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A machining test to evaluate geometric errors of five-axis machine tools with its application to thermal deformation test

Soichi Ibaraki[a]*, Yusuke Ota[a]

[a]*Dept. of Micro Engineering, Kyoto University, Katsura, Kyoto 615-8530, Japan*

* Corresponding author. Tel.: +81-75-383-3676; fax: +81-75-383-3676. *E-mail address:* ibaraki@prec.kyoto-u.ac.jp

Abstract

This paper proposes a machining test to calibrate position-dependent geometric errors, or "error map," of rotary axes of a five-axis machine tool. At given sets of angular positions of rotary axes, a simple straight side-cutting using a straight end mill is performed. By measuring geometric errors of the machined test piece, position and orientation of rotary axis average lines (location errors), as well as position-dependent geometric errors of rotary axes, can be numerically identified based on the machine's kinematic model. Furthermore, by repeating the proposed machining test consequently, one can quantitatively observe how the position and the orientation of rotary axes change with respect to the tool spindle due to thermal deformation induced mainly by tool spindle rotation. Experimental demonstration is presented.

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Keywords Five-axis machine tools; machining test; geometric errors; kinematic model; touch-triggered probe

1. Introduction

Machine tools with two rotary axes to tilt/rotate a tool and/or a workpiece, in addition to three orthogonal linear axes, are collectively called five-axis machine tools. On five-axis machine tools, error motions of each linear/rotary axis, as well as its alignment (assembly) errors, are accumulated in the positioning error of a tool relative to a workpiece. For efficient measurement of these errors, many "indirect" measurement methodologies, i.e. schemes to separately identify each error component from a set of measured tool center position (TCP) profiles, have been studied [1, 2]. ISO/DIS 10791-1 [3], currently under a revision process in ISO/TC 39/SC 2, contains quasi-static tests with a main interest in calibrating position and orientation errors of rotary axis average lines. The application of the ball bar to rotary axis dynamic measurements has been studied by many researchers [4,5] and is now included in ISO/DIS 10791-6 [6], also currently under a revision process in ISO/TC 39/SC 2. The R-test [7,8] is also in ISO/DIS 10791-6 [6]. A touch-trigger probe can be applied analogously to the 'chase-the-ball' test [9,10] and commercial probe-based calibration systems are now available.

Although it is important to evaluate geometric errors of rotary axes by such a non-cutting measurement, typical machine tool users consider more the machine's accuracy when it performs actual machining. Non-cutting tests are sometimes performed when the machine is "cold." In the machine's normal operating conditions, the spindle rotation, as well as environmental change, may potentially cause significant thermal deformation. In such a normal operating condition, the machine's geometric errors may be significantly different from those in 'cold' condition.

NAS (National Aerospace Standard) 979 [11], Clause 4.3.3.8.1, describes a cone frustum five-axis machining test. Since it is only standard well known describing a five-axis machining test, it is widely accepted by many machine tool builders as one of final performance tests. ISO/TC 39/SC 2 is currently discussing the inclusion of the cone frustum machining test in the revision of ISO 10791-7 [12]. Although it gives a good demonstration of the machine's overall machining performance, it is generally difficult to diagnose error sources from the measured geometry of the finished test piece [13,14].

The objective of this paper is to propose a new five-axis machining test such that geometric errors of rotary axes can be

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separately identified by evaluating the geometric error of the machined test piece. In [15], a part of the authors presented a machining test to identify position and orientation errors of the axis average line of two rotary axes. This paper presents its extension to the calibration of position-dependent geometric errors, or “error map,” of rotary axes.

Furthermore, the paper will present its application to the observation of thermal influence on geometric errors of rotary axes. Experimental demonstration will be presented.

2. Proposed machining test

This paper considers a five-axis machine configuration with a titling rotary table (driven by B- and C-axes) depicted in Fig. 1. In principle, the basic idea of this paper can be straightforwardly extended to any five-axis configurations.

The proposed machining test is illustrated in Fig. 2. At B_i=C_j=0°, a square-shaped step is machined by simple side-cutting using a straight end mill by driving X- and Y-axes only. The square step is machined at different heights at each combination of C_j=0, 90, 180, 270° (j=1~4) and B_i=0, -90, 90° (i=1~3). Total 4×3=12 finish cuts are made. Figure 3 shows an example of the nominal geometry of the finished test piece (adopted in the experiment in Section 4). The finishing condition must be properly chosen such that the influence of tool deflection or surface finish on the geometric measurement becomes sufficiently small. It is recommended to repeat the finishing with zero radial depth of cut (“zero cut”).

Then, the finished test piece's geometry is measured. Figure 4 shows an example of probed points. The measurement coordinate system is set up based on the position and the orientation of the uppermost step, machined at B_i=C_j=0°.

3. Identification of rotary axes geometric errors

3.1. Geometric error parameters to be identified

In ISO 230-1 [16], the *axis average line* of a rotary axis is defined as "the straight line representing the mean location and orientation of its axis of rotation." Position and orientation errors of a rotary axis average line, called *location errors* in ISO 230-7 [17], are clearly among the most fundamental error factors in the five-axis kinematics. Table 1 shows location errors sufficient to describe the kinematics for the configuration in Fig.1 [16, 18].

It is to be noted that they only represent 'average' position or orientation of a rotary axis. The axis of rotation may change its position and orientation with its rotation. Such an error motion can be parameterized by *position-dependent geometric errors* [13]. Table 2 shows position-dependent geometric errors for B-axis.

It is important to note that this paper assumes geometric errors of linear axes are negligibly small compared to those of rotary axes. Many five-axis error calibration methodologies, briefly reviewed in Section 1, are based on the measurement of the TCP relative to the table, and it is therefore not possible

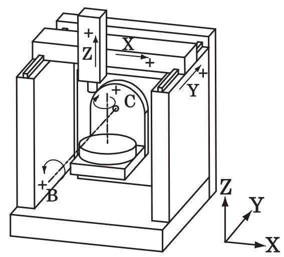

Fig. 1. Five-axis machining tool configuration.

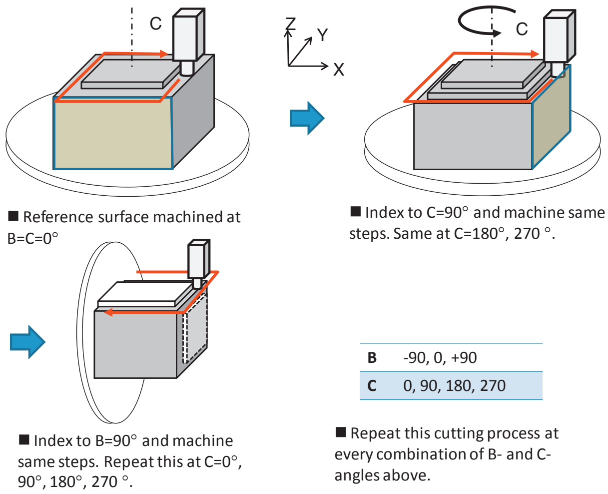

Fig. 2. Proposed machining test procedure

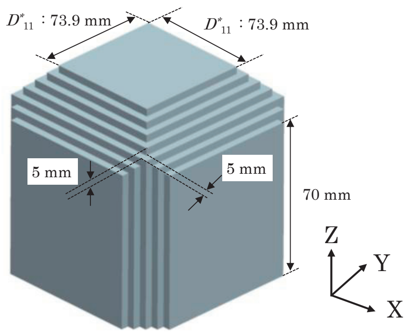

Fig. 3. Machined test piece geometry (example)

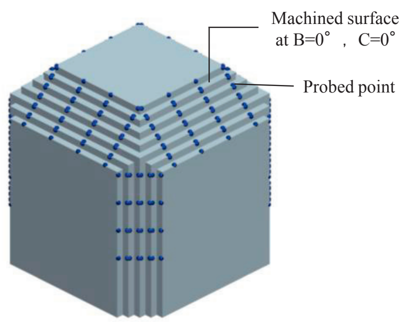

Fig. 4. Probed pints on machined test piece (example)