INFLUENCE OF THE VOLUMETRIC ACCURACY OF MACHINE TOOL ON THE WORKING SPACE SIZE

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Volumetric compensation of CNC machine tools can provide a significant progress in increasing the production accuracy and hence the product quality. This paper describes the influence of the volumetric accuracy of the machine tool on the size of the working space. Impact assessment was performed on the basis of tests of three-axis vertical CNC machining center. In the practical part, the planning of the experiment according to Shainin is described, the procedure of working with measuring instruments is described and the measurement of the geometric / volumetric accuracy of the machine tool, including statistical evaluation.

KEYWORDS

Machine tools, accuracy, volumetric accuracy, geometric accuracy, LaserTRACER

1 INTRODUCTION

Increasing the manufacturing accuracy of machine tools (MT) is one of the prerequisites for the competitiveness of machine tool manufacturers. Further, there are ever-increasing demands on how to achieve a more accurate and long-term stable production. Thanks to the progress in new technologies, especially more powerful hardware in machine tool control systems, it is possible to use a larger number of calculations oriented on production accuracy without slowing down the productivity of machines. It is the appropriate use of the available methods that can increase the geometric accuracy of the machines assessed on the circular deviation according to ISO 230-4 by up to 60 % [Holub 2020].

At present, geometric error compensation software is an integral part of every CNC machine tool and its importance is growing, especially with the development of the Industry 4.0. Quasi-static errors can be observed in machine tools. These are errors defined as relative position errors of TCP and workpiece, these errors change slowly over time. They are directly related to the structure of the machine tool itself and can be divided into geometric, kinematic and thermal errors. In the publication [Ahn 2000], quasi-static errors also include dynamic errors, which translate very slowly into the relative position of TCP and workpiece. Geometric errors are influenced by the production of individual components and form the structure of the machine. Kinematic errors are then the errors dependent on the direction of movement, machine compliance and also include thermal dilatations of individual parts. According to prof. Rameshe, a quasi-static error represents 60-70 % in the overall working accuracy of the machine [Ramesh 2000], these were mainly three-axis machining centres. Prof. Ibaraki has further expanded this estimate within the tests carried out on the five-axis machining centres, claiming that the quasi-static error rate is even higher, up to 80 % [Ibaraki 2010]. Therefore, from the point of view of subsequent production, these are significant sources of error on machine tools.

One of the advanced software compensations is a volumetric compensation through which it is possible to achieve an increase in volumetric accuracy by up to 85 % for a three-axis vertical machining centre [Holub 2016]. For these advanced compensations, it is necessary to take into account that they are time-consuming and due to this, also sensitive to ambient conditions. Therefore, it is necessary to make efforts to do measurements in the shortest possible time. Tracking interferometers, such as the LaserTRACER measuring devices and the Laser trackers described in the publications [Aguado 2012] and [Linares 2014] are most commonly used to measure machine volumetric accuracy. Furthermore, devices such as multiple beam interferometers are described in [Holub 2019A]. The main focus of publications [Schwenke 2009] and [Holub 2017] is to find a way how to implement the volumetric compensations as quickly as possible, Furthermore, it is necessary to have access to the machine to appropriately set up monitoring of the ambient conditions of the machine in order to minimize measurement uncertainty in terms of results [Holub 2019B].

It is the elimination of internal and external negative effects that plays an important role in the implementation of volumetric compensations and their resulting impact. This paper is focused on the use of volumetric compensations for a specific workspace with the aim to reduce the resulting time necessary for the entire process of compensation and verification. Furthermore, the aim is to verify the hypothesis whether, with a smaller compensated space, it will be possible to achieve a higher effect of volumetric error compensation.

2 DEMONSTRATOR

The MCV 754 QUICK CNC machining centre (Fig. 1) from Kovosvit MAS company was chosen in order to verify the effect of volumetric deviation on the workspace. It is a vertical machining centre with SINUMERIC 840D sl control system from Siemens with VCS A3 option for volumetric compensation. The machine specifications are given in Tab. 1 (according to ISO 230-2).

Figure 1. MCV 754 QUICK CNC machining centre

Item	[mm]
Travel of X axis	754
Travel of Y axis	500
Travel of Z axis	550
Bi-directional systematic positioning error of an axis	0.015
bi-directional positioning repeatability of an axis	0.005

Table 1. Specifications of MCV 754 QUICK, Kovosvit MAS.

3 EXPERIMENT

3.1 Experiment setup

The experiment was designed according to the Shainin method [Blecha 2006]. The task was defined as follows: whether there is a relationship between the compensated space sizes and the resulting MT volumetric deviation.

The current state of the art in the area of volumetric compensations does not include considerations of defining the size of the MT compensated space and its possible influence on the resulting volumetric deviation. In medium-sized and large MTs, only a specific space from the entire machine's workspace is often used for machining.

In the first phase of the experiment setup, three influencing factors were defined. These were also identified as the main factors. An overview of these factors with their designations and setups is described in Table 2.

Label	Designation	Setup		
		Good (+)	Wro ng (-)	Centre (0)
A	Size of space	WS1	WS3	WS2
B	Limit of laser stability [µm]	± 1.5	±2.5	-
C	Number of points [-]	11	6	-

Table 2. List of main factors and their setups.

The main factor is the size of the workspace and the individual spaces are shown in Figure 2. Other parameters include the laser stability limit and the number of measured points on the X, Y and Z axes. The size of the laser stability setting limit is set within the TRAC-CAL software from ETALON. The number of measured points per axis is chosen according to the recommendations of the methodological procedure of the company ETALON, the minimum number is given by six points per axis.

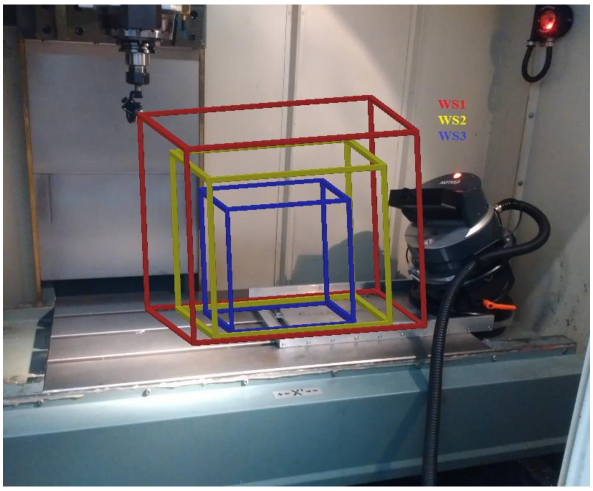

Figure 2. Size of measured space WS1, WS2 a WS3.

In Table 3, these spaces are specified in greater detail. The largest space is designated as WS1 and the smallest as WS3. All three spaces WS1 to WS3 have the same common base in the machine position Z = -450 mm and the centre of travel of the X and Y axes. The smallest space WS3 was chosen with respect to the smallest required travel of the axes for verification measurement by the Ballbar QC20-w, which uses the principle of the circular interpolation test. The test radius is 150 mm. The largest space WS1, in turn, reflected the requirements for the test setup using LaserTRACER. The central space of WS2 was chosen as the centre between WS1 and WS3.

Item	Length of axis [mm]			Volume [m^3]
	X	Y	Z	
WS1	600	500	450	0.135
WS2	460	410	385	0.073
WS3	320	320	320	0.033

Table 3. Size of workspace.

The main quality indicator was the size of volumetric deviation. Among the other quality indicators that are closely related to volumetric compensation were the parameters obtained from the Ballbar circular interpolation test. These are errors of circular deviation, squareness, position tolerance and straightness. The disturbing factors were machine temperature and ambient temperature. In the second step, it is necessary to evaluate the significance of the influencing factors. The significance of factors is shown graphically in Fig. 3. The graph shows the initial boot part according to Shainin, where the level factors are divided into good and wrong. First, a good value (g) was set for the observed level (AgRw, BgRw, CgRw) and a wrong value (w) for the remaining factors (R). Figure 3 shows that factor A (space) is likely to be significant, factor B (limit of laser stability) is likely to be significant, while factor C (number of interpolation points) is unlikely to be significant. These preliminary statements will be further proved or disproved on the basis of statistical data processing. The VCS value corresponds to the maximum value of the volumetric error in the assessed workspace.

Figure 3. Definition of good and wrong variables.

3.2 Measurement procedure

Nr. of measurement	Factors		
	A	B	C
1	+	+	-
2	+	+	+
3	+	-	-
4	+	-	+
5	0	+	-
6	0	+	+
7	0	-	-
8	0	-	+
9	-	+	-
10	-	+	+
11	-	-	-
12	-	-	+

Table 4. Scheme of measurement procedure.

The entire measuring cycle was performed within one day, which eliminated any possible changes in the structure of the machine influenced by the change of ambient conditions. The figure 4 shows the measurement waveforms with the SMARIS measuring station, which is installed on the MCV machine. The location and setting of the sensors is described in the publication [Holub 2019B]. Figure 4 shows the temperature course of the calibration (position 1-4) and verification measurement (position 5-8) of measurement setting nr. 9. The temperature difference was not greater than 0.3 °C during the measurement. During the entire measurement, a minimum temperature of 21.5 °C and a maximum measurement temperature of 25.5 °C were measured on the X, Y and Z axes of the machine. It can be seen from Figure 4 that there is a displacement between the individual axes with respect to the design of the machine and the location of the heat sources.

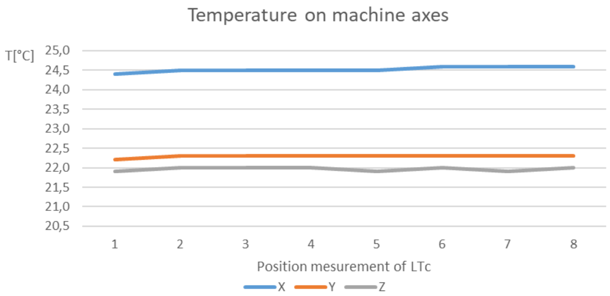

Figure 4. Temperature course on machine axes for setting nr. 9.

Figure 5 shows the results of measuring the maximum volumetric error according to the setting in Table 4. For each setting, the value with activated volumetric compensation (VCS on) and without activated volumetric compensation (VCS off) is displayed.

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Figure 5. Volumetric error according to measurement settings.

Other parameters checked included a circular deviation, which was evaluated in the Renishaw software and measured with a Ballbar QC20-w device and evaluated according to ISO 230-4. The results of the circular deviation are shown for individual measurements according to Table 4 in Figure 6.

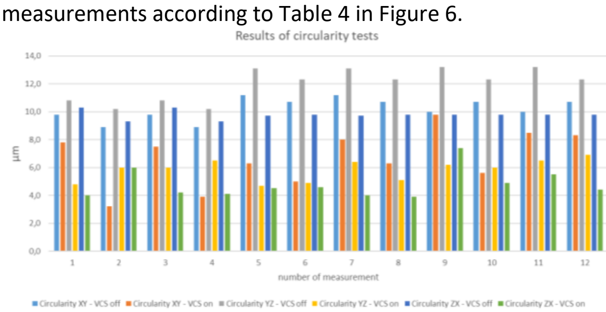

Figure 6. Circular deviation according to measurement settings.

Figure 7 shows a graph of the residues from measurements for the model without removing insignificant factors and interactions. From the graph of normal distribution, we can see that the residues are normally divided, P-value of 0.231. The residues show no increased variability in terms of response or measurement order. The shape of the histogram may appear misleading but is due to the number of replications of the experiment.

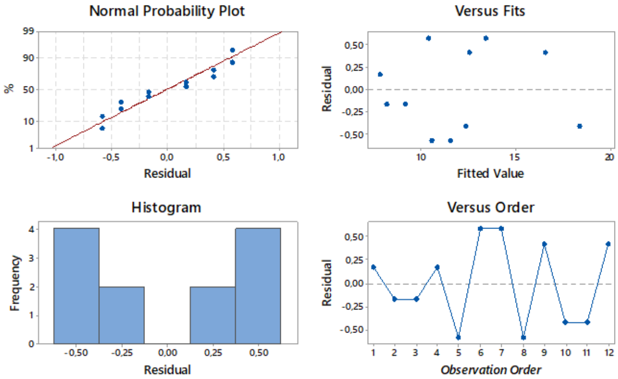

Figure 7. Graphs of residues for volumetric error.

3.3 Evaluation of planned experiment

An evaluation of the planned experiment was performed with the removal of insignificant factors with the interaction between them. The only significant factor is further studied size of space and the interaction of this space size with laser Fig. 8.

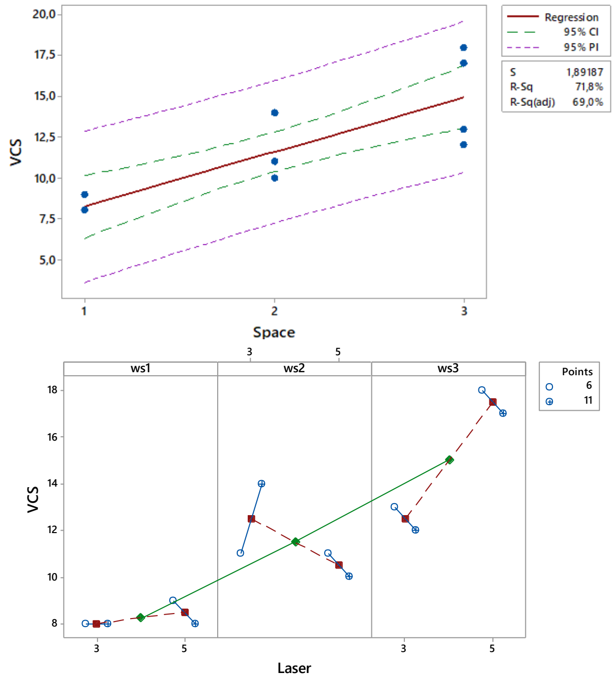

Figure 8. VCS regression curve, multivariate plot for VCS.

stability (P-value < 0.05). This model describes 91.66 % of the behavior of the volumetric error dependent on the investigated factors, indicating the coefficient of determination R2. The largest part of the variability is contributed by the factor - the size of the space, which describes 71.7 % of the variability of the measured data. This can be seen in the simplified node without the interaction of Fig. 8 above.

A VIF value for a coefficient close to 1 indicates that the factors examined are not correlated and the estimates of the coefficients are stable. They are robust towards minor changes. A desired dependence of volumetric error on factors can be described by regression equation. Fig. 8 above shows a regression curve with the confidence interval for the mean value and the confidence interval for the individual values. Fig. 8 below shows the multivariate plot for VCS by the number of interpolation points and the size of the space.

It is apparent from the previous results that the size of the space under investigation and then the interactions between the space size and the laser stability limit influence the volumetric error most. This can be seen in the different slope of the red lines in Fig. 8 above.

For setting nr. 6 (Table 4), which corresponds to setting WS2, the stability of the laser ± 1.5 µm and the number of interpolation points 6 and 11 is a higher variance value of 3 µm volumetric errors than for the other settings of 1 µm (Fig. 8 below). This variance is probably caused by a temperature increase on the X-axis between 4 and 5 points by measuring with LaserTRACER, where a temperature rises of 1.6 ° C was recorded (Fig. 9).

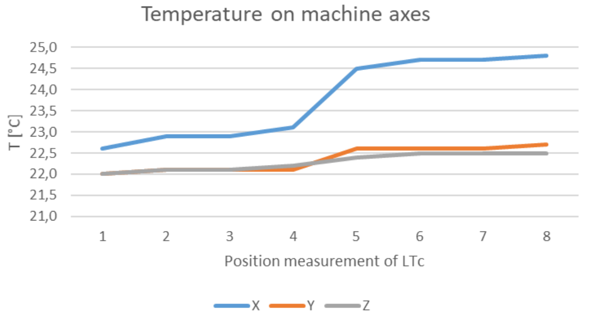

Figure 9. Temperature course on machine axes for setting nr. 6.

Furthermore, it was proved that the volumetric error is not dependent on the number of interpolation points. The factors of the laser stability limit and the number of interpolation points appear statistically insignificant (Fig. 8 above). Of course, the entire measurement depends on the time that is associated with changes in the ambience, but also with the economic costs in terms of necessary machine downtime.

4 DISCUSSION

The aim of this work was to prove the dependence between the volumetric deviation and the size of the investigated space and also with the interaction between the laser stability limit and the number of measured points. For a small CNC machine tool MCV QUICK 754, it has been proved that the smallest volumetric deviation is achieved with a combination of WS1 and limit of laser stability ± 2.5 µm (5 µm on Fig. 8). Furthermore, it can be stated that the model built according to the planned experiment describes 98 % of the behavior of volumetric deviation dependent on the investigated factors.The next part of the research activities will be focused on the verification of results for medium-sized and large CNC machine tools. Especially for large machines, significant financial savings would be achieved provided that the size of the volumetric deviation does not depend on the number of measured points.

Furthermore, in the case of large CNC machine tools, the opposite result could be obtained than that for small CNC machine tools depending on the size of the workspace. Here, larger changes in volumetric error are assumed depending on the TCP position in the space.

5 CONCLUSION

Volumetric compensation is a tool of how to effectively increase the geometric accuracy of CNC machine tools. A great number of works is focused on increasing the accuracy of machine tools by various methods. One of the options is to reduce the time required for measurement. This can be achieved, for example, by reducing the commonly used workspace of the machine, the number of measured points, or the size of laser stability limit.

In this work, based on the system approach and design of experiment, information was obtained on the interaction between selected factors and the resulting volumetric deviation.

For the MCV QUICK 754, it has been proved that the size of the workspace and the stability of laser have a significant influence on the resulting volumetric deviation. The best result was found for the largest WS1 space, which disproved the possible reduction in time savings while minimizing the machine's workspace exclusively to the part where the machining takes place. The greatest time savings can be achieved by selecting the minimum number (6 points) per axis and thus achieving time savings of around 30 minutes (40 %).

However, this approach could be more important for large machine tools. For medium and large machine tools, time savings of up to 120 minutes are expected, which would also lead to financial savings.

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