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Axis geometrical errors analysis through a performance test to evaluate kinematic error in a five axis tilting-rotary table machine tool

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ABSTRACT

Geometrical work piece errors in milling process are commonly generated by different error sources. Axis geometrical errors, such as the straightness error for linear axis and the offset location error of the origin of rotary axis, introduce kinematic error in the tool path. Direct measurement of kinematic error requires special devices such as laser interferometers, grid plate encoders or double ball bars, which impose production stop and specialized staff. These problems could be analyzed using indirect measurements obtained by means of a cutting performance test that is already a standard for three axis machine tools. Because of the different architectures of five-axis milling machines these tests are hardly standardizable, therefore this paper proposes a devised easy-to-use and time efficient cutting performance test to identify and quantify axis geometrical errors for a five axis tilting-rotary table machine tool. This test can be performed as a periodical checkup or, in case of production, as a re-start test. The main goal of this study is to develop a kinematic analytical model capable of correlating the work-piece geometrical errors to the axis geometrical errors of the machine tool. The model has been implemented on a multi-body software in order to simulate the axes motion sequence of the performance test and validated to decouple the kinematic error into the geometrical axis errors. The developed models have demonstrated to be capable of correcting a generic five axis tool path by predicting the tool-path error displacement. The overall validation of this approach has been carried out by comparing the simulated and experimentally measured profile of the NAS 979 standard five axis contouring cone frustum profile.

1. Introduction

The analysis of the machine accuracy starts from the study of quasi-static error sources where thermal, geometric and clamping errors are included. Schmitz presents a case study for the budget analysis of the most relevant error sources in high speed milling, employing a grid plate encoder in the circle-diamond square contouring tool path [1]. Five axis milling machines suffer of more relevant geometrical errors due to the need to maintain the optimal cutting parameters and the relative tool-surface orientation along all the surface, the kinematic error introduced by the five axis simultaneous motion is generally more relevant than the ones experienced in three axis processes [2]. The usual approach to analyze the geometrical source of errors is based on analytical models capable of correlating axis geometrical errors to tool-work piece errors. These models are then verified by means of specific experimental tests, employing direct measurement devices, such as ball bars [3], capacitance balls [4], laser interferometric devices [5] or master ball artifacts [6]. Many authors have developed kinematic or rigid-dynamic models for machine tools with linear [7] and rotary axes, or for even more complex architecture such as a parallel kinematic manipulator [8], in order to consider singularities, reversal characteristics and machine tool structure stiffness. The development of these analyses, such as rigid multi-body with uncompensated backlash drive or flexible joints allows to evaluate the tool-work piece displacement error caused by the imperfections of the machine tool axes. Nevertheless the imperfections of the machine tool axes must be firstly considered as axis geometrical errors, which are described in the ISO standards, and are called location errors and component errors. The first category includes the errors related to the position of the axis origin and the axis orientation and are usually constant values, while the second category is constituted by error position-dependent functions and are usually indicated using as first letter the character 'E' in the ISO standard (i.e. EXX, EXY). ISO 230-4 [9] tests circular contouring in two axes and points out the effects of orthogonality errors, the gap in the feed drives and feed-back errors. ISO 10791-1 to 3 test geometric

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errors in each single axis motion and ISO 10791-6 [10], recently revised, focuses on the rotational axis testing for machining centers with tilting-rotary table. Simplicity and ease of execution are fundamental requirements for performance tests as suggested in NAS 979 [11] for cone frustum cutting test. NAS 979 is suitable to test the total accuracy of five axis milling machine and it is accurate for machine tools with both rotary axes on the tool side, but for machine tools with tilting-rotary table NAS 979 requirements are incomplete, especially regarding the position of the cone in the machine tool work area which becomes crucial in the analysis of circular and cone form error. Starting from direct laser interferometer measurements for geometrical errors of linear axes Habibi and Arezoo [12] developed a compensated G-Code software able to reduce tool deflection and volumetric tool positioning error, validating the proposed approach with an experimental contouring cutting test. Bossoni [13] developed a critical analysis of cone frustum cutting test for five axis machine tools with different architectures, simulating the circular form errors due to each kinematic source of error of the machine tool, firstly introducing individually each source of error and then statistically introducing combinations of pairs of them and evaluating two synthesis parameters, circular and cone form error. Similar analysis has been made by Hong, then developed for two different values of taper and inclination of the cone frustum [14]. In his paper Hong has proposed an experimental case of study to demonstrate the application of R-test to measure the enlargement of a periodic radial error motion of C-axis with B-axis rotation. In the analysis of geometrical error sources for tilting-rotary table machine tools Ibaraki [15] proposed direct methods using trigger probes or performance test using linear axes, avoiding to consider their geometrical errors. In the literature complete modeling of the kinematic errors for three and five axis machine tools can be found, but, especially for five axis, problems of sensitivity and overlapping effects of different error sources must be solved. Often the tests are based on interferometric measurements for the linear axes and completed by coordinated motion tests for rotary axes using precision ceramic spheres or ball-bar devices. In conclusion an axis motions sequence test, aimed at obtaining the afferent kinematic error without overlapping the other geometric error contributions, is needed as shown by analyzing the actual standard test and the state of the art. The direct measurement of kinematic error displacement in the axis motions sequence test requires calibrated straightedges and versatile and accurate measurement devices, while the indirect measurement of a finished work-piece through the tool-path defined by the axis motions sequence test allows to obtain the kinematic error displacement more easily and off-line, therefore in this work a simple cutting and measurement performance test has been proposed starting from an analytical model adopting reduced parameters for the axis geometrical errors. Then the reduced parameters analytical modeling has been translated in a kinematic multi-body environment to predict and validate five axis tool-work piece displacement caused by the axis geometrical errors extracted from the indirect measurement of the performance test. The five axis tool-work piece displacement has been numerically and experimentally evaluated by simulating and machining the cone frustum test geometry proposed by NAS 979.

2. Axis geometrical errors

In this section, the location errors and errors component, as referred in the ISO standards, will be related to the architecture of the five axis machine tool under test, a Mori Seiki NMV 1500DCG, presented in Fig. 1, which is a vertical milling machine with tilting-rotary table. The axis geometrical errors are then modeled using a set of parameters, named reduced parameters.

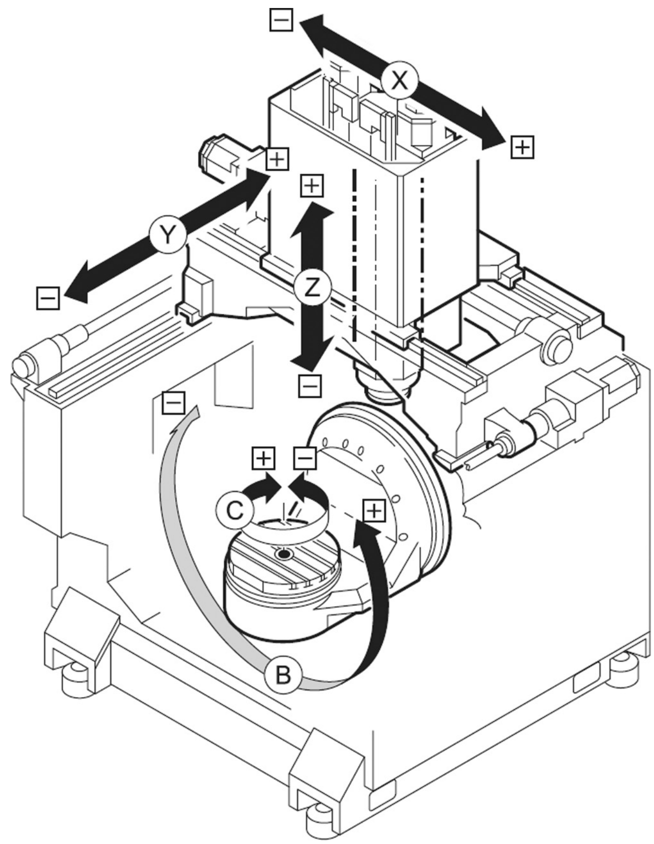

Fig. 1. Mori Seiki NMV 1500 DCG five axes scheme.

2.1. Location errors for linear axes

The vertical milling machine tool structure consists of three linear axes arranged in sequence *Y*–*X*–*Z* above the machine main body. In the analytical modeling the location errors are introduced using the ISO 230-1 nomenclature [16], therefore for the *Z* axis as an example ZOZ represent the origin error, AOZ the error of orientation about *X* axis i.e. squareness error between *Z* axis and *Y* axis, BOZ the error of orientation about *Y* axis i.e. squareness error between *Z* axis and *X* axis. Considering the three linear axes in the analytical modeling nine location errors can be introduced.

2.2. Location errors for rotary axes

The two rotary axes of the tilting-rotary table are placed in the lower part of the structure of the machine tool and they are arranged in sequence *B*–*C*. The location errors are introduced using the ISO 230-7 [17] nomenclature, therefore for the *B* axis as an example ZOB represent the offset error of the origin in *Z* direction in the *X*–*Z* plane, while XOB represent the offset error of the origin in *X* direction in the *X*–*Z* plane. About the orientation error AOB represent squareness error between *B* axis and *Z* axis, COB represents the squareness error between *B* axis and *X* axis. Considering the two rotary axes in the analytical modeling eight location errors can be introduced.

2.3. Component errors for linear axes

The component errors are introduced using the ISO 230-1 nomenclature, for the *Z* axis as an example there are two straightness component errors EXZ and EYZ, respectively in *X* and *Y* direction, the EZZ positioning component error in *Z* direction and three angular deviation about *X*, *Y* and *Z* axis, i.e. EAZ, EBZ and