tool. Then the link errors of all motion axes were identified according to the probing results. The machining accuracy after compensation can be also observed by performing the similar machining tests and OMM on the same workpiece again.

Hitherto only the touch trigger probe has been used in the OMM based on machining tests for geometric errors of machine tools [24,25]. For the improvement of measuring efficiency and minimization of contact measurement uncertainty, a non-contact measurement with higher sampling rate are necessary. A one-dimensional visual measuring instrument called laser

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displacement sensors (LDS) has been used by Hong and Ibaraki et al. [14] to measure the location accuracy of a ceramics ball. And the performance of LDS on location errors evaluation has already been validated [14].

1.2. Motivations

Previous methods have already made great contributions to the measurement of location errors on five-axis machine tools. However, some important aspects might not have been fully considered yet.

1) Most literatures and standards [20,23] focused on the configuration with a rotary-tilting table or a universal head. Only Lee et al. [5] proposed a measuring method of geometric errors on the configuration with a tilting head. Since the distribution of location errors changes with the variation of machine configuration, calibration method designed especially for one configuration cannot be performed on other ones directly.
2) Only Mayer et al. [15,25] have proposed identification method of all location errors (including the location errors of all linear and rotary axes). Other researches about location errors are all proposed based on the assumption that the geometric errors of linear axes have been already identified separately.
3) The method proposed by Mayer et al. [15,25] is designed based on an identification Jacobian matrix. All the location errors can be calculated after the entire measuring procedure has been performed consecutively. The relationship between location errors and measuring steps may be not intuitional enough so that the targeted measuring step spatially for a certain location error is difficult to be performed separately.
4) Morimoto et al. [26] proposed a set of machining tests for all location errors on a workpiece with an approximate size of $300 \times 300 \times 150$ mm. The workpiece with a big volume and long finished slots for squareness errors of linear axes make it costly and time-consuming.
5) All the proposed machining tests [23–26] are followed by the measurement of geometry of finished workpiece with a touch trigger probe. The measuring efficiency may be restricted by the deceleration of probe ball when the stylus approaches each target point.

1.3. Contributions

This paper proposes a new on-machine measuring method for the eleven location errors of both linear and rotary axes on five-axis machine tools.

1) The measuring method is designed based on the kinematic model of five-axis machine tools. The location errors of linear and rotary axes are decoupled so that the relationships between each location error and corresponding measuring step are intuitive enough for the separate identification of each location error.
2) The basic idea is to use a set of large rotations of rotary axes to prolong the moving distance of linear axes when squareness errors of linear axes are identified. Then, a set of small rotations of rotary axes are used to decouple the squareness errors of linear and rotary axes.
3) Since the relative movement between the cutting tool and workpiece can be minimized significantly by the cooperation of rotary axes, a series of short and shallow slots can be successively machined on one workpiece. Therefore, the measuring accuracy of squareness errors is guaranteed with the addition of less influence of cutting force and thermal deformation.
4) The mismatch between the bottoms of corresponding slots is measured by a LDS fixed on the spindle efficiently. A CMM is unnecessary here. The measuring errors of the OMM are also compensated. The measuring efficiency is increased by the significantly reduced material removal and high sampling rate of the LDS.
5) The basic idea of this OMM method is designed for the five-axis machine tools with a tilting head firstly. However, it has to be mentioned that the basic idea of this OMM can be used on five-axis machine tools with other kinds of configurations. The utilization of this OMM on the configuration with a tilting-rotary table is also introduced in Section 3.

1.4. Arrangement of the paper

In Section 2, kinematic model including eleven location errors of five-axis machine tools with a tilting head is established. In Section 3, five machining patterns and the corresponding algorithm are provided. In Section 4, the mismatch between corresponding machined surfaces is measured by a LDS. The influence of location errors on measuring accuracy is compensated and the measuring results are represented and used to calculate the location errors. Also, different measuring instruments are utilized to validate the identified location errors. In Section 5, uncertainty analyses of this OMM method are provided. In Section 6, conclusions are given and our future work is briefly introduced.

2. Kinematic model including location errors

2.1. Machine configuration

The machine tool considered is a five-axis machine tool with a tilting head and a rotary table as shown in Fig. 1. The three linear motions are generated by the linear axes *X*, *Y* and *Z*. And the two rotational motions are generated by *B*- and *C*-axis respectively.

2.2. Location errors to be identified

Location errors can be considered as assembly errors and structure errors which represent the relative location errors between each motion axes. For the configuration given in Fig. 1, it contains eleven location errors (Fig. 2) as listed in Table 1. It has to be mentioned that the all the squareness errors and δ_{xBZ} are inherent errors brought by the assembly. Other three linear offset are

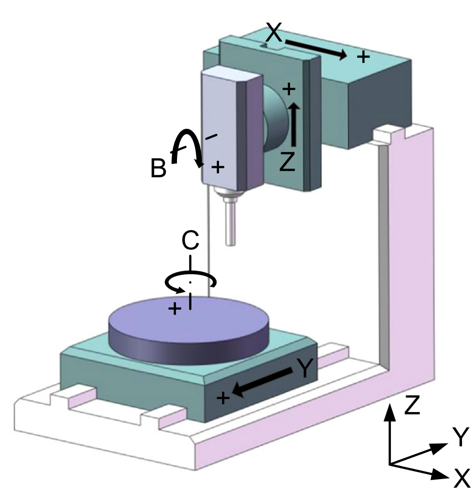

Fig. 1. The configuration of five-axis machine tool researched in this paper.