Research of accuracy of industrial robot at work as part of flexible machining cells

D S Morev[1], D A Blokhin[2], A G Koltzov[2]

[1]Joint-Stock Company «High technologies», Omsk, Russia

[2]Omsk State Technical University, 11 Mira ave., Omsk, 644050, Russia

Abstract. In this paper, the factors affecting the accuracy of an industrial robot with an articulated kinematic as part of flexible production modules were analyzed. The accuracy of the circular movements of the robot gripper depending on the position in the working area and the load applied to the robot. A method for measuring stiffness using a laser interferometer and optics for measuring straightness is proposed. According to the results of the experiments, the types of errors were determined, causing the greatest error in the accuracy of the industrial robot movements. Recommendations on the need to measure certain types of errors when setting up flexible production modules are given.

1. Introduction

Currently, at the engineering plants in the context of high-volume production, the issue of choosing the degree of automation, is being actively raised. And more often at the factories, the choice is given to flexible manufacturing cells (FMC). This choice is associated with an increase in productivity and economic efficiency of production, a decrease in the number of rejects and a decrease in the monotonous labor of the workers.

Therefore, at this condition of manufacture, the issues of determining the optimal ratio of accuracy of fixtures, multi-axis machining centers and industrial robots for processing a different range of parts in the FMC become relevant.

A distinctive feature of modern production solutions is exceptional flexibility not only in terms of the speed of changeover of the production cell from one part to another but also the possibility of moving the warehouse system with an industrial robot to another machining center, for example, the studied warehouse system from HALTER. However, despite the built-in matching means with another CNC machine tool and the possibility of self-installation using pre-prepared anchors, the issue of diagnostics and calibrating the accuracy of an industrial robot at the place of its further work remains an important issue. This is partly due to the kinematics of articulated robots: at different points in the workspace they provide different accuracy [1] and rigidity [2], therefore, when transferring a robot from a lathe to a milling machine and backward, as well as at different distances of the manipulator from the work area, diagnostics are necessary the accuracy of movements of an industrial robot in various parameters [3].

Since the complete diagnostics of all the accuracy of an industrial robot takes considerable time, up to several hours, the question of the operational determination of the main diagnosed values and methods of their control becomes relevant.

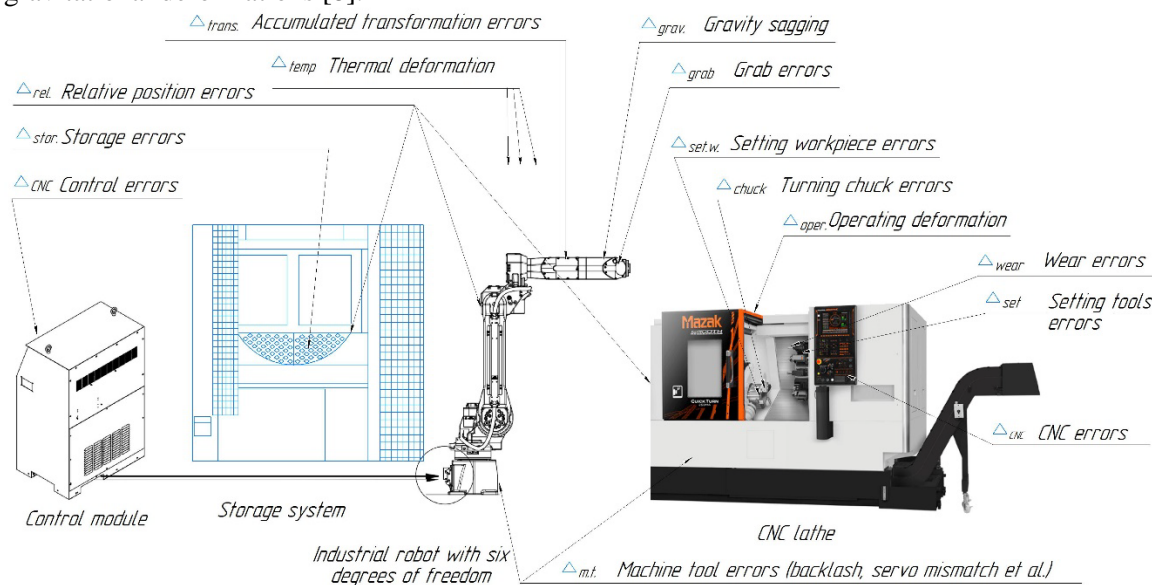## 2. Formulation of the problem

The aim of this work is developing a methodology for the operative diagnostics of the accuracy parameters of an industrial robot with articulated kinematics and six degrees of freedom as part of flexible manufacturing cells.

To achieve the purpose, the following tasks are set:

1. To study the accuracy of a flexible manufacturing module, which includes a CNC machining center and an industrial robot in test conditions at different loads and different points in the workspace;

2. To determine deviations that make the greatest impact on positioning accuracy during circular and linear movement and to choice control algorithm;

3. To give recommendations on the measuring methodology of an industrial robot's accuracy.

3. Theory

The determination of the most significant parameters for measurement in this work will occur according to the principle of functional diagnostics [4] since the goal of the developed method is to cover the maximum amount of movement inaccuracies in a minimum time, regardless of the reasons for their occurrence. The classification of deviation sources is given in various papers [5]. The main causes of inaccuracies in the positioning of the robot include the sequential articulation of the robot [6], which significantly increases mass and reduces rigidity, control system errors, thermal [7] and gravitational deformations [8].

Figure 1. Analysis of factors affecting the accuracy of a flexible production module with an industrial robot and warehouse system.
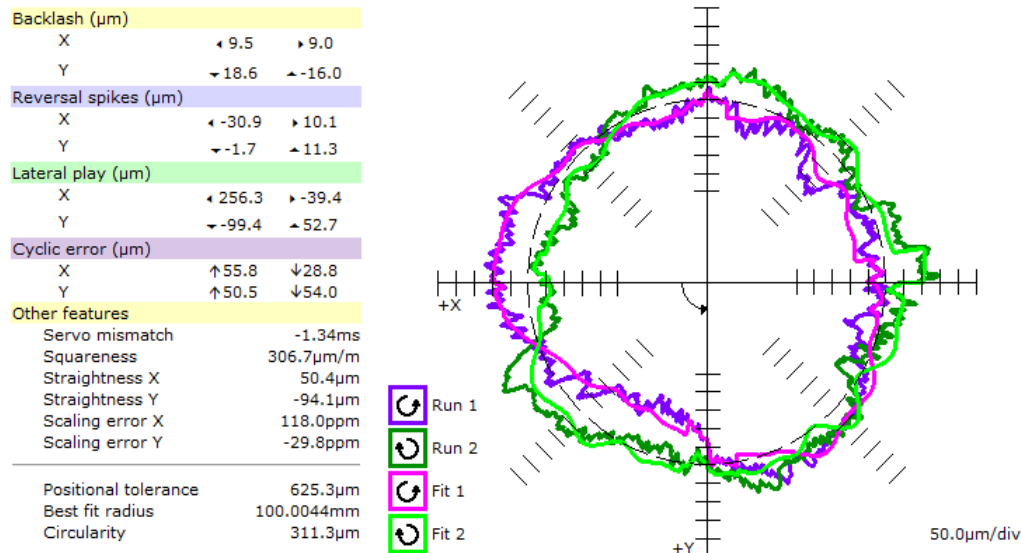
An industrial robot Fanuc Robot M-20iA with a lifting capacity of 20 kg and a certified positioning accuracy of 0.08 mm as part of the Halter LoadAssistant loading device was chosen as the object of study. As a measuring tool, a Renishaw Laser XL-80 laser interferometer with a measurement accuracy of ± 0.5 μm was used to assess linear displacements according to GOST R ISO 230-1-2010 [9], as well as a Ballbar QC-20W device to assess the accuracy of circular trajectories according to GOST ISO 230-4-2015 [10].

4. Experimental results

During the experiment, the dependences of the robot accuracy on the mass of the transported workpiece and the distance between the base and the gripper, the positioning accuracy, the performance of circular and rectilinear movements in various spaces of the working area were
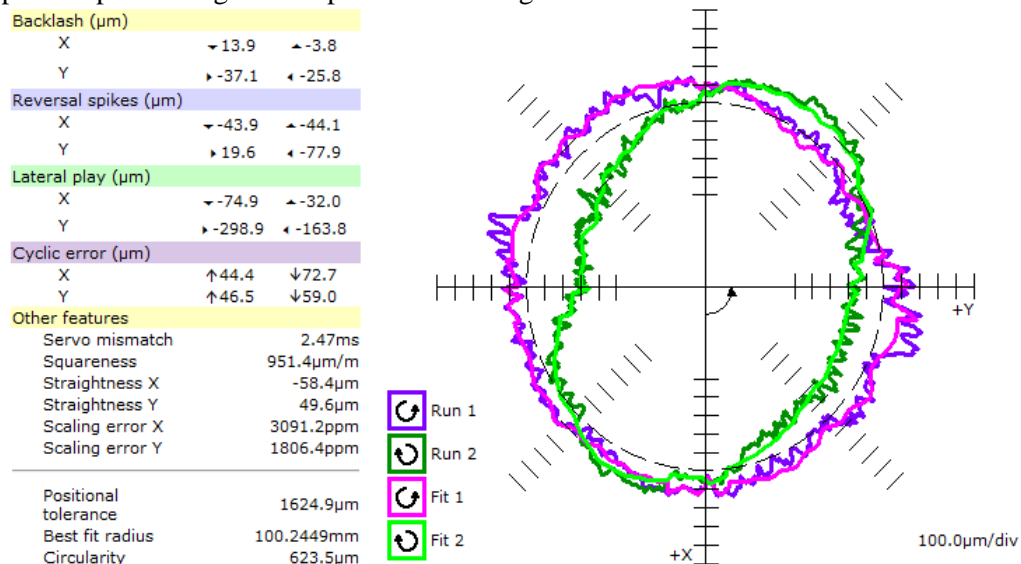
investigated. Thus, the select of studies under a workload are obtained similarly to diagnostic schemes on CNC machine tools [11].

In figure 2 shows the result of measuring the positioning accuracy of the Fanuc Robot M-20iA industrial robot in a horizontal plane in the stacking system area, experiments at each point were carried out repeatedly, the dispersion in error value did not exceed 5%.

Figure 2. Circular chart for measurement of the accuracy of the circular trajectories of the robot in a horizontal plane in the stacking system area without load.
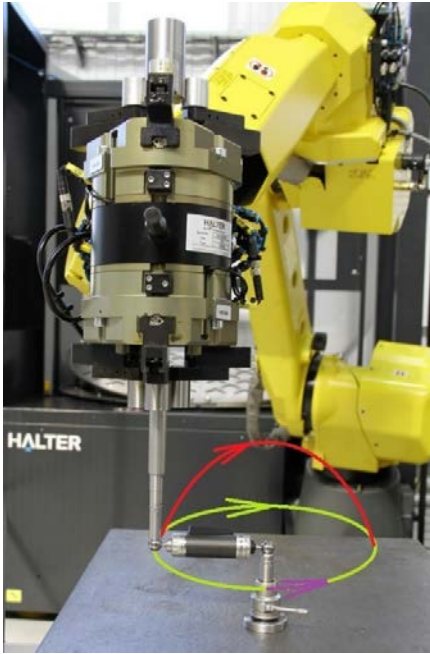
A multifactor experiment was conducted to study the dependence of the accuracy of working off circular paths on the transported mass and the range of the robot arm. For this, several blanks of various weights were selected in the range from 0 to 6 kg; the wrist displacement from the base of the robot varied between 300 and 1500 mm. The majority of robot manipulations are carried out related to the gripper and positioning of workpieces in the range of 400-800 mm.

Figure 3. Circular chart for measuring the accuracy of the circular trajectories of the robot in a horizontal plane in the stacking system area with load 4.62 kg.
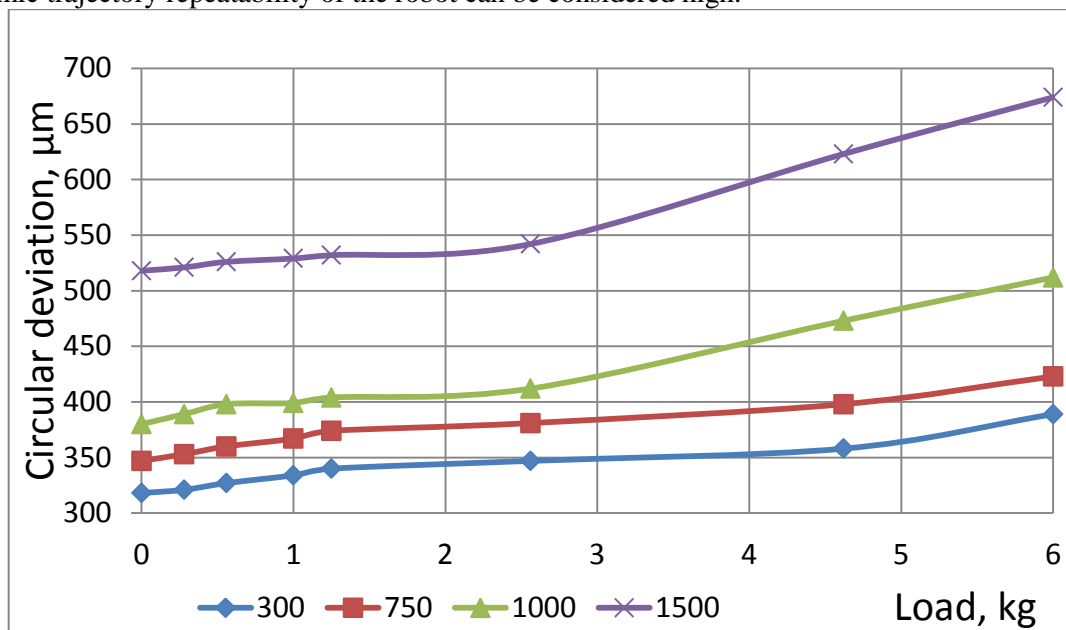
The accuracy of movements and positioning on the periphery of the working area is of particular interest because some schemes of flexible production systems use the remote location of metalworking

equipment, storage systems, and other FMC elements. The deviations value at the maximum distance from the robot base is significant and it is necessary to provide automated devices with the required setting tolerance for the correct operation of the system. The result of one of the measurements is presented in figure 3. The scheme for measuring the accuracy of circular movements is shown in figure 4.
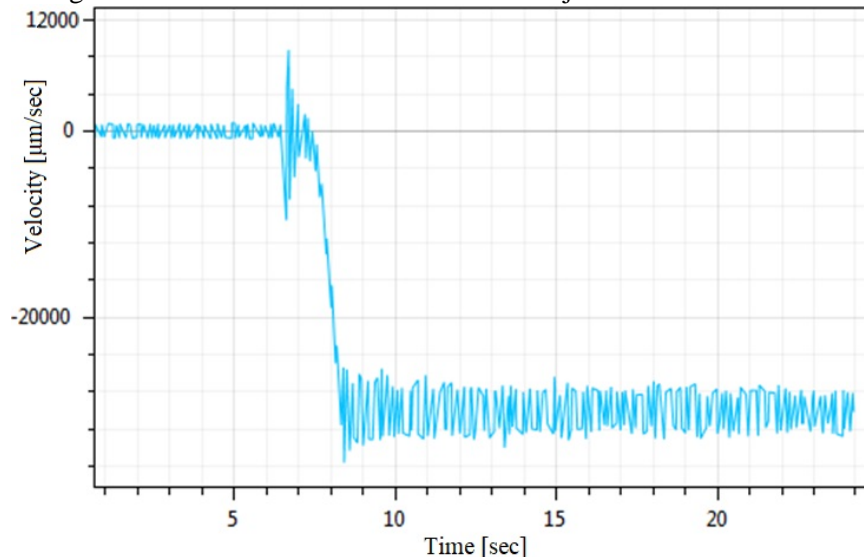

Figure 4. The measurement scheme of the accuracy of the robot circular movements in the horizontal plane at the maximum range with a load of 0.28 kg.

Based on the results of our studies, the dependences of the accuracy of Fanuc circular trajectories of an industrial robot on load and position change were plotted (figure 5). The graph is characterized by plotting the average values from the results of three measurements. The actual deviation between the results of repeated tests did not exceed 0.01 mm for given robot tolerance of ± 0.08 mm so that the dynamic trajectory repeatability of the robot can be considered high.

Figure 5. The dependence of the accuracy of positioning the robot in the horizontal plane on changes in load and measurement position.
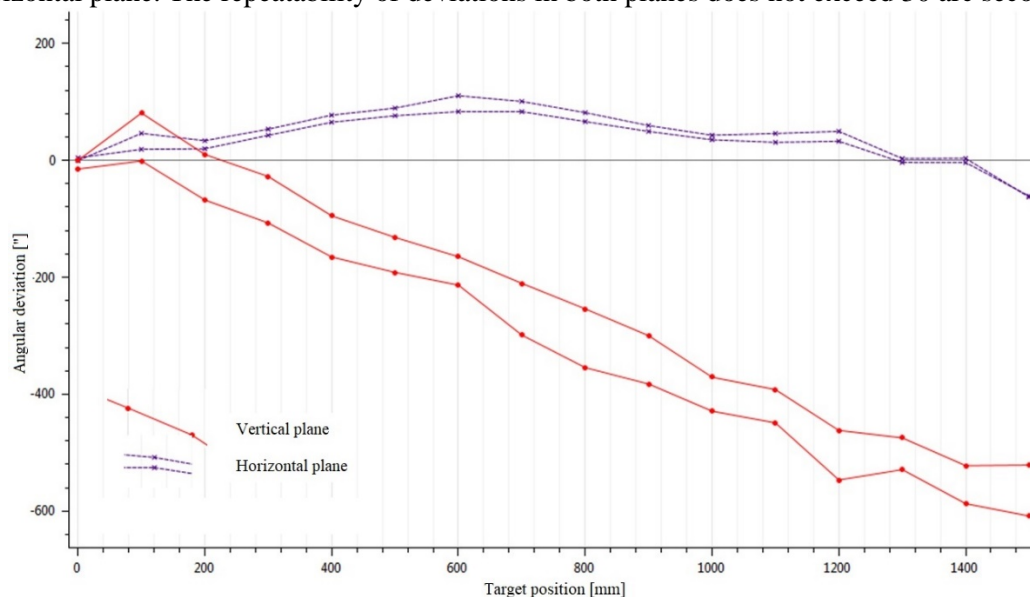
In figure 6 shows the results of measuring speed during dynamic acceleration to a path speed of 1800 mm/min. In general, the dynamic properties of the robot and the recommended speeds depend on the position of the robot, since in positions close to the singularity [3] small linear movements are performed due to significant circular movements of the robot joints.

Figure 6. The graph of the speed in the robot rectilinear movement.

Studies of the accuracy of robots conducted by other authors show that when the investigated trajectory is displaced in space, the values of all the studied parameters vary quite strongly. The paper presents measurements for the line connecting the storage area and the edge of possible working area, passing pretty close to the base.
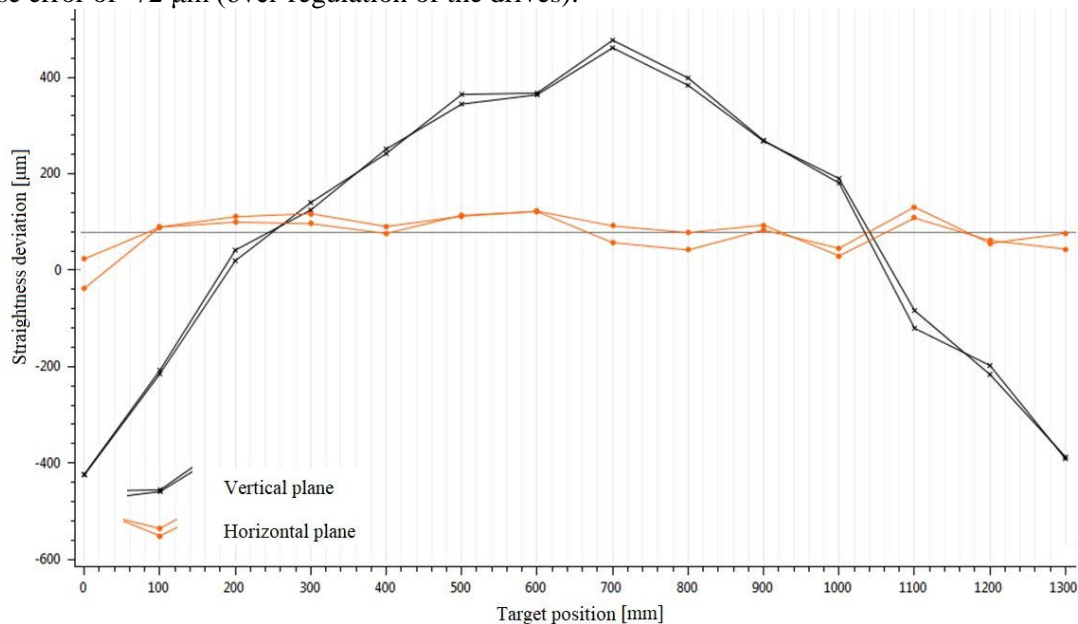
The maximum measured angular deviation when moving an industrial robot along the linear axis X under study with a length of 1500 mm was 12 arc minutes in the vertical plane and 3 arc minutes in the horizontal plane. The repeatability of deviations in both planes does not exceed 30 arc seconds.

Figure 7. The graph of the angular deviations of the robot during a rectilinear movement in the horizontal (upper dotted lines) and vertical plane (solid lines).
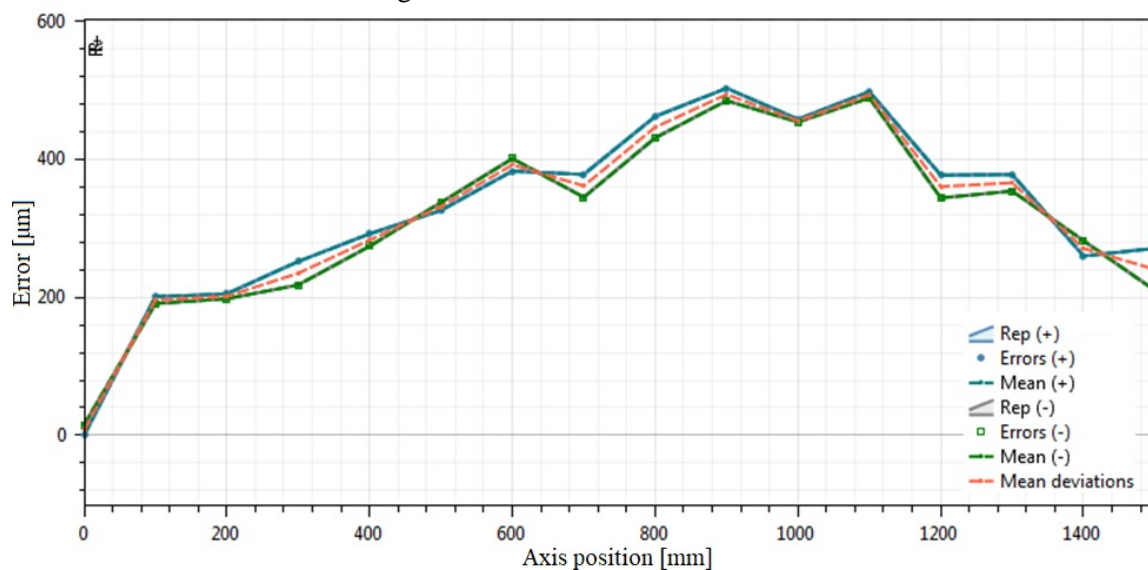
Straightness measurements were carried out using an appropriate set of optics for a laser interferometer. Unlike machining centers with classical Cartesian kinematics, the straightness of the

movements of the articulated robot under study in the horizontal plane largely depends on the direction of passage. This may because that when changing the direction of the approach, a backlash is sampled in the rotary axes of the rotary joints of the robot. The graph of the measurements is shown in figure 8. The absolute values of the deviation in the vertical plane (sagging of the robot arm) is 0.924 mm with two-sided repeatability of 69 μm and an average reverse error of 9 μm. For a horizontal plane, the maximum deviation is 0.17 mm with a two-sided repeatability of 113 μm and an average reverse error of -72 μm (over-regulation of the drives).

Figure 8. The graph of the linear deviations of the robot during rectilinear movement in the horizontal (red with dots) and vertical plane (black).

Along the studied axis the accuracy of positioning was measured according to GOST ISO 230-1-2010, the results of which are shown in figure 9.
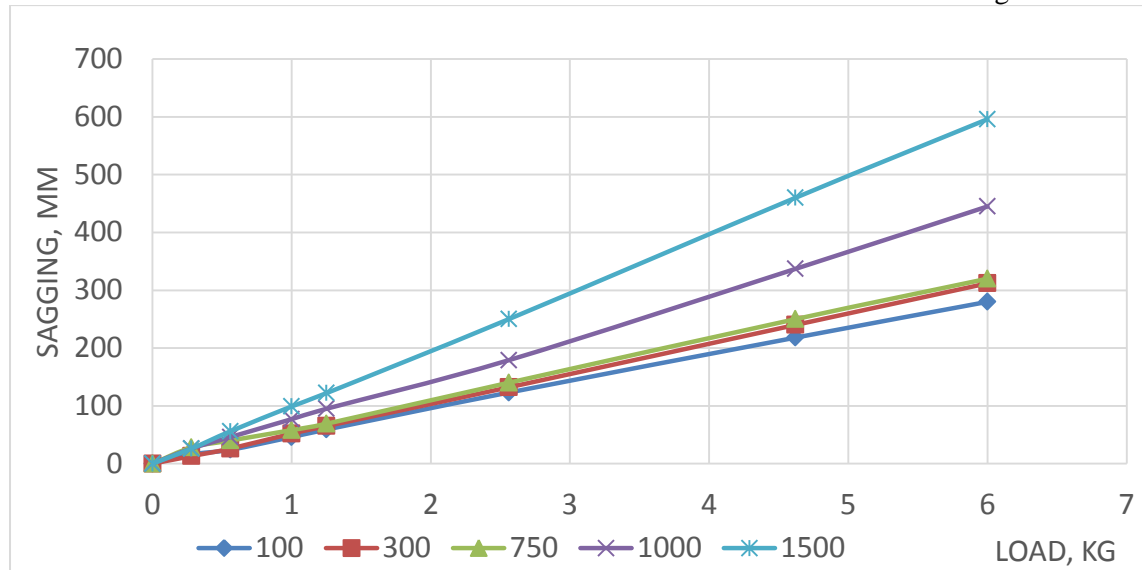

Figure 9. The graph of the accuracy of positioning the robot during rectilinear movement over the entire length of the working area.

The repeatability of robot positioning is on average 1 μm. Maximum in two unidirectional passes 3 μm is obtained when stopping after moving along the entire axis at a speed of 5000 mm / min.

The measurement was carried out according to the technique presented in [12]. Its main idea is to perform a bidirectional pass with a significant step to determine the zones with the greatest error and the subsequent study of this zone with a smaller step. However, for articulated robots, a decrease in the measurement step is uninformative due to the absence of an intra-step error and large tolerances on the accuracy of hand positioning.

After determining the main error of the robot as a sagging under its weight and the weight of the carried loads. In studying this effect were used straightness optics on sequential application and removal of the load. The measurements were carried out at five points with different projections of the center of the wrist above the center of the base. The measurement results are shown in figure 10.

Figure 10. The graph of the dependence of the mobile platform sagging of an industrial robot on the actual range and load.

The maximum value of the applied load is much less than the allowable load due to the fact that in addition to the absolute weight, there are also limitations on the torque of 22.0 N · m (2.2 kgf · m) on the last rotary axis and 44.0 N · m (4.5 kgf · m) on the fourth rotary axis, as well as the grip force of the manipulator.

5. Results and discussion

The payload of the studied FANUC M-20iA robot with its own weight of 250 kg is 20 kg. Statistically significant deviations in accuracy cause changes in the load in the robot arm over 500 grams. On average, an increase in the load for every 2.5 kilograms for an industrial robot tuned to a load of 20 kg causes a decrease in the movement's accuracy about 10%. In other words, when changing the FMC to extremely different parts by weight, the accuracy of installing the part with an industrial robot in the machine will not decrease by less than 0.25 mm. This must be taken into account while providing engineering operations.

The main error in the circular movements of the robot's grip is the increase in the radius of the best fit together with the mismatch of the scales associated with the sagging of the robot wrist carrying the ballbar's movable magnetic base. In some measured positions, it was possible to observe a close coincidence of the turning point of the trajectory with the significant movement of one of the rotary axes of the industrial robot. In such situations, reversal spikes (as a rule, only in one direction) up to 0.15 mm at a displacement speed of 5500 mm/min could be observed.

Based on the results of a study of the dependence of the accuracy of robot movements on the feed rate along a given path, the following observations were made: when the feed changes in the contour feed range of 1000-5000 mm/min, the absolute value of the drive mismatch and periodic cyclic error

decrease. When the robot's wrist moves in a straight line with a given path speed, fluctuations in the path speed occur: the difference between the minimum and maximum speeds at the moment is ± 5% (± 300 mm / min at a feed speed of 6000 mm / min).

At each point of the working area, there is a unique combination of deviations due to the position of the kinematic joints in space. Analysing the pattern of deviations, a significant periodic component of the error can be noted, as well as an increase in the deviation from roundness when the test section is removed from the base of the robot.

When diagnosed by the Renishaw Ballbar QC-20W instrument in the zone extremely close to the limit switches, significant fluctuations of the robot's wrist were noticed, caused by approaching the singularity point, significant distance from the base and insufficient articulated stiffness. Their amplitude was noticeable to the naked eye and exceeded 1.5 mm, which made it impossible to use the Ballbar device since its confidence interval is ± 1 mm. From this, we can conclude that the work close to the limits of the limit switch of the 2nd rotary axis should not be associated with precise movements or loads. Thus, it becomes impossible or difficult to layout flexible production systems with the completion of the part in the composition of the robot on the periphery of the working area. There are various both software and physical methods for reducing such conditions [13].

To study industrial robots with a declared positioning accuracy of more than 20 microns, it is justified to use a laser interferometer. For industrial articulated robots and medium dimensions, performing exclusively the function of changing the workpiece with a stated accuracy of 25 ... 150 microns, the use of laser trackers is permissible, and is a more comfortable and quick diagnostic method.

6. Conclusions

Based on the results of the study, the following conclusions can be drawn:

1. The analysis of factors affecting the accuracy of the industrial articulated robot as part of flexible production modules were completed.

2. The greatest contribution to the inaccuracy of movements and positioning of an industrial robot, and with it to its functional capabilities, is made by gravitational deformations (sagging), articulated kinematic transformations, fixation with an emergency brake. Industrial robots are characterized by high repeatability, so it is advisable to control it only in special cases.

3. When transferring and configuring flexible production modules, it is most advisable to measure the sag of the manipulator arm using an indicator, to control the accuracy of positioning and the rigidity of the fixation of the manipulator grip at the desired reach from the base. These tests allow the service team to cover the largest amount of errors with minimal time.

7. References

[1] Klimchik A, Ambiehl A, Garnier S, Furet B and Pashkevich A Experimental study of robotic-based machining 2016 *IFAC-PapersOnLine* **49-12** 174-9

[2] Semenov E N, Sidorova A V, Belomestnykh A S and Chapyshev A P Efficient zoning of the workspace of an industrial robot KUKA KR210 R2700 EXTRA 2015 *IrSTU Bull.* **12 (107)** 86-96

[3] GOST R ISO 8373-2014 *Robots and robotic devices. Vocabulary*

[4] Anikeeva O V Functional diagnostics of machine tools 2011 *Proc. of South-West State Uni.* **5-1 (38)** 106-12

[5] Balanev N V and Yanov R A Analysis of factors influencing the accuracy of the positioning of an industrial robot and methods for ensuring an adjusted accuracy 2016 *Achievements of sci. and educ.* **1 (2)** 11-4

[6] Brüning J, Denkena B, Dittrich M A and Park H S Simulation based planning of machining processes with industrial robots 2016 *Proc. Manuf.* **6** 17-24

[7] Mohnke C, Reinkober S and Uhlmann E Constructive methods to reduce thermal influences on the accuracy of industrial robots 2019 *Proc. Manuf.* **33** 19-26

[8] Sinaga N, Paryanto P, Widyanto S A, Rusnaldy R, Hetzner A and Franke J An analysis of the effect of gravitational load on the energy consumption of industrial robots 2018 *Proc. CIRP* **78** 8-12.

[9] GOST ISO 230-1-2010 *Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*

[10] GOST ISO 230-4-2015 *Test code for machine tools — Part 4: Circular tests for numerically controlled machine tools* 2016

[11] Archenti A, Nicolescu M, Casterman G and Hjelm S A new method for circular testing of machine tools under loaded condition 2012 *Proc. CIRP* **1** 575-80.

[12] Vasilyev E V, Nazarov P V, Koltsov A G, Blokhin D A, Bugay I A, Totik M A and Chernykh I K Calibration of the axes of an experimental CNC grinding machine for contouring plates on the rear surface using a laser interferometer 2017 *The Journal Omsk Sci. Bull.* **6 (156)** 23-8

[13] Klimchik A, Wu Y, Caro S, Dumas C, Furet B and Pashkevich A Modelling of the gravity compensators in robotic manufacturing cells 2013 *IFAC Proc. Vol.* **46-9** 790-795