# VOLUMETRIC COMPENSATION OF THREE-AXIS VERTICAL MACHINING CENTRE

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This contribution assesses the possibilities of application of volumetric compensation technology on a small three-axis vertical machining centre. These machine tools are designed for machining of small workpieces with various requirements on dimensional and shape accuracy. Small machine tools do not show large volumetric deviations across the entire working space as it is seen with medium-sized and large machining centres. To test volumetric compensation, detailed measurements on a small machining centre (demonstrator) were performed prior to activation of compensation set; other verification measurements were carried out with activated compensation set. Even if volumetric compensation is deployed, it is necessary to verify the achieved results in an appropriate manner. The accomplished study will offer pertinent conclusions on the appropriateness of the technology to be deployed for selected types of workpieces.

**KEYWORDS**

volumetric compensation, volumetric accuracy, machine tool, LaserTRACER, ballbar

## 1 INTRODUCTION

Volumetric accuracy of machine tool is defined as the ability of the machine to produce accurate 3D shapes. The task for improvement of volumetric accuracy is to minimize the cost of new or modified production processes, e.g. those related to the change of required accuracy of workpieces. Based on the information on the volumetric accuracy of the machine tool (MT) or a coordinate measuring machine (CMM) bound to the accuracy and traceble metrology, the machine tool can be characterized or the obtained data can be used for subsequent numerical compensation (volumetric compensation) to improve the accuracy [Schwenke 2008]. In our case, for accurate measurement and evaluation of volumetric accuracy, the technology of sequential multilateration was used. This approach is connected with the measuring instruments Laser TRACER and Laser Tracker which utilize the principle of tracking laser - intreferometry [Aguado2013] [Schwenke2005] [Linares 2014] [Brecher 2012a]. To identify the spatial variations of the individual parts of the machines, but also of the entire kinematic chain, tracking devices are used to evaluate the current deviation from the desired position, published in [Knobloch 2014], [Ibaraki 2014]. The publications [Usop 2015], [Marek 2009] refer to the increase in accuracy of vertical machining centre by implementing the axial corrections. Measurement of accuracy when the machine is approaching the position was realized by Laser interferometer, from which the correction tables for each axis were obtained. The increase in geometric accuracy was verified using a Ballbar device and a test of circular interpolation. This measurement was carried out before enlisting the corrections and after activating the compensation values. From the conclusion it can be stated that the deployment of axial compensations increased the geometric-kinematic accuracy in two axes. The method of measuring the volumetric accuracy by LaserTRACER has been described in [Holub 2014]. The publication presented two ways of measuring: by time response or a trigger. The results show that for the same conditions of measurement the method of measurement does not affect the final error and measurement uncertainty. Machine tools are increasingly subjected to requirements on performance and reliability of machines and production accuracy. New technologies offer the possibility of monitoring the variables such as temperature, displacement and deformation that serve as input information for compensation models of machine tools. One of the possible approaches how to increase the volumetric accuracy is to use the available options to volumetric compensation on the selected control systems. The present paper describes the measurement of volumetric accuracy by LaserTRACER on a demonstrator, including the process of verifying the results of circular interpolation test.

## 2 VOLUMETRIC ACCURACY OF VERTICAL MACHINING CENTRE

Volumetric accuracy for machining centres is described by geometric deviations. For kinematics of five-axis machining centre, it is 42 errors [Brecher 2012b] and for the kinematics of three-axis vertical centre, it is 21 errors [Holub 2014]. Geometric errors are described according to the ISO 841 standard. This system is based on a triaxial Cartesian coordinate system having translational axes X, Y, Z. In terms of error initiation on a translational axis, each axis has six degrees of freedom (DOF) which correspond to six geometrical errors. For example, for the Y axis there are the following errors: EYY, EXY, EZY, EAY, EBY, and ECY. Equally important are squareness errors; always between the two axes X-Y with the squareness error C0Y, and Y-Z with squareness error A0Z. All 21 geometric errors are shown in the following figure (Fig. 1)

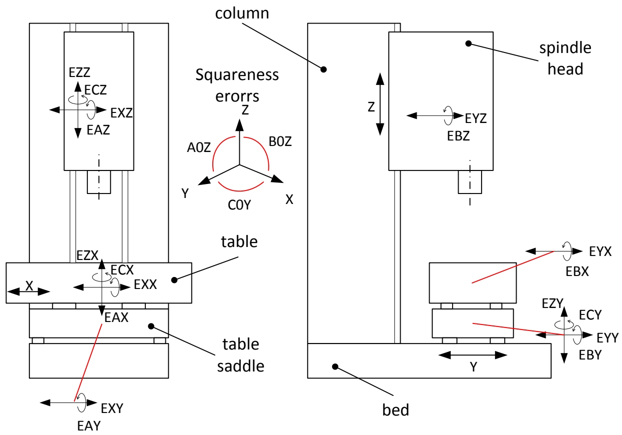


**Figure 1.** Geometric errors of three-axis vertical machining centre

## 3 CASE STUDY

### *3.1 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 (WS) and reduced measured space (MS). Reduction of workspace WS is necessary due to the deployment of the measuring instrument LaserTRACER that because of its dimensional and handling parameters does not allow measurements of the entire workspace WS.


**Figure 2.** Vertical machining centre MCV 754QUICK, KOVOSVIT MAS

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

| Axis | Start axis WS /start measure MS [mm] | End axis WS / end measure MS [mm] | Length [mm] |
|---|---|---|---|
| X | 0 / 0 | 754 / 750 | 750 |
| Y | 0 / 0 | 500 / 500 | 500 |
| Z | -550 / -400 | 0 / 0 | 400 |

**Table 1.** Milling conditions

### *3.2 Design and implementation of measurement*

As a measuring device for determining volumetric accuracy, the homing laser interferometer LaserTRACER was selected. LaserTRACER works with a laser interferometer resolution of 0.001 µm and measurement uncertainty of $U_{95}$ = 0.2 µm + 0.3 µm/m. The overall uncertainty of measurement is influenced by the ambient conditions (temperature, pressure, humidity, and vibrations), by the selection of kinematic model, design of measurement strategies, etc. The measuring device works on the principle of sequential multilateration, on which the requirements for setting the measurement strategy are based. For calculating the error and individual erroneous parameters, it is necessary to perform measurements from at least four working positions. To identify a total of 21 parameters of errors, it is necessary to perform measurements from the six positions that are defined within the preparation of strategy for measurement of volumetric accuracy. The selected positions of LaserTRACER in the machine workspace are shown in the following table (Table 2.), including reflector offsets.

| LAserTRACER Position | | | | Reflector Offset | | |
|---|---|---|---|---|---|---|
| Nr. | X [mm] | Y [mm] | Z [mm] | X [mm] | Y [mm] | Z [mm] |
| 1 | -140 | 70 | -480 | 0 | 0 | -122 |
| 2 | -140 | 305 | -480 | 0 | 0 | -122 |
| 3 | 810 | 95 | -320 | 0 | 0 | -122 |
| 4 | 810 | 230 | -320 | 0 | 0 | -122 |
| 5 | 810 | 230 | -320 | 0 | 127 | -50 |
| 6 | 810 | 230 | -320 | 127 | 0 | -50 |

**Table 2.** LaserTRACER position

The measurement strategy was created using the TRAC-CAL program from the company Etalon. The left side of the figure (Fig.3.) shows the parameters of 21 errors and their uncertainties based on the prepared measurement strategy.

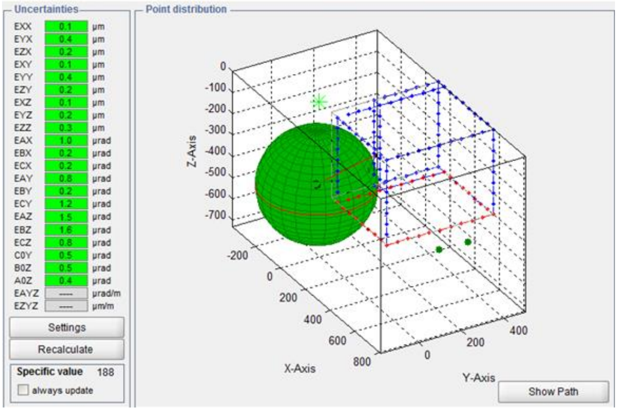


**Figure 3.** Definition of strategies

Measurements will be conducted using a trigger device at the machine feed rate of 4.000 mm / min. This will minimize the time required for measurement and also the impacts of the environment (temperature changes throughout the day).
Prior to the first measurement, the current state of the machine will be detected using a circular interpolation test. The monitored output will be the value of circularity and the values of squareness of axes; these values are processed in the expert software RenishawBallbar 20. The test will be performed by Ballbar measuring device. Circular interpolation tests were performed at machine working feed of 1.000 mm / min, test radius of 150 mm and air temperature of 21.6 ° C ± 0.5 ° C. The test was performed in the middle of the worktable, see Fig. 4.

**Figure 4.** Ballbar test for compensation of volumetric errors

After identifying the current state of the machine by Ballbar device in all three planes X-Y, Y-Z, Z-X, machine calibration was performed using LaserTRACER. An example of fixing the device on the machine tool is shown in the following Fig. 5.

Figure 5. LaserTRACER – Calibration

### 3.3 Results

Verification of the initial state (calibration) was first measured by length-calibrated device Ballbar. The basic parameters to compare are the values of circularity, squareness, straightness, scaling error and positional tolerance error (Tab. 5, Tab. 6 and Tab. 7). The shapes of the resulting calibration circles in both directions are shown in the following Fig.6.

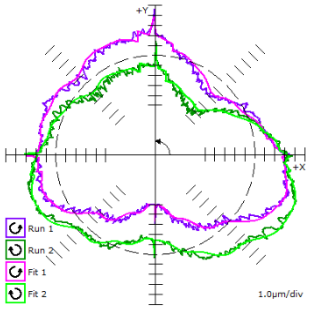


Figure 6. Ballbar test for volumetric errors compensation – Calibration, X-Y

All 21 parameters of errors obtained from the measurements with LaserTRACER are shown in the following Table. 3. As evident from the results, the largest machine errors are those of EXX, C0Y, B0Z and A0Z.

| Group | Parameter | Deviation (range) | $U_{max}$ (95 %) |
|---|---|---|---|
| Position [µm] | EXX | 26.1 | 0.3 |
| | EYY | 13.8 | 0.9 |
| | EZZ | 11.3 | 1.0 |
| Straightness [µm] | EYX | 6.5 | 1.0 |
| | EZX | 2.9 | 0.6 |
| | EXY | 1.9 | 0.2 |
| | EZY | 3.8 | 0.5 |
| | EXZ | 9.0 | 0.6 |
| | EYZ | 1.3 | 0.6 |
| Pitch / Yaw / Roll [µrad] | EAX | 11.1 | 3.6 |
| | EBX | 34.3 | 0.7 |
| | ECX | 24.2 | 0.7 |
| | EAY | 15.6 | 2.2 |
| | EBY | 15.7 | 0.5 |
| | ECY | 25.8 | 4.1 |
| | EAZ | 36.4 | 6.9 |
| | EBZ | 60.3 | 8.1 |
| | ECZ | 15.9 | 3.7 |
| Squareness [µrad] | C0Y | 35.5 | 3.5 |
| | B0Z | -68.5 | 2.9 |
| | A0Z | 40.7 | 2.1 |
| | *Volumetric Error* | *51.1 µm* | |

Table 3. LaserTRACER – Calibration

The obtained deviations were used to enter the corrections to the control system of machine tool. After their activation, verification measurement was carried out using LaserTRACER. The results of deviations of individual errors can be seen in Tab. 4. A mutual comparison of individual parameters of errors during calibration and verification are shown in Fig. 7. From here it is obvious that among the 21 assessed parameters of machine errors, 13 were improved while 8 showed deterioration. Among the 8 deteriorated parameters, 4 are negligible in terms of extent of deterioration and the actual measurement uncertainty, and only 4 show a more pronounced deterioration. This ratio of deteriorated and improved errors is due to the very principle of "flattening" of the workspace into an ideal cuboid. This also explains that some parameters must be deteriorated at the expense of more dominant errors that must be minimized. From the perspective of the overall volumetric accuracy of the machine, a significant improvement can be observed.

| Group | Parameter | Deviation (range) | $U_{max}$ (95 %) |
|---|---|---|---|
| Position [µm] | EXX | 4.4 | 0.4 |
| | EYY | 12.0 | 1.0 |
| | EZZ | 4.2 | 0.9 |
| Straightness [µm] | EYX | 7.3 | 2.1 |
| | EZX | 3.1 | 1.1 |
| | EXY | 3.5 | 0.2 |
| | EZY | 3.0 | 0.6 |
| | EXZ | 2.8 | 0.7 |
| | EYZ | 0.2 | 0.6 |
| Pitch / Yaw / Roll [µrad] | EAX | 21.4 | 6.7 |
| | EBX | 4.1 | 0.9 |
| | ECX | 10.1 | 1.1 |
| | EAY | 15.5 | 2.3 |
| | EBY | 5.1 | 0.4 |
| | ECY | 27.0 | 3.6 |
| | EAZ | 39.4 | 6.2 |
| | EBZ | 87.1 | 10.5 |
| | ECZ | 27.0 | 3.6 |
| Squareness [µrad] | C0Y | -15.3 | 2.4 |
| | B0Z | -5.0 | 3.6 |
| | A0Z | -6.5 | 1.3 |
| | *Volumetric Error* | *20.0 µm* | |

Table 4. LaserTRACER - Verification

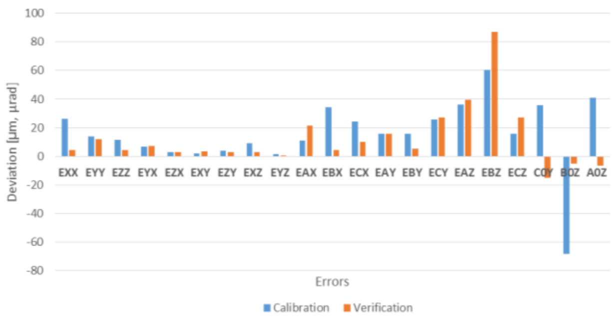


**Figure 7.** Comparison of calibration and verification results - LaserTRACER

Fig. 8 and Fig. 9 show spatial deviations using a deformation grid. The maximum volumetric error in the machine workspace prior to compensation (calibration) is 51.1 µm while after the machine compensation (verification) it is 20.0 µm.

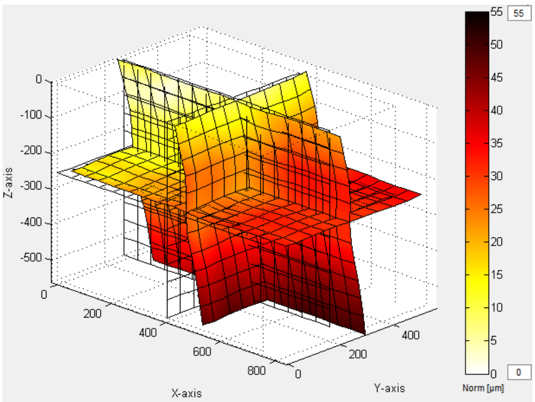


**Figure 8.** Presentation of volumetric error–calibration

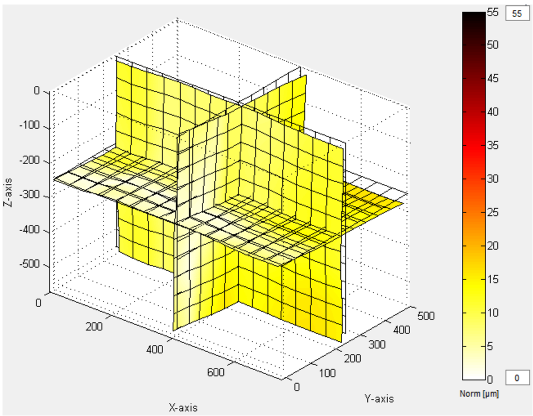


**Figure9.** Presentation of volumetric error - verification

The last step is to verify the workspace using the test of circular interpolation. Fig. 10 shows the improvement of circular shape compared to that in fig. 6. The following comparison presents the selected errors in the planes X-Y, Y-Z, and Z-X. The comparison is described in Tab. 5, 6, and 7. The impaired parameters vary mainly in units of micrometers and are negligible in terms of overall assessment of accuracy.

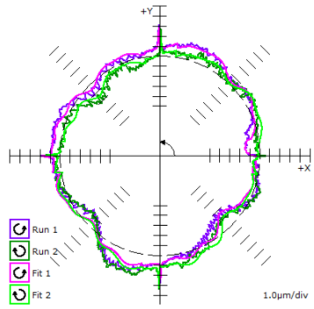


**Figure 10.** Ballbar Test of volumetric errors compensation – Verification, X-Y

| Error | Cal. | Ver. | Absolute Improved |
|---|---|---|---|
| Circularity [µm] | 10.7 | 5.6 | 5.1 |
| Squareness [µm / m] | 13.8 | - 6.4 | 7.4 |
| Straightness X [µm] | -5.2 | 1.1 | 4.1 |
| Straightness Y [µm] | -1.6 | 0.7 | 0.9 |
| Scaling Error X [µm] | 27.2 | - 16.0 | 11.2 |
| Scaling Error Y [µm] | 1.4 | - 10.6 | -9.2 |
| Positional tolerance [µm] | 21.8 | 13.5 | 8.3 |

**Table 5.** Comparison of Ballbar X-Y results

| Error | Cal. | Ver. | Absolute Improved |
|---|---|---|---|
| Circularity [µm] | 11.2 | 6.5 | 4.7 |
| Squareness [µm / m] | 58.7 | 12.5 | 46.2 |
| Straightness X [µm] | -0.4 | - 2.9 | - 2.5 |
| Straightness Y [µm] | - 1.3 | 3.0 | - 1.7 |
| Scaling Error X [µm] | 8.3 | - 11.2 | - 2.9 |
| Scaling Error Y [µm] | 26.2 | 1.3 | 24.9 |
| Positional tolerance [µm] | 26.6 | 13.5 | 13.1 |

**Table 6.** Comparison of Ballbar Y-Z results

| Error | Cal. | Ver. | Absolute Improved |
|---|---|---|---|
| Circularity[µm] | 8.4 | 8.0 | 0.4 |
| Squareness[µm / m] | 18.0 | - 7.8 | 10.2 |
| Straightness X[µm] | 9.2 | 4.0 | 5.2 |
| Straightness Y[µm] | 1.1 | - 2.7 | - 1.6 |
| Scaling Error X[µm] | 31.8 | 1.5 | 30.3 |
| Scaling Error Y[µm] | 32.4 | - 17.5 | 14.9 |
| Positional tolerance[µm] | 31.7 | 15.2 | 16.5 |

**Table 7.** Comparison of Ballbar Z-X results

## 4 CONCLUSIONS

Countless publications are devoted to the increase of geometric accuracy of machine tools. The presented work is focused on the implementation of volumetric accuracy for a small three-axis vertical milling machining centre. Based on the kinematic structure, a measurement strategy was designed for LaserTRACER, including verification of geometric accuracy by another technology. In our case, the accuracy of machining centre was verified by circular interpolation test using the measuring device Ballbar. This approach was verified; it enables to monitor the entire workspace of the machine. Within the calibration and verification, a moderate improvement by 22 % was achieved with LaserTRACER in 21 of the monitored parameters of errors. A volumetric error in the entire workspace improved from 51.1 µm to 20.0 µm, i.e. approximately by 60 %. With the circular interpolation test, the parameters were improved in the plane of X-Y circularity by 48 % and positional tolerance by 38 %, in the plane of Y-Z circularity by 42 % and positional tolerance by 49 % and in the plane of X-Z circularity by 5% and positional tolerance by 52 %.

The total time of calibration and verification lasted approximately 6.5 hours. Among the most time-consuming operations were those of relocating the LaserTRACER to the measuring positions. For small machines it is possible to use the device LaserTRACER-MT, which is, in terms of handling ability, much more user friendly; this would eliminate the time necessary for relocation of LaserTRACER. Longer measurement times can adversely affect the results of measurements due to the changes in the ambient environment.


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