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A method of testing position independent geometric errors in rotary axes of a five-axis machine tool using a double ball bar

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ABSTRACT

Ensuring that a five-axis machine tool is operating within tolerance is critical. However, there are few simple and fast methods to identify whether the machine is in a “usable” condition. This paper investigates the use of the double ball bar (DBB) to identify and characterise the position independent geometric errors (PIGEs) in rotary axes of a five-axis machine tool by establishing new testing paths. The proposed method consists of four tests for two rotary axes; the *A*-axis tests with and without an extension bar and the *C*-axis tests with and without an extension bar. For the tests without an extension bar, position errors embedded in the *A*- and *C*-axes are measured first. Then these position errors can be used in the tests with an extension bar, to obtain the orientation errors in the *A*- and *C*-axes based on the given geometric model. All tests are performed with only one axis moving, thus simplifying the error analysis. The proposed method is implemented on a Hermle C600U five-axis machine tool to validate the approach. The results of the DBB tests show that the new method is a good approach to obtaining the geometric errors in rotary axes, thus can be applied to practical use in assembling processes, maintenance and regular checking of multi-axis CNC machine tools.

1. Introduction

1.1. Background and preliminaries

One of the main criteria for modern manufacturing industry, i.e. aircraft building, mould manufacturing, is the ability to achieve high precision [1]. Due to high accuracy and minimal set-up operations required, five-axis machine tools are thus widely used [2]. Components like impellers are extremely difficult or impossible to machine using 3-axis machine tools but can be easily made by five-axis machines. A five-axis machine tool is generally configured with two rotary axes in addition to the three linear axes. They can be located in the spindle head, in the workpiece side or one rotary axis in the spindle head and one in the workpiece side [3].

However, the rotary axes introduce additional error sources which may lead to flaws and defects in finished components. According to Lei [4], rotary axes are the major error sources in five-axis machine tools. Therefore regular checks and calibration of rotary axes are essential in order to maintain the machine tool accuracy.

Errors existing in multi-axis machine tools are due to flaws in components and joints. They can be broadly classified as geometric errors, thermally induced errors and dynamic errors. As [2,5] pointed out, geometric errors are the most significant factor affecting a machine's accuracy. Therefore most of the recent research has focused on how to reduce or compensate for geometric errors. According to [6,7], geometric errors of a machine tool can be categorised as position dependent geometric errors (PDGEs) and position independent geometric errors (PIGEs), where “position” is the commanded location of the controlled axis. They are also referred to as component errors and location errors [5,8]. Since the PDGEs are caused by inaccuracies in the machine components and the PIGEs result from the imperfections in the assembly process of the machine components, the value of PDGEs varies from position to position, whilst the PIGEs are constant regardless of the positions of the axes. Much effort has been made to identify and understand PIGEs. In order to simulate these errors mathematically, various models have been developed for both PDGEs and PIGEs [9–11]. The most commonly used method for modelling the PDGEs is to describe them either by *n*th-order polynomials, Fourier or Taylor series [12–14]. Since the PIGEs do not rely on the positions of axes, they can be regarded as constant values [8]. Compared with the PDGEs, PIGEs are easier to determine, thus are examined first [5]. Considering the rotary axes are the major error source, this paper deals with the PIGEs of rotary axes on a tilting-rotary table type five-axis machine tool.

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1.2. Review on current approaches

A number of methods for testing the accuracy of rotary axes have been proposed recently. Methods included in ISO 230-1:2012 provide a variety of options for testing the geometric accuracy of axes of rotation [6]. The use of an optical polygon with an autocollimator is able to measure the angular positioning error motion. The combination of a reference indexing table with a laser interferometer/autocollimator is also capable of testing the angular positioning behaviour of a rotary axis. Recently a new commercial product which can be used together with an interferometer to test the positioning accuracy of a rotary axis has been proposed [15]. By having an opposite directional rotation of the retroreflector to the rotary axis under test, the laser beam emitted from the interferometer and the one reflected back from the rotary retroreflector are used as an indication of angular errors. Another application using a calibration sphere and strain gauge probes provides an accurate health check of rotary axis pivot points [16]. However, these measurement systems are expensive and the setup of the instrument is time consuming. Simple and fast methods are required for checking the rotary axes.

In this study, a DBB has been used to investigate the PIGEs of rotary axes in a five-axis machine tool [17]. A DBB is a piece of one-dimensional length measuring equipment and is ideal for quick checking of 3-axis machine tools. The standard testing scheme comprises three circular tests, namely XY, YZ and ZX planar tests. The DBB software is able to translate the length changes into errors based on the geometry of trace patterns of different individual errors.

In terms of DBB systems used for rotary axes measurement and calibration, previous research initially started from simultaneous movement involving one rotary axis and two linear axes, forming synchronous movements in three different directions [18]. Eight PIGEs were measured using this method. With a few changes in the testing configuration, error conditions of different types of five-axis machine tools can be estimated [19]. The idea of placing the centre of one of the two balls of a DBB on the rotary axis reference straight line has been used by a few researchers, and could simplify the error separation process of the eight PIGEs [8,20,21]. Lei et al. [22] proposed a new trajectory having the *A*- and *C*-axes moving simultaneously on a tilting rotary table type five-axis machine tool to test the motion errors of the rotary axes performance. An idea of mimicking the cone frustum cutting test using a DBB has been applied to drive all five axes simultaneously [5,23-26].

In terms of minimising the testing time and simplifying the testing procedure, a DBB is an ideal tool for machine diagnostic testing, compared with other methodologies that require longer setup time and greater financial investment [1,2]. However, simple, quick and effective methods using a DBB to test the rotary axes do not exist. This study will focus on the geometric identification and characterisation of the position and orientation PIGEs of rotary axes, in particular the *A*- and *C*-axes, of a tilting rotary type five-axis machine tool using a DBB system. For the purpose of isolating errors from other axes, only one rotary axis is driven and tested in each test. Individual rotary axes were tested by extending the DBB without having to move the centre pivot position. Another advantage of the proposed method lies in its simplicity in fixtures. A standard DBB toolkit can meet the requirement of all test steps. This will enhance the experiment accuracy and reduce the complexity of the measurement. The proposed method can also be used on five-axis machine tools with an indexing rotary table having one rotary axis. The following sections outline the approaches to minimise the set-up errors in the spindle tool cup and the centre pivot tool cup. Geometric models are developed to deduce the PIGEs from raw data collected using a DBB. Finally a brief conclusion is drawn to summarise the contribution of the work.

2. Machine structure and PIGEs of rotary axes

2.1. Five-axis machine tool

As depicted in Fig. 1, a tilting rotary table type five-axis machine tool consists of three linear axes *X*-, *Y*- and *Z*-axes, and two rotary axes *A*- and *C*-axes, which are rotations about the *X*- and *Z*-axes respectively. This type of five-axis machine tool can be seen as a combination of a 3-axis machine tool configured in a standard Cartesian coordinate system and a tilting rotary table.

2.2. PIGEs of rotary axes

According to ISO 230-1 [6], there are five PIGE components for each rotary axis. Fig. 2 shows the PIGEs of the *C*-axis in a 3D coordinate system. Corresponding to ISO 230-1 [6], the PIGEs are denoted as the letter "E" followed by a three character subscript where the first character is a letter representing the name of the axis corresponding to the direction of the error, and the second character is a numeral 0 (zero) and the third character is the name of the axis of motion.

There are two linear position errors E_{X0C} and E_{Y0C} in the XY plane, two orientation errors E_{A0C} and E_{B0C} tilting about the *X*- and *Y*-axes and one zero position angular error E_{C0C} for the *C*-axis. If only the position and orientation of the machine tool coordinate system are considered, the zero position error can be ignored [6]. Thus four errors, two position errors and two orientation errors, are needed for identifying the PIGEs for a rotary axis.

The reference straight line in Fig. 2 refers to an associated straight line fitting the measured trajectory of points [6]. It is calculated using least squares, providing a representation of the actual condition of axes [12,13]. Lines 1 and 2 represent the projections of the reference straight line onto the XZ and YZ plane respectively.

Errors in the *A*-axis, shown in Fig. 3, are defined in a similar way. The two position errors are E_{Y0A} and E_{Z0A} in YOZ plane and the two orientation errors are E_{B0A} and E_{C0A}, which are the rotations about the *Y*- and *Z*-axes respectively. Lines 1 and 2 are the projections of the reference straight line onto the XY and XZ planes respectively.

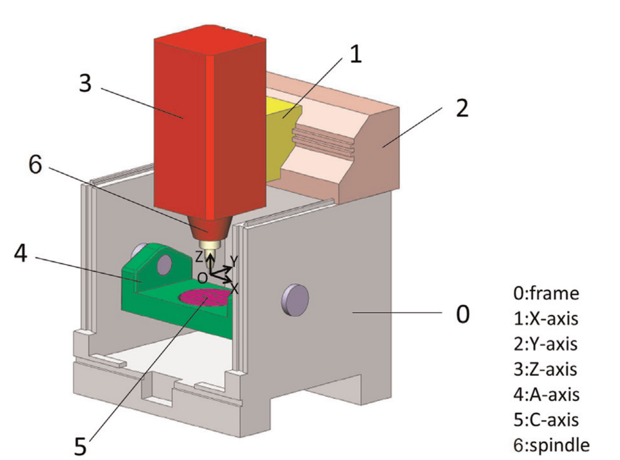

Fig. 1. The structure of a tilting rotary table type five-axis machine tool.