

CIRCULAR INTERPOLATION AND POSITIONING ACCURACY DEVIATION MEASUREMENT ON FIVE AXIS MACHINE TOOLS WITH DIFFERENT STRUCTURES

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Original scientific paper

The article is focused on the issue of circular interpolation and positioning accuracy measurement on five axis CNC machine tools. Measurement of circular interpolation accuracy was realized in one plane (XZ) and more planes (XY , YZ , XZ), positioning accuracy was measured in one axis direction. NC program modifications for each measurement on machine tools were carried out. The main characteristic of the paper is measuring system and principle of measurement of positioning by laser interferometer and circular interpolation measurement by ballbar. Experiment setup and conditions are described as well as results. Evaluation is based upon results gained from charts generated from Renishaw software. The results of circular interpolation deviations were compared with nominal values guaranteed by machine tool producer. The results showed that there are not significant differences in machine positioning accuracy in accordance with kinematics structure and drive's type. Visible effect was observed on the machine with two rulers on linear drives.

Keywords: accuracy, circular interpolation, laser interferometer, machine tool, measurement, positioning

Mjerenje devijacija točnosti kružne interpolacije i pozicioniranja na petoosnim alatnim strojevima različitih konstrukcija

Izvorni znanstveni rad

Članak se bavi problemom mjerenja točnosti kružne interpolacije i točnosti pozicioniranja na petoosnim CNC alatnim strojevima. Mjerenje točnosti kružne interpolacije je obavljeno u jednoj ravnini (XZ) i više ravnina (XY , YZ , XZ), a točnost pozicioniranja u smjeru jedne osi. Provedene su promjene NC programa za svako mjerenje na alatnim strojevima. Glavna karakteristika rada je mjerni sustav i princip mjerenja pozicioniranja laserskim interferometrom te mjerenje kružne interpolacije linearnim senzorom s kuglicama (ballbar). Daje se opis eksperimenta i uvjeta pod kojima je proveden kao i rezultati. Procjena se zasniva na rezultatima iz grafikona dobivenih računarskim programom Renishaw. Rezultati devijacija kružne interpolacije su uspoređeni s nominalnim vrijednostima koje garantira proizvođač alatnih strojeva. Rezultati su pokazali da nema značajnih razlika u točnost pozicioniranja stroja u odnosu na kinematičku konstrukciju i vrstu pogona. Vidljiv učinak je primijećen na stroju s dva ravnala kod linearnog pogona.

Ključne riječi: točnost, kružna interpolacija, laserski interferometar, alatni stroj, mjerenje, pozicioniranje

1 Introduction

Technology accuracy is one of the keystone parameters in machining. Many parameters affect achievable accuracy during the machining process. However, the machining parameters affect the process's accuracy, the first and most important thing is the construction of a machine tool. Beside the toughness and rigidity of a machine frame, most accuracy defects are provided by moving parts of a machine tool. The movement is characterized by kinematics' structure of machine tool and the accuracy is affected by the type of drives and engines. Machines, on which the experiments described in this article were performed, are equipped with linear drives and two rulers on each linear axis in addition to this. This construction, in combination with linear magnetic engines may provide excellent accuracy of positioning, as well as valuable results of circular interpolation accuracy. Experiments described in this article proved whether this assumption was correct or not and whether the machine tools could achieve the accuracy of positioning declared by producer after one year performance. Measurements were performed on three CNC machine tools with different construction: five axis milling machine tool DMG Ultrasonic linear with XYZAC axes construction, five axis milling machine tool DMG HSC 105 linear with XYZBC axes construction and turning machine tool DMG CTX APHA 500 with counter spindle and driven tools in cartridge. Measurement devices which were used: Renishaw XL 80 laser system and Renishaw QC 20 W-Ballbar. Experiments were performed at the Faculty of Materials

Science and Technology of Slovak University of Technology in cooperation with the Faculty of Machining of the University of Zilina.

1.1 Multi-axis Machines

One of the parameters of machine tools construction characteristics is its number of coordinate system axes. These axes can move simultaneously in real time during the machining process. Majority of CNC machine tools kinematics is based upon a rectangular Cartesian coordinate system [8]. According to the ISO 841:2000 standard the coordinate system of a machine tool is classified as X , Y , Z for linear axes and A , B , C for rotational axes. Z axis is parallel with spindle axis (Fig. 1).

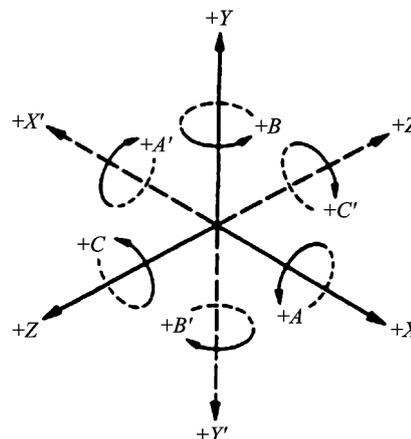


Figure 1 Cartesian coordinate system (ISO/FDIS 841:2000)

Five axis milling machines consist of three linear and two rotational axes. Three linear axes provide the position of a tool edge in the working space, two rotational ones provide the orientation of the tool [4]. Five axis machine tool has five joints where at least two of them are rotational [5]. The number of axes of machine tool is relative to degrees of freedom or the number of independent axes. To reach the maximum flexibility, five degrees of freedom are necessary, at the same time five degrees of freedom provide sufficient toughness [10]. Kinematics possibilities of five axis machine can be characterized as the following [7]:

- i. three linear and two rotational,
- ii. two linear and three rotational
- iii. one linear and four rotational,
- iv. Five rotational axes.

Most of the machine tools are in the first category; mostly robots are in the third and the fourth one. Another classification takes into account the movement of a work piece with regard to the movements of a tool. According to this classification, huge amount of combinations is theoretically possible [6, 7, 8]. Based upon the division made by [4] the following four types are the most common:

- i. Rotational moves by work piece, linear by tool,
- ii. Rotational by tool, linear by work piece,
- iii. Rotational by tool, linear and linear by tool and work piece,
- iv. Rotational and translational by tool.

According to previous characteristics multi-axis milling machines can be further organized into 3 major machine types like Table/Table, Head/Table, Head/Head.

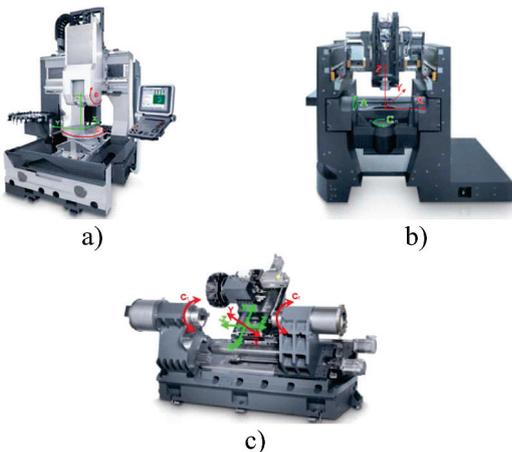


Figure 2 Different five axis machine structures: a) DMG HSC 105 linear head-table structure, b) DMG Ultrasonic 20 linear table-table structure, c) DMG CTX Alpha 500 head-table structure [1]

1.2 Circular interpolation

Circular interpolation is the translation of linear axis positions into curved tool motions. It is provided by numeric interpolator in machine PLC. The accuracy of circular interpolation is one of programmable parameters which most affect the shape and geometric tolerances of a part. For measurement of circular interpolation a Renishaw QC20-W Ballbar device was used. The heart of the system is ballbar itself, high accuracy, telescoping

linear sensor with precisely ground balls at each end. When used the balls are located between magnetic cups, one attached to the machine table and the other to the machine spindle or spindle housing. This arrangement enables the ballbar to measure minute variations in the radius as the machine follows the programmed circular path [9].



Figure 3 Principle of QC20-W Ballbar system by Renishaw [2, 3]

1.3 Positioning accuracy

Accuracy of positioning is an important characteristic of each machine tool which gives the production limits to achieve required dimensions in required tolerances. Renishaw Laser XL 80 measurement device was used. It is a laser interferometer optical device. Laser beam sent from transmitter is reflected by optical system and driven back to a transceiver through a splitter where it is combined with original beam. Due to a different polarization of each beam the device then analyses the signal and recalculates the information, in our case into the distance. Laser measurement accuracy guaranteed by producer is $\pm 0,5 \mu\text{m/m}$ in the temperature range of $0 \div 40 \text{ }^\circ\text{C}$ and the maximum air pressure of 115 kPa. To measure and compensate environment influences a special compensation unit is used. This unit records air temperature, air pressure, air relative humidity and material temperature each 7 seconds. This compensation is important especially for huge machine tools when each part of machine can record change of its shape with different values during the measurement. When the compensation unit is not in use, the error on measurement can reach values of $50 \mu\text{m}$ per one meter of linear positioning accuracy. Schematic principle of the measurement system is shown in Fig. 4.

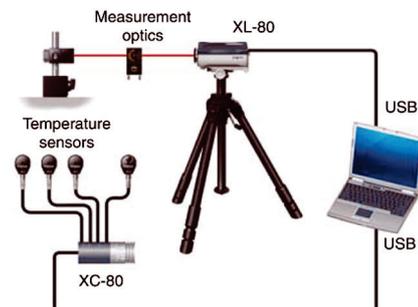


Figure 4 Measurement principles [11]

2 Experimental

Measurements were performed on three CNC machine tools (DMG HSC 105 linear, DMG Sauer Ultrasonic 20 linear, DMG CTX Alpha 500) with different construction figured in Fig. 2. Used

measurement devices were QC20-W Ballbar system and XL 80 Laser by Renishaw [1].

Measurement conditions for each measurement were as follows: air temperature was 20 °C with deviation of 0,1 °C, air pressure 1003,8 hPa, relative humidity 49 %, compensation coefficient 0,316.

2.1 Positioning accuracy measurement

Measurement was performed in the following conditions. The measurement optics was clamped onto the moving part (spindle/turret head*) and the reflector on static part (machine body/table*) in the direction of measured axis. Measured distance was set upon the machine’s possibilities. Machine tools were preheated one hour before measurement starts according to the ISO 230-2:2006 standard. The measurement was performed on unloaded machine/spindle. Positioning accuracy was recorded each 10 mm of the path with 5 s pause - this break is necessary for the measurement software to complete the measurement process. One measurement cycle consists of 5 moves from start point to end point and back (Fig. 5). Three cycles were measured with different feed rates for each machine.

* depending on machine type

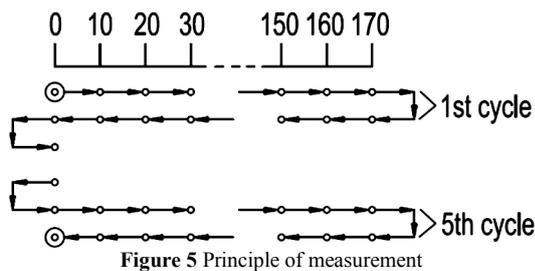


Table 1 Positioning accuracy measurement setup for DMG HSC 105

Measurement setup for DMG HSC 105 linear	
Measured axis	X
Measured distance	800 mm
Full distance	900 mm
Feed rates	1, 5, 22 m/min

Table 2 Positioning accuracy measurement setup for Ultrasonic 20

Measurement setup for Ultrasonic 20 linear	
Measured axis	Y
Measured distance	120 mm
Full distance	140 mm
Feed rates	1, 5, 22 m/min

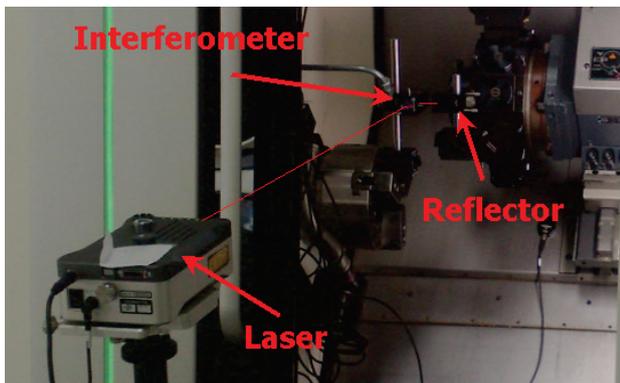


Figure 6 Positioning accuracy’s measurement setup for CTX Alpha 500

Table 3 Positioning accuracy measurement setup for CTX Alpha 500

Measurement setup for CTX Alpha 500	
Measured axis	Z
Measured distance	260 mm
Full distance	280 mm
Feed rates	1, 2,5, 5m/min

2.2 Circular interpolation accuracy measurement

The measurement was performed on turning machine DMG CTX Alpha 500 in XZ plane according to the kinematics’ structure of the machine tool (Fig. 2), on machining centre DMG HSC 105 linear in three planes XY, YZ and ZX and in XY plane on DMG Ultrasonic 20 linear. Details are summarized in Tabs. 4 ÷ 6. For HSC 105 linear there was no size restriction, however for path shape there was a restriction according to the machine tool kinematics’ structure. The measurement was performed in a circle path for plane XY and in a half circle for planes YZ and XZ. Starting point of the measurement was coincident with the last point of the measurement. Paths’ shapes were selected according to the machine tool kinematics’ structure XYZBC.

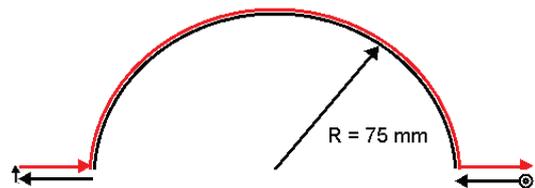


Figure 7 Principle of measurement

Table 4 Circular interpolation measurement setup for DMG HSC 105

Measurement setup for DMG HSC 105 linear	
Measured plane full circle	XY
Measured plane half circle	XZ, YZ
Circle path diameter	150 mm
Feed rate	1000 mm/min

Table 5 Circular interpolation measurement setup for Ultrasonic 20

Measurement setup for DMG Ultrasonic 20	
Measured plane full circle	XY
Measured plane half circle	-
Circle path diameter	80 mm
Feed rate	1000 mm/min

Table 6 Circular interpolation measurement setup for CTX Alpha 500

Measurement setup for DMG CTX Alpha 500	
Measured plane full circle	-
Measured plane half circle	XY
Circle path diameter	150 mm
Feed rate	500 mm/min

The software for Renishaw ballbar is equipped with NC programs for various machine tool structures in order to perform measurement; however the NC program written in Heidenhain code was not suitable either for lathe or milling machine tools due to the different size of the measured machine tools and the different kinematics structure. It was necessary to rewrite new NC programs, so the Renishaw NC programs were used as a starting point to program the new ones with regard to the machine tools kinematics and using postprocessor for Heidenhain iTNC 530 for HSC 105 linear and CTX Alpha 500, respectively postprocessor for Sinumerik 840D for

Ultrasonic 20 linear. Measurement results are summarized in the text that follows.

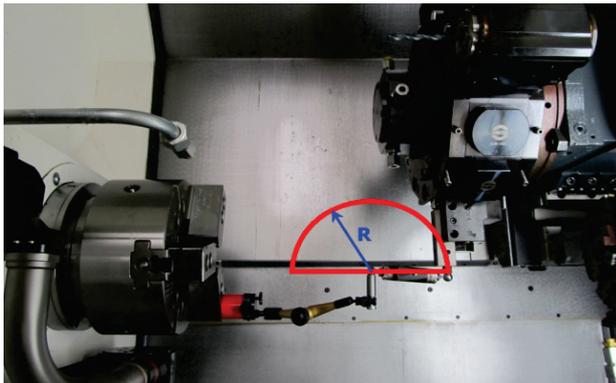


Figure 8 Circular interpolation's measurement setup on CTX Alpha 500

3 Measurement results

Results are represented by charts and recorded values figured in tables. Results are divided into two groups regarding measurement type; machine tools are listed in the same order for both measurement modes.

3.1 Positioning accuracy measurement results

Results are represented by charts shown in Figs. 9 ÷ 11 and adequate Tabs. 7 ÷ 9. These charts show the deviations of positioning for each machine and the repeatability which is represented by the accuracy of machine in reaching the same position from which the movement starts. Measured values are evaluated by Renishaw software for LASER XL 80. The review and comparison with declared values are found in conclusion.

Table 7 Ultrasonic 20 linear measurement results axis Y

Mean Dev. M	0,00172	Reversal B	0,00022
Sys. Dev. E	0,00176	Accuracy A+	0,001919
Repeat R+	0,000522	Accuracy A-	0,001887
Repeat R-	0,000358	Accuracy A	0,002037

Table 8 HSC 105 Linear measurement results axis X

Mean Dev. M	4,370	Reversal B	0,100
Sys. Dev. E	4,420	Accuracy A+	6,728
Repeat R+	3,162	Accuracy A-	6,866
Repeat R-	3,354	Accuracy A	6,981

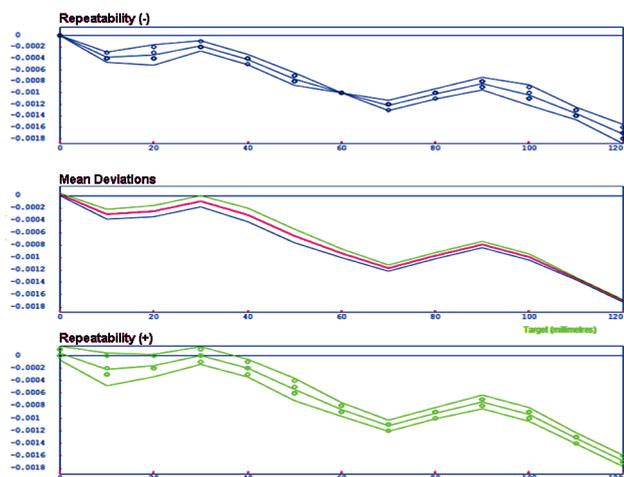


Figure 9 Ultrasonic 20 Linear measurement results axis Y

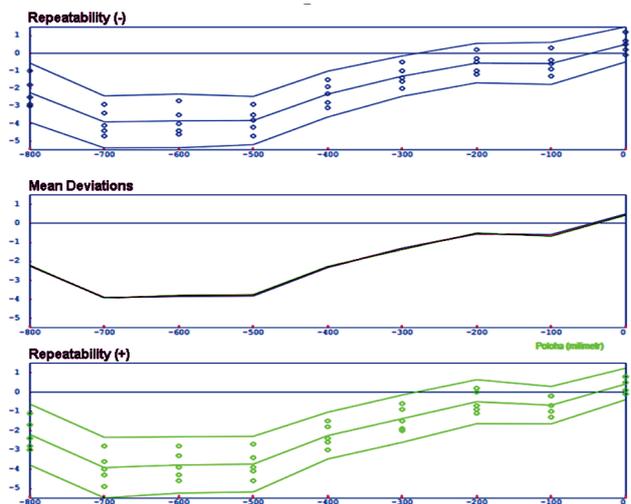


Figure 10 HSC 105 Linear measurement results axis X

Table 9 CTX Alpha measurement results

Mean Dev. M	4,560	Reversal B	1,200
Sys. Dev. E	4,960	Accuracy A+	5,927
Repeat R+	1,368	Accuracy A-	5,159
Repeat R-	1,004	Accuracy A	5,927

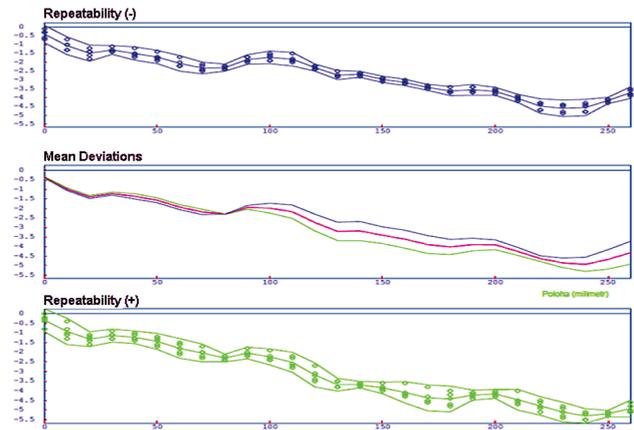


Figure 11 CTX Alpha measurement results

3.2 Circular interpolation accuracy measurement results

Following charts present circular interpolation accuracy of measured machine tools according to the measured plane. In Figs. 12 ÷ 16 there is the interpolation accuracy for DMG HSC 105 linear for XY, YZ and XZ plane. Fig. 15 shows interpolation accuracy of Ultrasonic 20 in XY plane and Fig. 16 shows interpolation accuracy of CTX Alpha 500 in XZ plane. Measured values with statistically significant parameters are figured in Tabs. 10 ÷ 14. Measured values were evaluated by Renishaw software for QC20-W ballbar, the review and comparison with declared values can be found in conclusion.

Table 10 HSC 105 Linear measurement results in the XY plane

26 %	Relative error	2,7 μm
12 %	Straightness Y	1,2 μm
10 %	Cyclic error X	↑0,6 μm ↓0,5 μm
10 %	Straightness X	1,0 μm
9 %	Cyclic error Y	↑0,4 μm ↓0,5 μm
	Best fit radius / mm	150,0003
	Circularity	3,1 μm

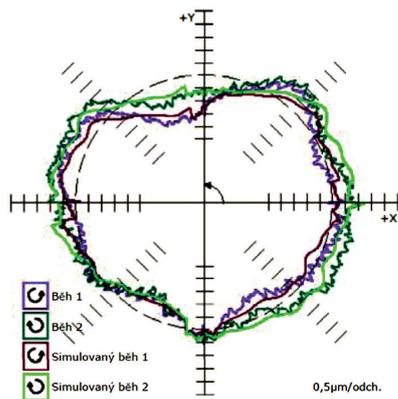


Figure 12 DMG HSC 105 Linear measurement results in the XY plane

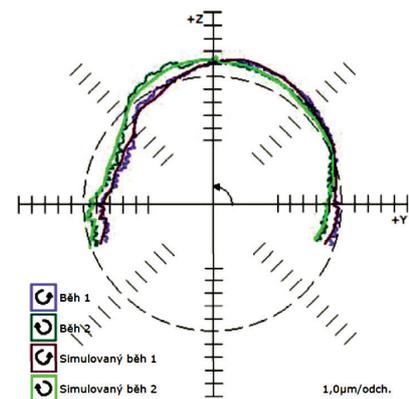


Figure 14 HSC 105 Linear measurement results in the XZ plane

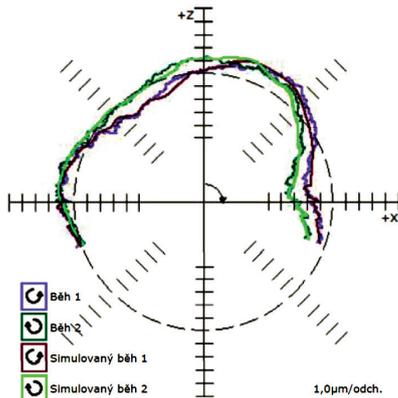


Figure 13 HSC 105 Linear measurement results in the YZ plane

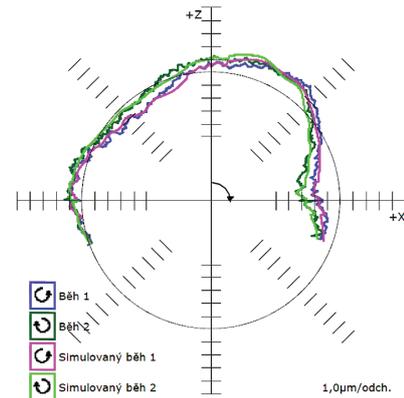


Figure 15 DMG CTX Alpha measurement results in the XZ plane

Table 11 HSC 105 linear measurement results in the YZ plane

53 %	Squareness	-14,5 µm/m
11 %	Lateral play Y	► -0,3 µm
		◄ 0,4 µm
8 %	Cyclic error Y	↑ 0,3 µm
		↓ 0,4 µm
8 %	Cyclic error Z	↑ 0,2 µm
		↓ 0,4 µm
4 %	Servo mismatch	0,01ms
Best fit radius / mm		150,0014
Circularity		4,3 µm

Table 12 HSC 105 Linear measurement results in the XZ plane

30 %	Squareness	9,0 µm/m
20 %	Lateral play X	► 0,8 µm
		◄ 1,0 µm
19 %	Lateral play Z	► 0,8 µm
		◄ 0,9 µm
9 %	Cyclic error Z	↑ 0,1 µm
		↓ 0,4 µm
7 %	Servo mismatch	-0,02 ms
Best fit radius / mm		150,0023
Circularity		5,4 µm

Table 13 DMG CTX Alpha measurement results in the XZ plane

Backlash	z ▲ 0,1 µm x ► 0,1 µm	◄ 0,0 µm
Reversal spikes	z ▲ 0,3 µm x ► -0,8 µm	◄ 0,3 µm
Lateral play	z ▲ 0,3 µm x ► 0,9 µm	▼ 0,5 µm ◄ 0,8 µm
Cyclic error	z ↑ 0,1 µm	↓ 0,4 µm
	x ↓ 0,2 µm	↓ 0,3 µm
Best fit radius / mm		150,0058
Circularity		5,1 µm

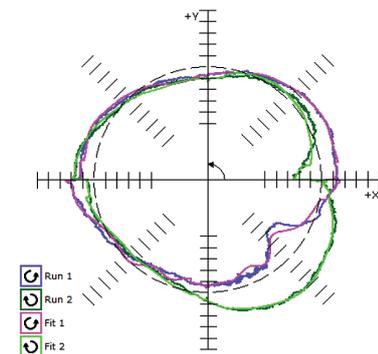


Figure 16 DMG Ultrasonic 20 measurement results in the XY plane

Table 14 Ultrasonic 20 Linear measurement results in the XY plane

32 %	Lateral play X	7,3 µm
		-1,1 µm
14 %	Lateral play Y	0,6 µm
		2,8 µm
10 %	Cyclic error X	↑ 1,6 µm
		↓ 0,6 µm
9 %	Backlash X	1,0 µm 0,5 µm
8 %	Straightness Y	↑ 2,2 µm
Best fit radius / mm		80,0002
Circularity		6,3 µm

4 Conclusion

Experiments described in this article provide the following results:

1. The kinematic structure has no significant effect on linear movement and positioning accuracy in milling machine tools. The question is how the kinematic structure may affect accuracy when the movements are

combined with the rotational ones. However the measurement device used in this experiment was not able to measure circular paths. This measurement was provided by different measurement devices and the results are described in what follows.

2. Positioning accuracy of machine tools shown in charts (Fig. 6 ÷ Fig. 8) in previous chapter makes it evident that one year operation of machine tools has no significant effect on accuracy of positioning. This statement is based on comparison of measured values with values declared by producer on the certificate of delivery. The maximum values of deviation for milling machine tool Ultrasonic 20 linear was 1,7 µm, declared value for positioning is 5 µm. HSC105 linear deviations maximum measured value was 4,37 µm, declared value 8 µm. The conventional screwbar drive on turning machine declares a value of 10 µm positioning, measured value was 4,56 µm. Declared values were checked according to the standard VDI/DGQ 3441, measurements were taken according to the standard ISO 230-2.

3. Accuracy of repeatability is at a very high level. It is clear from the charts that the deviation of position accuracy has raised with the distance from the start point. Thanks to the fact that each measurement was performed in both up and down direction we can see that the spindle came back to the same position when it started with the accuracy of 0,0002 mm for Ultrasonic 20 machine tool. For HSC 105 linear machine repeatability fell down to the values of 0,0035 mm and for the CTX Alpha machine tool to 0,0013 µm. From the previously mentioned results it is clear that machine drives have negligible effect on machine positioning accuracy, however the construction with two rulers on ultrasonic machine has a visible effect.

4. Circular interpolation of machine tools is in levels accepted by ISO 230-4 standard. Circularity values are as well acceptable.

Results will be used for the next research in circular interpolation and they will be used for machine deviation compensation by including repair coefficient into the machine's system.

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