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Examination of the positioning accuracy of the machine tool with hybrid kinematics

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Abstract *The intensive development of machine production in recent years has enabled the emergence of machine tools with parallel and hybrid kinematic structure and their integration into industrial production. Therefore, extensive research has been conducted in recent years to examine the exploitation possibilities of such machines and the justification of their application in certain areas of mechanical engineering. An important part of that research is the examination of accuracy and the possibility of calibrating machine tools with non-trivial kinematics.*

The paper presents a part of the research carried out to determine the influence of the characteristics of individual machine components on the overall positioning accuracy of the machine tool prototype based on the O-X glide hybrid mechanism.

Keywords *machine tool, hybrid kinematics, accuracy positioning*

1. INTRODUCTION

Machine tools have been the basis of production systems in the industry for more than two hundred years. In that period, there were significant changes in the driving and building elements of the machines, which enabled the intensive development of the industry. However, in that period, changes in the kinematic conception of machine tools were minimal. In modern conditions, most machine tools are based on a serial kinematic structure, as in the first industrial revolution.

The idea of using closed kinematic structures contained in parallel mechanisms as a supporting structure of machine tools arose in the middle of the 20th century (Stewart's platform from 1965) [1].

The main obstacle to making such machines was the impossibility of realizing a control system with non-linear kinematics. Commercial application, due to the specifics of management, began only in the last thirty years (at the IMTS fair in Chicago in 1984) [2]. During that period, a significant number of conceptual solutions for machine tools with parallel and hybrid (serial/parallel) kinematic structures were developed.

The paper discusses the problem of positioning accuracy of machine tools with hybrid kinematics according to the ISO 230-2 [3] standard, conducted on the example of a machine tool based on the original O-X glide mechanism [4].

The basic problem of testing the positioning accuracy of machine tools based on non-trivial kinematics is the fact that testing determines the state of the programmed (external) axes of the machine, which are formed by the

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combination of movements performed by two or more machine axes (internal coordinates) [5].

Therefore, the machine test defined by the standard does not give an image of the condition of the machine components, but of the movement that is the result of their movement following the laws of inverse kinematics of the mechanism [6], [7].

The research presented in the paper represents a step in the definition of a general methodology for calibrating machine tools regardless of their kinematic structure.

2. KINEMATIC STRUCTURE OF THE O-X GLIDE MECHANISM

The prototype of machine tool based on the O-X glide mechanism contains a planar parallel mechanism that moves on a gantry structure using a serial linear axis (Fig. 1). At the same time, the parallel mechanism contains a movable platform connected to rods of constant length by means of corresponding joints. The other end of the rods is connected to the rotary joints for the sliders, which move linearly along their own guide [4].

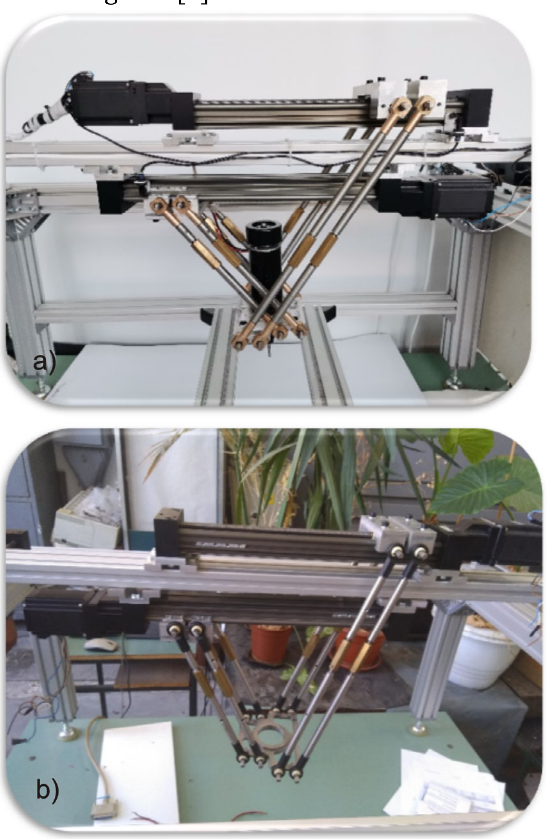

Fig. 1. O-X glide hybrid kinematic machine tool

In order to increase the movement possibilities of the slider, they are arranged in height at different distances, enabling passing in the plane of movement. This gives the original ability to reconfigure the mechanism from an extended (O) to a crossed (X) shape and vice versa. The parallel mechanism enables the movement of the moving platform in the (XZ) plane, and the translational movement of the parallel mechanism is realized by linear movement along the Y axis [2]. Figure 1 (a) shows the X configuration and Figure 1 (b) shows the O configuration of the machine tool.

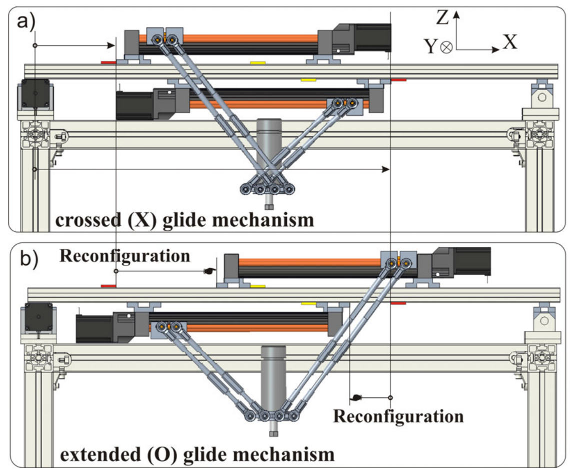

Fig. 2. Configurations of hybrid machine tools [4].

The analysis of positioning accuracy realized for work purposes was carried out on the X configuration of the mechanism whose kinematic model is shown in Fig.3.

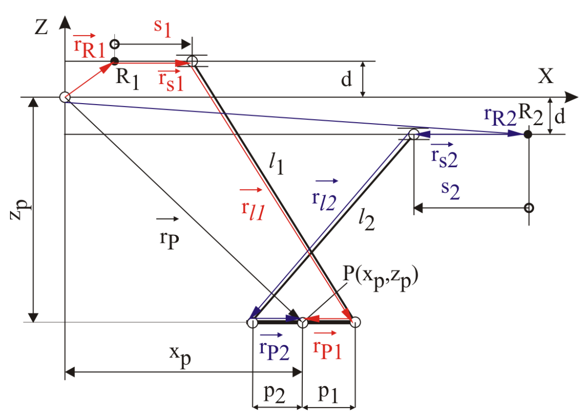

Fig. 3. Kinematic model of the parallel mechanism [4]

The parallel mechanism of Figure 3 is shown in an arbitrary position for the crossed (X) variant of the mechanism. Solving kinematic problems is performed in the plane (X, Z). The internal coordinates of the parallel mechanism are the positions of the sliders s1 and s2, while the external coordinates are the position of the platform P (Xp, Yp). The solution of kinematic problems is given in detail in [4], while here only the final solutions of IKP are given as:

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

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

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

The same expressions and equations of the direct kinematic chain were used when configuring the control system based on the LinuxCNC platform, which is shown in detail in [4].

3. PROCEDURE FOR TESTING THE ACCURACY OF POSITIONING

Testing the positioning accuracy of linear axes of numerically controlled machine tools is one of the most important indicators of the current state of machine tools. The procedure for testing and calculating the results is covered by the ISO 230-2 [3] standard. Basically, this standard is intended for the testing of medium-heavy and light machine tools, where certain test details such as the method of movement, the number of measuring points, and the number of repetitions can be adapted to the specific machine. That is why it was chosen for the evaluation of a specific machine tool whose prototype belongs to the category of midi or mini machine tools.

ISO 230-2 is the most frequently mentioned standard in professional literature for determining the accuracy of machine tool positioning. It defines the methods of testing and evaluating the accuracy and repeatability of the positioning of individual numerically controlled axes of machine tools. The standard provides for two methods of movement of machine elements during measurement, a minimum number of 8 measurement points and 5 repetitions of measurement when moving in the + and - direction of a particular axis.

The results obtained by testing machines according to this standard are used to assess the state of the machine, calibrate the control system, categorize the machine according to applicability for certain types of processing, etc.

Testing the positioning accuracy of the O-X glide machine tools was realized by using laser measuring instrumentation, the content and characteristics of which are prescribed by the standard. Instrumentation consists of:

- Measuring head that contains a laser beam source and two receiving channels (detail 1 in Figure 4),
- Electronic display,
- Interferometer and retroreflector (details 2 and 3 in Figure 4),
- External conditions compensator

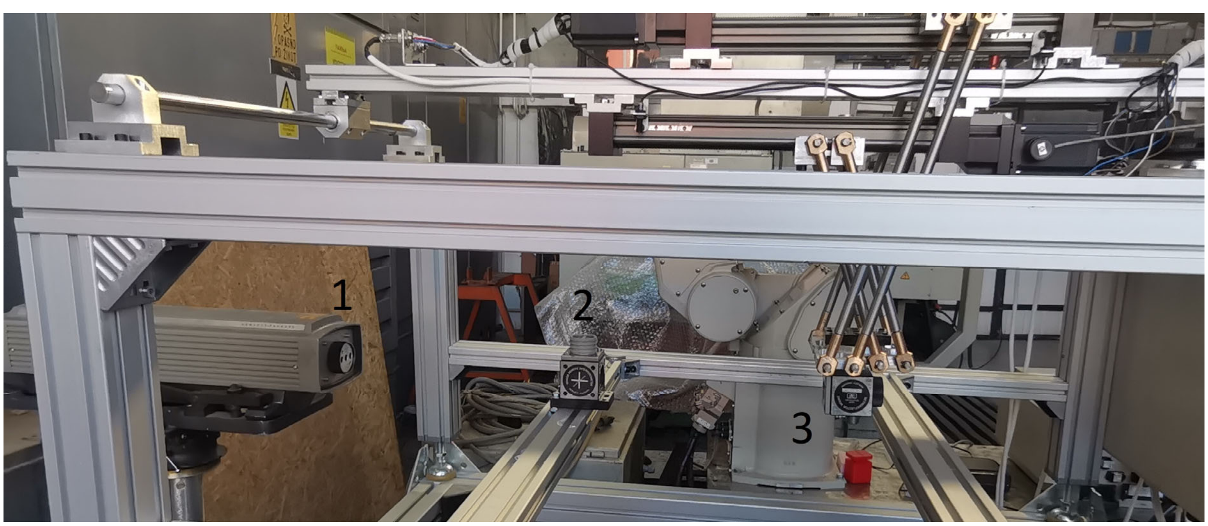

Fig. 4. Measurement procedure

Memorization of the obtained results and their processing were realized using the original acquisition system and software solution [8].

4. RESULTS

Testing the positioning accuracy of the machine tool based on the O-X glide hybrid mechanism includes testing the state of the external coordinates of the machine tool movement (coordinates with which the tool moves) in all three orthogonal axes (X, Y, and Z). Analysis of machine characteristics includes defining errors in internal coordinates. The movement of the slider according to the internal coordinates in the X configuration of the mechanism takes place by the movement of the slider in the same (when moving in the direction of the X axis) or opposite (when moving in the direction of the Z axis) directions. Analysis of the inverse kinematics equations (1-3) for both axes of the XZ plane provides the values of S1 and S2. Tables 1, 2, and 3 show the results of positioning accuracy measurements for S1, S2, and serial Y axis. The test was carried out using the following parameters:

- • Movement cycle of machine elements - linear
- • Number of measurement points –
    - X and Y axis – 11
    - Z axis - 21
- Speed of auxiliary movement of the machine - v=200mm/min
- Dwell time at the measuring point – t=3s

The results shown in the tables and graphs include the display of the less favorable measurement variant.
Table 1 and Figure 5a show the results for the internal S1 axis.

Table 1. Values obtained for the S1 axis

Test parameter	**Value [mm]**
Maximum deviation range of mean values – B	0.0312
One-way repeatability of position by axis – R↑ and R↓	0.0167
Maximum two-way repeatability of position per axis – R	0.0521
One-way systematic error of positioning along the axis - E↑ and E↓	0.1001
Two-way systematic error of axis positioning – E	0.1293
Maximum two-way positioning error by axis – M	0.1012
One-way positioning error along the axis – A↑ and A↓	0.1181
Two-way axis positioning error – A	0.1340

The results of the second internal axis of the planar parallel mechanism, the S2 axis, which is structurally parallel to the S1 axis but with a different direction of movement, are shown in Table 2 and Figure 5b:

Table 2. Values obtained for the S2 axis

Test parameter	**Value [mm]**
Maximum deviation range of mean values – B	0.0447
One-way repeatability of position by axis – R↑ and R↓	0.0216
Maximum two-way repeatability of position per axis – R	0.0615
One-way systematic error of positioning along the axis - E↑ and E↓	0.1101
Two-way systematic error of axis positioning – E	0.1193
Maximum two-way positioning error by axis – M	0.0912
One-way positioning error along the axis – A↑ and A↓	0.1176
Two-way axis positioning error – A	0.1240

The results of the third axis of the O-X glide mechanism, the Y axis that provides the translation of the parallel mechanism Y are given in Table 3 and shown in Figure 5c:

Table 3. Values obtained for the Y axis

Test parameter	**Value [mm]**
Maximum deviation range of mean values – B	0.0537

Test parameter	Value [mm]
One-way repeatability of position by axis – R↑ and R↓	0.0718
Maximum two-way repeatability of position per axis – R	0.1038
One-way systematic error of positioning along the axis - E↑ and E↓	0.1106
Two-way systematic error of axis positioning – E	0.1616
Maximum two-way positioning error by axis – M	0.1757
One-way positioning error along the axis – A↑ and A↓	0.1873
Two-way axis positioning error – A	0.2044

Figures 5a, 5b, and 5c. shows diagrams of positioning accuracy for the S1 and S2 axes obtained by calculating the X and Z-axis tests, respectively, and the Y axes.

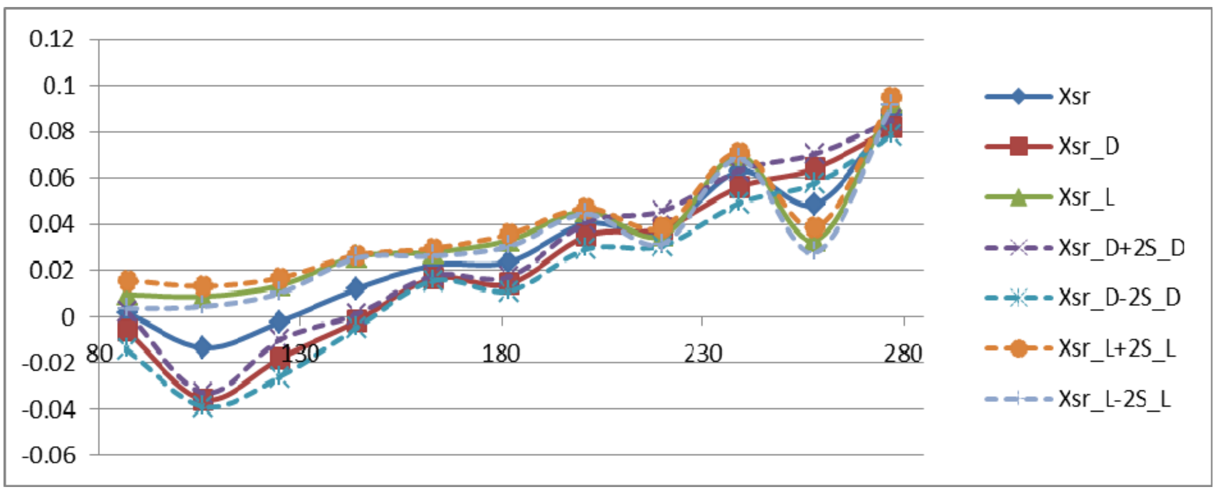

Fig. 5a. S1 axis positioning accuracy

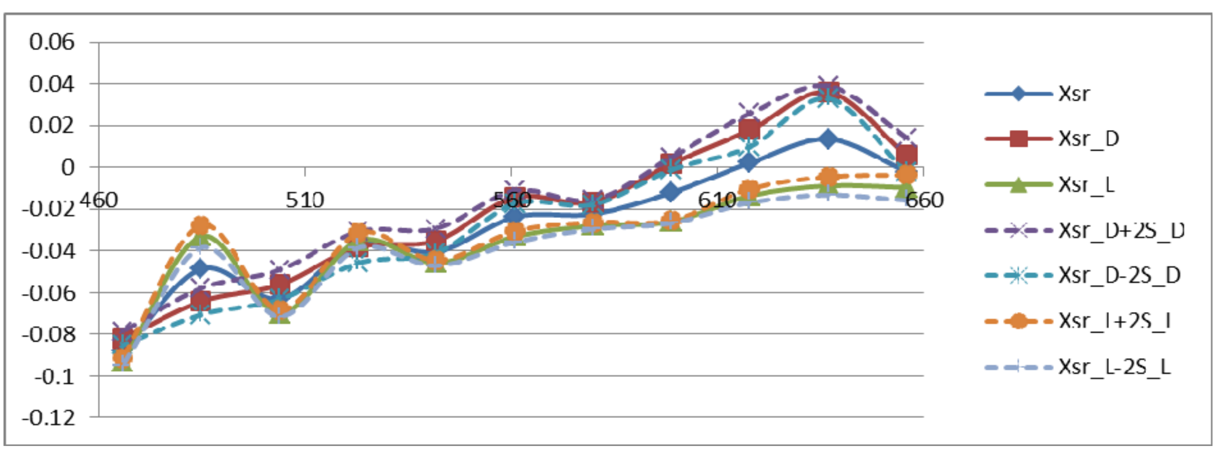

Fig. 5b. S2 axis positioning accuracy

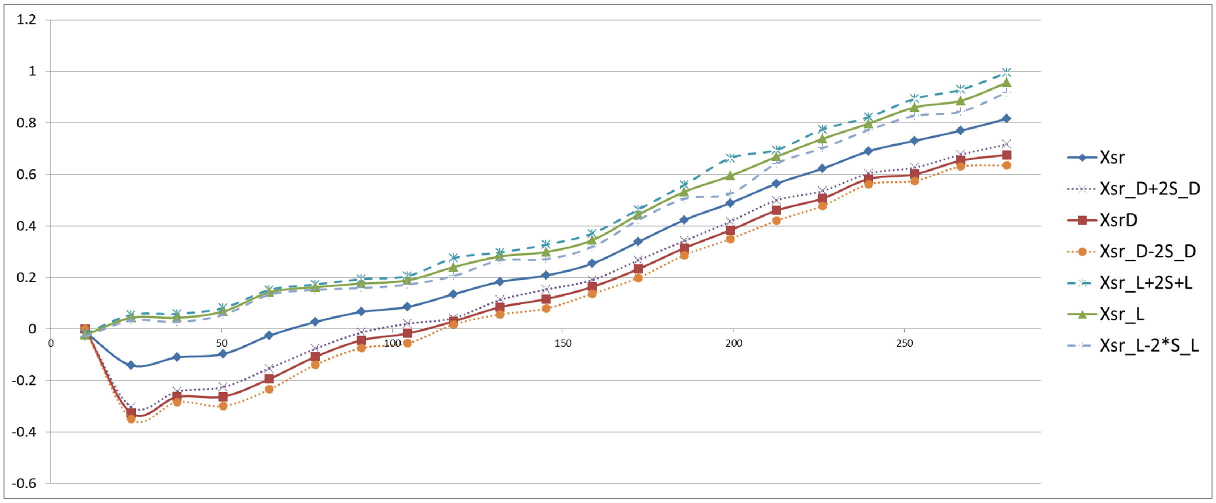

Fig. 5c. Y axis positioning accuracy

All analyzes were carried out with the monitoring of the measurement conditions (air pressure, relative humidity as well as the temperature of the environment and the machine) and automatically compensating the measurement results accordingly.

5. DISCUSSION

Based on the analysis of the test results of the machine tool based on the O-X glide mechanism, conclusions can be formed about the construction of the machine tool, the condition of its elements, as well as potential adjustments to the testing methodology. It should be noted that the presented prototype was developed for the purpose of proving the concept of usability of the proposed mechanism, as well as for determining the methodology for its evaluation in relation to machine tools with serial kinematics. Therefore, linear axes with a helical spindle have been used for its production, it has a frictional connection between the spindle and the nut, as well as an open loop control system. This resulted in results that are not comparable to commercial machine tool solutions.
The conversion of the test results of the external axes of the machine tool enables the analysis of the construction solution of the tested prototype. This primarily refers to the state of linear axes based on an open loop control where the definition of the position is based on the calculation of the position based on the set control values without an additional measurement of the realized movements. The obtained results per axis are several times higher than the results expected for linear axes of machine tools with modern closed loop control. This is most pronounced with the Y axis, which is the longest and where the movement of the plane parallel mechanism is constructed by a linear axis located on one side of the mechanism and the movement is transmitted to the other by a rigid connection. Since the length of the portal on which the planar parallel mechanism is placed is about 600mm (due to the possibility of testing the reconfiguration feature), this greatly affected the systematic error of measurement, but also the occurrence of pronounced random errors in certain movement zones.
In addition, it can be observed that the building elements of the machine tool provide relatively good results, which are applicable for the construction of prototypes. The entire machine tool is suitable for compensating systematic errors by applying the process of calibrating the control system of the machine tool
Finally, the conducted research indicates the possibility of applying a standardized methodology for determining the state of machine tools and machines based on hybrid and parallel kinematics.

6. FINAL CONSIDERATIONS

The conducted research made it possible to confirm the initial hypothesis that by applying the procedure defined by the ISO230-2 standard, it is possible to test the positioning

accuracy of machine tools with a kinematic structure that is not based on serial kinematics.
In addition, the research indicates that the mentioned methodology enables obtaining several different results for the internal axes of the mechanism, based on which conclusions can be drawn about random and systematic errors that, when combined with another internal axis, affect the creation of a smaller or larger resultant error of the entire mechanism.
The obtained results are of great importance for defining the process of calibration of machine tools with hybrid kinematics and the formation of solutions that, with relatively simple components, ensure the development of machine tools competitive with higher quality commercial solutions based on a serial kinematic structure. In addition, the obtained results represent the basis for research of improving machine tools and defining the optimal area on application of machine tools with non-trivial kinematics in modern mechanical engineering.

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