



machines and their geometric errors are homogeneous transformation equations (HTM). Calculations and their use are described in the literature [Yang, 1996, Ibaraki2012]. Calculations of errors in the workspace of CNC machine by dual numbers are discussed by the authors in the publication [Holub 2015b].

For calculation of the resulting standard deviations, the procedures described in ISO 230 can be used. As a measuring device, we can use, for example, precision level vials, dial gauges with surface plates, auto collimators, single-axis laser interferometers, homing laser interferometers. To assess the state of machines, devices such as Ballbar (DBB) [Holub 2015a] and grid sensors (KGM) are used.

For measurements on three-axis machine tool shown in Fig. 2, the following instruments for measurement of selected geometric errors can be used. For measuring and creating compensation data for straightness and angular errors, the industry uses precision level vials, auto collimators, single-axis laser interferometers, and homing laser interferometers. Squareness errors are evaluated and compensated for using angled plates and dial gauges, single-axis laser interferometers and homing laser interferometers. Positioning errors can be measured and evaluated using a single-axis laser interferometer and homing laser interferometers. All the above errors, 21 geometric errors, can then be evaluated and measured with one instrument per one measurement cycle [Holub 2014]. The next chapter of this publication presents the results of measurements and procedures to compensate for errors EXX, EYX, EZX, EYY, EXY, EZY, EZZ, EXZ and EYZ, measured with a single-axis laser and verified with interferometer and Ballbar (DBB) and LaserTRACER (LTc).

## 4 EXPERIMENTAL SET-UP

### 4.1 Demonstrator

The case study is carried out on the three-axis vertical machining centre MCV 754QUICK (Fig. 2.) The coordinate system of demonstrator corresponds to the kinematic chain W (Workpiece)-X-Y-Z-T(Tool) with machine workspace and reduced measured space.



Figure 2. Vertical three-axis machining center MCV 754QUICK

Table 1 defines the start of the individual axes and the beginning and end of the measured workspace of vertical centre.

Axis	Start axis /start MS [mm]	WS measure	End axis WS / end measure MS [mm]	Length [mm]
X	0 / 2		754 / 752	750
Y	0 / 2		500 / 498	496
Z	-550 / -401		0 / -1	400

Table 1. Measurement range on CNC machine tool

### 4.2 Design and implementation of measurement

Implementation of corrections CEC and VCS was performed in the four resulting configurations C1A, C1B, C2A, and C2B (Fig. 3).

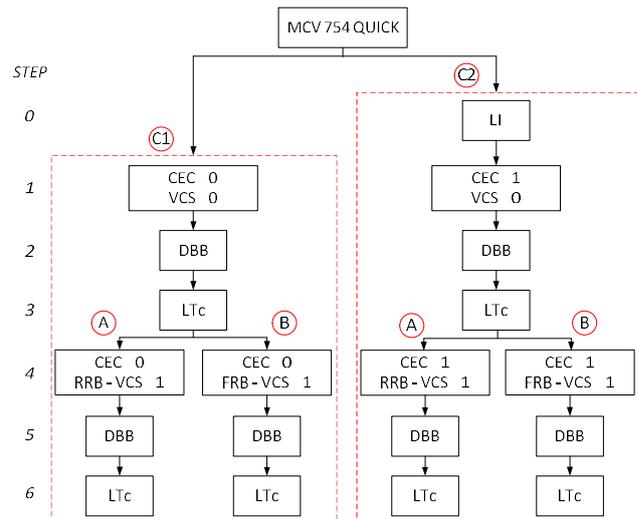


Figure 3. Design of measurement on MCV 754 QUICK

Configuration C1 describes the machine without software compensations; only VCS compensations are activated. Compensations VCS are further divided depending on the computational model into Reduce rigid body model (RRB) for the configuration C1A and Full rigid body model (FRB) for the configuration C1B. In the configuration C2, the first compensation performed on the machine was according to ISO 230-2 (CEC 1); it was subsequently followed by compensation for three-axis CNC machine tool labelled VCS A3. VCS compensations were reactivated in RRB for configuration C2A and in FRB for configuration C2B. Before implementation of corrections and after their activation, we performed a test of circular interpolation with Ballbar (DBB). In this test, we assessed the effects of compensation on geometric errors such as squareness of axes, straightness of axes, scalling error, and then the dimensional error of position tolerance and assessed error according to ISO 230-4 - circularity error. Tests of circular interpolation were always carried out in the planes X-Y, Y-Z and X-Z in a defined position of the machine. All settings and positions for measurements with devices LI, LTC and DBB and the machine MCV were identical for all configurations C1A - C2B.

Measurement of accuracy through the approach to the position in axes X, Y and Z (EXX, EYY, EZZ) was performed with the traverse speed of 1000 mm / min in the ranges described in Table 1. The number of measurement points in the axes X, Y and Z was equal to 11 in a bidirectional cycle with repeated number of approaches in five cycles. Fig. 4 on the left shows a sample measurement with laser interferometer in the configuration for measurement of approach to the position of the Z axis (EZZ).



**Figure 4.** Measuring positioning error EZZ with Laser interferometer and volumetric accuracy FRB model with LaserTRACER

Verification measurements with diagnostic instrument DBB are shown in Fig. 5 to the left. The aim of this rapid diagnosis is to assess the accuracy of corrections loading and assess the effectiveness of activation for configurations C1A, C1B and C2A and C2B. DBB measurement was carried out in the defined machine coordinates and with the traverse speed of 1000 mm / min in the planes X-Y, Y-Z, X-Z.



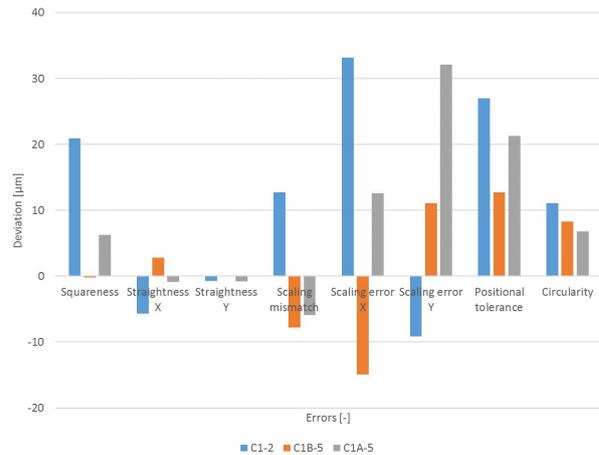
**Figure 5.** Measuring of circularity test with Ballbar and volumetric accuracy RRB model with LaserTRACER

Another deployed instrument for calibration and verification is LaserTRACER (LTc). LTc operates on the principle of homing laser interferometer using the method of sequential multi lateration to calculate deviations; it is shown in Figs. 4 and 5 to the right. Measurement procedures and results of basic tests on the machine MCV are described in detail in publications [Holub 2014, Holub 2015a]. Calibration and verification were performed for a range of axes according to Table 1. Measurements were carried out with the measurement method using a trigger (publications) with traverse speeds of axes of 2000 mm / min. For calculating the deviation, FRB and RRB were selected. The model FRB provided 21 geometric deviations for three-axis kinematics of machine MCV 754QUICK. A total number of measurement points in the machine workspace is equal to 1834. On the basis of calibration measurements, a compensation file was calculated for three-axis kinematics VCS A3 and activated in the control system of the machine.

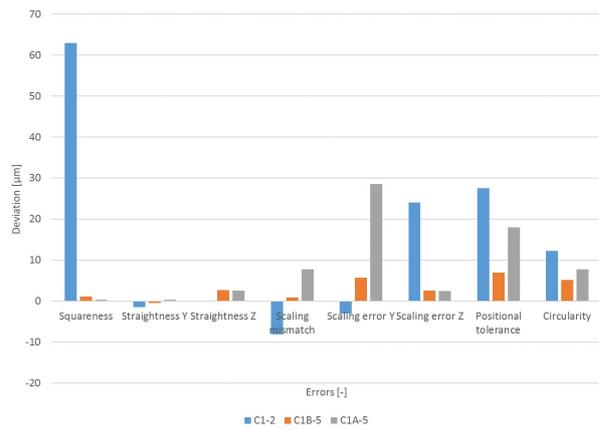
Subsequent verification measurements were carried out immediately after activation under the same measurement conditions and in the same environs. The model RRB provided 17 geometric deviations for three-axis kinematics of the machine. A total number of measurement points in this setting is equal to 828. After the calibration measurement and activation of compensation file for three-axis kinematics VCS, verification measurements were performed under the same measurement conditions and in the same environs. The next chapter presents the results of calibration and verification of measurements including the assessment of time demands and verification of the results using the DBB instrument.

### 4.3 Results

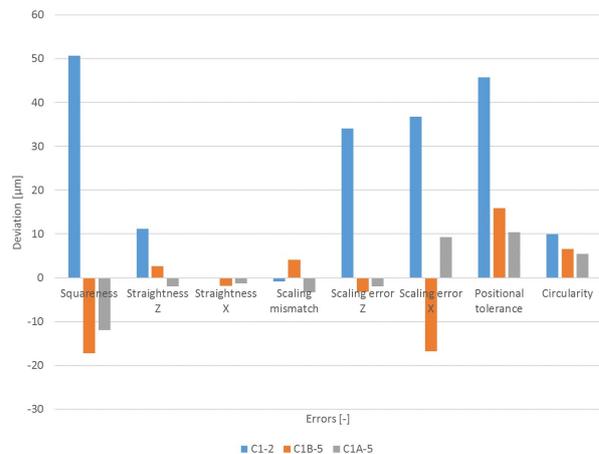
In the first part of the experiment, designated as C1, the machine without activated software compensations ENC, CEC, VCS was evaluated. This configuration is reported in Fig. 3 as C1-1. In the step C1-2, measurement was performed with DBB, wherein the resulting value of circularity (main parameter under consideration) is equal to 11.1  $\mu\text{m}$  in the X-Y plane, 12.2  $\mu\text{m}$  in Y-Z, and 9.9  $\mu\text{m}$  in X-Z. Other evaluated parameters from DBB measurements are shown in Fig. 6 for the X-Y plane, in Fig. 7 for the Y-Z plane and in Fig. 8 for the X-Z plane.



**Figure 6.** Plane X-Y for configurations C1-2, C1A-5, C1B-5.



**Figure 7.** Plane Y-Z for configurations C1-2, C1A-5, C1B-5.



**Figure 8.** Plane X-Z for configurations C1-2, C1A-5, C1B-5.

The spatial deviation in the step C1A-4 is equal to 37.0  $\mu\text{m}$ , and in the step C1B-4 to 52.0  $\mu\text{m}$  (Fig. 15). Other evaluated parameters obtained from the calibration measurement in configuration C1A-4 (RRB) and C1B-4 (FRB) by LaserTRACER are

shown in fig. 9. Subsequently, compensations VCS A3 were activated and verification measurements were carried out with DBB and LTc. In the point C1A-5 (RRB), verification measurement was carried out with DBB with results of circularity deviations  $6.8 \mu\text{m}$  in the plane X-Y,  $7.7 \mu\text{m}$  in Y-Z, and  $5.4 \mu\text{m}$  in X-Z. In the point C1B-5 (FRB), verification measurement was carried out with DBB with results of circularity deviations  $8.3 \mu\text{m}$  in the plane X-Y,  $5.2 \mu\text{m}$  in Y-Z, and  $6.6 \mu\text{m}$  in X-Z. Other evaluated parameters are shown in Fig. 6 for the plane X-Y, in Fig. 7 for the plane Y-Z and in Fig. 8 for the plane X-Z. Spatial deviation in the configuration C1A-6 (RRB) was equal to  $12 \mu\text{m}$  and in a configuration C1B-6 (FRB) also to  $12 \mu\text{m}$ . Other evaluated parameters obtained by verification measurement using the LTc device in configurations C1A-6 (RRB) and C1B-6 (FRB) are shown in Fig. 9.

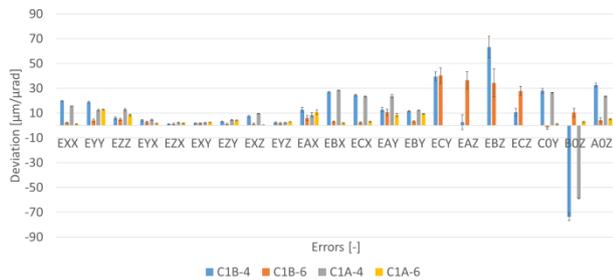


Figure 9. LaserTRACER results for configurations C1A-4, C1B-4, C1A-6 and C1B-6.

The second part of the experiment is consistent with measurements according to configuration C2. In the point C2-0, calibration measurement was performed using the accuracy test for approach into the position for axes X, Y and Z. From this measurement, compensation data were generated and activated in tables CEC (C1-1). Subsequently, verification measurement was performed. Both calibration and verification data for errors EXX, EYY and EZZ are shown in the graph of Fig. 10.

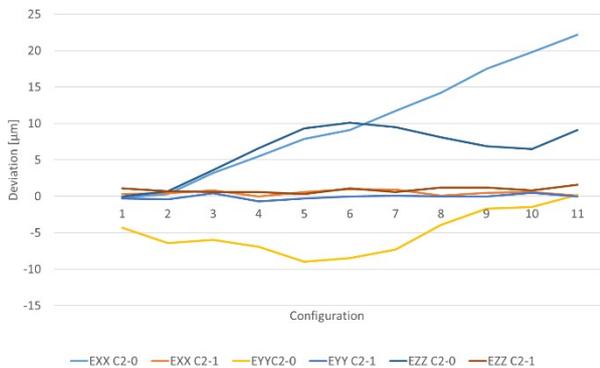


Figure 10. Laser interferometer results of errors EXX, EYY, EZZ

In the point C1-2, control measurement was performed with DBB instrument in the same machine coordinates and at the same traverse speed as that in configuration C1. The value of circularity in configuration C2-2 was equal to  $9.4 \mu\text{m}$  in the plane X-Y, to  $5.10 \mu\text{m}$  in Y-Z and to  $8.7 \mu\text{m}$  in X-Z. Other parameters obtained from the measurement with DBB instrument are shown for the plane X-Y in Fig. 11, for Y-Z in Fig. 12 and for X-Z in Fig. 13.

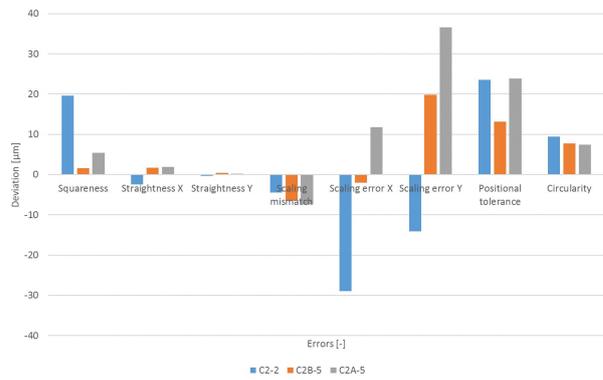


Figure 11. Plane X-Y for configurations C2-2, C2A-5, C2B-5.

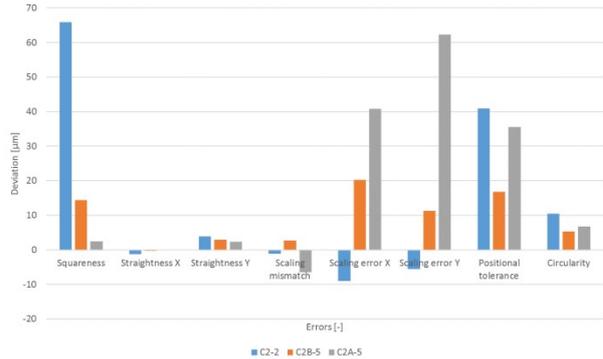


Figure 12. Plane Y-Z for configurations C2-2, C2A-5, C2B-5.

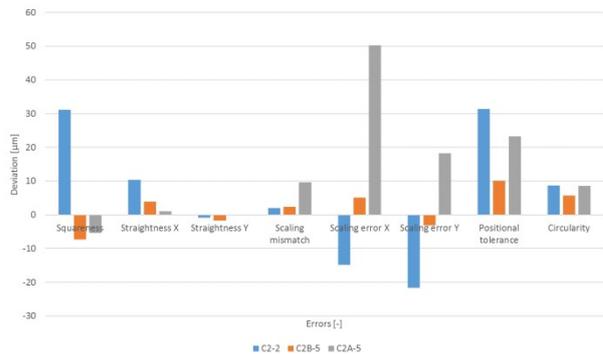
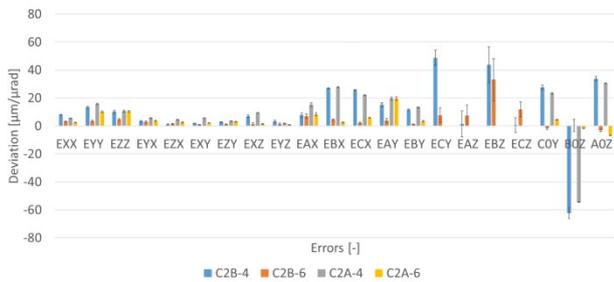


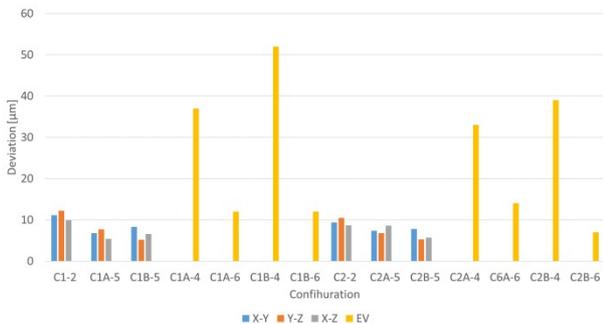
Figure 13. Plane X-Z for configurations C2-2, C2A-5, C2B-5.

In the point C2-3, measurement of volumetric accuracy of the machine workspace was performed. Volumetric accuracy was equal to  $33 \mu\text{m}$  for configuration C2A-4 (RRB) and to  $39 \mu\text{m}$  for configuration C2B-4 (FRB), see Fig. 15. Subsequently, DBB verification measurement was performed for configuration C2A-5 having a circularity of  $7.4 \mu\text{m}$  in the X-Y plane,  $6.8 \mu\text{m}$  in the plane Y-Z and  $8.6 \mu\text{m}$  in the plane X-Z. To configure C2B-5, circularity in the X-Y plane was equal to  $7.8 \mu\text{m}$ , in the Y-Z plane to  $5.3 \mu\text{m}$  and in the X-Z plane to  $5.7 \mu\text{m}$  (Fig. 11, Fig. 12 and Fig. 13, respectively). In the last step, verification measurement was carried out with LTc instrument with a resultant spatial deviation of  $14 \mu\text{m}$  for configuration of C2A-6 (RRB) and  $7 \mu\text{m}$  for configuration C2B-6 (FRB). The results are shown in Fig. 15. Fig. 14 shows other errors obtained from LTc measurement in configurations C2B-4, C2B-6, C2A-4 and C2A-6.



**Figure 14.** Laser TRACER results for configurations C2A-4, C2B-4, C2A-6 and C2B-6.

A final summary of the examined parameters (circularity – C, Error volume - EV) of the two configurations is shown in Fig. 15. From this it is evident that the best result of EV is for configuration C2B-6 and the highest error is in configuration C1B-4. Configuration C2B-6 with the lowest spatial error corresponds to volumetric compensation with the FRB model and to positioning compensation CEC for all axes. In terms of the circularity value, the best configuration seems to be C2B setting while the worst is C1B. It must be taken into consideration that the values of circularity are different for each plane and setting within the range of 1 µm.



**Figure 15.** Comparison of results for planes X-Y, Y-Z, X-Z and EV

## 5 CONCLUSIONS

Implementation of software compensations to the control systems of CNC machine tools is a way how to increase their geometric, work and manufacturing accuracy. Control systems offer various options for software compensations of geometric accuracy. Choosing the type of compensation may influence the effectiveness of increase in geometric accuracy of the machine, costs and time required for compensation deployment.

This article discusses the increase in geometric accuracy of the machine using two selected compensations offered by the systems SIEMENS Sinumerik. The first compensation is the cross error compensation and the other is volumetric compensation system. To obtain the compensation data, measuring instruments based on laser interferometry were used - laser inetrferometer XL-80 and LaserTRACER. For verification of the initial state of CNC machine and the subsequent activation of compensations, the instrument Ballbar was used. Among the evaluated parameters, spatial error and circularity error were chosen.

From the conducted study and the obtained results, it is obvious that the individual compensations and combinations thereof affect both the circularity error and spatial accuracy. The most appropriate setting for measurements and compensation was the configuration C2B, both for spatial error and circularity error. There was a significant difference in the spatial error, which was equal to 7 µm for C2B and to 12 µm and more for other configurations. In assessing the circularity

error with respect to the assessment of all three planes, the values ranged from  $\pm 1.0 \mu\text{m}$ , which is negligible for a small CNC machine.

The assessment of the effectiveness of increasing the geometric accuracy of the machine includes also the time required for activation and validation of compensation. Here the worst results were found in configuration C2B while the best in configuration C1A.

Further possibilities for increasing the geometric accuracy of CNC machine tool are offered by compensation of errors arising from squareness and straightness. Furthermore, it can be assumed that in medium-heavy and heavy machinery such differences are more significant.

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