CNC machine tool, diagnostic systems, positioning errors

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LINEAR POSITIONING ERRORS OF 3-AXIS MACHINE TOOL

Abstract

This paper presents results of 3-axis CNC machine tool diagnostics performed with XL-80 laser interferometer and XC-80 environmental compensation unit, including pressure, humidity and temperature sensors. Furthermore, the paper includes the methodology and results of conducted measurements of linear positioning errors, which supplied data for further analysis. The conclusion section presents important results of conducted experiments. Measurement results were presented in figures, charts and tables.

1. INTRODUCTION

Machining and machine tool technology has been developing very dynamically for many years. This results from increasing requirements for the performed parts. The development of CNC machines is focused on finding new solutions and improving existing ones. Despite great advances in machine precision (motors, spindles, gears, measurement and control systems, etc.) the need for compensation of linear and angular positioning errors has not been thus far eliminated [1, 2]. The errors enabling assessment of technical condition of the machine include linear and angular error motions, their repeatability and backlash.

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These values are affected by many external and internal factors, inter alia, geometry and kinematics of machine tools, thermal factors, drive, controller and measurement system errors, or machining-induced errors. Errors generated by the machine tool can be divided into systematic and random [1–4].

All systematic errors regardless of their type (geometric, kinematic, thermal) can be compensated with accuracy dependent mainly on the accuracy of their identification and the rate of change [5–7]. It is difficult to compensate for the dynamic errors [8–11]. Errors that occur regularly, predictably and with little dynamics can be compensated with high accuracy provided that the nature of their changes is known. Temperature changes of machine tool systems are generally slowly variable processes of inertial first-order member characteristics, relatively easy to compensate by *e.g.* linear extension of the rolling screws of a machine tool [12–14]. The main source of thermal changes are all systems which generate heat in the machine tool, such as engine, bearings, pump and the cutting process itself [1]. All systems that generate heat should be placed on the outside of the body in order to limit the effect of heat on the machine frame. These activities are designed to prevent inducing thermal deformation of the machine frame. The purpose of these procedures is to avoid the shift of shaft axes and spindles [13].

The second group of errors are stochastic problems. The errors belonging to this group are much more difficult to compensate, owing to the lack of functional equations describing their occurrence. It is during the planning stage that active vibration reduction systems are designed and applied to limit the occurrence of such errors. Factors which contribute to random errors are predominantly vibrations induced while cutting, the weight of the machine and the heat from the production hall [11, 12].

2. THE MEASUREMENT SYSTEM AND TESTING METHODOLOGY

Experimental tests were conducted at Engineering Studies Center of The State School of Higher Education in Chełm. The accuracy and repeatability of positioning tests were performed on a vertical machining centre DMU 635 with Heidenhain TNC 620 (Fig. 1a). The measurement was performed with a portable laser measurement system XL-80 with a dedicated software driver [5, 6] (Fig. 1b), which employs the light of a known wavelength as a measure of length.

a) **b)**

Fig. 1. Diagnostic stand during tests: a) vertical machining center DMC 635, b) laser interferometer XL-80 [5]

The measurement consists in counting the wavelength of the light incident on the optical detector. This allows high precision positioning measurements [3–5]. According to the manufacturer of the interferometer, the accuracy of the measurement of linear displacement with no thermal expansion compensation is MPE = ± 0.5 ppm. Detailed analysis of the uncertainty of this measurement allows accuracy at a 95% confidence level ($k = 2$), at a level of about 6 microns per meter length of the axis and at a temperature difference of 5° C of normal temperature. Temperature, pressure and humidity conditions during the measurements necessitated the compensation of laser wavelength, which significantly increased measurement accuracy [13].

The system is based on a set of laser sensors, compensator and tripods with a table. The measurement points for each axis were programmed at 50 mm intervals, including the zero point, to the farthest point of the machine at a predetermined pitch. The measurement range of the X-axis is 635 mm, of the Y-axis is 510 mm and in the case of the Z-axis up to 460 mm [3–7]. Programmed measurement points for each axis are presented in Table 1.

Tab. 1. Programmed measurement points for each axis [source: own study]

Axis	**Programmed measurement points Pi [mm]**												
X	0	50	100	150	200	250	300	350	400	450	500	550	600
Y	0	50	100	150	200	250	300	350	400	450	500	-	-
Z	0	50	100	150	200	250	300	350	400	450	-	-	-

Tab. 2. Positioning tolerances of axes up to 800 mm [10]

Tolerance		Axis measurement range [mm]	
		≤500	>500 ≤800
Bi-directional positioning accuracy of an axis	A	0.022	0.025
Unidirectional positioning accuracy of an axis	A↑ and A↓	0.016	0.020
Bi-directional repeatability of an axis	R	0.012	0.015
Unidirectional repeatability of an axis	R↑ and R↓	0.006	0.008
Reversal value of an axis	B	0.010	0.010
Mean reversal value of an axis	$\bar{B}$	0.006	0.006
Bi-directional positioning systematic error of an axis	E	0.015	0.018
Unidirectional positioning systematic error of an axis	E↑ and E↓	0.010	0.012
Mean bi-directional positioning error of an axis	M	0.010	0.012

The tests employed a bi-directional alternate strategy. The number of passes for the X-axis and Z is 3, and the Y-axis is 4. In order to diagnose the precision of machine tools the tolerance table for machining centers with normal accuracy contained in the standard ISO 10791-4: 2001 was employed (Table 2). The obtained results were subsequently processed according to the standard ISO 230-2 with the use of XCal-View 2.2 software [11].

3. RESULTS AND ANALYSIS

Conducted measurements produced a positioning accuracy waveform changes as a function of length of measured axis. The tests were repeated bi-directionally with double precision for each axis.

Fig. 2 shows the results of the X-axis accuracy according to the standard ISO 10791-4:2001. Figs. 2 and 3 show that the maximum error is 10.5 μm at the measurement point of 500 mm. Fig. 2 shows that the bi-directional positioning accuracy is 12.5 μm and the mean error is 0.2 μm. The trend observed in X-axis measurement is degressive (decreasing). The absolute value of deviation equals 10.5 μm.

Fig. 3 presents the results of the Y-axis measurements developed in accordance with the standard PN-ISO 10791-4: 2001. Y-axis exhibited highest bi-directional positioning accuracy of 4.6 μm. The analysis of the error changes leads to the conclusion that the test of Y does not represent any growing trend. The resulting values do not exceed 2 μm with the exception of the last measurement point, where the value of 2 μm was by 0.7 μm.

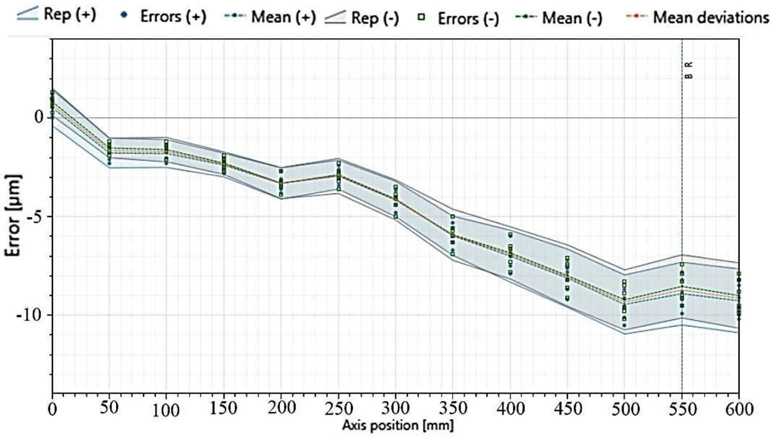

Fig. 2. Bi-directional positioning accuracy of X-axis of 3-axis milling machine DMU 635 eco as function of measurement point position [source: own study]

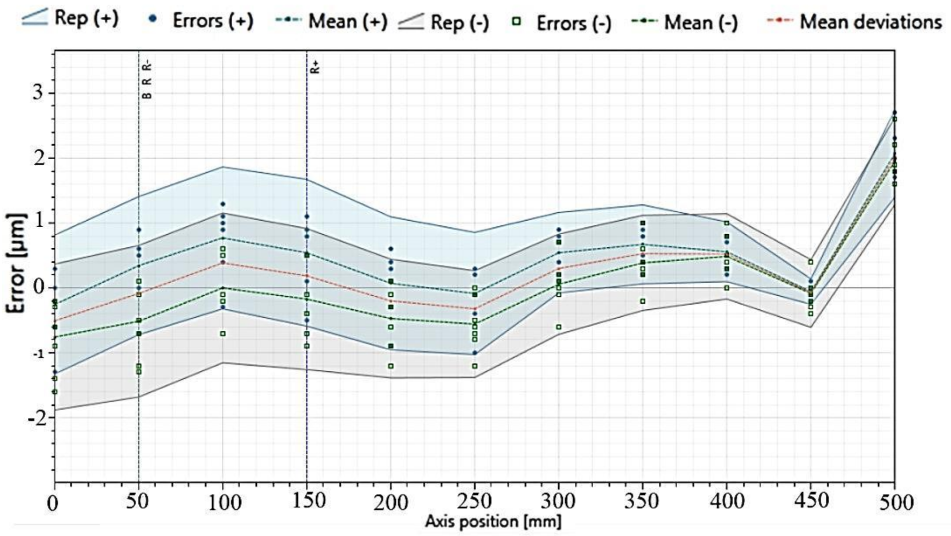

Fig. 3. Bi-directional positioning accuracy of Y-axis of 3-axis milling machine DMU 635 eco as function of measurement point position [source: own study]

Fig. 4 presents the tests results of the Z-axis. The results were prepared in accordance with the standard ISO 10791-4: 2001. Fig. 4 presents error values amounting to 23.7 microns occurring at the last measurement position of the axis, 450 mm. The value obtained at the position of 450 mm exceeds the tolerance for bi-directional positioning error. The changes indicate growth of inaccuracy in the positive direction.

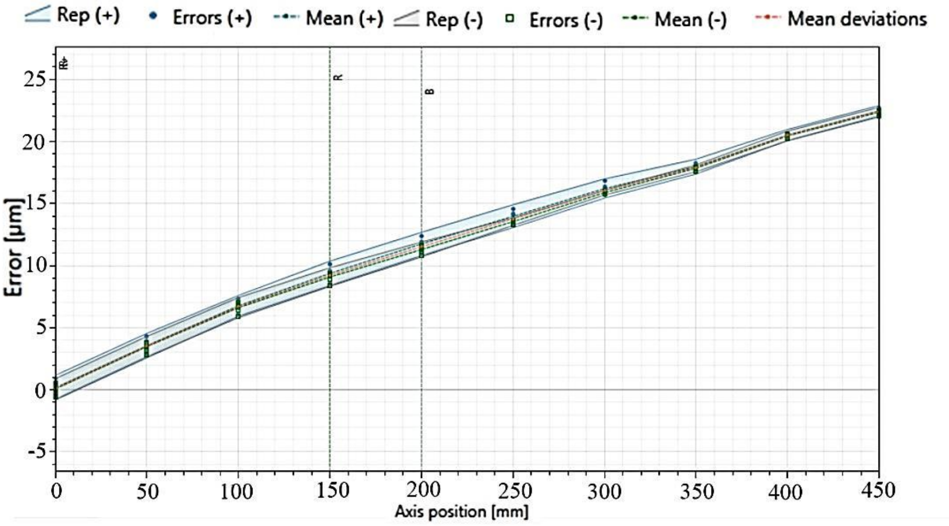

Fig. 4. Bi-directional positioning accuracy of Z-axis of 3-axis milling machine DMU 635 eco as function of measurement point position [source: own study]

Fig. 5 shows experimental results of linear positioning of a 3-axis machining center DMC 635 in all analysed axes. The graph shows that the lowest error values were observed in the Y-axis.

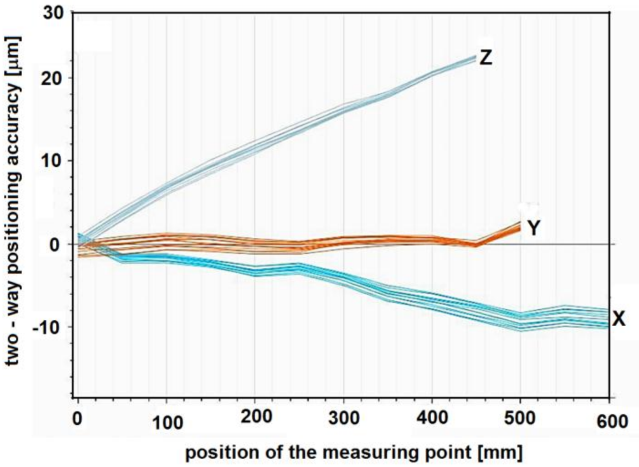

Fig. 5. Bi-directional positioning accuracy of X, Y, Z-axis of 3-axis milling machine DMU 635 eco as function of measurement point position [source: own study]

Table 3 shows a comparison of obtained accuracy parameters with the standard tolerances described in the norm ISO 10791-4: 2001. Green bars denote compliance with the standard, whereas red indicate the lack of compliance (marked as "-" in Table 3) as they exceed the tolerances presented in the standard (Table 3).

Tab. 3. Comparison of the received parameters of table positioning accuracy tolerance [source: own study]

Tolerance		**measurement range of axis [*mm*]**		**measurement results of errors [μm]**					
		≤500	>500 ≤800	X		Y		Z	
Bi-directional positioning accuracy of an axis	A	22.0	25.0	12.5	✓	4.6	✓	23.7	-
Unidirectional positioning accuracy of an axis	A↑ and A↓	16.0	20.0	12.3	✓	4.5	✓	23.7	-
Bi-directional repeatability of an axis	R	12.0	15.0	3.6	✓	3.1	✓	2.0	✓
Unidirectional repeatability of an axis	R↑ and R↓	6.0	8.0	3.3	✓	2.3	✓	2.0	✓
Reversal value of an axis	B	10.0	10.0	0.4	✓	0.9	✓	0.5	✓
Mean reversal value of an axis	$\overline{B}$	6.0	6.0	0.2	✓	0.4	✓	0.2	✓
Bi-directional positioning systematic error of an axis	E	15.0	18.0	10.3	✓	2.8	✓	22.4	-
Unidirectional positioning systematic error of an axis	E↑ and E↓	10.0	12.0	10.1	✓	2.7	✓	22.3	-
Mean bi-directional positioning error of an axis	M	10.0	12.0	10.0	✓	2.5	✓	22.3	-

For the X-axis tolerances are specified for the measurement range from 501 to 800 mm. Y and Z are compared with measurement tolerances of up to 500 mm. In the Z-axis unidirectional and bi-directional positioning accuracy exceeded the tolerances of the standard ISO 10791-4: 2001. Unidirectional and bi-directional positioning systematic error, mean deviation bi-directional positioning also exceeded the prescribed tolerances. The tolerances for the X and Y are within the range of values allowed by ISO 10791-4: 2001.

Table 3 and Fig. 6 show that the Y-axis achieved the highest accuracy. Best values for the Y-axis were obtained for bi-directional positioning accuracy and for bi-directional systematic positioning error, mean bi-directional positioning error produced the best results in the case of this axis, in comparison to the X-axis and Z. Only the positioning repeatability is slightly worse than for the Z-axis.

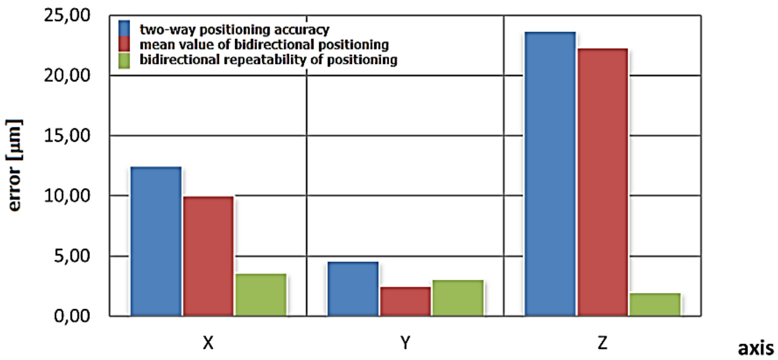

Fig. 6. Bi-directional positioning accuracy, mean bi-directional positioning error, bi-directional repeatability in micrometers [source: own study]

Table 4 presents the values inserted into the machine control system to compensate the Z-axis errors.

Tab. 4. Table of error compensation in Z-axis [source: own study]

Table of error compensation in Z-axis					
Rate	Location [mm]	Connectedly [µm]	Rate	Location [mm]	Connectedly [µm]
1	0	0	6	250	-3
2	50	-3	7	300	-2
3	100	-4	8	350	-2
4	150	-2	9	400	-2
5	200	-2	10	450	-2

Table 4 was generated automatically by software XCal-View based on the results shown in Fig. 5.

4. SUMMARY AND CONCLUSIONS

Vertical machining center DMC 635 shows high accuracy in X and Y-axis. The results of the X and Y-axis compared with Table 3 demonstrate excellent performance accuracy. In the X-axis a characteristic decrease of the positioning accuracy is noticeable. Z-axis exceeds 5 of 9 deviations contained in the PN-ISO 10791-4: 2001, as presented in Table 3. The overrun of the tolerances of bi-directional positioning accuracy is noticeable in Fig. 5. Error compensation table for the Z-axis is shown in Table 4. The Z-axis demonstrates an increasing positioning error trend with the increase of distance from the first measurement point, in the positive direction.

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