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A STUDY OF THE APPLICATION OF VOLUMETRIC COMPENSATION BY DIRECT AND INDIRECT MEASUREMENT METHODS

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Abstract

The present article deals with the measurement methods based on experimental tests and their impact on the resultant volumetric error of CNC machine tools (MT). Volumetric error compensations represent a promising technology to increase the production accuracy of machine tools. This article studies direct and indirect methods to measure the volumetric accuracy on a MT. The assessed parameters are not only the resultant volumetric error of the machine, but also time consumption of measurement, repeatability, and evaluation of individual geometric errors. Finally, recommendations are made to improve the effect of volumetric errors compensation using the above-mentioned methods for three-axis MT.

Keywords:
Geometric accuracy; Volumetric accuracy; Direct method; Indirect method

1 INTRODUCTION

One of the key indicators of machine tools is geometric accuracy. The increasing requirements for dimensional and form precision of workpieces and process quality result in higher demands on machine tool geometric accuracy.

There are several approaches to increase machine tool accuracy that differ not only in time consumption and costs but also in their efficiency (of individual machine tool producers). Essential know-how of individual machine tool producers lies in alignment methods to achieve sufficient mechanical accuracy. In this case time demands for such alignment must be taken into account.

Another approach to increase geometric accuracy is to apply subsequent numerical compensation on an already mechanical aligned machine. There is constant development in measurement procedures and associated software tools for such compensations, among others numerical compensations of geometric errors dependent on two machine axis.

Finally the nowadays most progressive methods are based on the mapping geometric errors in the whole working volume. The impact of such volumetric compensation increases with machine size and number of controlled axis. According to [Ramesh 2000], [Ibaraki 2010] the quasi-static errors contribute to an overall workpiece errors up to 60 – 70 % for three axis and up to 80 % for five axis machine tools.

With application of volumetric compensation on machine tools deal authors [Lau 1986], [Takatsuji 1998], [Schwenke 2005], [Brecher 2012], [Linares 2014]. Papers [Linares 2014], [Holub 2016] investigate impact of strategy set-up on resulting compensation effectiveness.

With further development of the volumetric compensation in the machine tool controllers new calibration devices appeared on the market. Nevertheless, the application of new calibration devices must be examined to estimate factors that influence the measurement uncertainty with the goal to optimize the application procedures.

The impact of activated volumetric compensations can be verified with several methods. One of the most applied procedures is based on the circular interpolation according to the standard ISO 230-4 for three axis and the ISO 10791–6 for five axis machine tools [Schwenke 2008], [Holub 2018]. In certain cases there is also recommended to perform positioning measurement according to ISO 230-2 or diagonal displacement tests described in ISO 230-6 in multiple locations.

In the current state of art it is possible to map volumetric errors using direct or indirect measurement approaches.

This paper compares time demands and overall effectiveness of direct and indirect approach representatives applied on a three axis machine tool. The each test consists of a calibration procedure, an activation of the correction tables in the control system and a verification with the same calibration procedure on one hand and on the other with a circular tests. The results are shown in chapter Results. Among analyzed parameters belong individual values of geometric errors and achieved circularity errors in the circular tests ISO 230-4.

2 GEOMETRIC ACCURACY MEASUREMENT BY MEANS OF DIRECT AND INDIRECT METHODS

2.1 Direct method of measurement

Direct calibration methods identify measurand – geometric parameters of one axis directly without involvement of other

axes. Direct methods can be classified into three groups according to the type of metrological reference used. The material-based methods use artifacts, i.e. straightedges, step gauges or linear encoders. To eliminate the drawback of elementary material standards which represent only one certain use, multidimensional artifacts are applied. As an example can be given a linear artifact with calibrated co-ordinates of spheres or 2D ball plates manufactured from carbon fiber.

Further, the measurements can use laser light's wavelength as another type of reference. This interferometric method is very suitable for length measurements keeping precision even for long distances. Laser interferometric systems are equipped with optical accessories which make distance, angular or straightness measurements possible. There are measurement systems that combine multiple optical sensors to perform simultaneous measurement.

Another group of direct methods is based on the direction of the gravitational vector. By measuring angle over a stepwise lengths, straightness, perpendicularity or planarity can be evaluated. Levels and electronical inclinometers especially provide very precise measurements.

2.2 Indirect method of measurement

Indirect methods utilize a TCP measurement and require multi-axes movement of the tested machine. These methods are in general less accurate but are also far less time demanding [Ibaraki 2012]. Test pieces can be machined and measured on CMM or special calibrated artifacts can be probed. Another measurement methods use simultaneous movement of two or more axis and evaluate the produced trajectory, e.g. circular paths or straight diagonals of machine working volume. Incorporating kinematical modelling and numerical computing these methods can be very effective in calibrating the machine tools. On the other hand, there is in general a larger number of factors that can influence an indirect measurement rather than direct measurement.

3 CASE STUDY

The study is performed on a small three axis vertical milling machine. The calibrated working volume is restricted to 400 mm x 400 mm x 400 mm. The workshop environment temperature was between 19.5 °C and 20.5 °C.

3.1 Equipment of experiments

For the test are used measurement systems that represent nowadays most widespread methods for volumetric compensation (Tab. 1). An independent verification of the impact of calibrations is performed with a ballbar measurement.

Tab. 1: Representatives of analyzed methods.

Test	Measurement system
Direct method	Renishaw XM-60
Indirect method	ETALON LaserTRACER
Verification	Renishaw Ballbar XC-20W

As representative of a direct measurement the calibrator XM-60 was chosen. The XM-60 is a laser-based multi-axis system that can measure six degrees of freedom simultaneously – incorporating positioning, straightness and angular errors. The system is shown in Fig. 1.

Fig. 1: Principle of direct measurement with XM60 [Renishaw].

- Set-up of strategy

The set-up of XM-60 is shown in Fig. 2. A laser unit is attached to the machine table, whereas a receiver is mounted as near to TCP as possible. To perform a measurement the calibrator must be aligned with a machine axis. That implies for the case machine three independent machine axis measurements. Intentionally, the positions of the measurement axis are aligned in a center point of subsequent ballbar verification. Only for direct measurement this set-up is possible and it enables to measure geometric errors close to the verification point. A number of measured points is set to 9 for each axis resulting in the step of 50 mm. Machine feed is 1500 mm/min. Each bidirectional cycle is repeated five times to comply with ISO 230-2 requirement. Totally, for single calibration of defined machine volume a number of 513 points is needed.
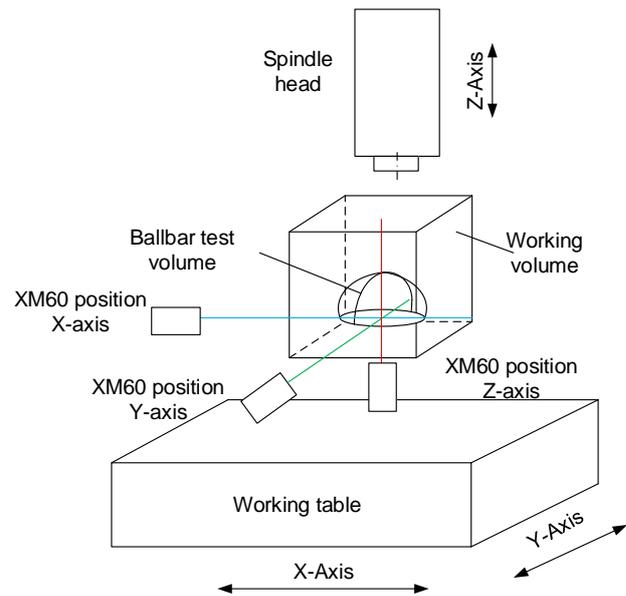

Fig. 2: The setup of XM-60.

The indirect volumetric measurement was performed with a LaserTRACER – a calibrator based upon a multilateration technique [Schwenke 2005] of the distances measured by a tracking laser interferometer. The system is shown in Fig. 3.
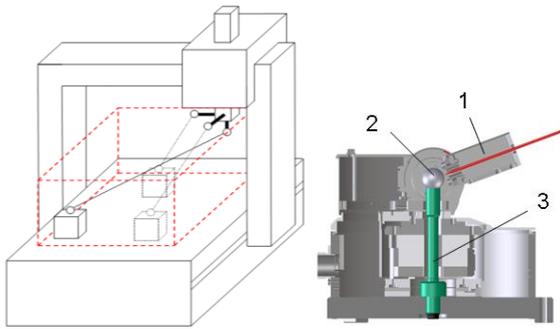
Fig. 3: Principle of indirect measurement with LaserTRACER [Schwenke 2005].

It requires that paths of a retroreflector located in a TCP are tracked from at least three positions of the interferometer. From the sets of measured distances, applying a self-calibration method both TCP and interferometer positions can be numerically calculated. Unlike the direct method described above, all machine axis are measured simultaneously. The geometric errors are calculated by means of mathematical machine error modelling indirectly. The configuration of measured TCP paths and interferometer positions give significant variation in measurement uncertainty.

- Set-up of strategy

The measurement strategy is tailored to the type of machine tool. Because of the three axis machine kinematics a reduced rigid body model (RRB) is applied, which consider 17 out of overall 21 geometric errors. To be compliant with previous direct measurement, 9 points per each axis was chosen. An "optimal" strategy for indirect measurement with the LaserTRACER was applied. This strategy refers to [Holub 2016]. This strategy uses 4 positions of the tracking interferometer and approximately 732 measured TCP points. A necessary condition for evaluating geometric errors is to measure the points at the edges of the calibrated volume (Fig. 4).
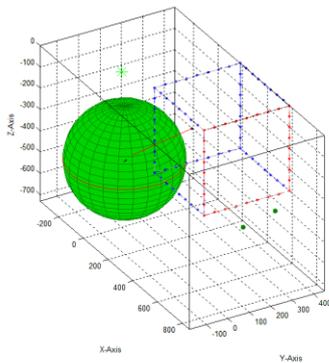

Fig. 4: Positions of the tracking interferometer.

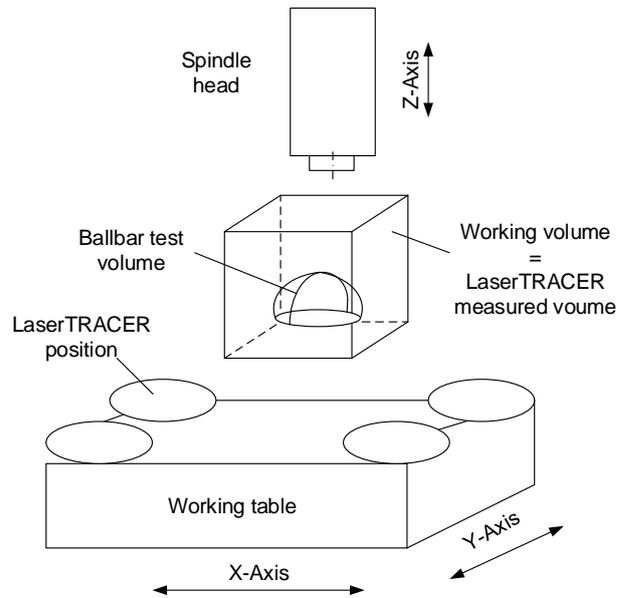The representation of the system's set-up is shown in Fig. 5.

Fig. 5: The set-up of LaserTRACER.

3.2 Experiment strategies

A ballbar test is proposed as an independent method to compare machine tool compensation impact. The test procedure is described in Tab.2 for the direct method. Then a preliminary compensation table with average measured data is in a CNC system activated. The relative angle between machine axis (squareness) is measured by other means. This procedure neglects the effect of axis straightness on a squareness values. In the case study squareness was derived from a ballbar test but in principle any direct or indirect method can be applied. The squareness values are subsequently included in the compensation table. To test the stability of the measurand each cycle is performed 3 times.

Tab. 2: Test cycle for the direct method with XM-60.

Cycle step	Test performed	Parameter
1	Ballbar test	Circularity
2	X axis calibration	6 error par.
3	Y axis calibration	6 error par.
4	Z axis calibration	6 error par.
5	Ballbar test	Squareness
6	Z axis verification	6 error par.
7	Y axis verification	6 error par.
8	X axis verification	6 error par.
9	Ballbar test verification	Circularity

The test procedure is described in Tab.3 for the indirect method. To test the stability of the measurand each cycle is performed 3 times.

Cycle step	Test performed	Result	Feed [mm/min]
1	Ballbar test	Circularity	1000
2	Volumetric calibraion	21 error par.	2000
3	Volumetric verification	21 error par.	2000
4	Ballbar test verification	Circularity	1000

For the circularity tests a calibrated radius of 150 mm was chosen. The tests were performed in three perpendicular planes – XY, XZ and YZ. Therefore, the circular trajectories located on a sphere will cover the volume sufficiently and will not be distorted at the edges of the calibrated volume. Geometric errors induce inaccuracy of the interpolated circles. It can be used to analyze the impact of compensation procedure in the tested machine volume. Next figure (Fig. 6) shows the set-up of the circularity test.

Fig. 6: The set-up of ballbar test.

4 RESULTS AND DISCUSSION

Based on the tests following parameters were analyzed and compared:

- time demands of measurement system set-up;
- time demands of measurement solely;
- comparison of error parameters from the calibration and the verification procedure, evaluation of the compensation impact;
- evaluation of circularity tests according to ISO 230-4.

Fig. 7 shows average time demands for measurement set-up and average demands for measurement solely from the 3 tests. Time includes set-up, alignment and disassembly the system's components, software settings, data evaluation and generation of compensation tables. Further, the set-up time includes necessary time to allow the measurement system to stabilize its temperature too. The box plot shows the span of the time measured in the individual tests.

The average measurement time is almost identical for the both measurement systems.

The difference is less than 1 minute, what relative to the span intervals is negligible. Where can be seen the difference, is the set-up time. Necessary set-up time for the

LTc is relative to the XM-60 33% shorter. This is mainly due to the difference in a generation of the compensation tables, because for the XM-60 it is necessary to measure and set in the software the relative positions of the laser unit and the receiver. There is an imbalance in the number of evaluated geometric parameters. The Reduced rigid body model, which was chosen for LTc measurement, evaluates only 18 out of 21 geometric errors. Although this model is fully correct for the three axis milling machine, if a full rigid body kinematical model with all 21 geometric error parameters was applied, based on the historical data the measurement time would increase approximately by 30 % and the sum of times would become almost equal.
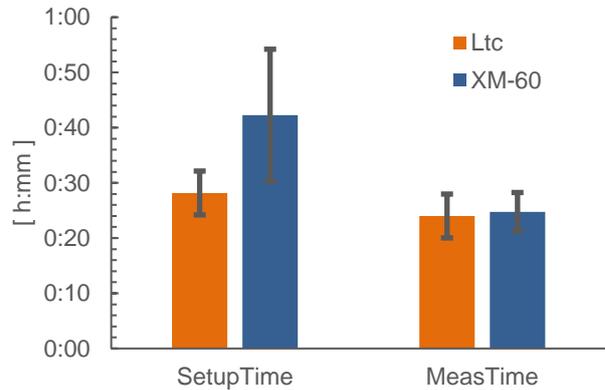

Fig. 7: Time demands of measurement system set-up and measurement.

Especially time demands are an important aspect when scheduling a machine standstill for the calibration. Naturally, longer standstill inflicts higher costs for the machine users. LaserTRACER can be synchronized with the machine in the mode On-The-Fly, which reduces measurement time up to 50 % [Schwenke 2009], [Holub 2014], [Holub 2017]. Lower time has a positive impact on the measurement uncertainty as well, because both the machine and the device is less deformed with thermal expansion of material. Further, lower time also limits the changes of environmental conditions (temperature, pressure, humidity) that are for laser-based measurements crucial, especially for large machine tools.

In the next figures (Fig. 8, Fig. 9) results from both XM-60 and LTc are compared. The bar graph shows calibration and verification values of geometric error parameters both from XM-60 and LTc evaluation software. Missing values of angular errors ECY, EAZ, EBZ and ECZ of LTc are the consequence of the reduced rigid body model that was applied.
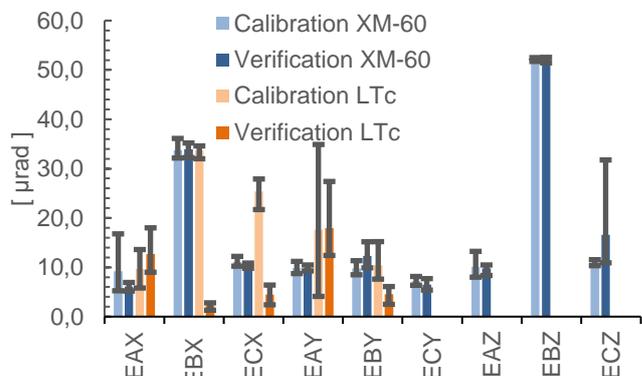

Fig. 8: Comparison of calibration / verification results both of XM-60 and LTc – angular errors.

The difference between two sets of calibration data for positioning errors is equal to 3 µm, for straightness error approximately to 1.5 µm and to 16.3 µrad for angular errors Therefore, the best agreement show the straightness errors, whereas the angular errors the worst.
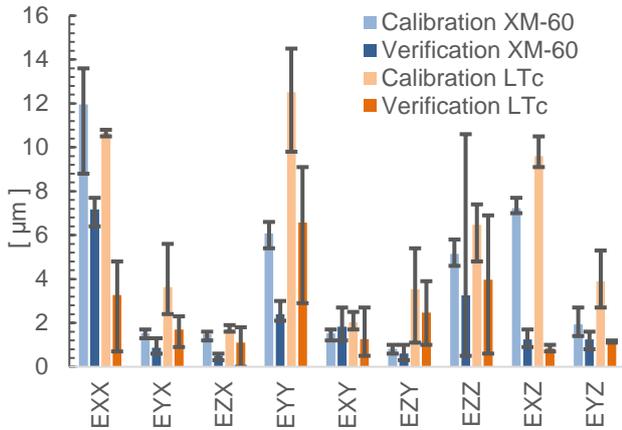

Fig. 9: Comparison of calibration / verification results both of XM-60 and LTc – translational errors.

The verification results of circularity tests provided with Ballbar QC20-W are shown in Fig. 10. Both set of data were acquired within 12 days. The average value of circularity error obtained before XM-60 compensation procedure in XY plane is equal to 10.5 µm and 4.7 µm after the compensation. The circularity errors for LTc are equal to 10.7 µm and 5.2 µm respectively. It follows that the impact of compensation procedure in XY plane is 10 % better in case of the XM-60 set of data compared with the data acquired with LTc.

The average circularity errors obtained in YZ plane are equal to 11.2 µm and 6.9 µm after activating XM-60 correction table and to 9.1 µm and 5.3 µm after LTc procedure. Correction tables acquired by LTc provides better results with the relative difference of 23 % compared to XM-60.

In the XZ plane are the same average values 11.8 µm and 5.8 for XM-6, whereas for LTc are equal to 13.3 µm and 6.2 µm. In this case correction tables of LTc provide better results with resulting relative difference equal to 6 %.
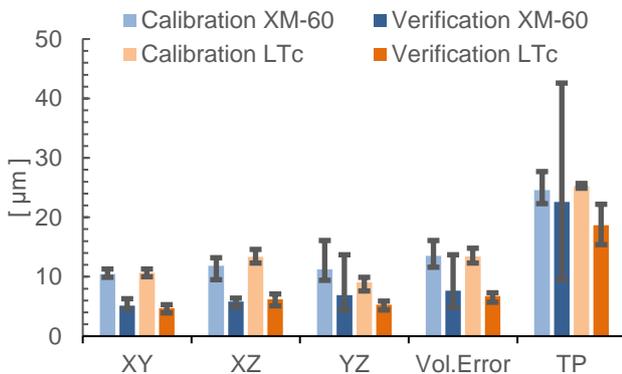

Fig. 10: Visualization of ballbar error parameters.

Among other considered parameters belongs a volumetric error or in another words a spherical error that is calculated from all three planes. The value of this parameter is 13.5 µm before and 7.7 µm after the activating XM-60 correction tables. The same parameter in the case of LTc is 13.4 µm and 6.2 µm, representing the difference of 19 %.

The last considered parameter is a position error retrieved from ballbar calibration software. This value can be interpreted as an indicator of length error. It reflects the bidirectional positioning errors in the calibrated volume. The average value acquired before calibration routine is 24.6 µm (XM-60) ad 25.2 µm (LTc), therefore the difference is almost negligible. After the activating of correction table error decreased slightly to 22.6 µm (XM-60) and 18.7 µm (LTc).

The direct method of compensation represented by XM-60 improved the circularity error within interval of 38 % to 51 %. The value of volumetric error was improved by 43 % and position error by 8 %. The indirect method represented by LTc improved circularity error within interval of 42 % to 56 %, the volumetric error was improved by 50 % and position error by 26 %.

5 SUMMARY

An option for volumetric compensation is applied more and more often in the CNC control systems. This is made possible by new measuring devices that appeared on the market in last years. The present paper deals with the tests of direct and indirect acquisition of correction tables. From the results it can be stated that the calibration and subsequent compensation with LTc is less time demanding than with XM-60. However, a non-negligible effect has the type of the kinematical model. In this case applied a reduced rigid body provide only 17 geometric parameters. If a full rigid body model was applied, the time demands would be almost equal.

Comparing the results of both XM-60 and LTc, there are significant differences in the results of geometric parameters, because LTc calculates geometric errors from deviations of TCP solely. Therefore, some deviations can be numerically interpreted in the wrong way. The most compliant results are in the group of straightness errors, on the other hand results of angular errors are in a strong mismatch.

The results of circularity tests shows the difference in the plane XY of 0.2 µm for calibration and 0.5 µm for verification. In the plane the difference is of 1.5 µm for calibration and 0.4 µm for verification. Further, in the plane YZ the difference of 2.2 µm for calibration and a 1.0 µm for verification. The resulting volumetric error acquired by ballbar differ by 1.0 µm in the radius of 150 mm. Because the time span is 12 days, the difference can be neglected.

In the next test it will be compensated larger machine volume. Therefore, there can be more calibrated more positions with ballbar test. This will provide more comprehensive overview of the achievable compensation impact. The calibrated spheres will be also located outside the measurement axis of XM-60. Results will help to describe the behavior of volumetric errors in the whole volume. Another issue to deal with is the large position error in the ballbar results. The goal will be to adapt the compensation strategy both for XM-60 and LTc to minimize the error.

6 ACKNOWLEDGMENTS

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