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Research Article

MEASUREMENT UNCERTAINTY ANALYSIS OF DIFFERENT CNC MACHINE TOOLS MEASUREMENT SYSTEMS

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ABSTRACT
In this paper the results of measurement uncertainty tests conducted with a Heidenhain TS 649 probe on CNC machine tools are presented. In addition, identification and analysis of random and systematic errors of measurement were presented. Analyses were performed on the basis of measurements taken on two different CNC machine tools with Heidenhain control system. The evaluated errors were discussed and compensation procedures were proposed. The obtained results were described in tables and figures.

Keywords: measurement uncertainty, inspection probe, control system, CNC machine tool.

INTRODUCTION

Application of inspection probes in computer numerical control machine tools is becoming increasingly popular. The spectrum of their uses includes zero point measurement at workpiece surface and, to an increasing extent, inter-operational dimension control. In order to use it as a measuring device, the knowledge on its metrological characteristics should be required. However, the metrological characteristics of this meter circuit, which a computer numerical control machine tool with a mounted probe, are not known. Admittedly, manufacturers of the inspection probes provide unidirectional repeatability (2s) as the parameter characterising measurement uncertainty, however, it is only one of many components of uncertainty budget of the whole measuring system. Other components that characterise inspection probe include: geometric and kinematic accuracy of the machine tool, probe calibration accuracy as well as kinematics of the measurement process. Multiple research centres, both domestic and foreign, use probes in their research. Research works aim, *inter alia*, at integrating control and technology design processes in order to increase the efficiency of production processes (CLM-closed-loop machining) [1, 10-13, 18], the possibility and ways of utilizing inspection probes in control processes [17], comparing accuracy of measurement conducted on CMM and CNC machines [9] or assessing positioning accuracy of 5-axix CNC machine tools using measurements taken with inspection probes and based on a theoretical mathematical model [10, 14, 15].

At the Department of Production Engineering of the Mechanical Engineering Faculty at Lublin University of Technology a series of tests aiming at determining the manner of testing metrological characteristics of the measuring system CNC machine – inspection probe were conducted. The tests were focused on determining one-dimensional and two-dimensional measurement uncertainty [2, 3], repeatability of probe fix (a component of the measurement uncertainty budget) [5], the correlation between CNC machine tool spindle bearing failure and measurement uncertainty [6] as well as the influence of thermal deformations resulting from processing on inaccuracy of inspection probe measurement [4]. Moreover, potential application of inspection probes for automatic control and correction of dimensional inaccuracies of the workpiece [7] as well as uncertainty of laser probes measurement were investigated [8, 16].

The development of interfaces and software, such as PC-DMIS NC GAGE and STEP-NC proves that measurement control systems used on CNC machine tools are in constant progress. Not only do they aid taking measurement but also allow preparing reports. The user is equipped with modern software for planning control procedures and machining allowances based on three-dimensional models.

The aim of this paper was to determine one-dimensional measurement uncertainty of machining centre DMC 635V with a Heidenhain TNC 620 control system equipped with a DMG TS649 probe as well as to compare test results with the measurement system: machining centre DMC 635V with a FANUC 0iMC control system – OMP60 touch trigger probe.

EXPERIMENTAL SETUP

The research consisted of determining one-dimensional measurement accuracy (repeatability and accuracy) for each axis of the machine tool using end gauges. This required measurement-taking of gauge blocks of length equal to 50 mm, 75 mm and 100 mm along each machine tool axis (X, Y, Z).

The tests were conducted in The State School of Higher Education in Chełm. The measurement system consisted of a DMC 635V machining centre with the Heidenhain TNC 620 control, equipped with DMG TS 649 touch probe. The maximum travel of the table and machine tool spindle are as follows: for the X axis: 0 – 635 mm, for the Y axis – 510 mm, and for the Z axis – 460 mm. The probe technical specifications are presented in Table 1.

In order to program the measuring motions, measurement cycles implemented in the control system of the machining tool were used. The length of the gauge block along X and Y axes was measured using measuring cycle 426. Gauge block measurement parallel to the Z axis was indirect. The surface of the gauge block clamped to the machine table, in order to eliminate the influence of the table's geometric features, was adopted as the measuring base. The gauge block was connected with an identical gauge block already fixed on the table to form a stack. The 427 measuring cycle was used for measurement. An example of the 426 measuring cycle (50 mm long gauge block) is presented in Figure 1. and the process of measurement is presented in Figure 2.

Prior to the measurement, gauge blocks were positioned at the machine table and left for 24 hours with the aim of temperature equalization. In accordance with the Central Office's of Measures directions, measurements of each gauge block were repeated thirty times [19].

Table 1. Technical specifications of DMG TS 649 probe

Sense directions	±X, ±Y, ±Z
Signal transmission	infrared radiation $0^0 – +30^0$
Probe accuracy with a standard gauge plunger	≤ ± 5 µm
Unidirectional repeatability 2σ with sampling speed equal to 1 m/min	≤ 1 µm
Stylus trigger force: XY +Z	 1 N 8 N
Maximum measuring speed	5 m/min

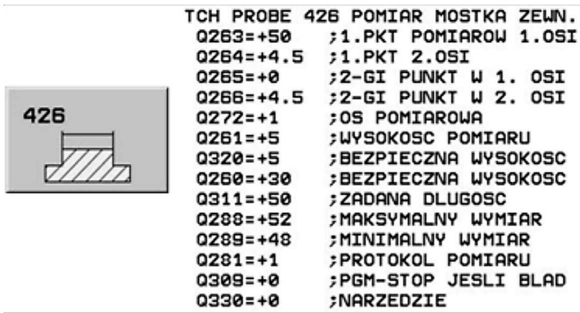

Fig. 1. Structure of 426 measuring cycle of 50 mm gauge block measurement

RESULT ANALYSIS

The conducted tests allowed calculating: arithmetic mean, standard uncertainty u_a, combined standard uncertainty u, expanded uncertainty U as well as correction P_{Ex}. Measurement results for individual machine tool axes are presented in Table 2.

The calculations were conducted by the following formulas in accordance with EA-4/02 [19]:

- arithmetic mean $\overline{L}$ of a series of measurements

$$\overline{L} = \frac{1}{n}\sum_{i=1}^{n} L_i \tag{1}$$

where: L_i – measured length of gauge block.

a) b)

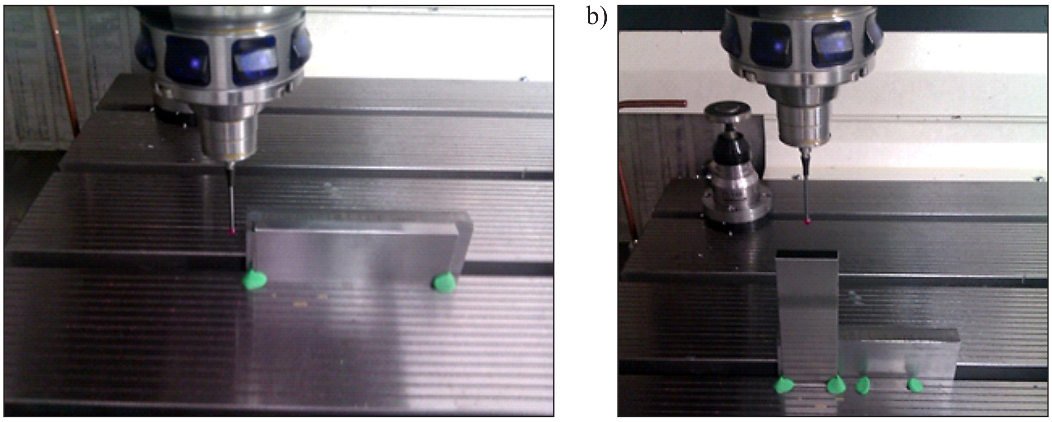

Fig. 2. Measurement of gauge block length: a) X axis, b) Z axis

- systematic indication error E_x:

$$E_x = \overline{L} - L_N \tag{3}$$

where: L_N – nominal length of gauge block.

- correction P_{Ex}:

$$P_{Ex} = -E_x \tag{4}$$

- standard uncertainty u_a:

$$u_a = \sqrt{\frac{\sum_{i=1}^{n}\left(L_i - \overline{L}\right)^2}{n(n-1)}} \tag{5}$$

where: n – number of measurements,
L_i – length of gauge block in i – this measurement.

- combined standard uncertainty u:

$$u = \sqrt{u_a^2 + u_L^2 + u_R^2} = \sqrt{u_a^2 + \frac{te^2}{6} + \frac{r^2}{3}} \tag{6}$$

where: u_a – standard uncertainty,
u_L – is the uncertainty of the gauge length,
u_R – is the resolution uncertainty,
t_e – limit deviation of the gauge block length,
r – variation of indications.

The triangular probability distribution was assumed, with the centre in the nominal dimension of the gauge block. The measurement system resolution equalled 0.001 mm. The variability of indications was estimated at r = ±0.0005 mm, assuming the rectangular probability distribution. The values of t_e for the gauge blocks used in the tests (for L_N nominal values) had the following values: t_e = ±0,4 mm (for L_N = 50 mm), t_e = ±0,5 mm (for L_N = 75 mm), t_e = ±0,6 mm (for L_N = 100 mm).

- expanded uncertainty U:

$$U = k \cdot u \tag{7}$$

where: k – coverage factor,
u – combined standard uncertainty. The coverage factor is commonly set to 2. This corresponds to expanded certainty at the trust level of 95%.

The analysis of results presented in Table 2 indicates that uncertainty of measurement using inspection probe DMG TS 649 is much lower than the systematic indication error determined for each analysed controlled axis. It is furthermore noteworthy that the standard uncertainty is lesser than the one-dimensional repeatability 2σ as declared by the manufacturer.

The combined standard uncertainty and extended uncertainty analysis proves that regardless of the length of the gauge block measured or the type of controlled axis, their variation range does not exceed 0.0002 mm, which makes it an exceptionally good result. At the same time, those values are considerably lower than measurement accuracy declared by the probe manufacturer.

When analysing systematic indication error E_x what should be highlighted is that for X axis its value equalled ±2 mm, for Y axis 2.5 mm, and for Z axis it produced the highest values, approximately 11 mm. High values of systematic indication error for Z axis (when compared to values of this error for X and Y axes) may indicate poor calibration of probe length, which furthermore seems to be corroborated by the fact that P_{Ex} correction value was practically identical in the case of Z axis, regardless of the length of the analysed gauge block. Test results are presented in the form of graphs (Figures 3–5).

The main goal of this article was to compare measurement uncertainty of two different measuring systems. One of them is DMC 635V machine tool with DMG TS 649 touch probe, and the

Table 2. Measurement results analysis of gauge block lengths on numerically controlled vertical milling machines

Measuring system	DMC 635V - Heidenhain TNC620. DMG TS 649			FV 580A - Fanuc 0iMC OMP 60
	X Axis			
Gauge block dimension. mm	**50**	**75**	**100**	**100**
Mean. mm	49.9984	74.9981	100.0014	100.011
Standard uncertainty u_A. mm	0.0001	0.0001	0.0001	0.0004
Combined standard uncertainty u. mm	0.0003	0.0004	0.0004	0.0006
Extended uncertainty U. mm	0.0007	0.0007	0.0008	0.0112
Systematic indication error E_x mm	-0.0016	-0.0019	0.0014	0.011
Correction P_{Ex}. mm	0.0016	0.0019	-0.0014	-0.011
	Y Axis			
Gauge block dimension. mm	**50**	**75**	**100**	**100**
Mean. mm	49.9979	74.9956	99.9948	100.009
Standard uncertainty u_A. mm	0.0001	0.0001	0.0001	0.0004
Combined standard uncertainty u. mm	0.0003	0.0004	0.0004	0.0005
Extended uncertainty U. mm	0.0007	0.0007	0.0008	0.0010
Systematic indication error E_x mm	-0.0021	-0.0040	-0.0050	0.009
Correction P_{Ex}. mm	0.0021	0.0040	0.0050	-0.009
	Z Axis			
Gauge block dimension. mm	**50**	**75**	**100**	**100**
Mean. mm	50.0110	75.0111	100.0114	100.041
Standard uncertainty u_A. mm	0.0001	0.0001	0.0001	0.0001
Combined standard uncertainty u. mm	0.0003	0.0004	0.0004	0.0004
Extended uncertainty U. mm	0.0007	0.0007	0.0008	0.0008
Systematic indication error E_x. mm	0.0110	0.0111	0.0114	0.041
Correction P_{Ex}. mm	-0.0110	-0.0111	-0.0114	-0.041

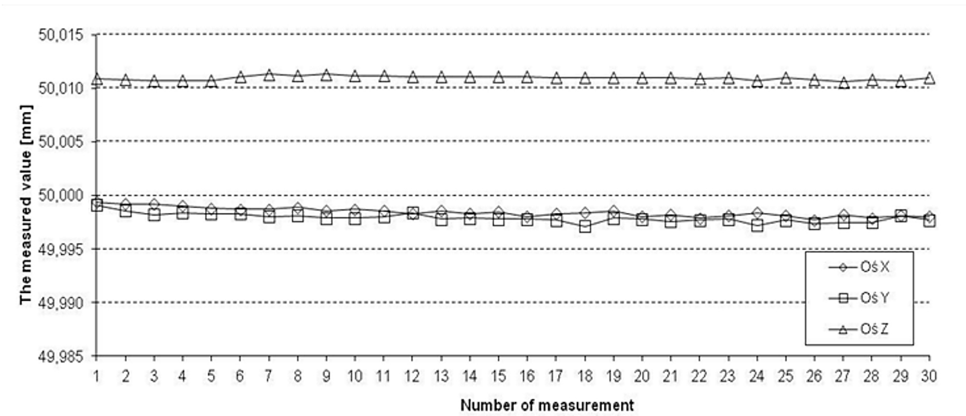

Fig. 3. Measurement results of 50 mm gauge block on DMC 635V machine tool with a DMG TS 649 touch probe

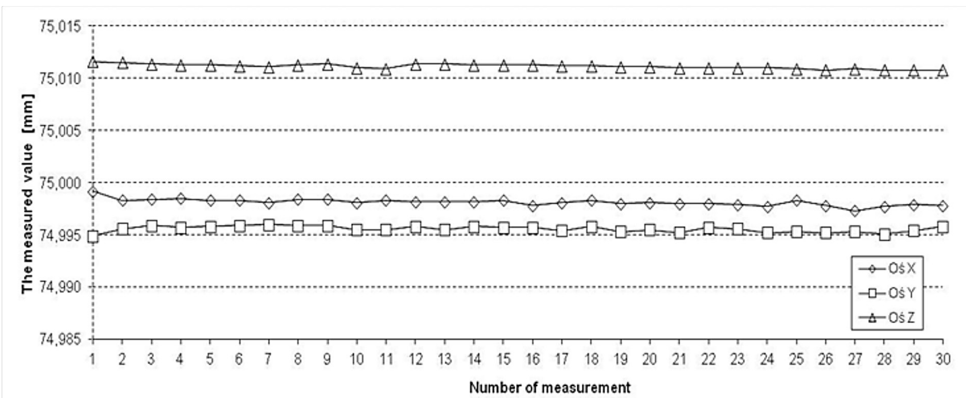

Fig. 4. Measurement results of 75 mm gouge block on DMC 635V machine tool with DMG TS 649 touch probe

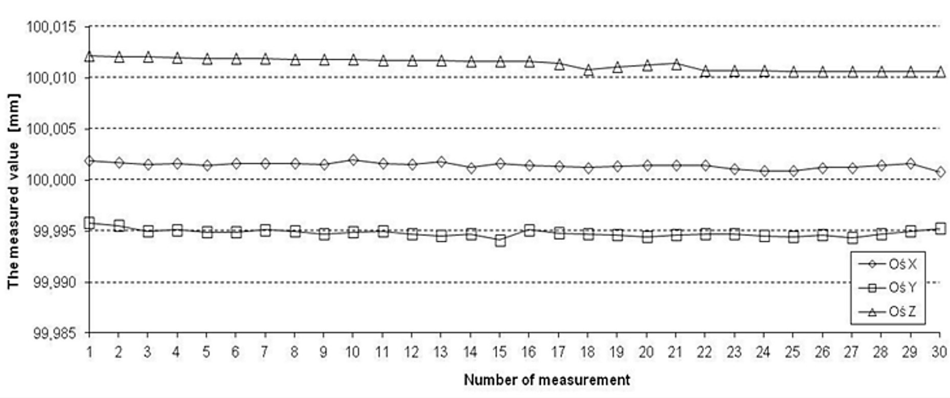

Fig. 5. Measurement results of 100 mm gouge probe on DMC 635V machine tool with DMG TS 649 touch probe

other one is FV 580A machine tool with OMP60 touch probe. Measurement uncertainty analysis was conducted on a 100 mm gauge probe. Graphic representation of the measurement results is shown in Figures 6–8.

What should be unambiguously stated when analysing Figure 6. and 7. is that the scatter of results is greater for FV 580A machine tool. This may indicate inaccurate machine tool spindle positioning. This situation may be a consequence of worse geometric and kinematic accuracy resulting from machine tool wear (over 700 hours of operation). DMC 635V is a new machine tool. It may be, therefore, assumed that measurement accuracy depends largely on the operation life of the machine tool.

Figure 8. shows that scatter of results along Z axis is similar for both machine tools. However, a considerable difference can be noticed in systematic indication errors. As mentioned previously, this can result from poorly calibrated probe length in both of the analysed instances.

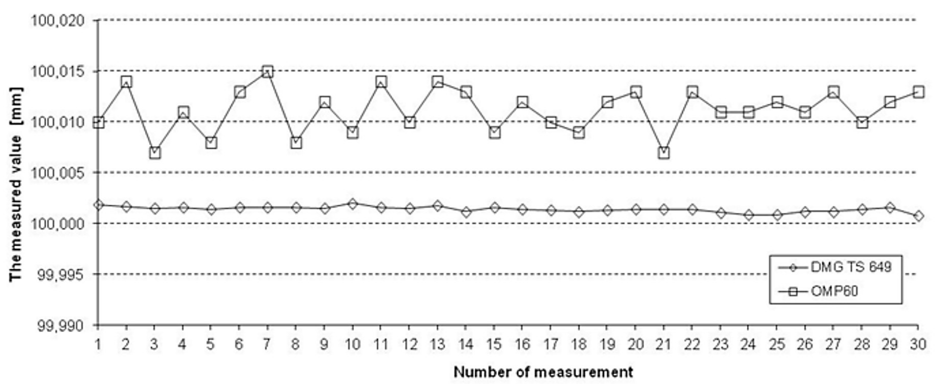

Fig. 6. Comparison of measurement results of 100 mm gauge block along X axis on DMC 635V machine tool with DMG TS 649 touch probe and FV 580A machine tool with OMP60 touch trigger probe

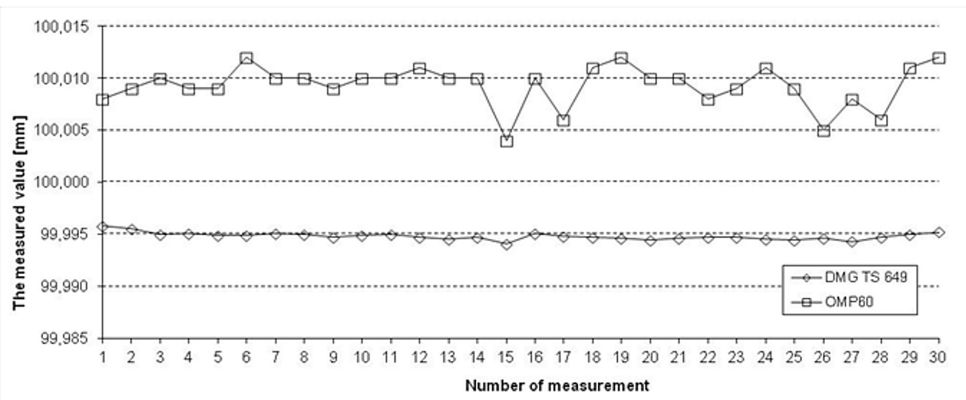

Fig. 7. Comparison of measurement results of 100 mm gauge block along Y axis on DMC 635V machine tool with DMG TS 649 touch probe and FV 580A machine tool with OMP60 touch trigger probe

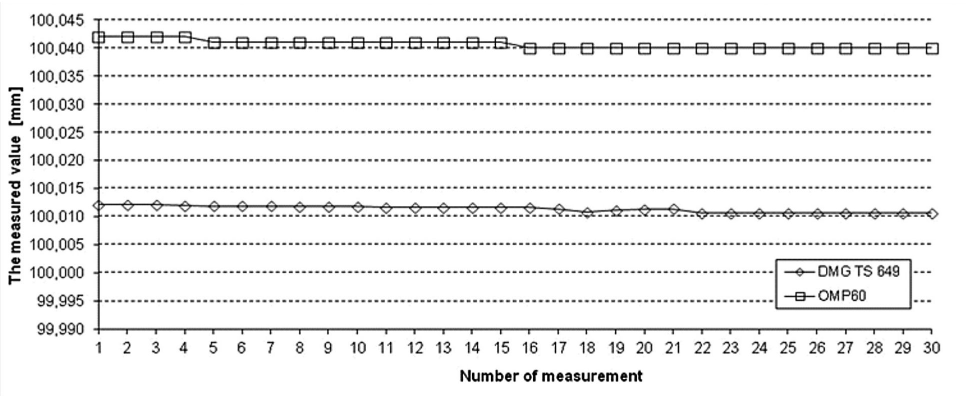

Fig. 8. Comparison of measurement results of 100 mm gauge block along Z axis on DMC 635V machine tool with DMG TS 649 touch probe and FV 580A machine tool with OMP60 touch trigger probe

CONCLUSIONS

Based on the measurement results for two different machine tools with different exploitation time, the following observations concerning measurement uncertainty of both systems can be made:

1. Exploitation time is a key factor influencing geometric and kinematic accuracy of the machine tool, which influences uncertainty of measuring systems measurements with the application of inspection probes. CNC machine tools require constant control of the machine condition, especially with the occurrence of collision.
2. Regular scatter of results analysis with end gauges can prove beneficial to diagnosing technical condition of machine tools, in particular the accuracy of spindle positioning. This method does not seem to demand extensive amount of labour and its cost is considerably low. An increase in scatter of results may be a signal for detailed diagnosis with the application of specialist diagnostic equipment (e.g. Ballbar QC20).
3. Probe calibration cannot be disregarded though. Measurement results show that careless calibration may cause systematic errors which lower the ‘quality’ of measurements. Z axis provides an ample evidence here. For this reason, calibration accuracy tests of the probe should be conducted. This would allow eliminating factors causing incorrect correction data entering into the machine tool control system.
4. The application of inspection probes on CNC machine tools should induce constant measurement accuracy diagnostics. This type of error can influence workpiece geometric features forming, especially the ones that are produced in a number of fixings. Determining zero point of the workpiece in each fixing accumulates errors arising from subsequent measurements. Consequently, the accuracy of geometric features location of the workpiece is affected.

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