euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024
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Face diagonal positioning and straightness error motions of machining centres according to ISO standards

Morteza Dashtizadeh, Andrew Longstaff, Simon Fletcher[1]

[1]*Centre for precision technologies, University of Huddersfield, UK*

Morteza.dashtizadeh@hud.ac.uk

Abstract

According to ISO 230-6:2002, diagonal tests can be applied to evaluate the volumetric performance of a machine tool. In the mentioned standard, "positioning errors" of four body diagonals are measured separately and compared with each other. The same can be done for every pair of face diagonals in XY, YZ and ZX planes. The latest revision of ISO 230-1 in 2012 introduced the concept of "diagonal straightness tests" of the linear trajectories made by interpolation of two or three linear axes of a machine tool on its face and body diagonals respectively. In this research work, some positioning and straightness tests are conducted along linear trajectories at different angles (partial face diagonals) in the horizontal XY plane of a vertical machining centre with kinematic chain of [w X' Y' b Z (C) t]. To present the results, we introduce two components of face diagonal straightness, not yet covered in current ISO standards. These additions offer a more comprehensive analysis of the results and performance of the machine tool under test. The results of experiments are compared with the predicted results obtained by simulation computed based on the homogeneous transformation matrices (HTM) method in XY plane via error motions of the linear axes and their squareness error.

Keywords: Machine tools performance, ISO standards, diagonal tests, face diagonal straightness, face diagonal positioning, volumetric accuracy of machine tools, planar accuracy of machine tool

1. Introduction

ISO 230-6:2002 [1] specifies positioning tests to be carried out along face and body diagonals of machine tools as a metric to evaluate their planar and volumetric performance. ISO 230-1:2012 [2] not only explains positioning errors of linear trajectories obtained from interpolation of multiple linear axes, but also mentions the straightness of these linear trajectories. This standard states "The (simultaneously coordinated) two or more linear axes are moved nominally on a straight line, on a face or a body diagonal of the prismatic work volume. During such movement, the positioning or straightness error motions are measured, and deviations are recorded and evaluated." while in the current ISO 230-6, only positioning of the linear trajectories (diagonal tests) is checked which is probably not a complete indicator of the volumetric behaviour of the machine under test. However, ISO 230-1 does not define straightness components for face/body diagonals and only expresses the main concept. From a practical point of view and for the reproducibility of test results, it is evident that these two straightness components must be defined thoroughly. In some machine-specific standards such as ISO 10791-6:2014 [3] and ISO 13041-6:2015 [4] for evaluating the interpolation performance of machining centres and turning centres respectively, there is a test in which straightness of a linear trajectory is checked over a length of 100 mm. This test determines behaviour of the machine while interpolating with two linear axes to generate a linear trajectory. Since this trajectory is very short, it cannot show the planar/volumetric performance of the machine.

There have been some controversial research on using body diagonal tests to identify errors of machine tools, as well as for compensation purposes. Wang and Liotto [5] proposed step diagonal tests and expanded the use of side information from this test for identifying different error motions of linear axes of the machine along with its squareness errors. They also attempted to compensate machine tool errors with mathematical computations derived from diagonal tests. Chapman [6] explained limitations of body diagonal measurements and provided a simple example of a machine tool with two linear axes equal in their axis stroke, one with negative scaling error and another with identical positive scaling error. Considering the ideal third axis, he argued that in this situation, the body diagonal positioning test according to ISO 230-6 does not provide a useful metric for volumetric performance of the machine. By this ideal example, he conveyed the message that the diagonal positioning tests individually cannot be used reliably as volumetric index without the results of regular tests. However, he did not provide any reasons how a liear axis might show straightness and angular error of zero. It is obvious that all these errors are synthetised together and their cumulative effects are observed as diagonal positioning test results. Even if in some special cases the diagonal positioning component might become zero, but the other two straightness components are very unlikely to show zero deviations simultaneously. Svoboda [7] carried out some diagonal experiments and rejected Wang's approach by demonstrating some contradictions in practical results. Ibaraki and Hata [8, 9] highlighted the necessary conditions such as the alignment of the laser, flat mirror, and test direction under which Wang's formulations are valid for taking advantage of the results of step diagonal tests for error compensation.

This research work defines straightness components of face/body diagonal trajectories. Then, based on this definition, it shows some experimental test results conducted with a laser system on a 3-axis VMC, along with the simulation outputs employing Homogeneous Transformation Matrices (HTM) method. Discussing the main applications of diagonal tests is another major message of this article

2. Defining diagonal straightness components

For any body diagonal trajectory, a vertical plane can be crossed in a way that it contains the nominal body diagonal trajectory. The direction of the positioning deviation at any target, e_{DD}, is the same as the direction of the nominal body diagonal. Since two straightness components must be mutually perpendicular to the positioning deviation, the first straightness deviation, e_{S1D}, lies in the passing vertical plane. The positive sign of e_{S1D} is defined like the positive direction of the Z-axis. By having positive sign and direction of e_{DD} and e_{S1D}, the positive direction of e_{S2D} is determined by the cross product of e_{DD} to e_{S1D} as shown in equation (1).

$$u_{eS2D} = u_{eDD} \times u_{eS1D} \quad (1)$$

where u_{eDD} , u_{eS1D}, and u_{eS2D} are unit vectors of the positioning deviation, straightness 1, and straightness 2 deviations respectively.

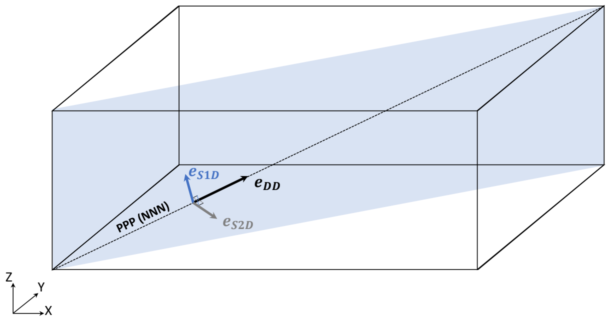

Figure 1. Direction and sign of straightness components of body diagonal trajectories

Figure 1 shows a PPP(NNN) body diagonal with its positioning and two straightness deviations at an arbitrary target position in the working volume of a machine tool. In this research work, face diagonal trajectories in XY plane are studied. Therefore, a simplified form of **Figure 1** is used to determine directions of straightness components. ***Figure 2*** shows e_{S1D} and e_{S2D} for a face diagonal trajectory located in XY plane with Positive-Positive directions of X and Y-axes. In this case, e_{S1D} is parallel to Z-axis and e_{S2D} is derived from the cross product of e_{DD} to e_{S1D}.

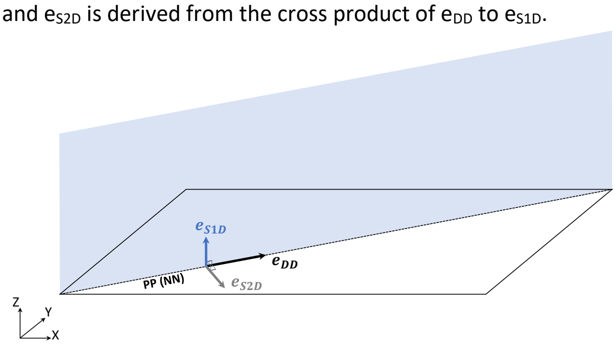

Figure 2. Direction and sign of straightness components of face diagonal trajectories

A plane whose normal vector is the body diagonal trajectory is depicted in **Figure 3**. From analytical geometry point of view, e_{S1D} and e_{S2D} vectors lie in this plane. As shown in this schematic figure, the resultant vector of these two straightness deviations is a dashed orange segment. This resultant vector can be decomposed into infinite numbers of straightness pairs. In other words, two straightness deviation components can be defined in many ways. Therefore, by passing a vertical plane from the body diagonal, the location of e_{S1D} is fixed. As illustrated in **Figure 1** and **Figure 2**, e_{S1D} direction is unique for any individual body and face diagonals.

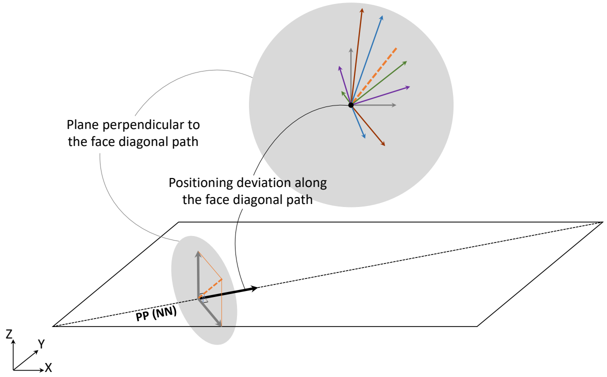

Figure 3. Possible directions of straightness components

3. Volumetric error modelling

To derive volumetric errors of machine tools, Homogeneous Transformation Matrices (HTM) method was applied to 2-axis and 3-axis machines by Donmez et al [10] , and Okafor and Ertekin [11], respectively. Dashtizadeh et al [12] demonstrated probable volumetric errors of machining centres made with conformance to tolerances of ISO 10791 series for machines with 500 mm stroke of all linear axes using the HTM method.

HTM method can compute error vectors at all target positions at which experimental data is available. To derive volumetric error vectors at the other coordinates, mathematical interpolation of captured data is employed. If the machine axis under test behaves differently in areas where there is no captured data, the error model shows some deviations from the experimental data gathered from different linear and other free-shape trajectories.

To derive the aforementioned e_{DD}, e_{S1D}, and e_{S2D} for any diagonal trajectory, some geometrical computations need to be executed. Firstly, all volumetric error vectors along the diagonal trajectory is to be calculated. These vectors result in the positioning deviation at any target position. The same operation is implemented to derive e_{S1D} and e_{S2D}. For this study, a MATLAB code was developed to predict the positioning and two straightness components. As input, error motions of the linear axes of the machine along with their squareness values were entered into the MATLAB code. Then, any linear trajectory with its E_{DD}, E_{S1D}, and E_{S2D} as the peak-to-peak value of all deviations were extracted for any input coordinates of start and end positions.

For this study, a 3-axis vertical machining centre with the kinematic chain of [w X' Y' b Z (C) t] was modelled. **Figure 4** shows this configuration with the coordinate frames attached to its components used for generating HT matrices.

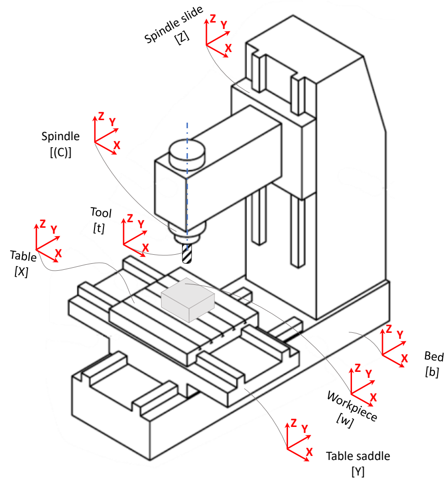

Figure 4. VMC with kinematic chain of [w X' Y' b Z (C) t] and its c oordinate frames (modified from ISO 10791-2 [13])

4. Experimental tests

Some experiments were conducted on Cincinnati Arrow 500 3-axis VMC with the same kinematic chain shown in **Figure 4**, at different angles between X and Y-axes along face diagonals. These tests were carried out with Renishaw XM-60 laser system. **Figure 5** and **Figure 6** show the setup of the experiments for face diagonal trajectories of PP 46.397 and PN 53.123, respectively. PP 46.397 denotes that both X and Y-axes move along their positive directions while the diagonal trajectory makes an angle of approximately 46.397 degree with the X-axis direction.

Figure 5. Experimental setup with Renishaw XM-60 laser system for f ace diagonal tests in XY plane of a VMC at PP 46.397 deg.

With the setup shown in **Figure 5** and **Figure 6**, the Renishaw XM-60 directly measures E_{DD}, E_{S1D}, and E_{S2D} errors. However, its current commercial software does not provide appropriate notations for diagonal tests. As a practical approach, the diagonal trajectory (D), can be set as one of the usual linear axis (e.g. X-axis). In this case, E_{ZX} and E_{YX} will represent E_{S1D} and E_{S2D}, respectively, for the face diagonal under test. One challenge in the execution of this test is the proper setting of the correct sign of diagonal straightness components.

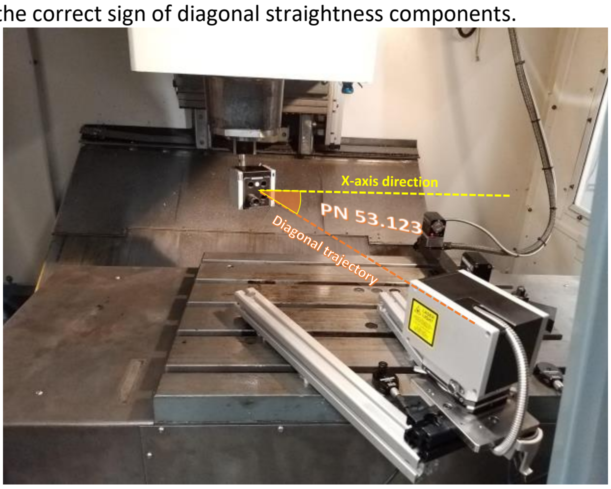

Figure 6. Experimental setup with Renishaw XM-60 laser system for f ace diagonal tests in XY plane of a VMC at PP 46.397 deg.

5. Results of the tests and simulations

As an example, **Figure 7** shows positioning deviations, e_{DD}, derived by HTM and those measured by the laser system at 10.388 degrees when X and Y-axes move along their positive directions.

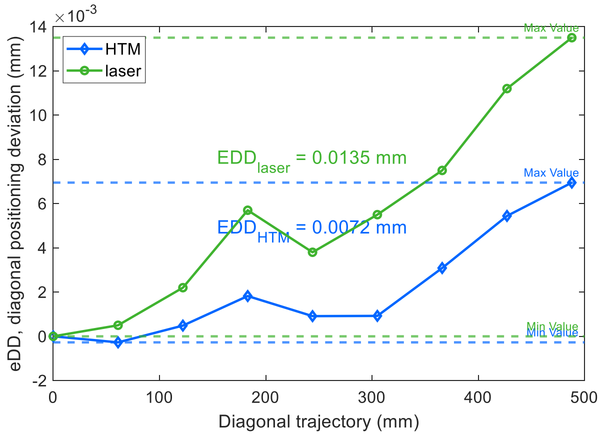

Figure 7. Face diagonal positioning deviations, measured by laser and derived by HTM at PP10.388

Figure 8 and **Figure 9** illustrate e_{S1D} and e_{S2D} for the same direction/angle, respectively. As demonstrated, pattern of the experimental data and HTM simulations follows the same shape with some deviations from each other.

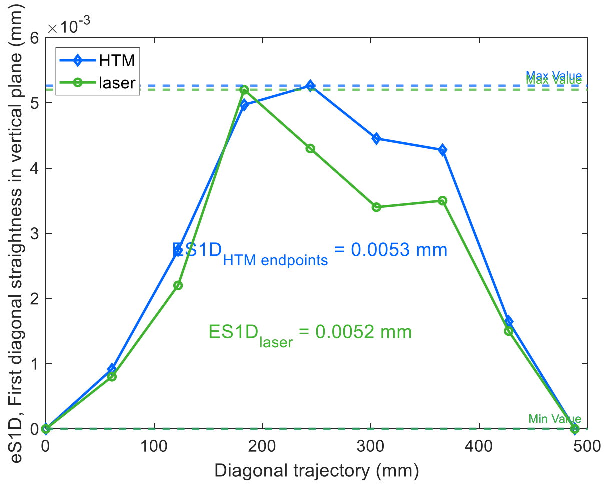

Figure 8. Face diagonal straightness 1 deviations, measured by laser and derived by HTM

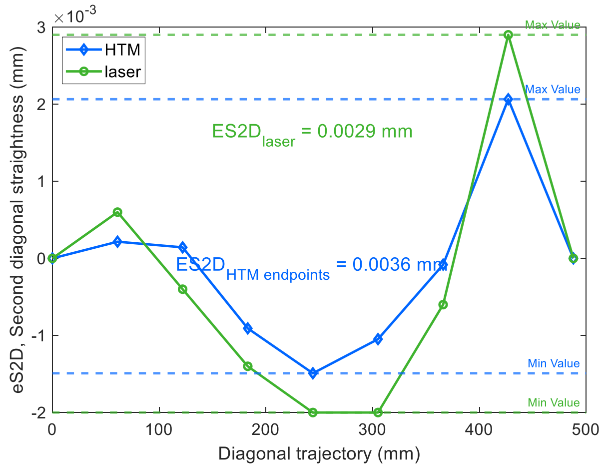

Figure 9. Face diagonal straightness 2 deviations, measured by laser and derived by HTM

Face diagonal tests were conducted at 18 different direction/angles. Comparative results of experiments versus HTM simulations are depicted in **Figure 10**, **Figure 11**, and **Figure 12** for positioning (E_{DD}), straightness 1 (E_{S1D}) and straightness 2 (E_{S2D}) errors respectively.

As explained in ISO 230-1 and ISO 230-6, squareness between linear axes can be extracted from a pair of face diagonal positioning tests (PP and PN at the same angle). This technique is quite useful to measure squareness of large machines with small uncertainty. The range and uncertainty of current measuring instruments commonly used for squareness measurements pose challenging issues for large machine tools with tight tolerances.

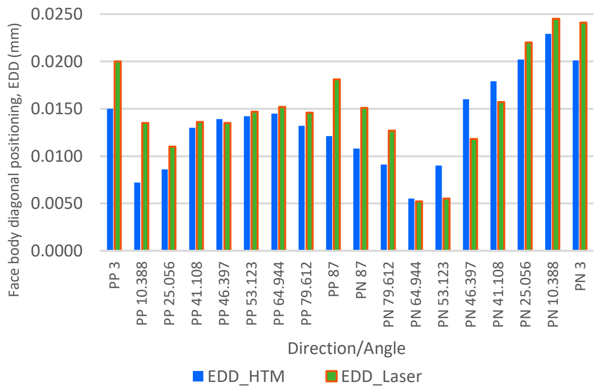

Figure 10. Comparison between laser readings and HTM output for positioning error at different direction/angle

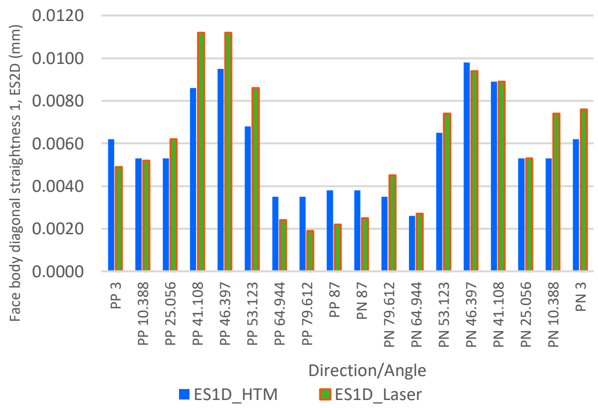

Figure 11. Comparison between laser readings and HTM output for straightness 1 error at different direction/angle

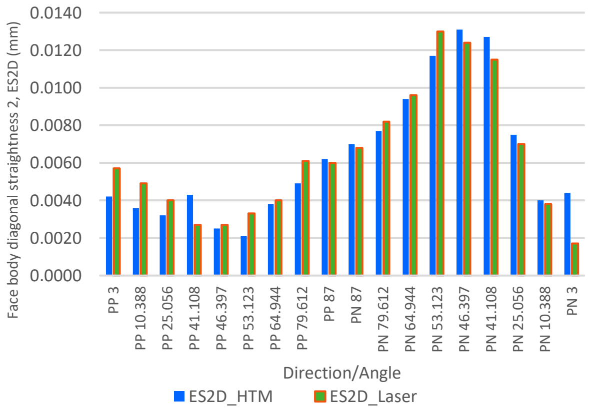

Figure 12. Comparison between laser readings and HTM output for straightness 2 error at different direction/angle

By combination all these three errors, one diagonal positioning and two diagonal straightness errors, a better understanding of volumetric behaviour of any machine tool is achievable. Furthermore, it can be used as a suitable index to check whether the compensation of the linear axes of the machine was implemented properly.

Body and face diagonal test results could also be used to check non-rigid body behaviour of machine tools within a short time, which is a useful tool for research studies as well as for specific industrial applications.

6. Summary and conclusion

This paper defined straightness components of body/face diagonal trajectories and demonstrated the practicality of face diagonal straightness measurements. It also presented some experimental tests conducted at different direction/angles in the XY plane of the machine. The experimental results were compared with the output of computer simulations. These new definitions of diagonal straightness could potentially be introduced to ISO 230-6 to provide a clearer view of planar/volumetric performance of machine tools. The diagonal tests can efficiently be used for verification of machine tools compensation. Additionally, these tests can be applied for fast regular checks on large-size machines.

In near future, body diagonal positioning and straightness components of machines with various kinematic chains will be investigated.

Acknowledgement

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of the Future Metrology Hub (Grant Ref: EP/P006930/1) and UKRI-funded Advanced Machinery and Productivity Initiative (84646). Furthermore, the authors extend their gratitude to Andrew Bell, the senior application engineer at CPT (University of Huddersfield), for his valuable contribution to the setup and execution of face diagonal tests.

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