SET OF GEOMETRIC ERRORS EVALUATION BASED ON R-TEST MEASUREMENT

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Presented paper deals with the development of a procedure for fast measurement and evaluation of the set of basic geometric errors of the five-axis milling machines. Based on R-test measurement a rotary axes pivot point position and orientation errors and linear axes squareness errors are evaluated. The developed procedure is experimentally verified on a five-axis milling machine. Using the kinematic model, the significance of the considered geometric errors to the overall volumetric accuracy of the test machine tool is tested. The results obtained using the developed procedure are verified by comparing with the measurement and evaluation of results obtained using conventional measurement methods. The results shows that the set of evaluated geometric errors has major influence on the machine's motion accuracy along the measured five axis interpolated trajectory

KEYWORDS

geometric error, volumetric error, machine tool, R-test, accuracy

1 INTRODUCTION

The growing demands on geometric accuracy and shape complexity of produced parts, along with an unsatisfactory effort to reduce production times and costs, increases the need for use of five-axis machining tools.

[Abbaszadeh-Mir 2002] mentioned the main advantages of the five-axis milling machines. They are good geometric positioning of the tool with respect to the workpiece surface, the technologically correct setting of the tool along the cutting track, the small number of tools, clamps and especially the possibility of complete machining of a complex piece. [Zargarbashi 2009] also pointed out that five-axis machine tools are more prone to work accuracy due to the more complex kinematic structure and more complicated control of machine tool servo-drives. [Florussen 2001] stated the main factors influencing the accuracy of machine tool work and divided them into four categories:

1. geometric errors of machine tool axis components
2. stiffness of structural loops under static load
3. deformation of machine tool components caused by temperature changes
4. dynamic properties of the machine tool

[Florussen 2001] also pointed out that groups 1. to 3. are so-called quasi-static sources of errors. They are defined as sources causing a error of tool position relative to the workpiece. They cause more than 70% of the overall machine tool accuracy. This fact was also experimentally verified by [Andolfatto 2011].

The above-mentioned findings show a clear need to test the accuracy of five-axis milling machines in a comprehensive and effective manner, generate data for their diagnosis and compensation, and thus achieve higher accuracy of its work.

2 PROCEDURE FOR MEASURING AND EVALUATING A SET OF GEOMETRIC ERRORS

The proposed procedure allows fast measurement and subsequent evaluation of a set of basic geometric errors of the five-axis milling machines at one point in terms of machine tools termo-mechanical behaviour (approximately 5 minutes). For measuring as part of the proposed procedure, it will be useful to use the MT-Check measuring instrument from IBS PE.

2.1 *Determination of the set of geometric errors considered*

At the beginning of the procedure development for measuring and evaluating a set of geometric errors, it is necessary to determine which geometric errors will be evaluated. According to the relevant standard [ISO 230-1 2012], the movement of each machine tool axis is accompanied by six geometric errors. It is also necessary to consider errors in the relative position of the individual machine tool axes.

In the case of a five-axis milling machine, 41 geometric errors are considered. At the same time, consideration should be given to the fact that the measurement procedure should be fast enough and undemanding for preparation and execution itself. It follows that the total set of all geometric errors that occur on a five-axis milling machine needs to be reduced and only those geometric errors which have a significant effect on the resulting volumetric accuracy of the machine tool will be considered. The influence of individual geometric errors on specific kinematic configurations of three-axis and five-axis milling machines was studied by [Moravek 2011] and [Moravek 2014]. It is evident that the position errors of the individual machine tool axes have a significant effect on the resulting volumetric accuracy, regardless of the kinematic configuration of the specific machine tool. Similar conclusions can be found in publication of [Svoboda 2007]. On the basis of these findings, it is possible to determine a set of geometric errors having a crucial influence on the resulting volumetric accuracy of the machine tool. Generally, these are errors of the relative position and orientation of the machine tool axes, namely the squareness errors between the linear axes and the rotary axes position and orientation pivot point errors (POPPE). Rotary axes POPPE plays a crucial role if the machine tool moves along the trajectory interpolated by linear and rotary axes.

2.2 *Method of geometric errors calculation*

The trajectory interpolated by the movement of linear and rotary axes is deformed due to the individual geometric errors influence. Each of the geometric error has a characteristic influence to ideal trajectory deformation. To evaluate a set of selected geometric errors, a numerical method of fitting lines, circles, and ellipses to the projection of the measured trajectory into the individual planes of the machine tool coordinate system is used.

Rotary axes pivot point position and orientation errors

Rotary axes POPPE are described for example in standard [ISO 230-1 2012]. They can be very efficiently evaluated from a circle trajectory, or part thereof, obtained by interpolation of one rotary and two linear axes. Such a trajectory ideally lies in one of the plane of the coordinate system of the machine tool. The centre of the trajectory lies in the centre of rotation of the rotary axis. Because of the rotary axes POPPE, the actual centre of the trajectory is different. These errors are obtained by fitting a circle to actual trajectory (in the plane of interpolation) or a straight line (in two planes perpendicular to the plane of interpolation). The position difference between centre of fitted circle and centre of ideal trajectory represents rotary axis pivot point position errors (*EYOA* and *EZOA* for axis A or *EXOC* and *EYOC* for axis C). The angle between fitted straight line and coordinate system line represents rotary axis pivot point orientation errors (*EBOA* and *ECOA* for axis A or *EAOC* and *EBOC* for axis C). Fitting the circle and a straight line to the trajectory is done using the least mean squares method. A description of the application of the required mathematical apparatus is given in [GANDER 1994]. In the case of fitting a circle on the measured data, the resulting solution minimizes the sum of squares of deviations from each equation, that is, the distance of individual points from the centre of the circle being searched [Gander 1994].

Squareness errors of linear axes

The squareness error is calculated from the resulting trajectory (interpolated with one rotary and two linear axes) in the same way as in the diagonal adjustment test according particular standards [ISO 230-1 2012] and [ISO 230-6 2002]. The squareness error C is calculated according to the equation (1). Where *ΔD* is the difference in the diameter of the circular trajectory in ± 45 ° and D_0 is the nominal diameter of the interpolated circular trajectory [ISO 230-1 2012].

$$C = \frac{\Delta D}{D_0} \qquad (1)$$

The equation for the calculation of the squereness error C will then be in the form (2). Where D_{45} is the diameter of the ellipse elongated at 45 ° and D_{135} is the diameter at an angle of 135 °. D_0 is the nominal diameter of the interpolated circular trajectory.

$$C = \frac{(D_{45} - D_{135})}{D_0} \qquad (2)$$

The equation (2) can be applied to interpolation tests of one rotary and two linear axes, where the trajectory lies in one of the plane of the machine tool coordinate system (Figure 1). In the case of a five-axis milling machine of the classic concept (three linear and two rotary axes), this way, it is possible to obtain a maximum of two of three squareness errors between the linear axes. The evaluation of all three squareness errors requires the measurement of two symmetrical trajectories, see Figure 2. In the projections on individual planes of the machine tool coordinate system, we find the perpendicular diameters D_{45} and D_{135} needed for the calculation of the individual errors. The intersection of the set of measured points by the ellipse is taken from [GANDER 1994]. Gauss-Newton's non-linear method for least mean squares is used.

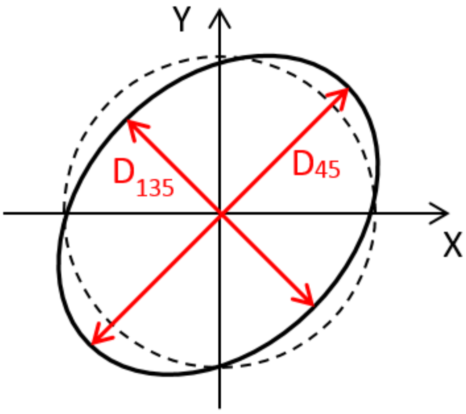

Figure 1: Calculation of the squareness error between the linear axes from the trajectory located in one of the plane of the machine tool coordinate system. Interpolation axes X, Y and C, error of CXY.

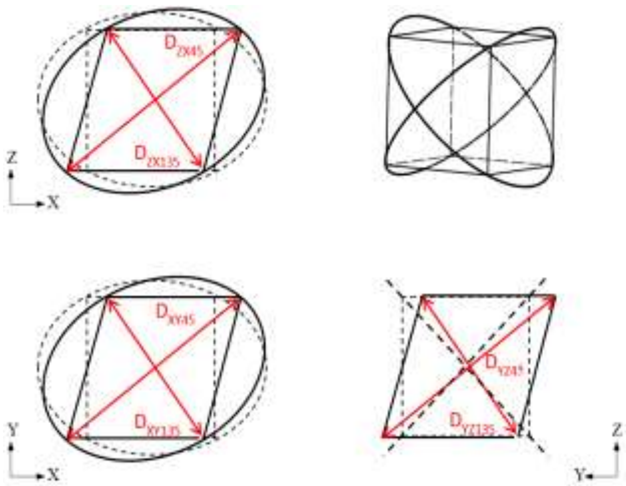

Figure 2: Calculation of squereness errors between linear axes from two symmetrical trajectories outside the plane of the machine tool coordinate system. Interpolation axes X, Y, Z and C, when the A axis is tilted by ± 45 °.

3 MEASUREMENT AND VERIFICATION

Measurement of volumetric error along interpolated trajectory is generally known as the R-test. A series of volumetric accuracy tests along the interpolated trajectory needed to evaluate selected geometric accuracy parameters were performed. These were XYC, YZA and XYZAC interpolation. In the first two cases, measurements were made to determine the A and C rotary axes POPPE. In order to evaluate the squareness errors between the linear axes, XYC axes interpolation tests were performed when the axis A ± 25 was tilted. The XYZAC interpolation test was last performed in the series. From the results of this test, the effect of rotary axes POPPE and the squareness errors between the linear axes was subsequently eliminated using kinematic model of tested machine tool.

3.1 Results of the measurement

Using the procedure proposed in Chapter 2, a set of basic geometric errors of the 5-axis milling machine was evaluated from the measured data. The proposed procedure was applied to five-axis milling machine MCU630 from Kovosvit MAS. It is gantry type machine with tilting and rotary table. Machine has common kinematic structure ZXYFAC, see Figure 3.

The graphical representation of A and C rotary axes POPPE evaluation is shown in Figure 4 and Figure 5. The values of individual geometric errors are given in Table 1 and Table 2.

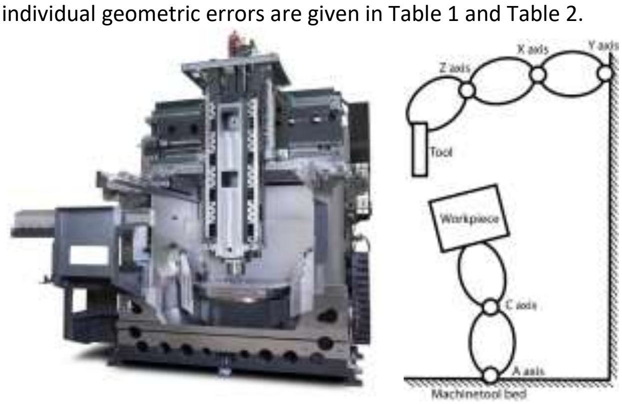

Figure 3: Tested 5-axis machine tool and its kinematic structure.

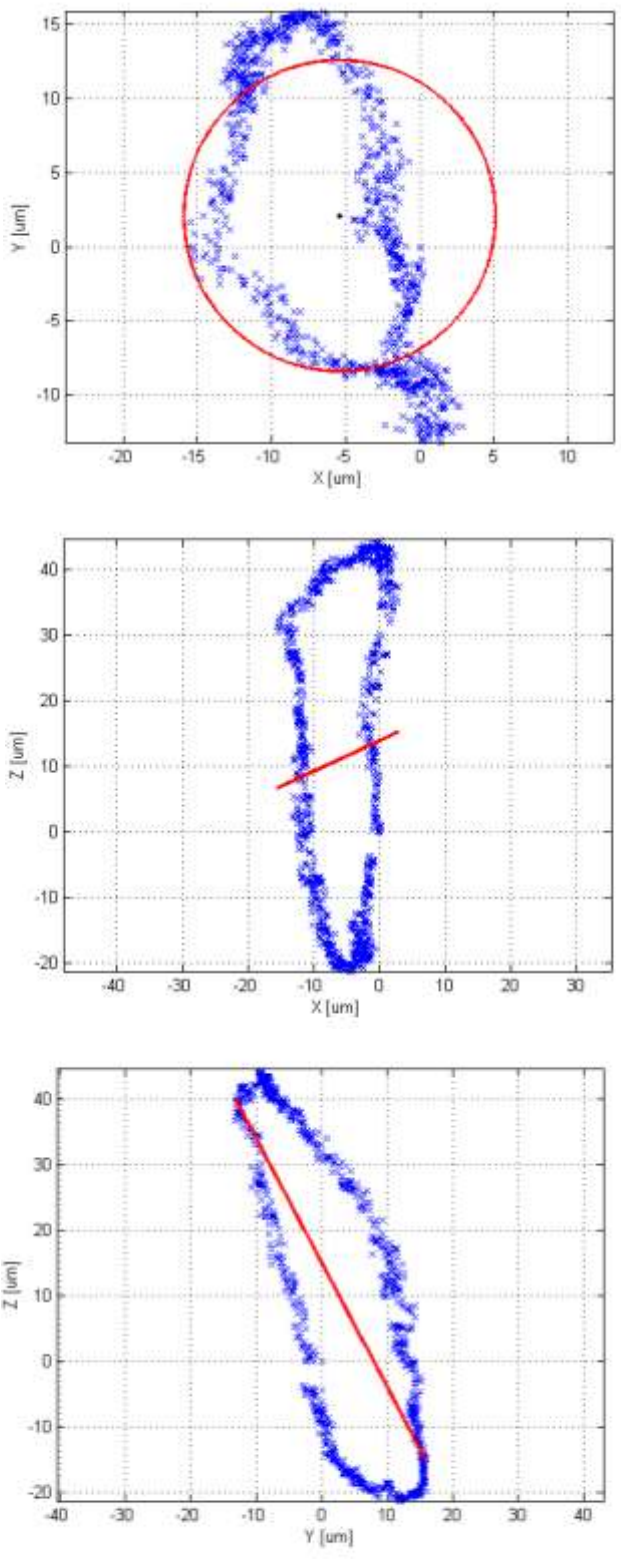

Figure 4: A graphical representation of the C axis POPPE.

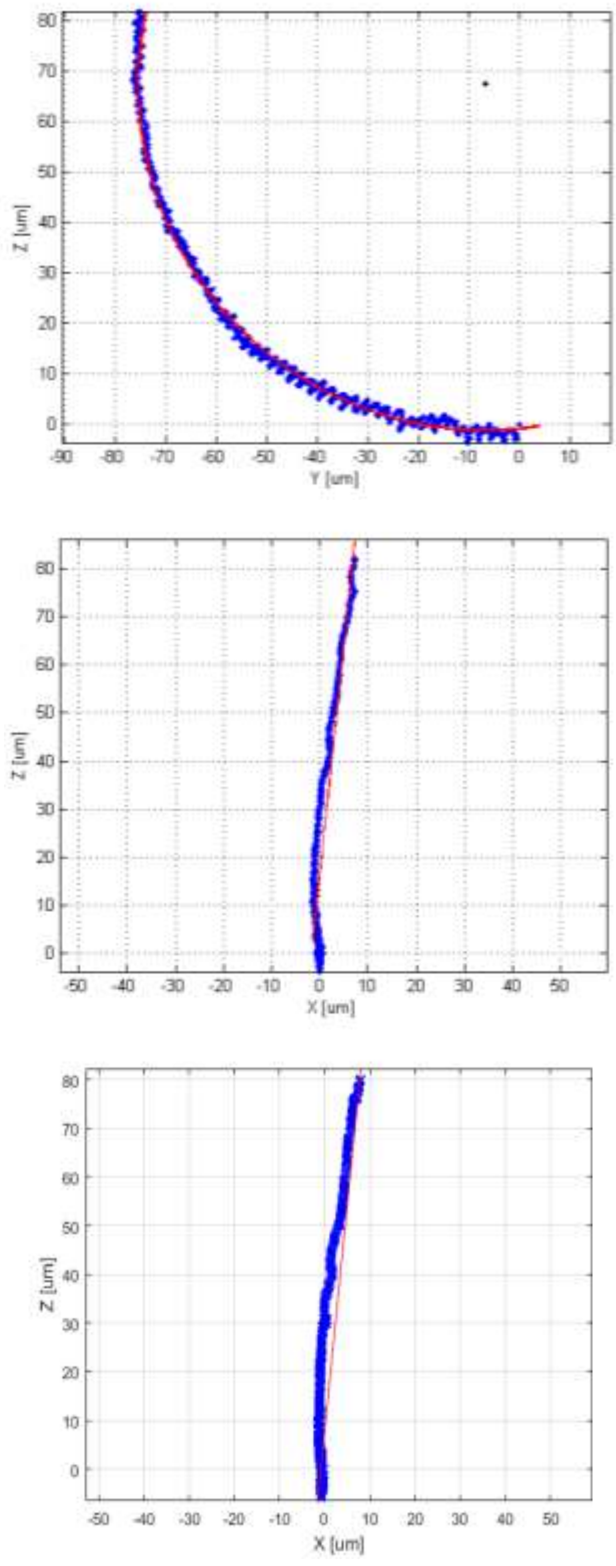

Figure 5: A graphical representation of the A axis POPPE.

EYOA [μm]	EZOA [μm]	EBOA [μm/mm]	ECOA [μm/mm]
-5	-68	-167	147
EXOC [μm]	**EYOC [μm]**	**EAOC [μm/mm]**	**EBOC [μm/mm]**
-5	-2	-14	-88

Table 1: Squareness errors between linear axes.

EXOY [μm/mm]	EZOX [μm/mm]	EYOZ [μm/mm]
-2	12	35

Table 2: Rotary axes A and C POPPE.

3.2 Development of a machine´s volumetric error model

The mathematical model for calculating the volumetric error is used. It is based on the full model of machine tool mechanical structure which is completed using the basic kinematics laws

presented by [STEJSKAL 1996]. A homogeneous transformation matrix (HTM) is used to describe machine tool kinematics chains, including geometric errors. This issue is also described in detail in publications [Moravek 2011] and [Moravek 2014].
The kinematic structure of the machine consists of a tool kinematic chain and workpiece kinematic chain (see Figure 6).

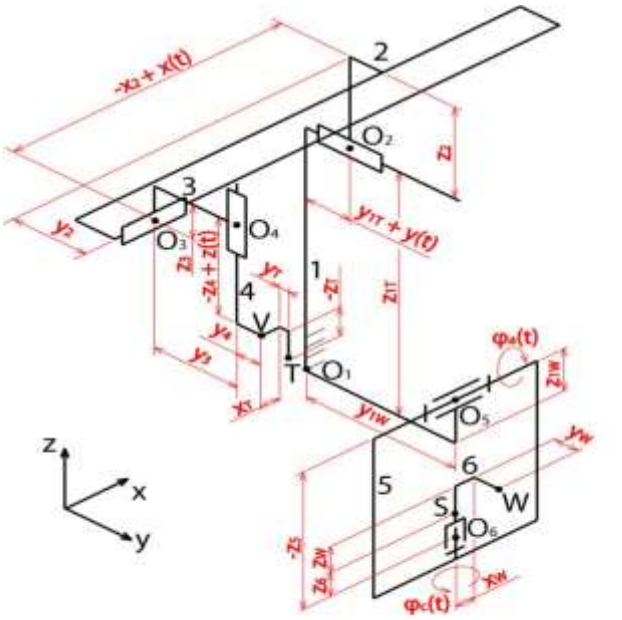

Figure 6: Kinematic structure of tested machine.

HTM describes the sequence of fundamental movements in both kinematic chains. Tool kinematic chain is expressed by equation (3) and in detail by equations (4) to (8). Workpiece kinematic chain is expressed by equatin (9) and in detail by equations (10) to (13).

$$r_{1T} = T_{12} \cdot T_{23} \cdot T_{34} \cdot T_{4V} \cdot r_{VT} \tag{3}$$

$$T_{12} = T_Z(z_{1T}) \cdot T_Y(y_{1T}) \cdot T_Y(y(t)) \tag{4}$$

$$T_{23} = T_Z(z_2) \cdot T_Y(y_2) \cdot T_X(-x_2) \cdot T_X\big(x(t)\big) \tag{5}$$

$$T_{34} = T_Z(z_3) \cdot T_Y(y_3) \tag{6}$$

$$T_{4V} = T_Z(-z_4) \cdot T_Z(z(t)) \cdot T_Y(y_4) \tag{7}$$

$$r_{VT} = \begin{bmatrix} x_T \\ y_T \\ z_T \end{bmatrix} \tag{8}$$

$$r_{1W} = T_{15} \cdot T_{56} \cdot T_{6S} \cdot r_{SW} \tag{9}$$

$$T_{15} = T_Y(y_{1W}) \cdot T_Z(z_{1W}) \tag{10}$$

$$T_{56} = T_{\varphi x}(\varphi_a(t)) \cdot T_Z(-z_5) \tag{11}$$

$$T_{6S} = T_{\varphi z}(\varphi_z(t)) \cdot T_Z(z_6) \tag{12}$$

$$r_{SW} = \begin{bmatrix} x_W \\ y_W \\ z_W \end{bmatrix} \tag{13}$$

Equations (14) and (15) describes tool and workpiece kinematic chains including HTM of geometric errors.

$$r_{1T}^{*} = T_{12} \cdot T_{EY} \cdot T_{23} \cdot T_{EX} \cdot T_{34} \cdot T_{EZ} \cdot T_{4V} \cdot r_{VT} \tag{14}$$

$$r_{1W}^{*} = T_{15} \cdot T_{EA} \cdot T_{56} \cdot T_{EC} \cdot T_{6S} \cdot r_{SW} \tag{15}$$

The resulting volumetric error between tool and workpiece is the sum of volumetric errors of the tool and workpiece chains. Volumetric error components are obtained by subtracting equations of ideal and error description in equation (16).

$$\Delta r^{lin} = \Delta r_T + \Delta r_W = (r_{1T}^{*} - r_{VT}) + (r_{1W}^{*} - r_{1W}) = \begin{bmatrix} E_X \\ E_Y \\ E_Z \end{bmatrix} \tag{16}$$

The mathematical model of the machine is linearized, so the angle components of the volumetric error can be added together (see equation (17).

$$\Delta r^{rot} = \begin{bmatrix} EAA(a) + EAC(c) + EAX(x) + EAY(y) + EAZ(z) + EYOZ + EAOC \\ EBA(a) + EBC(c) + EBX(x) + EBY(y) + EBZ(z) + EXOZ + EBOA + EBOC \\ ECA(a) + ECC(c) + ECX(x) + ECY(y) + EC(z)Z + EXOY + ECOA \end{bmatrix} = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \tag{17}$$

3.3 Influence of considered geometric errors

Comparison of the measured error ErrMTCH with the error calculated by model (ErrCALC) is shown in Figure 7 to Figure 9. The blue deltaERR curve represents the residual error. It is difference between ErrMTCH and ErrCALC. ErrCALC error is calculated using a kinematic model, with geometric errors (see Table 1 and Table 2) included. Overall, 11 geometric errors (3 squareness errors between linear axes and 8 POPPE of rotary axes A and C) are considered in the model.
From the results (Figure 7 to Figure 9), it is well evident that a set of 11 selected geometric errors has a major influence on the accuracy of the machine tool movement along the measured trajectory interpolated by XYZAC axes. The residual error deltaERR is therefore caused by superposition of the remaining 30 geometric errors (positioning errors, straightness errors, angular errors, and rotary axes movement errors).

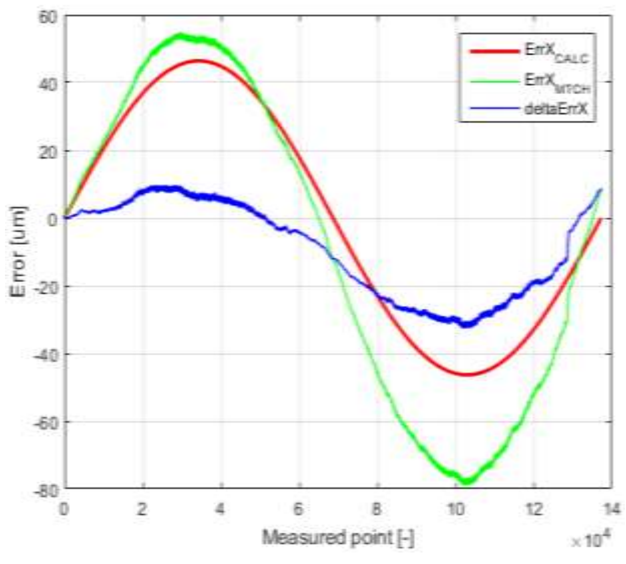

Figure 7: Comparison of measurement and simulation results of volumetric error along trajectory interpolated by XYZAC axes - errors in X direction.

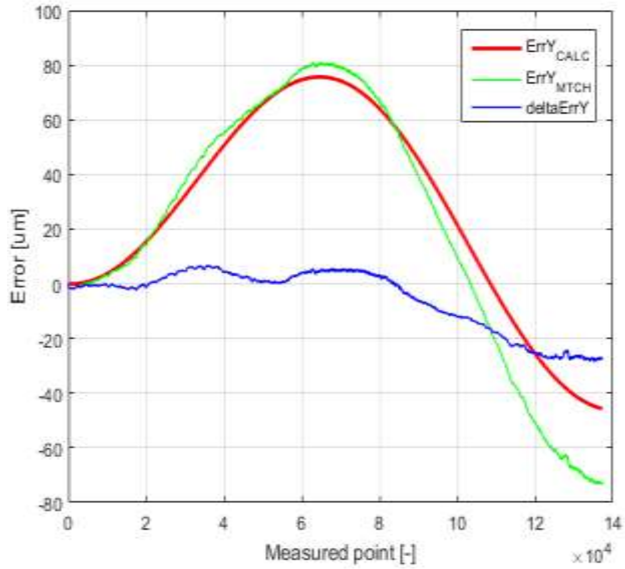

Figure 8: Comparison of measurement and simulation results of volumetric error along trajectory interpolated by XYZAC axes - errors in Y direction.

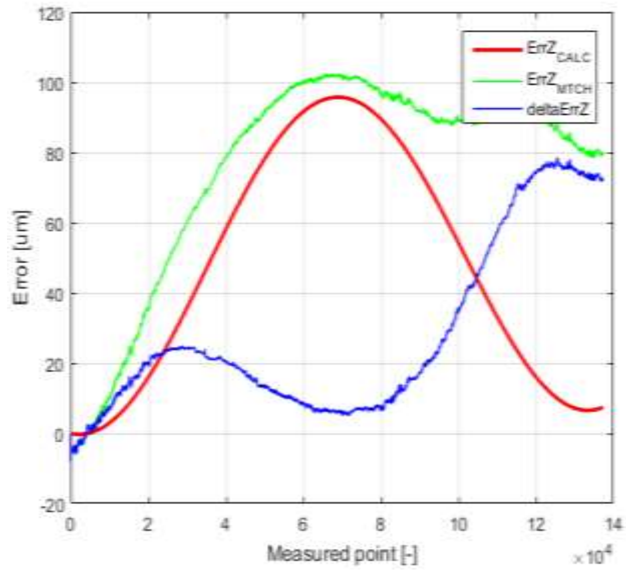

Figure 9: Comparison of measurement and simulation results of volumetric error along trajectory interpolated by XYZAC axes - errors in Z direction.

3.4 Comparison with conventional measurement

In order to verify the proposed method, the obtained results are compared with the results obtained using conventional measurement methods of the considered geometric errors. The squareness errors between the linear axes were measured using a dial gauge and a 400 x 400 mm granite prism. A and C rotary axes POPPE were evaluated using the commercially available IBS PE software and measured using a dial gauge and gauge block. Table 3, Table 4, Table 5 presents comparison of evaluated and conventionally measured geometric errors.

	EXOY [µm/m]	EZOX [µm/m]	EYOZ [µm/m]
Evaluation	-2	12	35
Conv. measurement	4	15	39

Table 3: Comparison of evaluated and conventionally measured errors – squareness errors

	EXOC [µm]	EYOC [µm]	EAOC [µm/m]	ABOC [µm/m]
Evaluation	-5	2	-14	-88
Conventional measurement	-	-	-15	-84
SW IBS	-6	4	-	-

Table 4: Comparison of evaluated and conventionally measured errors – C axis POPPE

	EYOA [µm]	EZOA [µm]	EBOA [µm/m]	ACOA [µm/m]
Evaluation	-5	68	-145	-168
SW IBS	-9	70	-	-

Table 5: Comparison of evaluated and conventionally measured errors – A axis POPPE.

4 CONCLUSION

The procedure for fast measurement and subsequent evaluation of the set of basic geometric errors of the five-axis milling machines is introduced and experimentally verified.

A series of volumetric accuracy tests along the interpolated trajectories needed to evaluate a selected set of geometric errors were performed. These were movements along XYC, YZA, and XYZAC trajectories. In the first two cases, measurements were made to determine A and C rotary axes POPPE. In order to evaluate squareness errors of linear axes, XYC axes interpolation tests were performed, with the A axis swept by a constant angle $\pm\varphi_A$.

From the data obtained by the measurement, a set of selected geometric errors was subsequently evaluated using the proposed procedure. The geometric errors obtained using the proposed procedure were compared with the results of measurements obtained using conventional measurement methods. The entire evaluation procedure for the selected geometric errors was verified.

The set of selected geometric errors evaluated by the proposed procedure served as input data for the kinematic models of the tested machine tools. Volumetric error along the tested five-axis trajectories formed by the superposition of the evaluated geometric errors was calculated using kinematic model of tested machine tool. The results of the comparison of the measured and calculated errors show that the squareness error of linear axes and rotary axes POPPE account for more than half of the final volumetric error along the XYZAC axes interpolated trajectory. The residual volumetric error is formed by another 30 geometric errors.

The above-mentioned procedure for volumetric error and its components of a five-axis machine tool is effective for fast in-proces calibration, for example during a working shift. Evaluated geometric errors values can be entered in to the machine tool control system as a SW correction. Proposed procedure is also useful for further research, for example, to study accuracy changes during machine tool thermally unstable conditions.

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