sciendo
ISSN 1335-8871

MEASUREMENT SCIENCE REVIEW

Journal homepage: https://content.sciendo.com

The Influence of the Movement Method on the Results of Machine Tool Positioning Accuracy Analysis

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Abstract: The improvement of machine tools, and therefore, of industrial production, requires high accuracy of machining while adapting to the different dimensions of the workpieces and to the machines themselves. As a result, the improvement of testing procedures and the analysis of positioning accuracy results represent an important research task in modern manufacturing engineering. The paper presents the results of the research carried out with the aim of determining the influence of the choice of parameters for standardized testing of positioning accuracy on the measurement results with reference to the characteristics of the machines from the point of view of the size of the workspace and the machines themselves. In this way, it is possible to choose the appropriate test parameters of the machine tools depending on their geometrical characteristics and test conditions and within the existing standards.

Keywords: ISO 230-2, machine tools, positioning accuracy, motion strategies, NC machine.

1. Introduction

The development of the precision engineering theory plays an important role in improving the efficiency of quality control in production and ensuring processing accuracy in the process of developing machining technology at the micro, meso and macro levels. Hence, there is a growing need for special machines that enable processing with submicron accuracy with narrow tolerance characteristics that meet the requirements of new inventions in high-tech industries [1].

Increasing demand for high accuracy components with lower investment requirements has made it necessary to maximize existing resources. Verification and compensation are effective methods to improve the accuracy of a machine tool (MT) to increase its capacity. MT accuracy is affected by various sources of error such as machining conditions, tooling, environmental conditions, machine design and components, and the assembly process. Verification is an attempt to detect the effect of MT system errors, called geometric errors, on motion control components. These errors change slowly and cause differences between the workpiece and the tool, even under no-load conditions [2].

The basis for assessing the state of accuracy of individual axes of numerically controlled machine tools and, therefore, the quality of future production is the testing of positioning accuracy [3]. The procedure of testing positioning accuracy is regulated by a large number of national and international standards [4]-[7] and recommendations of professional associations [8]. The results of these tests are used for numerical compensation of errors in the control systems of modern machine tools [9]. In the past period, a large number of studies has been carried out to improve the procedure for testing the positioning accuracy of machine tools. This primarily refers to analyses of the influence of individual components of measuring equipment on the results [10] and their application in the process of machine tool calibration [11].

The paper describes a segment of the research conducted at the Faculty of Technical Sciences in Novi Sad with the aim of examining the influence of measurement parameters on positioning accuracy results. The paper includes an analysis of the influence of speed and mode of movement, as well as dwell time in the examined position, on the characteristic parameters of the test results according to the ISO 230-2 standard. The mentioned parameters are crucial for determining the quantitative values of positioning accuracy. However, the standard does not define their limit values nor the recommended values used for machine tools with different dimensions, purposes, and characteristics. The aforementioned research aims to formulate recommendations that will enable positioning accuracy tests to be carried out and the characteristic errors of auxiliary movement elements to be determined in accordance with ISO 230-2 for machines of different sizes and with a minimum of test time.

DOI: 10.2478/msr-2023-0018

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2. METHODS OF TESTING NUMERICALLY CONTROLLED MACHINE TOOLS

According to [12], the concepts of accuracy and the difference between accuracy, repeatability, and resolution need to be clarified:

- Accuracy is the difference between actual and nominal values. Also called "error". Statistical accuracy is measured by the mean measured value.
- Repeatability is the range of deviation for the same position value due to a random source of error.

In some literature sources, repeatability is referred to as precision. In a general sense, however, precision refers to a qualitative aspect, including accuracy and repeatability.

Several classifications of machine tool errors can be found in the literature [13]. It is based on systematic and random errors. According to a broader classification there are:

- Geometric and kinematic errors
- Errors caused by heat
- Errors caused by processing forces
- Errors caused by clamping the preparation
- Operating system errors

One segment of geometric accuracy testing of machine tools addresses accuracy and repeatability with a series of simple positioning tests under no-load conditions. The standards specify the measurement methods and give acceptable tolerances for linear and rotary axes.

The second group of geometric accuracy testing procedures includes testing procedures in which a series of target points is established and accuracy and repeatability are measured with multiple approximations for each target point. The results are flatness, parallelism, normality of linear axes, and concentricity errors of rotary axes. These errors are measured with high-accuracy devices and gauges such as laser interferometers, collimators or calibrated rulers, so that the measurements are simple.

A. Standards and recommendations

With the aim of generalizing the standardization of testing and analysis of accuracy and repeatability of machine tools, certain international standards have been established. The most important of these are ISO 230-2, JISB6201-1993, VDI/DGQ 3441, and ASME B5.54. These standards establish both test procedures and statistical parameters to be measured to calculate accuracy and repeatability for linear and rotary axes of milling, turning and EDM machines. However, there are significant differences between these standards, especially in the number of target positions and measurements required to determine the accuracy of the machine.

As a result, the position accuracy and repeatability values given for a machine may vary depending on which standard was used. Since all standards are equally valid, it is beneficial to know how the standards differ from each other and how the various calculated values compare [14].

ISO 230-2 is one of the most widely used standards, which according to its content is intended for the most common machines in operation, medium heavy and light. When testing according to this standard, the following conditions should be met:

- Uniform temperature: all tests must be performed at a temperature of 20 °C
- Warm-up cycle: all tests include a warm-up cycle to simulate the actual operating conditions of the machine.
- One-way and two-way acquisition: all tests include one-way and two-way approaches to target positions.
- Number of target positions: linear axes require a minimum of 5 target positions per meter (for axes up to 2000 mm) and rotary axes require a minimum of 3 target positions at 90 .
- Number of measurements per target position: each test requires a minimum of 5 tests per target position and per movement direction.

The Japanese industry standard JISB6201 represents a non-statistical calculation of accuracy and repeatability and differs significantly from the ISO 230-2 standard. For example, to test each axis, they are based on three target positions along the entire axis, two endpoints, and the middle point of the path in the direction of the axis. When positioning to the target points, the slide moves in only one direction, and the actual position is measured by a laser interferometer and compared to the reading of the position of the control system (CNC). The error is the difference between the two values [5].

Assessment of accuracy and repeatability using the JISB6201 standard results in lower numerical values than ISO 230-2, which is due to a smaller number of target positions and non-statistical calculations of measurement values. However, ISO scores are much more useful in terms of the actual machine tool accuracy (in the general term of accuracy), since the operating errors of the machine tool follow a statistical distribution.

ISO 230 is the lead for several ISO standards that define more specific tests for each type of machine tool. Therefore, ISO 230-1 describes the general concepts of flatness and straightness, defining the basic measurement methods. ISO 230-2, as described earlier, defines accuracy and repeatability. There are several ISO standards for CNC lathes (ISO 13041), machining centers for drilling and milling (ISO 10791), bridge type milling machines (ISO 8636), wire EDM machines (ISO 14137), die sinking EDM machines (ISO 11090), surface grinding machines with vertical grinding wheel spindle (ISO 1985), and many other types of machines.

B. ISO 230-2

The standard ISO 230-2 specifies methods for testing and evaluating the positioning accuracy and repeatability of numerically controlled machine tools by direct measurement of individual machine axes. The methods apply equally to linear and rotary axes. This part of the ISO 230 standard can be used for type tests, machine tool acceptance tests, comparative tests, periodic check, machine inaccuracy compensation, etc.

The test conditions in the standard specify the environmental conditions, the condition of the machines and the procedure for the correct testing of machine tools.

Under laboratory conditions, the measurement is performed at a temperature of the object to be measured of 20 °C. If it is not possible to ensure the required ambient temperature, the measurement results are harmonized by introducing a correction for the expansion factor between the axes of the positioning system (or the workpiece/tool holder) and the measuring equipment, and reducing it to a temperature of 20 °C. The measurement can be performed with a measuring sensor with correction of a single measured value or by measuring the ambient conditions and mathematically correcting the measured values when processing the results.

The relationship between measurement noise and thermal conditions strongly affects the verification results. This relationship can be characterized by two quadratic polynomial equations with $R^2 > 0.99$. Thus, the influence of measurement noise and temperature on verification can be estimated [2].

A temperature variation of four degrees does not significantly affect the repeatability, but it does affect the positioning accuracy [15].

The machine and equipment for the experiment should be in the test room long enough to reach a thermally stable condition before measurements are made. They must be protected from external influences such as sun rays, radiators, air heaters, and others.

The machine must be fully equipped and ready for use. If necessary, leveling and geometric accuracy testing should be fully completed before starting the positioning accuracy test. If the control system is set to compensate for errors measured in the previous period, this should be indicated in the test report. All tests should be performed in a no-load condition.

The testing of machine tools should be preceded by heating the machine elements to the working temperature according to the procedure specified by the manufacturer. In any case, if there are no procedures for warming up the machine, it is necessary to perform a test without saving the data.

The positioning accuracy test for individual numerically controlled axes up to 2000 mm in length (with the possibility of application to smaller axes up to 100 mm in length) is performed along the maximum available segment of each axis for "m" measurement positions. The measuring positions are chosen so that the mutual distances are unevenly distributed in a controlled manner, i.e. "m" selected samples with index "i" are involved. In each measuring position, the moving element (slider) of the machine tool comes several times from both directions of movement. Thus, "n" individual measured values are obtained for the defined measurement positions, which are marked with the index "j".

In this context, the following terms are defined:

Reference position, P_i – the final programmed position of the moving element of the machine

Actual position, P_{ij} – the measured final position of the moving element of the machine at the reference positions i and j

Deviation from position, X_{ij} – the actual final position of the moving element of the machine minus the reference position:

$$X_{ij} = P_{ij} - P_i \tag{1}$$

The positioning directions for the selected measurement position are indicated by:

- ↑ - positive direction (in the direction of movement of the positive axis +X, +Y, +Z),
- ↓ - negative direction (in the direction of movement of the negative axis -X, -Y, -Z).

Since these are random errors, the distribution of these values has the form of a normal distribution.

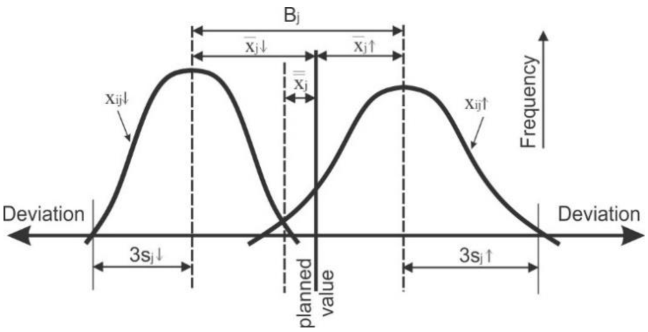

Fig. 1. Distribution of measurement results in one measuring point "j".

For the law of distribution of measured values in a measurement position defined in this way, when positioning in both directions, certain parameters can be calculated as follows:

- Mean unidirectional positioning deviation at a position in the positive and the negative direction

$$\bar{x}_i \uparrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \uparrow \tag{2}$$

$$\bar{x}_i \downarrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \downarrow \tag{3}$$

- Mean bi-directional positioning deviation at a position "i" during two-way positioning represents a systematic deviation from the value at point "i"

$$\bar{x}_i = \frac{\bar{x}_i\uparrow + \bar{x}_i\downarrow}{2} \tag{4}$$

- Reversal error at a position "i" – Bi

$$B_i = |\bar{x}_i \uparrow - \bar{x}_i \downarrow| \tag{5}$$

- Reversal error of an axis – B

$$B = max[|B_i|] \tag{6}$$

- Mean reversal error of an axis – $\bar{B}$

$$\bar{B} = \frac{1}{m}\sum_{i=1}^{m} B_i \tag{7}$$

- Estimator for the unidirectional axis positioning repeatability at a position "i" – si↑ and si↓

$$s_i \uparrow = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{ij} \uparrow - \bar{x}_{ij} \uparrow\right)^2} \tag{8}$$

$$s_i \downarrow = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{ij} \downarrow - \bar{x}_{ij} \downarrow\right)^2} \tag{9}$$

- Unidirectional positioning repeatability at a position "i"– R_i↑ and R_i↓

$$R_i \uparrow = 4s_i \uparrow \tag{10}$$

$$R_i \downarrow = 4s_i \downarrow \tag{11}$$

- Bi-directional positioning repeatability at a position - R_i

$$R_i = max[2s_i \uparrow +2s_i \downarrow +|B_i|; R_i \uparrow; R_i \downarrow] \quad (12)$$

- Unidirectional positioning repeatability of an axis - R↑ and R↓

$$R \uparrow = max[R_i \uparrow] \quad (13)$$

$$R \downarrow = max[R_i \downarrow] \quad (14)$$

- Bi-directional positioning repeatability of an axis - R

$$R = max[R_i] \quad (15)$$

- Unidirectional systematic positioning error of an axis - E↑ and E↓

$$E \uparrow = max[x_i \uparrow] - min[x_i \uparrow] \quad (16)$$

$$E \downarrow = max[x_i \downarrow] - min[x_i \downarrow] \quad (17)$$

- Bi-directional systematic positioning error of an axis - E

$$E = max[x_i \uparrow; x_i \downarrow] - min[x_i \uparrow, x_i \downarrow] \quad (18)$$

- Mean bi-directional positioning error of an axis - M

$$M = max[\overline{x_i}] - min[\overline{x_i}] \quad (19)$$

- Unidirectional positioning error of an axis - A↑ and A↓

$$\mathrm{A} \uparrow = max[\overline{x_i} \uparrow +2s_i \uparrow] - min[\overline{x_i} \uparrow -2s_i \uparrow] \quad (20)$$

$$\mathrm{A} \downarrow = max[\overline{x_i} \downarrow +2s_i \downarrow] - min[\overline{x_i} \downarrow -2s_i \downarrow] \quad (21)$$

- Bi-directional positioning error of an axis - A

$$\mathrm{A} = max[\overline{x_i} \uparrow +2s_i \uparrow; \overline{x_i} \downarrow +2s_i \downarrow] -$$

$$min[\overline{x_i} \downarrow -2s_i \downarrow; \overline{x_i} \downarrow -2s_i \downarrow] \quad (22)$$

A graphical representation of the above parameters for one axis is shown in Fig. 2.

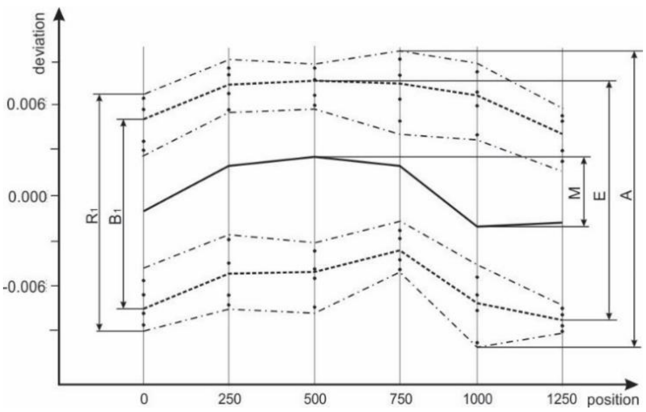

Fig. 2. Graphical interpretation of machine tool errors [4].

In this way, the mathematically defined values of certain parameters defining the positioning accuracy can also be expressed by certain definitions, as stated below.

- Bi-directional positioning error of an axis (A), the value obtained by combining the maximum two-way systematic positioning error and the deviation from repeatability in two-way positioning using the expansion factor k = 2
- Mean bi-directional positioning error of an axis (M) - the difference between the algebraic maxima and minima of the largest two-way positioning values at any position along the axis
- Estimator for the repeatability of the unidirectional axis positioning at a position (s_i) includes a series of n approaches to the position in one direction P_i.

C. *Movement methods*

The ballscrew spindle and the ball nut are heated by frictional energy during the test. This causes an increase in the length of the ballscrew, which may be reflected in the measurement results when machines are tested with an indirect position measurement system. Therefore, three different movement strategies for recording measurement positions were defined in [16].

For all movement methods, it is important to record as many measurement positions as possible and to approach each measurement position at least five times. To avoid periodic errors, the distances of the measurement positions should be different. Guidelines and standards indicate that the position tolerance specified by the machine manufacturer (the total permissible deviation in the working range of the machine axis) must be observed regardless of the movement method [16].

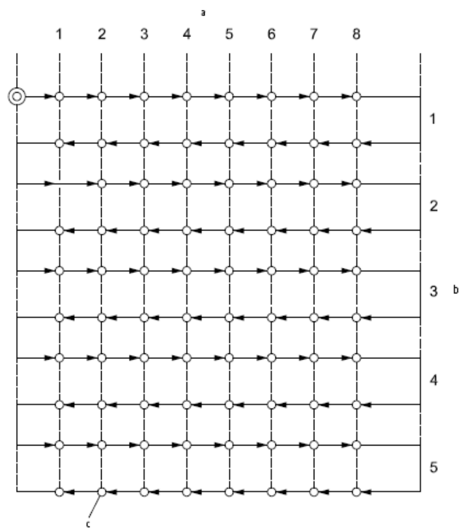

Fig. 3. Linear movement method [4].

The linear movement method (Fig. 3), which is frequently used and recommended by the ISO 230-2 standard, is characterized by a short length of the measurement path and a short measurement time for the entire measurement procedure. Due to the long time delay between approaching the first measuring position from different directions, the elongation of the ballscrew spindle, e.g., due to heating, is noticeable both in the range of the change of direction and in the expansion of the position.

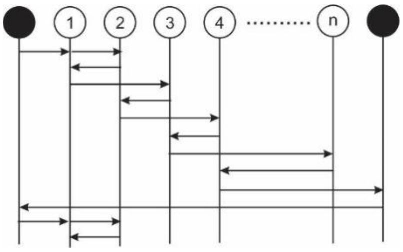

Fig. 4. Pilgrim movement method [16].

With the pilgrim movement method (Fig. 4), the time difference in approaching all measurement positions from different directions is small, but due to the greater length of the measurement path, the measurement time for the entire measurement procedure is longer. The effects of temperature influence at the point of change of direction are compensated, but the temperature induced changes of length occur within the examined axis noticeably in a part of the systematic error.

The pendulum method (Fig. 5) (which is attached to the ISO 230-2 standard) allows the smallest displacement when all measurement positions are approached from different directions, but the time period for recording different measurement positions is longer. The effect of temperature appears as a systematic component of the error of positioning inaccuracy, while the direction change range and position range are almost unaffected by machine heating.

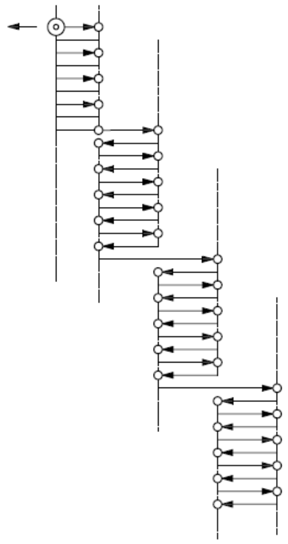

Fig. 5. Pendulum movement method [4].

D. Plan of the experiment

Accuracy and repeatability of positioning have a great influence on the quality of material processing in numerically controlled machine tools. These parameters are measured and analyzed according to standards, and each standard prescribes several measurement parameters. According to ISO 230-2, the parameters used to evaluate machine accuracy are:

- Reversal error of an axis - B
- Mean reversal error of an axis - $\bar{B}$
- Unidirectional positioning repeatability of an axis - Ri↑ and Ri↓
- Bi-directional positioning repeatability of an axis - Ri
- Unidirectional systematic positioning error of an axis - E↑ and E↓
- Bi-directional systematic positioning error of an axis - E
- Mean bi-directional positioning error of an axis - M
- Unidirectional positioning error of an axis - A↑ and A↓
- Bi-directional positioning error of an axis - A

The speed of movement of the slider and the dwell time are not defined in the standard, but are left to the agreement between the manufacturer and the user, while there is no data on the influence of these parameters on the measurement results. There is also no data on the influence of the movement method on the test results, only the linear movement method is shown in the basic part of the text of the standard. However, due to the statistical evaluation, the movement methods lead to different results for thermally induced movements during measurement [16]. In the indirect position measurement system, the ballscrew and ball nut also heat up due to friction in the recirculating ball nut and play a dominant role.

In the linear method of movement, frictional heat is distributed along the length of the ballscrew, whereas in the pendulum method, the movement results in more localized heating. The former leads to additional differences in the machine accuracy results obtained depending on the movement method.

Factors controlled in experimental tests are:

- Slider movement speed - v
- Dwell time - t
- Movement method - c

Noise factors:

- Temperature - minimization of the influence and built-in correction of the measuring instrument
- Natural ground oscillations, oscillations caused by other machines

Slider speed factor levels depend on the capabilities of the machine tool on which the tests are performed.

The experimental test was performed on a numerically controlled machining center type H&H FM38 installed at the Faculty of Technical Sciences in the Laboratory for Machine Tools in Novi Sad. The maximum speed of the slides is 5,000 mm/min, and the maximum speed of movement during the experimental tests is limited to 1,200 mm/min. In addition, the speed of the slider dramatically affects the time of the experimental test. Therefore it does not make sense to perform measurements at very low speeds, as the time of the experiment would drastically increase.

Measurements were made with a system containing a HP 5500C, He-Ne gas laser, manufacturer number 1920A02247, a HP 5505A laser display, manufacturer number 2240A02798, a remote interferometer, a remote reflector, and a HP 5510A automatic compensator, manufacturer number 2044A02748.

Measurement systems based on the principle of laser interferometry have the characteristic that they need a certain time to provide accurate and highly reliable measurement data. For the collection of data during measurement, our own software solution was developed, as well as a connection with laser measurement instrumentation. In the literature you can find information about the range in which the dwell time should be, so that the obtained data contain as little error as possible. The recommendation for a minimum dwell time is three seconds [16].

According to the standards, recommendations, and literature, three movement methods can be observed, which have already been described in Chapter 2 Subchapter C.

The interactions between these factors are not considered in this paper. The levels of the previously discussed factors are shown in Table 1.

Table 1. List of factors and the matching levels.

Factors	Levels		
	1	2	3
v – slider movement speed [mm/min]	200	500	1200
t – dwell time [s]	3	5	7
c – movement method	Linear	Pilgrim	Pendulum

According to the previously adopted procedures, the experimental tests are performed as follows:

- The measurement is performed according to the requirements of the ISO 230-2 standard.
- Positioning accuracy is measured at m = 8 measurement positions, which are located at equal distances from each other on the "X" axis, total n = 6 measurements at one position.
- The measurement is performed in an experimental setup, i.e. 5 times in certain factor levels, in order to obtain a sufficiently large number of results for statistical analysis.
- Thus, a total of 9 x 5 = 45 measurements were performed according to the standard.
- Based on the obtained results and according to the standard, the parameters of positioning accuracy of machine tools are defined.
- Fig. 6 and Fig. 7 show the installed test equipment at the machining center.
- The positioning accuracy parameters are analyzed and classified according to the Taguchi method. The principle "The lower the value, the better" was chosen to calculate the S/N ratio.
- The orthogonal $L_9(3^4)$ Taguchi array is used for the experiments.

Fig. 6. The experimental configuration.

Fig. 7. Interferometer and reflector on the work table.

3. Results

The raw values of measurement in the process of testing the machine are not reported in the paper because they contain 6000 numerical values in 10 tables. In the following, the results according to ISO 230-2 will be given, as well as them the statistical analysis

Table 2 shows the S/N ratios of the parameter according to the experimental settings.

The ranking of factors according to parameters B (Table 3 and Fig. 8), Bav (Table 4 and Fig. 9), R (Table 5 and Fig. 10), and A (Table 6 and Fig. 11) is shown.

Table 2. S/N ratios by parameters.

Experi-ment	B	Bav	R↑	R↓	R	E↑	E↓	E	M	A↑	A↓	A
1.	-18.95	-14.92	-8.96	-8.83	-9.17	-15.56	-16.54	-21.71	-14.62	-18.20	-18.68	-23.02
2.	-17.89	-14.07	-22.02	-20.67	-22.05	-27.16	-26.01	-28.87	-26.60	-30.29	-29.25	-31.20
3.	-17.83	-14.59	-9.88	-9.81	-10.69	-29.58	-28.61	-30.78	-29.11	-30.04	-29.06	-31.20
4.	-18.29	-13.89	-20.71	-20.22	-20.88	-24.48	-22.45	-26.47	-23.43	-26.64	-25.27	-28.16
5.	-17.87	-14.28	-9.02	-8.38	-9.49	-27.59	-26.05	-28.90	-26.85	-28.17	-26.64	-29.32
6.	-18.07	-13.75	-5.75	-5.38	-5.95	-28.75	-30.75	-30.98	-29.68	-29.19	-31.06	-31.32
7.	-18.66	-14.02	-9.06	-8.82	-9.76	-31.10	-29.82	-31.92	-30.48	-31.56	-30.27	-32.28
8.	-18.17	-14.02	-11.06	-9.84	-11.06	-27.67	-29.96	-30.18	-28.76	-28.66	-30.68	-30.91
9.	-16.72	-11.36	-10.63	-6.19	-10.63	-22.93	-20.95	-24.24	-21.95	-24.22	-21.94	-24.93

- Maximum deviation range of mean values - B

Table 3. Ranking of B.

Level	Factor 1-v	2-t	3-c
1	-18.22	-18.63	-18.40
2	-18.08	-17.98	-17.63
3	-17.85	-17.54	-18.12
Δ	0.37	1.09	0.77
Place	3	1	2

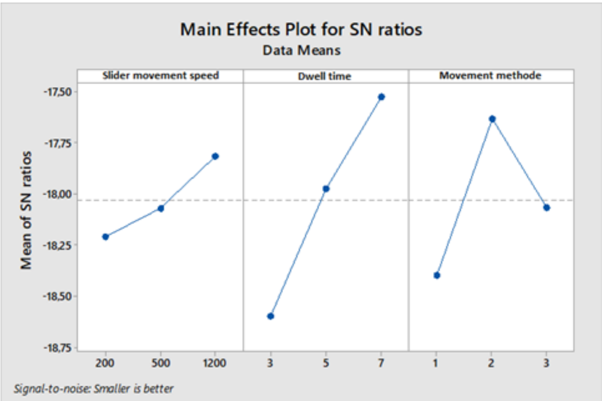

Fig. 8. Response S/N plots for parameter B.

- Mean reversal error of an axis - B_{av}

Table 4. Ranking of B_{av}.

Level	Factor 1-v	2-t	3-c
1	-14.53	-14.28	-14.23
2	-13.97	-14.12	-13.11
3	-13.13	-13.23	-14.29
Δ	1.40	1.05	1.19
Place	1	3	2

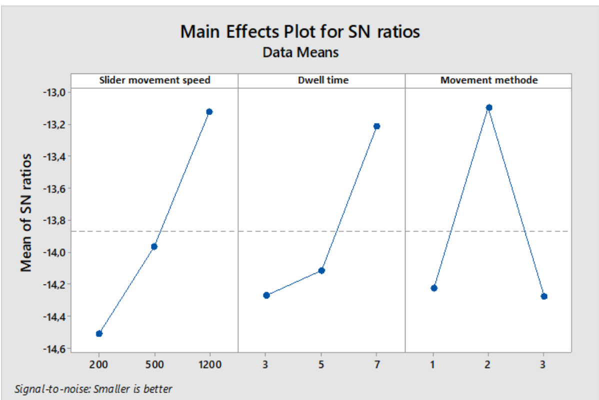

Fig. 9. Response S/N plots for the parameter B_{av}.

- Bi-directional positioning repeatability of the "X" axis

Table 5. Ranking of R.

Level	Factor 1-v	2-t	3-c
1	-13.97	-13.27	-8.73
2	-12.11	-14.20	-17.85
3	-10.49	-9.09	-9.98
Δ	3.49	5.11	9.13
Place	3	2	1

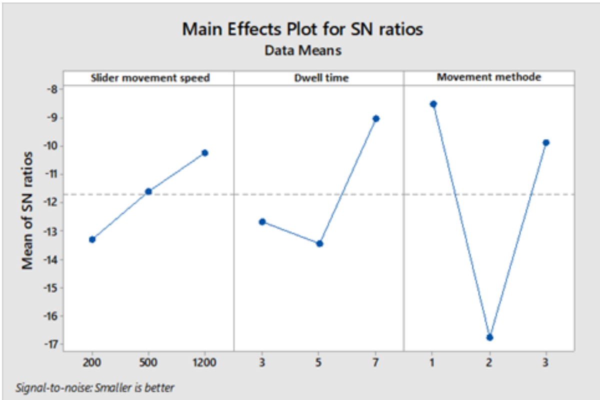

Fig. 10. Response S/N graphs for parameter R.

- Bi-directional positioning error of the "X" axis – A

Table 6. Ranking of A.

Level	Factor 1-v	2-t	3-c
1	-28.47	-27.82	-28.42
2	-29.60	-30.48	-28.10
3	-29.38	-29.15	-30.93
Δ	1.12	2.66	2.84
Place	3	2	1

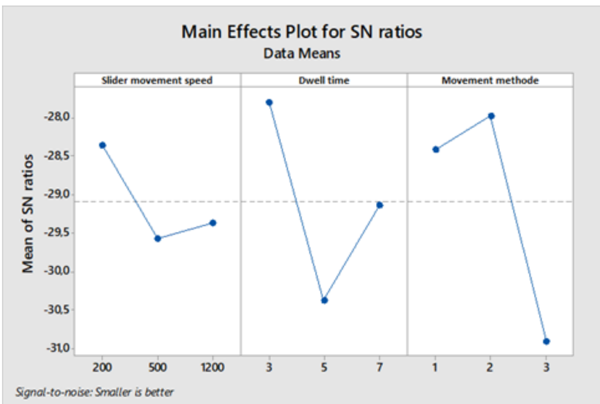

Fig. 11. Response S/N plots for the A parameter.

The ranking of the S/N parameters showed that the maximum range of deviation of the mean values (B) has the greatest influence on the dwell time, on the mean value of the range of deviation of the mean values (B_{av}), the movement speed of the slider, and on all other parameters the movement method has the greatest influence.

The ANOVA analysis for the parameters B, B_{av}, R, and A is shown in Table 7 - Table 10.

Table 7. ANOVA table for the parameter B.

Factor	DoF	Sum of squares	Variation	F-test	Percentage share
v	2	0.1813	0.0906	1.6653	7%
t	2	1.4459	0.7229	13.2838	59%
c	2	0.7163	0.3581	6.5808	29%
Error	2	0.1088	0.0544		4%
In total	8	2.4523			

Table 8. ANOVA table for the parameter B_{av}.

Factor	DoF	Sum of squares	Variation	F-test	Percentage share
v	2	0.8361	0.4181	6.5973	38%
t	2	0.5080	0.2540	4.0085	23%
c	2	0.7262	0.3631	5.7301	33%
Error	2	0.1267	0.0634		6%
In total	8	2.1972			

Table 9. ANOVA table for the parameter R.

Factor	DoF	Sum of squares	Variation	F-test	Percentage share
v	2	8.0452	4.0226	0.8073	11%
t	2	12.0672	6.0336	1.2109	16%
c	2	45.9767	22.9884	4.6136	60%
Error	2	9.9655	4.9827		13%
In total	8	76.0545			

Table 10. ANOVA table for the parameter A.

Factor	DoF	Sum of squares	Variation	F-test	Percentage share
v	2	13.0751	6.5375	0.0279	2%
t	2	58.8943	29.4472	0.1255	9%
c	2	141.9110	70.9555	0.3024	21%
Error	2	469.3242	234.6621		69%
In total	8	683.2045			

Table 7 - Table 10 show the significance of each factor using the F test. The results obtained by the Taguchi method are mostly in agreement with the results of the ANOVA analysis.

Factors whose F-value is greater than $F_{(0,05,2,8)} = 4.46$ are significant.

4. DISCUSSION

Based on the conducted research and the performed series of experimental measurements, it is possible to draw conclusions about the influence of the choice of measurement parameters on the results.

The speed of movement of the slider, the dwell time, and the method of movement are factors that are taken for consideration. The standard does not provide pre-ordered values or limits for any of them. The experiment was planned using the Taguchi method, as it allows to reduce the number of measurements and to obtain a general picture of the influence of these three factors on the output parameters. The values of the test parameters were chosen according to previous experience as well as expected values suitable for application to machine tools with geometric characteristics that fall into the light and medium-heavy categories.

Tests have shown that the choice of movement method has the greatest impact on the following parameters, which define positioning accuracy:

- Unidirectional positioning repeatability of an axis - R↑ and R↓
- Bi-directional positioning repeatability of an axis - R
- Unidirectional systematic positioning error of an axis - E↑ and E↓
- Bi-directional systematic positioning error of an axis - E
- Mean bi-directional positioning error of an axis - M
- Unidirectional positioning error of an axis - A↑ and A↓
- Bi-directional positioning error of an axis - A

Dwell time has the greatest influence on the reversal error of an axis - B.

The speed of movement of the slider has the greatest influence on the mean reversal error of an axis - B_{av}.

Using the Taguchi method, it was found that there is a significant difference between the obtained parameters.

The ANOVA analysis showed that the factors have a significant influence on the random errors, i.e. on the parameters B, B_{av}, R, and R↑. Among the observed factors, the speed of the slider has the greatest influence, which was also confirmed by the analysis using the Taguchi method.

In contrast to the previously analyzed factors, there was no significant influence on the parameters A, A↑, and A↓, M, E and E↓, R↓.

Globally speaking, the method of movement has the greatest impact in general. Table 11 summarizes for all 12 parameters describing positioning accuracy the influence of the movement method according to the Taguchi method "The smaller the value, the better" on the results in terms of the best or worst influence. From Table 11 it can be concluded that the best results are obtained in the case of movement by the pendulum method and that the linear and pilgrim movement methods have a similar negative influence.

Table 11. Matrix of the distribution of the worst and the best obtained results of parameters during measurements by the movement methods.

	Movement method		
Results	Linear	Pilgrim	Pendulum
The worst	5	7	0
The best	1	3	8

Based on the analysis of the presented results, it can be concluded that random errors are influenced by the slider movement speed parameter and the dwell time. At the same time, the dwell time has a greater influence on the reversal error of an axis (B), and the speed of movement of the slider has a greater influence on the mean reversal error of an axis (B_{av}). It can also be concluded that the mentioned parameters are significant, since the influence of the uncontrollable parameters is relatively small (4% and 6%). The relative difference in the deviation range of the mean values at the maximum and minimum dwell time is 5.866%, while the relative difference in the mean values of the deviation range of the mean values at the maximum and minimum movement speed of the slider is 9.596%.

Among the considered parameters, the movement cycle has the greatest influence on system character errors, bi-directional systematic positioning error of an axis (E) and the mean bi-directional positioning error of an axis (M). At the same time, the smallest inaccuracy is when moving with the pendulum cycle, while there are no significant differences in terms of accuracy for the other two cycles of movement,.

In this specific case, the test was carried out on a medium-sized machine with a relatively small work space, guides and sliders based on sliding technology, and a prestressed ballscrew. These features make the machine suitable for determining the influence of the test parameters. For the observed output positioning error during the test, it can be concluded that the smallest measurement error is given by using the pendulum method with a longer stopping period (due to the mechanical calming of the system) at a minimum movement speed (where this parameter has the least influence on the results). On the other hand, this choice of parameters increases the test time by about 4 times with relatively little effect on the result values. This makes the process uneconomical for calibration of machines with medium and large work space, while it is useful for meso and micro machines.

5. CONCLUSIONS

The accuracy of numerically controlled machine tools, expressed by the corresponding positioning accuracy parameters, is one of the most important criteria for their selection. The quality of production of workpieces largely depends on the current condition of the machine, which can be evaluated by analyzing its accuracy.

Test procedures based on international and national standards help ensure the highest level of accuracy for the specific machine construction and built-in elements through regular checks using defined procedures and through the calibration process.

The performed tests indicate that the two-way positioning error for one axis - A, as a parameter that includes the influence of both random and systematic errors, concludes that the considered parameters are not significant and that the influence of the uncontrollable parameters is significantly greater. It can be concluded that the presented tests provide an answer to the question why the standard used does not contain recommendations for the limits of these parameters and their choice is left to the skill of the examiner.

Also, by looking at the test results for different methods, movement speeds, and dwell times, conclusions can be drawn about the parameters that must be used when testing large machines as well as small and micro machines. Further research should confirm the limits of machine sizes for which testing with the pendulum movement is more appropriate and provides recommended values for movement speed and dwell time. On the other hand, for machines with large dimensions, for which, as the research has shown, the linear movement method is more suitable, the determination of the maximum speed of movement and the minimum dwell time in accordance with the design and exploitation characteristics of the machines is expected.

REFERENCES

[1] Ibrahim, S. M., Saedon, J., Radzi, A., Omar, R. (2019). Improvement of positional accuracy of developed dicing machine. *International Journal of Mechanical Engineering and Robotics Research*, 8 (5), 680-684. http://dx.doi.org/10.18178/ijmerr.8.5.680-684

[2] Aguado, S., Pérez, P., Albajez, J. A., Velázquez, J., Santolaria, J. (2022). Inaccuracy of machine tools due to verification conditions. *Measurement*, 188, 110629. https://doi.org/10.1016/j.measurement.2021.110629

[3] Kureková, E., Halaj, M., Palenčár, R.. (2011). The positional deviation in two numerically controlled axes. In *Measurement 2011: Proceedings of the 8th International Conference*. Slovakia: IMS SAS, 88-91. ISBN 9788096967247.

[4] ISO. (2014). *Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes*. Standard 230-2:2014.

[5] Japanese Standards Association (JSA). (1980). *Test code for performance and accuracy of numerically controlled machine tools*. Standard JIS B 6330.

[6] China National Standards. (2016). *Test code for machine tools -- Part 2: Determination of accuracy and repeatability positioning numerically controlled axes*. Standard GB/T 17421.2-2016.

[7] ASME. (2005). *Methods for performance evaluation of computer numerically controlled machining centers*. Standard B5.54 - 2005.

[8] Deutsches Institut fur Normung E.V. (DIN). (1977). *Statistical testing of the operational and positional accuracy of machine tools*. Standard VDI/DGQ 3441.

[9] Sokolov, V., Basalaev, K. (2014). Laser measurements based for volumetric accuracy improvement of multi-axis systems. *Physics Procedia*, 56, 1297-1304. https://doi.org/10.1016/j.phpro.2014.08.054

[10] Aguado, S., Santolaria, J., Samper, D., Aguilar, J. J. (2013). Influence of measurement noise and laser arrangement on measurement uncertainty of laser tracker multilateration in machine tool volumetric verification. *Precision Engineering*, 37, 929-943. https://doi.org/10.1016/j.precisioneng.2013.03.006

[11] Linares, J.-M., Chaves-Jacob, J., Schwenke, H., Longstaff, A., Fletcher, S., Flore, J., Uhlmann, E., Wintering, J. (2014). Impact of measurement procedure when error mapping and compensating a small CNC machine using a multilateration laser interferometer. *Precision Engineering*, 38, 578-588. https://doi.org/10.1016/j.precisioneng.2014.02.008

[12] López de Lacalle, L. N., Lamikiz, A. (eds.). (2008). *Machine Tools for High Performance Machining*. Springer. https://doi.org/10.1007/978-1-84800-380-4

[13] Mekid, S. (ed.) (2008). *Introduction to Precision Machine Design and Error Assessment*. CRC Press. ISBN 978-0849378867.

[14] Mullany, B. (2007). *Evaluation and comparison of the different standards used to define the positional accuracy and repeatability of numerically controlled machining center axes*. Ph.D. Dissertation, University of North Carolina, Charlotte, US.

[15] Artimon, F. P. G., Stochioiu, C., Popan, G. (2021). Thermal influence on positioning error and position repeatability at a machining center axes. *UPB Scientific Bulletin, Series D: Mechanical Engineering*, 83 (2), 181-188. ISSN 1454-2358.

[16] Weck, M., Brecher, C. (2013). *Werkzeugmaschinen 5: Messtechnische Untersuchung und Beurteilung, dynamische Stabilität.* Springer. https://doi.org/10.1007/978-3-540-32951-0

Received February 02, 2023
Accepted June 26, 2023