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A machining test to calibrate rotary axis error motions of five-axis machine tools and its application to thermal deformation test

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ABSTRACT

This paper proposes a machining test to parameterize error motions, or position-dependent geometric errors, of rotary axes in a five-axis machine tool. At the given set of angular positions of rotary axes, a square-shaped step is machined by a straight end mill. By measuring geometric errors of the finished test piece, the position and the 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 consequently performing the proposed machining test, one can quantitatively observe how error motions of rotary axes change due to thermal deformation induced mainly by spindle rotation. Experimental demonstration is presented.

1. Introduction

Machine tools with two rotary axes to tilt 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. ISO/DIS 10791-1 [1], currently under a revision process in ISO/TC 39/SC 2, contains quasi-static tests to calibrate alignment errors (location errors) of rotary axes. ISO 230-7 [2] describes the tests to observe error motions of rotary axis (ISO 230-7 [2] mainly targets a spindle but can be in principle applied to any rotary axes). Such a "direct" measurement [3] requires a different setup for each error, and thus full evaluation often takes significant time.

For more efficient error calibration, many "indirect" measurement methodologies, where each alignment error or error motion is indirectly identified from a set of tool center point (TCP) profiles measured with respect to the work table, have been studied. A comprehensive review can be found in [3,4]. The application of the ball bar test to dynamic measurement for rotary axes has been studied by many researchers [5–7] and is now included in ISO/FDIS 10791-6 [8], also currently under a revision process in ISO/TC 39/SC 2. The R-test [9,10] is also in ISO/FDIS 10791-6. The static version of analogous "chase-the-ball" test [10] can be done by using a touch-triggered probe [11,12]. Commercial probe-based calibration systems are now available from several vendors, e.g. Renishaw [13].

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." Although the accuracy test standards, e.g. [1,8], strongly suggest performing sufficient machine warm-up before tests, the machine's thermal condition may not be exactly the same as actual machining conditions, since the spindle stops in measuring cycles. In "normal" operating condition with spindle rotation, the machine's geometric errors may be significantly different from those in "cold" condition.

The heat generated by spindle rotation most typically displaces the TCP to the *Z*-direction. In the three-axis machining, such a simple translational error may not cause significant geometric error of the machined workpiece, as long as the deformation does not vary much throughout the machining process. In five-axis machining, even such a constant expansion changes the position of rotary axes with respect to the machine coordinate system, which likely results in the machined workpiece's geometric errors. ISO 230-3 [14], describing thermal tests for machine tools, only investigates thermal influence on the positioning by linear axes. No test is specified for five-axis machine tools. The importance of thermal tests for rotary axes has been discussed only lately in the literature. Recent works include the application of the R-test [15–17].

A machining test can evaluate the machine's error motions when it performs the machining. NAS (National Aerospace Standard) 979 [18], Clause 4.3.3.8.1, describes a cone frustum five-axis machining test. Since it is only standard well known describing a

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five-axis machining test, it is widely accepted by many machine tool builders as one of the final performance tests. ISO/TC 39/SC 2 is currently discussing its inclusion in the revision of ISO 10791-7 [19]. 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 [20,21]. Some five-axis machining tests have been proposed in the literature or the industry, e.g. the truncated square pyramid [22], a set of surfaces machined by a ball end mill at different angular positions [23] and the S-shaped thin wall [24]. None of them aims for the diagnosis of error causes from the geometry of the finished test piece.

The objective of this paper is to propose a new five-axis machining test such that geometric errors of rotary axes can be separately identified by evaluating the geometric error of the machined test piece. In [25], a part of the authors presented a machining test to identify position and orientation errors of the axis average line (location errors) of two rotary axes. More lately, a rather complex test was presented in [26] that enables the identification of rotary axis location errors. This paper presents a new machining test by extending [25] to position-dependent geometric errors, or error motions, of rotary axes. While location errors only represent “average” position and orientation errors of rotary axes, the proposed test fully parameterize how the position and the orientation of the axis of rotation change with its rotation.

Furthermore, the paper will present the observation of the machine's thermal stability by consequently performing the proposed machining test. 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. The swivel axis (*B*-axis) rotates over $-90\sim+90^{\circ}$. 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 $B_i = C_j = 0^{\circ}$, a square-shaped step is machined by a straight end mill with driving *X*- or *Y*-axis only (the reference step). Then, the square step is machined at different heights at $C_j = 90,\ 180,\ 270^{\circ}$. This is repeated at every combination of $B_i = -90,\ 0,\ 90^{\circ}$ and $C_j = 0,\ 90,\ 180,\ 270^{\circ}$. Total $4 \times 3 = 12$ finish cuts are made. Fig. 3 shows the nominal geometry of the finished test piece. The finishing condition must be properly chosen such that the influence of tool deflection or surface roughness becomes sufficiently small. It is recommended to repeat the finishing with zero radial depth of cut, i.e. “zero cut.”

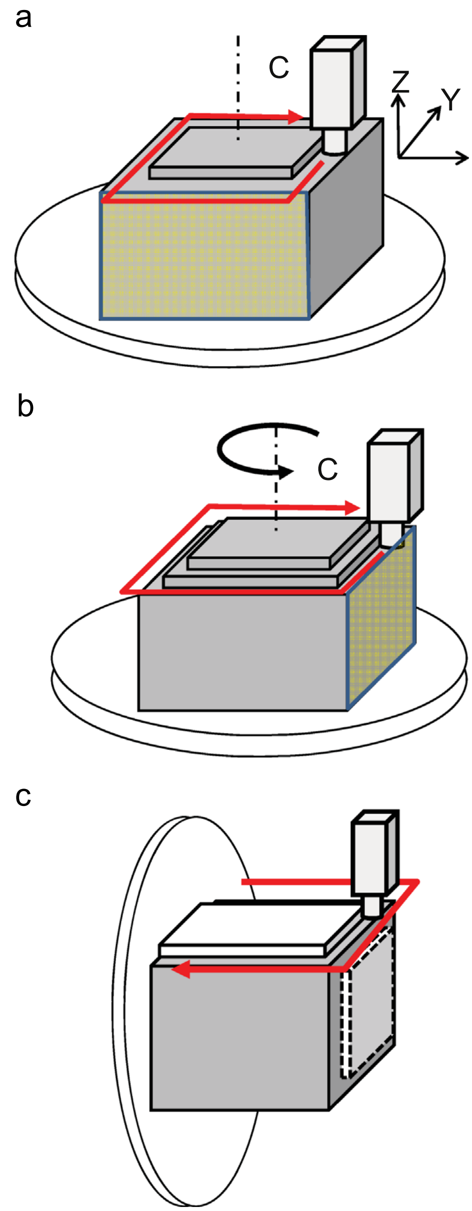

Fig. 2. The proposed machining procedure; (a) machine the reference square at $B=C=0^{\circ}$. (b) Rotate to $C=90^{\circ}$ and machine the same square. Repeat this at $C=180^{\circ}$ and 270°. (c) Rotate to $B=90^{\circ}$ and machine the same square. Repeat this at $C=0$, 90, 180, 270°. Repeat this at every combination of $B=-90$, 0, 90° and $C=0$, 90, 180, 270°.

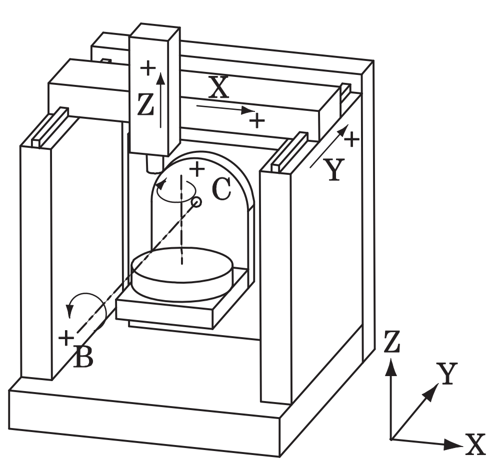

Fig. 1. The configuration of the five-axis machine tool considered in this paper [33].

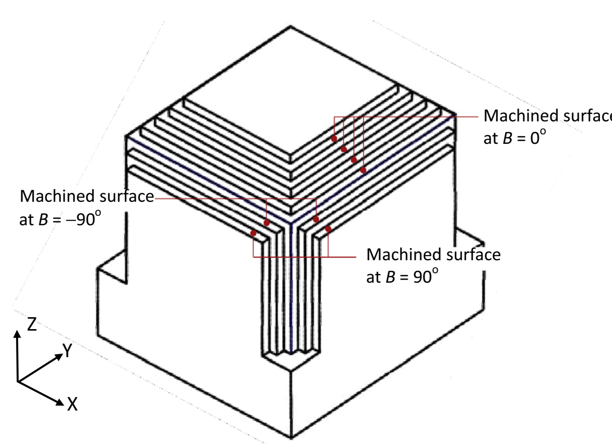

Fig. 3. Finished test piece geometry.