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Analysis of Positioning Accuracy of Prototype Machine Tools with Hybrid Kinematics

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***Abstract*— Machine tools with a hybrid kinematic structure represent an unconventional type of machine tools whose characteristics depend on the kinematic configuration. Therefore, it is necessary to perform a separate accuracy analysis for each machine configuration. The analysis of the characteristic values obtained by examining the accuracy of positioning is the starting point for further improvement and calibration of this type of machine. In the case of conventional machine tools with a serial kinematic structure, appropriate standards and recommendations are used to evaluate the state of the machine through testing the positioning accuracy. The paper describes the preliminary measurement of the condition of the machine tool with the hybrid kinematic structure "O-X glide" according to the ISO 230-2 standard, carried out in order to adjust the mechanical subassemblies of the machine, which precedes the process of calibrating the machine's control system.**

***Keywords*— Hybrid machine tools, O-X glide, Positional accuracy, ISO 230**

I. Introduction

Machine tools based on parallel mechanisms even today, after almost thirty years since the appearance of the first commercial models, can be considered machine tools of a new generation. The main reason for this is a large number of variants of the kinematic structure, specific solutions of the management process and the characteristic of speed [1].

The paper discusses the problem of initial testing of the prototype of the original O-X glide mechanism, which is configured by combining a planar parallel mechanism and a mechanical structure that enables its translational movement. The O-X glide planar-parallel mechanism is configured so that it can realize the planned parts of the workspace in two configurations: O-extended and X-crossed [2,3]. This mechanism also has the feature of reconfiguration because it behaves as a dual parallel mechanism with different characteristics in terms of: workspace, stiffness, speed, the position of reference points, etc.

The traditional method of forming a hybrid mechanism in the kinematic sense includes the connection of at least two mechanisms that form a kinematic connection between a moving and a stationary platform. At least one should be a parallel mechanism. A unique approach called mechanism hybridization is to embed a serial mechanism inside a parallel mechanism, which significantly changes its characteristics [5].

If we describe the accuracy of a machine as a characteristic that is a consequence of a series of characteristics of the mechanical and control structure, then one of the best indicators of the characteristics of the machine is the state of the positioning accuracy. Professional literature mentions the importance of accurate positioning of machine tools with a parallel kinematic mechanism and with a hybrid kinematic mechanism [1], [5], primarily due to the calibration of the control system. However, due to the diversity of the structure of hybrid machine tools, they have not been sufficiently studied from the point of view of positioning accuracy, and calibration based on the obtained data on positioning accuracy. Papers [4] and [6] dealt with that topic, but the observed machine tools were not with hybrid kinematics, such as the considered O-X glide mechanism in this paper.

The paper analyzes the positioning accuracy of a three-axis machine with hybrid kinematics, which basically has an O-X glide parallel mechanism and a serial translator axis, [7]. This is carried out in order to determine the indicators of mechanical characteristics, sliders, joints and elements of the winding spindle in order to adjust the machine as an introduction to the process of calibration and preparation for exploitation. The test was carried out in accordance with the ISO 230-2 standard.

II. Testing Methods of Numerically Controlled Machine Tools

A. Standards and recommendations

Within the geometric accuracy test, measuring the accuracy and repeatability of movement along linear axes is one of the most important indicators of the state of machine tools. The group of standards ISO 230 includes methods of measurement, equipment and the procedure for calculations of results for such analyses.

Test procedures involve defining a series of target points, and accuracy and repeatability are measured with several approximations for each target point. ISO 230 defines, among other things, the testing of flatness, parallelism, normality of linear axes and concentricity error of rotational axes.

In order to generalize the definition of accuracy and repeatability of machine tools, some international standards and recommendations have been established. In the case of positioning accuracy, which is often considered, the most important 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 machine tools. However, there are significant differences between these standards, mainly in the number of target points and measurements required to determine the machine's accuracy value.

B. ISO 230-2

ISO 230-2 is probably the most accepted standard in the field of positioning accuracy of machine tools in the world and it specifies methods for testing and evaluating the positioning accuracy and repeatability of numerically controlled machine tools by direct measurement of individual axes on the machine. This part of the ISO 230 standard can be used for checking the condition of the machine, calibrating the control system, etc.

The test conditions in the standard provide for the test conditions, the state of the machines in which it is carried out, as well as the preparatory activities:

- 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 real machine operating conditions.
- One-way and two-way approach: all tests include one-way and two-way approaches to target points.
- Number of target points: linear axes require at least 5 target points per meter and rotary axes require at least 3 target points at 90°.
- Number of measurements per target point: each test requires at least 5 tests per target point and per movement direction.

Testing the accuracy of positioning for individual axes is performed along the maximum available segment of the axis for "m" measuring points (positions). The measuring positions are chosen so that the mutual distances are unevenly distributed in a controlled manner, i.e. it is about "m" of selected samples with index "i". In each measuring position, the 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 marked with the index "j". In doing so, the following terms are defined:

- Reference position, Pi – the final programmed position of the moving part of the machine
- Actual position, Pij – measured final position of the moving part of the machine in the i-th and j-th reference positions
- Deviation from the position, Xij – the actual final position of the moving part of the machine minus the reference position:

$$Xij = Pij - Pi \qquad (1)$$

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).

The parameters that are observed when analyzing the positioning accuracy of machine tools are the following [7]:

- Maximum deviation range of mean values – B,
- Mean value of the range of deviations of mean values - $\overline{B}$,
- One-way repeatability of position by axis - R↑ and R↓
- Maximum two-way repeatability of position per axis – R,
- One-way systematic error of positioning along the axis - E↑ and E↓,
- Two-way systematic error of axis positioning – E,
- Maximum two-way positioning error by axis – M,
- One-way positioning error along the axis -A↑ and A↓,
- Two-way axis positioning error – A.

C. Measuring equipment

To test the positioning accuracy of the numerically controlled parallel-serial machine tool, laser measuring instrumentation was used, Fig. 1. The instrumentation consists of:

- He-Ne gas laser heads,
- A laser pointer with 9 characters and an additional character for the positive or negative sign of the displayed value,
- Interferometer and retroreflector (details 2 and 3 in Figure 1b),
- Automatic compensator, which aims to compensate the obtained data in relation to the ambient temperature, air humidity, spindle temperature and air pressure.

The laser head 1 is placed on a suitable tripod.

a. Laser head and display

b. O-X Glide machine with measurement equipment

Fig. 1 Measurement of positional accuracy

D. O-X glide mechanism

The basic sub-assembly of the planar parallel mechanism contains a movable platform that is attached to rods of constant length via swivel joints. At the other end, the rods are connected by swivel joints (with one degree of freedom) to the corresponding sliders, each of which moves along its own guide [8]. In order to increase the autonomy of the movement of the sliders, they are placed at different distances in the direction of the vertical axis, which allows them to bypass each other. This allows easy reconfiguration of the mechanism from an extended (O) to a crossed (X) shape and vice versa. The parallel mechanism enables movement in the (XZ) plane, while the translational movement of the entire parallel mechanism is realized by one serial axis along the Y axis [2]. Fig. 2(a) shows the X configuration and Fig. 2(b) shows the O configuration of the machine tool.

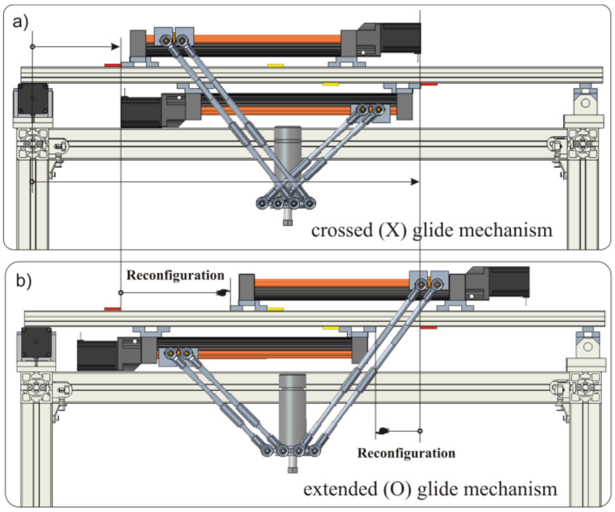

Fig. 2 Example of reconfiguration in X and O configuration of hybrid machine tool [2]

The test carried out in the paper was carried out on the X configuration of the mechanism.

For such a configuration, the equations of inverse kinematics, which determine the positions of the sliders for a defined position of the moving platform, read [2]:

$$s_1 = x_p - x_{R1} + p_1 - \sqrt{l_1^2 - (z_p - d)^2} \qquad (1)$$

$$s_2 = -(x_p - x_{R2} - p_2 + \sqrt{l_2^2 - (z_p + d)^2}) \qquad (2)$$

$$s_3 = y_p \qquad (3)$$

Following the reverse procedure of defining the position of the moving platform for the defined positions of the slider of the parallel mechanism and the additional serial axis, expressions are obtained that determine the direct kinematics of the mechanism [2]:

$$z_p = \frac{-t_9 - \sqrt{t_9^2 - 4t_8 t_{10}}}{2t_8} \qquad (4)$$

$$x_p = t_6 + t_7 \cdot z_p \qquad (5)$$

where are:

$$t_1 = x_{R1} - p_1 + s_1, \quad t_2 = x_{R2} + p_2 - s_2 \qquad (6)$$

$$t_3 = 2t_2 - 2t_1, \quad t_4 = -4d \qquad (7)$$

$$t_5 = t_1^2 - t_2^2 - l_1^2 + l_2^2, \quad t_6 = -(t_5/t_3) \qquad (8)$$

$$t_7 = -(t_4/t_3), \quad t_8 = 1 + t_7^2 \qquad (9)$$

$$t_9 = 2(t_6 - t_1) \cdot t_7 - 2d, \quad t_{10} = (t_6 - t_1)^2 + d^2 - l_1^2 \qquad (10)$$

One of the most important characteristics of parallel and hybrid mechanisms is the workspace that determines the usable volume of the moving platform. The description of the workspace of the entire hybrid machine based on the O-X glide mechanism is mostly influenced by the workspace of the parallel mechanism, since the total available workspace of the parallel-serial mechanism is created by translating the workspace of the planar parallel mechanism along the Y-axis. Fig. 3(a) shows the boundary of the workspace of the parallel mechanism in the X configuration, as well as the parts of the bounded parts of the workspace, suitable for use, which have a regular geometric shape.

Fig. 3(b) presents the machining simulation using the program for roughing and finishing of the test workpiece, which is correctly positioned within the boundaries of the workspace, for X configuration.

This paper analyzes the data obtained by testing a hybrid machine tool with an O-X glide mechanism set in the X configuration.

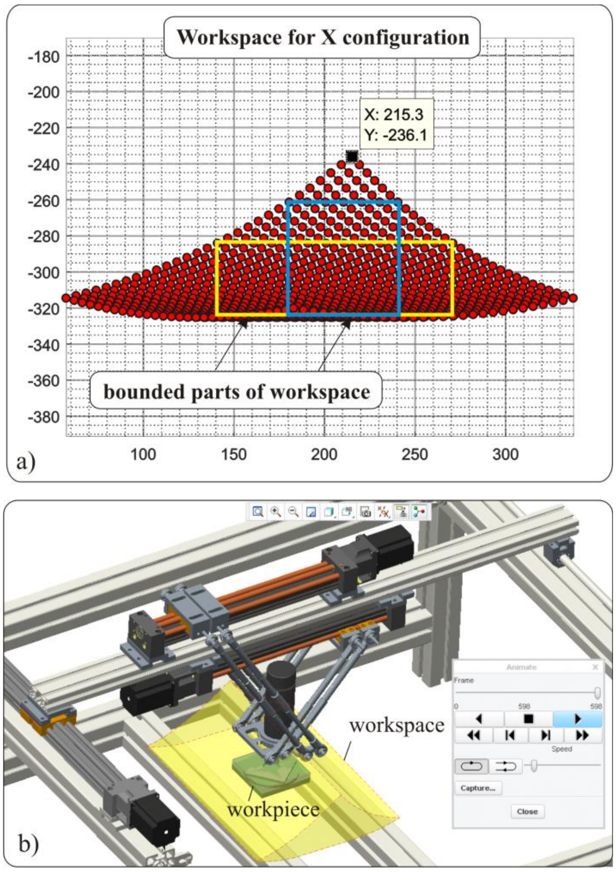

Fig. 3 Workspace in X configuration of mechanism [2]

Table I shows the basic parameters, which concern the axes and the data related to the positioning accuracy measurement. For the Y axis, measurements were made in a total of 8 points, and for the X and Z axes only in 7 points. The reason for this is the double length of the Y axis in relation to X and five times in relation to Z, and in order to get the appropriate density of measured points along one axis, it was necessary to increase the number of the Y axis. The Z axis was measured in the coordinate X: 100, and the X axis was measured in the coordinate Z: 200, where the maximum possible strokes for the given axes are, which can be concluded from Figure 3. Since Y is a serial axis, its maximum stroke is not depends on the other two axes, the only obstacle is the possibility of installing measuring equipment.

TABLE 1. BASIC PARAMETERS OF HYBRID MACHINES IN X CONFIGURATIONS

	Axis		
	X	**Y**	**Z**
Maximum axis travel [mm]	200	400	80
Observed stroke travel [mm]	180	336	64,8
Number of measured points	7	8	7
Distance between measured points [mm]	30	48	10,8

III. TEST RESULTS

The results obtained from the measurements are given in Table II. The ISO 230-2 standard, among other things, provides for the presentation of the obtained data by measured points along the measuring axis in the form as presented in Figs. 4, 5 and 6. From those diagrams, conclusions can be drawn regarding the error along the observed axes in the observed measuring positions and carried out calibration of machine tools.

TABELA I. REZULTATI MERENJA TAČNOSTI POZICIONIRANJA PREMA ISO 230-2 STANDARDU

Osa	B	$\bar{B}$	$R\uparrow$	$R\downarrow$	R	$E\uparrow$	$E\downarrow$	E	M	$A\uparrow$	$A\downarrow$	A
X	27.63	13.57	42.34	14.68	42.34	236.74	201.89	236.74	219.32	237.41	195.75	237.41
Y	309.48	134.56	111.15	176.09	176.09	1055.74	865.88	1100.08	916.97	1164.61	909.32	1173.26
Z	34.24	20.04	10.94	10.02	10.94	631.82	648.02	648.92	639.92	637.47	654.26	655.62

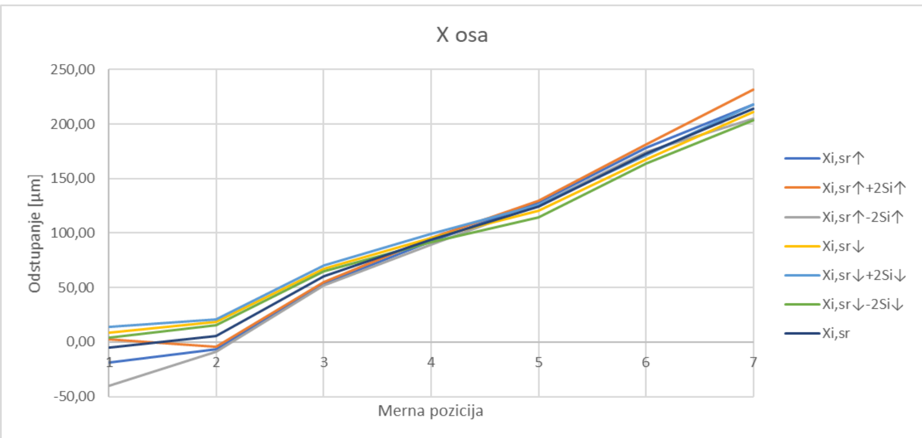

Fig. 4 Graphic representation of X-axis positioning accuracy according to ISO 230-2

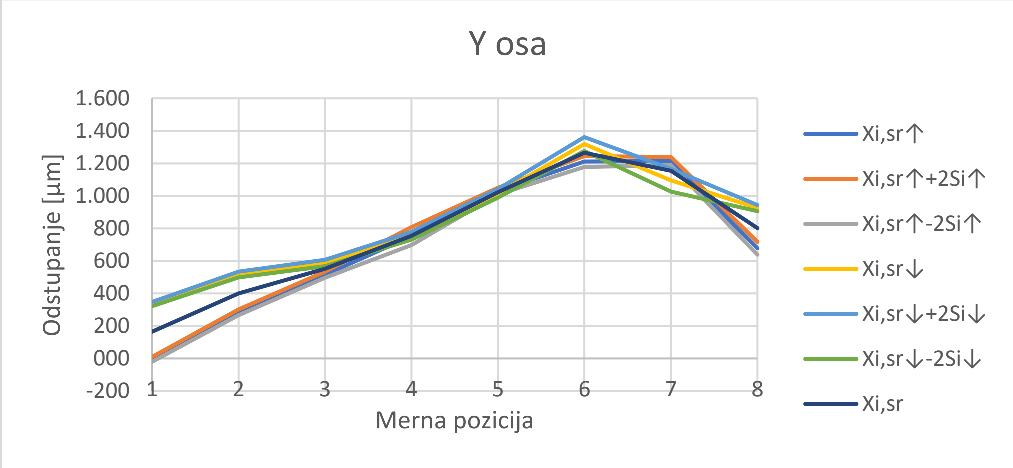

Fig. 5 Graphic representation of Y-axis positioning accuracy according to ISO 230-2

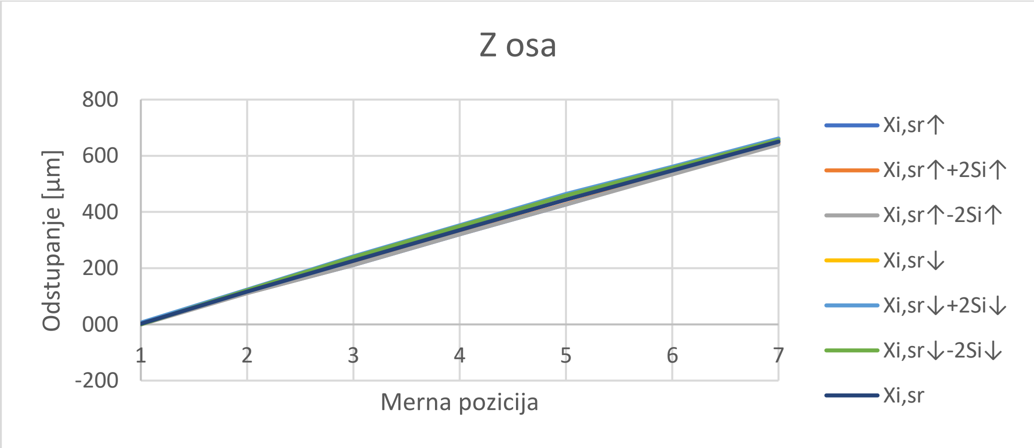

Fig. 6 Graphic representation of Z-axis positioning accuracy according to ISO 230-2

IV. Discusion

The analysis of the results obtained from the experimental testing of positioning accuracy indicate several facts related to the operation of the machine in operational conditions. First of all, it is observed that the value of the maximum deviation of positioning accuracy is very large, more than 30 times higher than the expected values for modern machine tools. The main reason for this is the lack of control feedback, which limits the accuracy of movement only to the characteristics of stepper motors that represent the drive of individual sliders. In addition, some elements of the machine require additional settings before starting the machine calibration process. This refers primarily to the joints of the parallel mechanism, which have a significant impact on accuracy in the Y and Z directions, as well as the need to adjust the spiral spindle nut on all three virtual axes. Among the shortcomings of the prototype, which affects the overall results, is the fact that the screw spindle nut is not made with rolling elements, which means that friction in the contact elements is an additional source of errors.

On the other hand, the high repeatability of the measured positions during movement indicates a well-conceived kinematic structure, creating prerequisites for calibration and reducing measured errors by about 80%. Prepared in such a way, this group of machines can be compared in terms of characteristics to all machine tools that have an open control coupling.

V. Conclusion

The hybrid kinematic structure applied to the O-X glide mechanism for the purposes of making laboratory machine tools, with its characteristics, indicates the possibility of application in different variants of machine tools for the production of workpieces using the technology of processing by removing material, processing by cutting, laser engraving, as well as the application of additive technologies. Based on the conducted research, according to the ISO 230-2 standard, it can be concluded that before the process of calibrating the machine, it is necessary to perform certain mechanical adjustments and then to perform the calibration with the introduction of bidirectional error compensation, which the application of open architecture control systems (LinuxCNC) makes possible.

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REFERENCES

[1] S. Živanović, “Konfigurisanje novih mašina alatki,” doktorska disertacija, Univerzitet u Beogradu, Mašinski fakultet, 2010.

[2] S. Zivanovic, S. Tabakovic, M. Zeljkovic, Z. Dimic, “Modelling and analysis of machine tool with parallel–serial kinematics based on OX glide mechanism,“ Journal of the Brazilian Society of Mechanical Sciences and Engineering vol.43:456, pp.1-15, 2021.

[3] S. Tabakovic, S. Zivanovic, M. Zeljkovic, Z. Dimic, “Konfigurisanje nove edukacione mašine alatke na bazi mehanizma sa hibridnom kinematikom,” Tehnika, Časopis saveza inženjera i tehničara Srbije, Vol. 71(5), str. 603-612, 2021.

[4] Z. Gao, D. Zhang. “Performance analysis, mapping, and multiobjective optimization of a hybrid robotic machine tool,” IEEE Transactions on industrial electronics, vol.62(1), 423–433, 2015.

[5] S. Tabaković, “Razvoj programskog sistema za automatizovano projektovanje mašina alatki na bazi paralelnih mehanizama i optimalni izbor njihovih komponenti doktorska disertacija,” Univerzitet u Novom Sadu, Fakultet tehničkih nauka, 2008.

[6] P. Huang, J. Wang, L. Wang, R. Yao, “Kinematical calibration of a hybrid machine tool with regularization method,” International Journal of Machine Tools and Manufacture vol. 51(3), pp.210-220, 2011.

[7] ISO, DIN.230-2: 2011-11: “Test code for machine tools-Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes (ISO 230-2: 2006),” 2011.

[8] S. Tabaković, S. Živanović, “Simulation of kinematic of virtual prototype of a machine tool based on hybrid O-X mechanism,” Proceedings of 3rd International Scientific Conference Conference on Mechanical Engineering Technologies and Applications COMETa 2016, pp.199-206, University of East Sarajevo, Faculty of Mechanical Engineering, Jahorina, B&H, Republic of Srpska, 7-9. December 2016