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IMPROVEMENT OF POSITIONAL ACCURACY OF PRECISION MICRO MILLING CENTRE USING PITCH ERROR COMPENSATION

Goran Mijušković, Peter Krajnik, Janez Kopač

Original scientific paper
An experimental procedure was performed on precision micro milling centre to improve positional accuracy and keep tolerances within the required range for precision manufacturing in tool and die industry. The micro milling processes play an important role in tool and die industry, which is facing increasing demands on global market, namely demands related to positional accuracy and repeatability. Laser interferometer was used for measurements of 3-axis machining centre, where the values for positional accuracy and repeatability were calculated according to ISO 230-2 standard for all three axes. Values of positional accuracy for *X*- and *Y*-axes were out of manufacturer's tolerance (3 μm), while positional repeatability was satisfactory and below 0,7 μm for all axes. Based on determined positional errors, correction of pitch error compensation table was performed. The improvement of positional accuracy was significant, with values around 1 μm and below. Finally, measurement uncertainty for accuracy and repeatability was estimated for all axes according to the same standard.

Keywords: *laser interferometer, micro milling, pitch error compensation, positional accuracy and repeatability, precision*

Poboljšanje pozicijske točnosti preciznog mikro obradnog centra s uporabom kompenzacije pogreške koraka

Izvorni znanstveni članak
Na preciznom mikro obradnom centru rabljen je eksperimentalni postupak za poboljšanje pozicijske točnosti i održavanje tolerancija unutar zahtijevanog područja za preciznu proizvodnju u alatnoj industriji. Procesi mikro glodanja imaju važnu ulogu u alatnoj industriji, koja je suočena s povećanim zahtjevima na globalnom tržištu, naime zahtjevi se odnose na pozicijsku točnost i ponovljivost. Laserski interferometar rabljen je za mjerenje 3-osnog obradnog centra, gdje su vrijednosti za pozicijsku točnost i ponovljivost izračunate prema ISO 230-2 standardu za sve tri osi. Vrijednosti pozicijske točnosti za *X* i *Y* osi bile su izvan proizvođačeve tolerancije (3 μm), dok je pozicijska ponovljivost zadovoljavajuća i ispod 0,7 μm za sve osi. Na osnovu utvrđenih pozicijskih pogrešaka napravljena je korekcija tablice kompenzacije pogrešaka koraka. Poboljšanje pozicijske točnosti je značajno, jer su vrijednosti pogreške oko 1 μm i ispod. Na kraju je prema standardu procijenjena nesigurnost mjerenja za točnost i ponovljivosti za sve osi.

Ključne riječi: *laserski interferometar, mikro glodanje, kompenzacija pogreške koraka, pozicijska točnost i ponovljivost, preciznost*

1 Introduction

The miniaturization of products is drastically increasing in a number of industries such as: tool and die, aerospace, biomedical, electronic, and automotive [1]. Machine tools and machining processes have to be continuously improved to fulfil the requirements necessary in the miniaturization of products and higher machining precision.

Cost-efficient mass production of the miniaturized products can be achieved only by using moulding processes (injection moulding, hot embossing, and casting). The quality of products and reliability of these processes is highly dependent on manufactured moulds. Micro milling is one of the most promising processes for production of complex 3-D micro-forms with high dimensional accuracy and good surface finish [2]. Micro-milling is not only intended for micro-moulds, but also for complex machining of micro-features on electrodes and larger moulds. Definition of micro milling is downsizing of conventional milling with the use of end-mills with diameters smaller than 1 mm [3]. For these types of precision machining it is necessary to measure and compensate motional deviations.

The static and dynamic accuracy of machine tool movements along with the computer numerical control (CNC) have significant impact on machining performance, such as dimensional accuracy and repeatability, surface finish, productivity and tool wear [4, 5, 8]. The three main system elements of precision machine tools are spindle, bed, workholding system, and controller. Machine tools for micro milling have some of the following features [6, 7, 8]:

- High precision linear motor drives in all axes.
- Guideways with low friction.
- Adequate cooling system for spindle and linear drives and/or some means of compensation.
- Very high speed spindles (40 000 rpm and higher).
- Bed with high damping and/or damped column, vibration damped palletization for workholding.
- A glass scale feedback with nanometre resolution.
- A CNC unit capable of processing and displaying nanometre units.
- Additional equipment for non-contact cutting tool referencing, precision touch probe for setting up the workpiece, and precision collets for tool clamping.
- Temperature control.

2 Geometric accuracy

New CNC machine tools are delivered with inspection certificate, where detailed information about geometric accuracy is given, including measuring procedure, nominal tolerances and measurements results of manufacturer. When installing a machine tool in a new environment measuring procedure is carried-out to ensure no damage is caused during transport and that machine tool performance complies with tolerances. Different guidelines and standards for inspecting machine tools (ISO 230-2, ISO 230-3 and ISO 230-4, and VDI/DGQ Directive 3441) can be used for such inspection and acceptance testing.

Accuracy of the CNC-machine tool deteriorates throughout its lifecycle due to wear, environmental effects, and undesirable events, such as crashes and movements/re-instalments. It is essential to carry out regular geometric accuracy check-ups, as well as annual calibration in order to minimise rejection of workpieces with tight tolerances. Laser interferometer system is used for calibration after major mechanical intervention on CNC machine tool-tool, while Ballbar QC10 device is used for quick and frequent control of the machine tool accuracy to establish preventive maintenance [9]. The linear measurement is the most common form of measurement used for determining positional accuracy and repeatability. Most CNC machine tools have a pitch error table in their controller to compensate for errors in axis positioning and motion. Linear positioning errors are determined by comparing the programmed position with the real position measured by a laser interferometer on the machine tool axis [10]. With additional optical devices, several measurements on the CNC machine tool can be performed; linear measurements, angular measurements, straightness measurements, squareness measurements, flatness measurements, rotary axes measurements, etc. Generally, there are 21 geometric errors of 3-axes vertical machining centre, which are shown in Tab. 1.

Table 1 Geometric errors [11]

	Number of error components
Linear positioning errors (scale error)	3
Straightness errors	6
Angular errors (pitch, yaw and roll)	9
Orthogonality (squareness) errors of machine tool axes	3
Total	21 error components

3 ISO 230-2

General definition of accuracy and repeatability is given in international standards such as ISO 230-2, JIS B6201-1993, and ASME B5.54. These standards describe both test procedures and methods for calculating the accuracy and repeatability under unloaded conditions for linear and rotary machine tool motions. Nevertheless, standards differ mainly in the number of target points and measurements needed, as well as the statistical parameters to calculate the values of machine tool accuracy and repeatability. The ISO 230-2 is the most accepted standard in the world. Performing measurement according to standard ISO 230-2 has the following characteristics [12]:

- Uniform temperature
- Warm up cycle
- Uni- and bi-directional approaches
- Number of target points: linear axes require at least 5 target points per metre and rotary axes require at least 3 target points per 90 degrees.
- Number of measurements per target point: each test requires at least 5 cycles of forward and reverse direction.

The positioning error x_{ij} is defined as movement to the i target point in j direction. The standard defines $x_{ij}\uparrow$ and $x_{ij}\downarrow$ approaches in the positive and negative directions. If m target points are selected and n cycles are made for each target point, the mean values of the position errors are calculated as:

$$\overline{x}_i\uparrow=\frac{1}{n}\sum_{j=1}^{n}x_{ij}\uparrow;\ \overline{x}_i\downarrow=\frac{1}{n}\sum_{j=1}^{n}x_{ij}\downarrow. \quad (1)$$

The bi-directional deviation is calculated as the mean value between the unidirectional positioning errors:

$$\overline{X}_i=\frac{\overline{X}_i\uparrow+\overline{X}_i\downarrow}{2}. \quad (2)$$

The error due to the change of the motion between the positive and negative direction is defined as reversal value at a position:

$$B_i=\overline{X}_i\uparrow-\overline{X}_i\downarrow. \quad (3)$$

Whereas reversal value of axis is defined as maximum of reversal values of all target positions:

$$B=\max[|B_i|]. \quad (4)$$

On the other hand, the standard deviations for each target point can be calculated as:

$$s_i\uparrow=\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij}\uparrow-\overline{x}_i\uparrow\right)^2};\ s_i\downarrow=\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij}\downarrow-\overline{x}_i\downarrow\right)^2}. \quad (5)$$

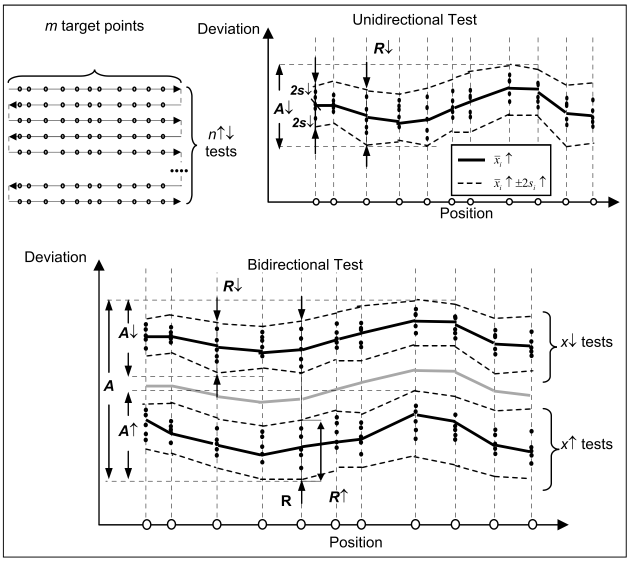

Figure 1 Definition of accuracy and repeatability according to ISO 230-2 standard procedure for uni-directional and bi-directional tests [6]

The ISO 230-2 uses an error band ±2 times the standard deviation, so the repeatability for a uni-directional test for each target point is:

$$R_i\uparrow=4s_i\uparrow, R_i\downarrow=4s_i\downarrow. \quad (6)$$

Therefore, the bi-directional positional repeatability at a target is:

$$R_i=\max\left[2s_i\uparrow+2s_i\downarrow+|B_i|; R_i\uparrow; R_i\downarrow\right]. \quad (7)$$

And the bi-directional positional repeatability is:

$$R = \max\,[R_i]. \quad (8)$$

The bi-directional positional accuracy of an axis is determined by the following equation:

$$A=\max(\bar{x}_i\uparrow+2s_i\uparrow;\bar{x}_i\downarrow+2s_i\downarrow)-\min(\bar{x}_i\uparrow-2s_i\uparrow;\bar{x}_i\downarrow-2s_i\downarrow). \quad (9)$$

Fig. 1 illustrates the accuracy and repeatability for unidirectional and bi-directional tests as defined by the ISO 230-2 standard. Measurement consists of m target points, where each test cycle in the n^{th} position is measurement in forward and reverse direction. Once the position errors are measured, the uni-directional and bi-directional accuracy and repeatability can be calculated.

4 Linear positioning errors

Positional error measurements were performed with laser interferometer (Renishaw Gold Standard ML10). Laser has a measurement uncertainly of ±0,7 µm/m. It is equipped with EC10 environmental compensation unit, integrating air pressure sensor and relative humidity sensor, while air and material temperature sensor are separated in order to be mounted on machine tool to have exact values. This makes it possible to perform accurate measurement of position in workshop conditions. In order to ensure stable temperature conditions, we shaded all windows to avoid direct sunlight, and turned off the light in machine tool working space to remove any heat source. Laser head was stably mounted on a tripod and placed outside of the machine tool. For this one side cover of the machine tool had to be removed, so that laser beam had access to working area (Fig. 2). For coarse alignment tripod, stage and laser head was used, while fine adjustment was made with laser steerer.

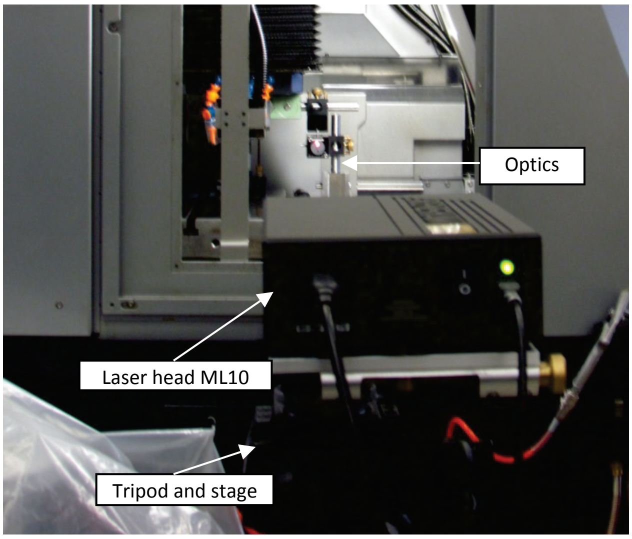

Figure 2 System set-up for measuring position of the *Z*-axis

Measuring set-up for the *X*-axis is shown in Fig. 3, where interferometer optic is mounted on the table and reflector optic on spindle. Air and material sensor were placed on the middle of the table. Similar set-up was used for the *X*-axis, whereas for the *Y*-axis interferometer was placed on the spindle and reflector optic on the table. Renishaw laser10 software was used to capture the positional errors of the axes of micro milling center (Sodick MC 430 L). Characteristics of precision milling machine tool are given in Tab. 2.

Table 2 Characteristics of Sodick MC 430 L

Axis travel range (*X*, *Y*, *Z*) / mm	420 × 350 × 200
Max. spindle speed / rpm	40 000
Tool clamping interface	HSK-E25
Tool holder	Shrink fit
Tool setting	BLUM Micro
Workpiece setting	Precision touch probe
Resolution / µm	0,1
Max. acceleration	1*g*
Max. feed rate in *X*/*Y*/*Z* / m/min	36
Cooling units for spindle and linear drives	✓
MQL	✓
Control unit	Windows based LN2X

At the beginning of measurement beam alignment with machine tool axis was carried-out, where for all three axes maximum power of reflected beam was achieved. Moreover, the warm-up cycle was done before measuring the axis in the form of measurement without data acquisition. The parameters used for measurements of positional errors are described in Tab. 3. The starting point of the *X*-axis and the *Y*-axis was 0,5 mm from machine tool reference point, and 199,5 mm for the *Z*-axis.

Table 3 Parameters of measurements

Type of scale	Incremental linear encoder Heidenhain LF 481
Coefficient of thermal expansion	10 µm/(m·°C)
Feed rate	4000 m/min
Dwell time at each target position	4 s
Distance between targets	50 mm (*X*-, *Y*-axes), 25 mm (*Z*-axis)
Number of test cycle	5
Overrun	0,5 mm

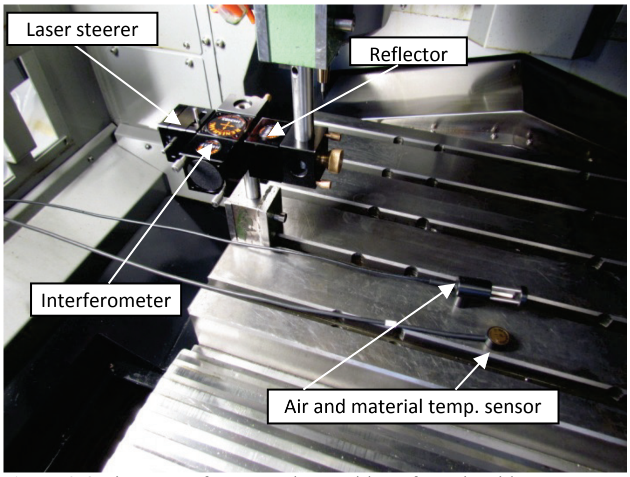

Figure 3 Optics set-up for measuring position of *X*-axis with emperature sensors

4.1 Initial measurements

Axes with shortest range, in general, yield better positional accuracy, shown in Tab. 4. One can observe that repeatability in all axes does not exceed 0,7 µm, which is in agreement with manufacturer measurement of 1 µm, where the tolerance is 2 µm. Adequate trends in repeatability, where positive and negative directions of 5 approaches are very close to the mean value, are shown in Figs. 4 ÷ 6.

Table 4 Linear measurement results of axes according to ISO 230-2 (initial state)

Axis	Axes lengths / mm	Bi-directional positional accuracy A / µm	Bi-directional positional repeatability R / µm	Reversal value B / µm
X	420	7,76	0,59	0,32
Y	350	5,99	0,66	0,26
Z	200	2,24	0,48	0,12

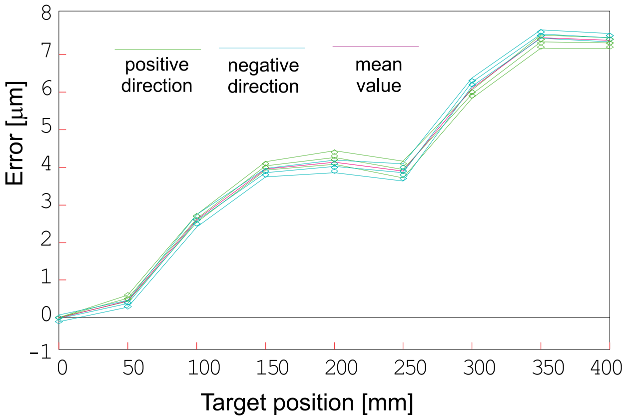

Figure 4 Positional error of the *X*-axis for initial state (ISO 230-2)

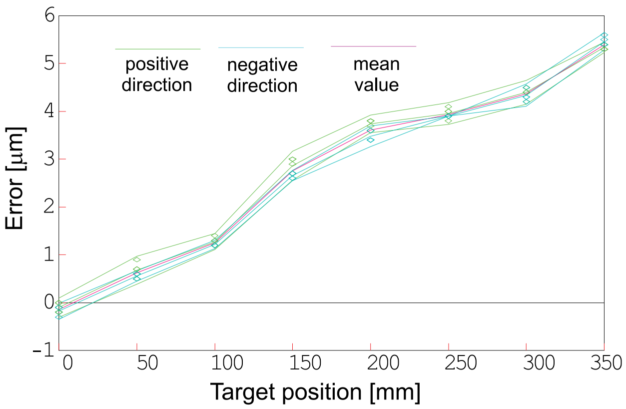

Figure 5 Positional error of the *Y*-axis for initial state (ISO 230-2)

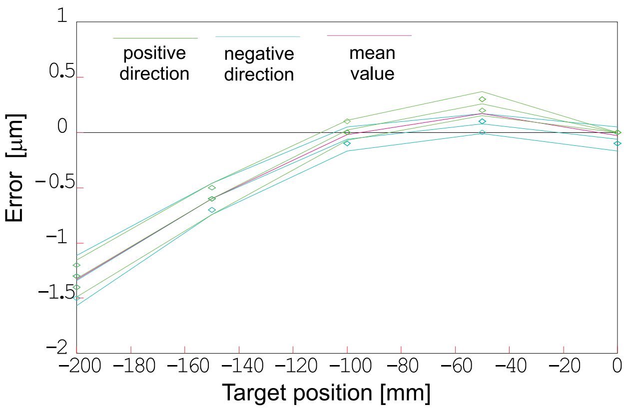

Figure 6 Positional error of the *Z*-axis for initial state (ISO 230-2)

On the other hand, results for positional accuracy are not as good, since the accuracies for the *X*-axis and the *Y*-axis of 7,76 mm and 5,99 mm are out of manufacturer's tolerance (3 µm). Only the shortest *Z*-axis has accuracy of 2,24 µm, which is within the tolerance. Nevertheless, manufacturer's machine tool inspection certificate states the accuracy of the axes at 1,5 µm, which means that the accuracy can be improved, especially because the repeatability was not deteriorated. Improvement of accuracy mainly depends on the repeatability, while achievable accuracy is approx. 30 % higher in case of new machine tool according to manufacturer. Based on the results of repeatability we assume that no damage or excessive wear of machine tool parts is present, which is a good foundation to improve positional accuracy based on correcting the values of a pitch error in compensation table (CNC-based solution). Reversal value of the axes did not exceed 0,4 µm, which means there is practically backlash free movement, due to linear motor drives.

4.2 Pitch error compensation

The pitch error compensation is a widely used method of machine tool controllers to compensate for positional errors caused by the pitch of the ballscrew, and the pitch of linear or rotary scales [13]. In order to access the compensation table, password is usually needed to access the relevant CNC commands. Pitch compensation interval of 5 mm is used by the controller LN2X, which means that for the *X*-axis of 420 mm length, there are 85 target positions starting with reference point of the axis (Tabs. 5 ÷ 6). Values are entered as absolute compensations in micrometers multiplied by factor 10, meaning that over travel error of 1 µm equals compensation value of −10 in the table.

Table 5 Original pitch error compensation table for the *X*-axis

No	00	01	02	03	04	05	06	07	08	09
00	0	−3	−6	−8	−9	−5	−6	−7	−8	−10
01	−10	−10	−12	−12	−10	−11	−16	−22	−23	−22
02	−22	−24	−25	−23	−22	−22	−25	−28	−27	−28
03	−30	−36	−37	−36	−32	−31	−34	−33	−29	−29
04	−29	−30	−32	−31	−32	−34	−35	−36	−35	−35
05	−40	−42	−39	−34	−31	−32	−32	−33	−35	−38
06	−42	−45	−46	−46	−46	−49	−50	−46	−45	−45
07	−47	−46	−44	−43	−47	−49	−51	−52	−54	−60
08	−62	−62	−63	−64	−68					
09										

Table 6 New pitch error compensation table after the second correction for the *X*-axis

No	00	01	02	03	04	05	06	07	08	09
00	0	−2	−5	−9	−11	−7	−7	−9	−10	−13
01	−16	−24	−30	−33	−35	−35	−40	−45	−47	−48
02	−50	−54	−55	−56	−57	−62	−67	−71	−70	−75
03	−76	−78	−76	−75	−73	−73	−78	−77	−75	−76
04	−78	−82	−84	−83	−86	−88	−91	−94	−93	−90
05	−91	−91	−92	−89	−93	−99	−100	−101	−102	−104
06	−109	−113	−115	−116	−118	−120	−123	−122	−123	−127
07	−129	−130	−127	−128	−133	−134	−131	−129	−130	−137
08	−144	−149	−150	−153	−159					
09										

The distance between target positions was fixed for compensation interval (5 mm) in order to achieve better results. Between this interval, machine tool and axis position is compensated by interpolated value. Uni-directional measurements were performed, since bi-directional repeatability (made evident in initial measurements) was adequate. Measured compensation values (Tab. 6) were manually transferred into the controller's compensation table. For the *X*-axis, two corrections were needed in order to get positional errors less than ±0,5 µm, which can be seen in Fig. 7. Here one can observe that the *X*-axis was exceeding the command position, so compensations values were negative.

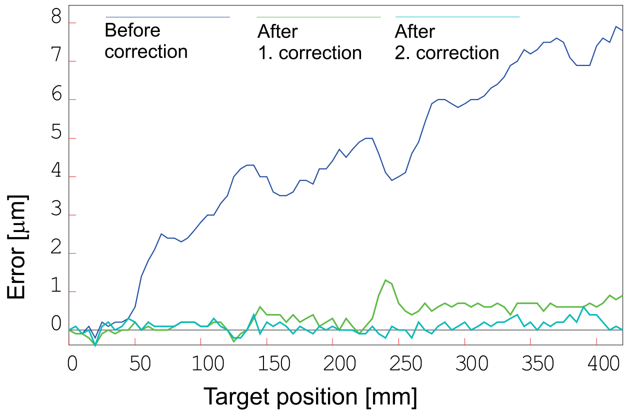

Figure 7 Positional error of the *X*-axis before and after correction of pitch error compensation table

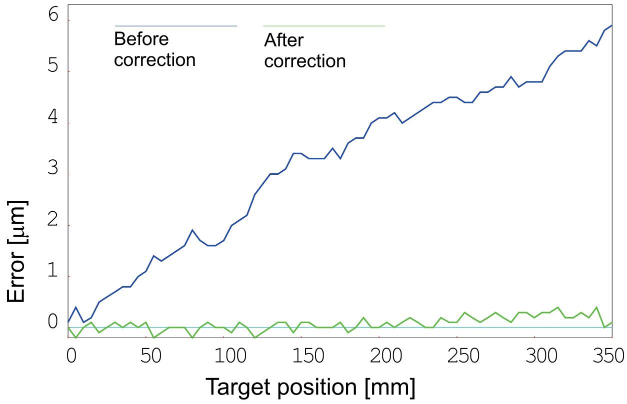

Figure 8 Positional error of the *Y*-axis before and after correction of pitch error compensation table

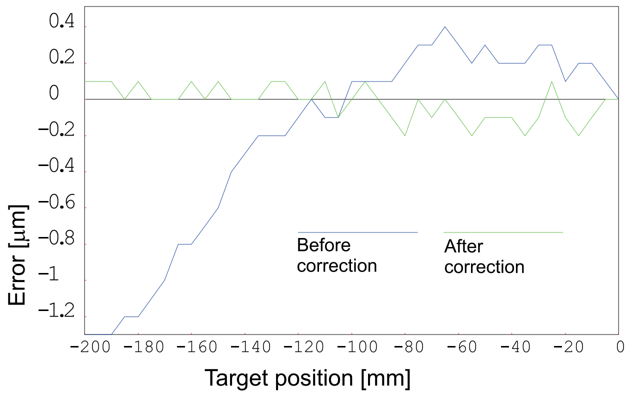

Figure 9 Positional error of the *Z*-axis before and after correction of pitch error compensation table

Errors of positive values for the *Y*-axis (Fig. 8) result from over-travel. On the contrary, negative values for errors in *Z*-axis (Fig. 9) relate to under-travel. For the *Y*-axis and the *Z*-axis just one correction was needed to achieve positional errors within ±0,5 μm range. It should be noticed that the compensation tables were corrected with measured positional errors in the same manner as in the case of the *X*-axis.

4.3 Verification

Compensation of pitch error was followed by measurements of all three axes according to ISO 230-2 (repeated under same measuring parameters) in order to verify the improvement of positional accuracy. The improvement of bi-directional positional accuracy is significant (Tab. 7), especially accuracy for the *X*-axis and the *Y*-axis, which are within the tolerance of 3 μm - even better than manufacturer's measurement of 1,5 μm (Figs. 10 ÷ 12).

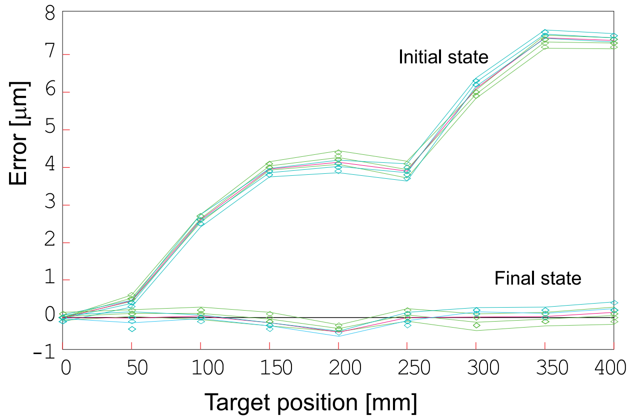

Figure 10 Positional error of the *X*-axis for initial vs. final state (ISO 230-2)

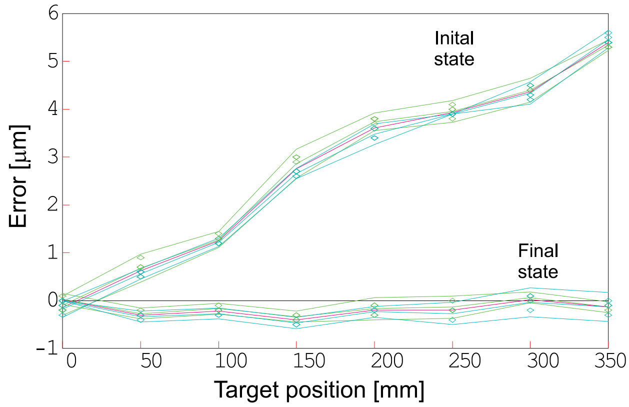

Figure 11 Positional error of the *Y*-axis for initial vs. final state (ISO 230-2)

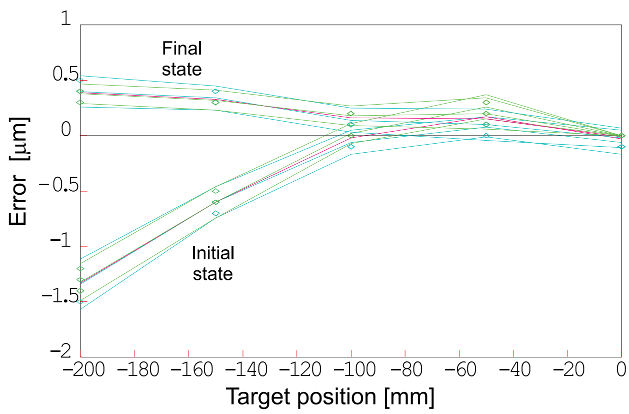

Figure 12 Positional error of the Z axis for initial vs. final state (ISO 230-2)

Table 7 Comparison of bi-directional accuracy (*A*) before and after correction of compensation values (initial versus final state)

Axis	Axes lengths	(*A*) initial state	(*A*) final state
X	420 mm	7,76 μm	1,06 μm
Y	350 mm	5,99 μm	0,85 μm
Z	200 mm	2,24 μm	0,65μm

The shortest *Z*-axis is again the most accurate and quite below the accuracy of 1 μm (Fig. 11). All values of bi-directional repeatability and reversal values are similar to those in initial measurements, thus they are not stated here. Achieved accuracy values in all axes are not higher than 50 % of the repeatability values, which is a good indicator that machine tool's parts are not worn or damaged. It is assumed that accuracy was deteriorated, because machine tool had moved a few times.

4.4 Measurement uncertainty

Measurement uncertainty is an important characteristic that is used to further quantify the improvement of positional accuracy. Annex A of the ISO 230-2:2006 standard defines estimation of measurement uncertainty for linear measurement of positioning. There are many factors affecting measurement uncertainty: e.g. measuring device, misalignment between the measuring device and the machine tool axis, the uncertainty due to the compensation of the machine tool temperature (measurements at temperatures other than 20 °C), and environmental variation errors (thermal drift) [10]. Each effect value was calculated separately, whereas uncertainty of bi-directional accuracy and repeatability was assessed (Tab. 8). The temperature of the machine tool was within 20 ÷ 20,5 °C range for the assessment of *X*- and *Y*-axes, while for the *Z*-axis, the temperature was between 19 ÷ 20 °C; therefore temperature-related errors were kept at minimum. The most significant influence on accuracy is the compensation of the machine tool temperature, which depends on thermal expansion coefficient (10 μm/m) and uncertainty of a temperature sensor (±0,1 °C). The highest measurement uncertainty refers to the longest, *X*-axis (values are similar to bi-directional positional repeatability). Measurement uncertainties of bi-directional repeatability are the same for all axes, because it only depends on environmental error or thermal drift.

Table 8 Measurement uncertainty for bi-directional accuracy $U(A)$, bi-directional repeatability $U(R)$

Axis	Axes lengths / mm	$U(A)$ / μm	$U(R)$ / μm
X	420	0,75	0,36
Y	350	0,69	0,36
Z	200	0,65	0,36

5 Conclusion

An experimental improvement procedure was used for micro milling centre to minimize positional errors of linear scale. The improvement was based on the correction of the pitch error compensation table. Bi-directional accuracy (ISO 230-2) was improved from 7,76 μm to 1,06 μm (732 %) in the *X*-axis, from 5,99 μm to 0,85 μm (705 %) in the *Y*-axis and from 2,24 to 0,65 μm (345 %) in the *Z*-axis. The most likely cause for deterioration of positional accuracy was that machine tool was moved a few times along with environmental effects. Finally, it was proved that using the pitch compensation table high positional accuracy in all axes can be simply achieved, which is essential for micro milling operations.

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Authors' addresses

Goran Mijušković, Bsc. Mech. Eng.
University of Ljubljana, Faculty of Mechanical Engineering
Aškerčeva 6, 1000 Ljubljana, Slovenia
E-mail: goran.mijuskovic@fs.uni-lj.si

Peter Krajnik, PhD.
University of Ljubljana, Faculty of Mechanical Engineering
Aškerčeva 6, 1000 Ljubljana, Slovenia
E-mail: peter.krajnik@fs.uni-lj.si

Prof. Janez Kopač, PhD.
University of Ljubljana, Faculty of Mechanical Engineering
Aškerčeva 6, 1000 Ljubljana, Slovenia
E-mail: janez.kopac@fs.uni-lj.si