ACCURACY ANALYSIS OF MOTION ALONG CIRCULAR TRAJECTORIES OF THE MANIPULATORS BUILT ON DRIVES WITH ONE MOTOR AND PRECISION DUAL-MOTOR DRIVES

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Fields of implementation of precision technological robots

- Precision laser cutting, welding and marking of parts with complex shapes of surfaces;
- Assembly operations, which require increased positioning accuracy of manipulator end-effector;
- Robotic measurement operations of large-sized items;
- Robotic milling, grinding and other technological operations, in which high motion accuracy is required to be provided at the force interaction between tool and processed part;
- Technological operations where the usage of robots suggests realization of analytical programming without possibility to implement teaching methods.

Basic requirements to precision technological robots

Requirements to motion accuracy. Positioning error of the end-effector is within a range of 20...100 μm.

Requirements to manipulator stiffness. Elastic compliance, reduced to manipulator tool centre point (TCP), and caused by elasticity and backlash of mechanical gears, must aspire to zero in static states.

The major factors, which provoke deviations of TCP of angular manipulator with geared servo drives from a desired position, set by control program:

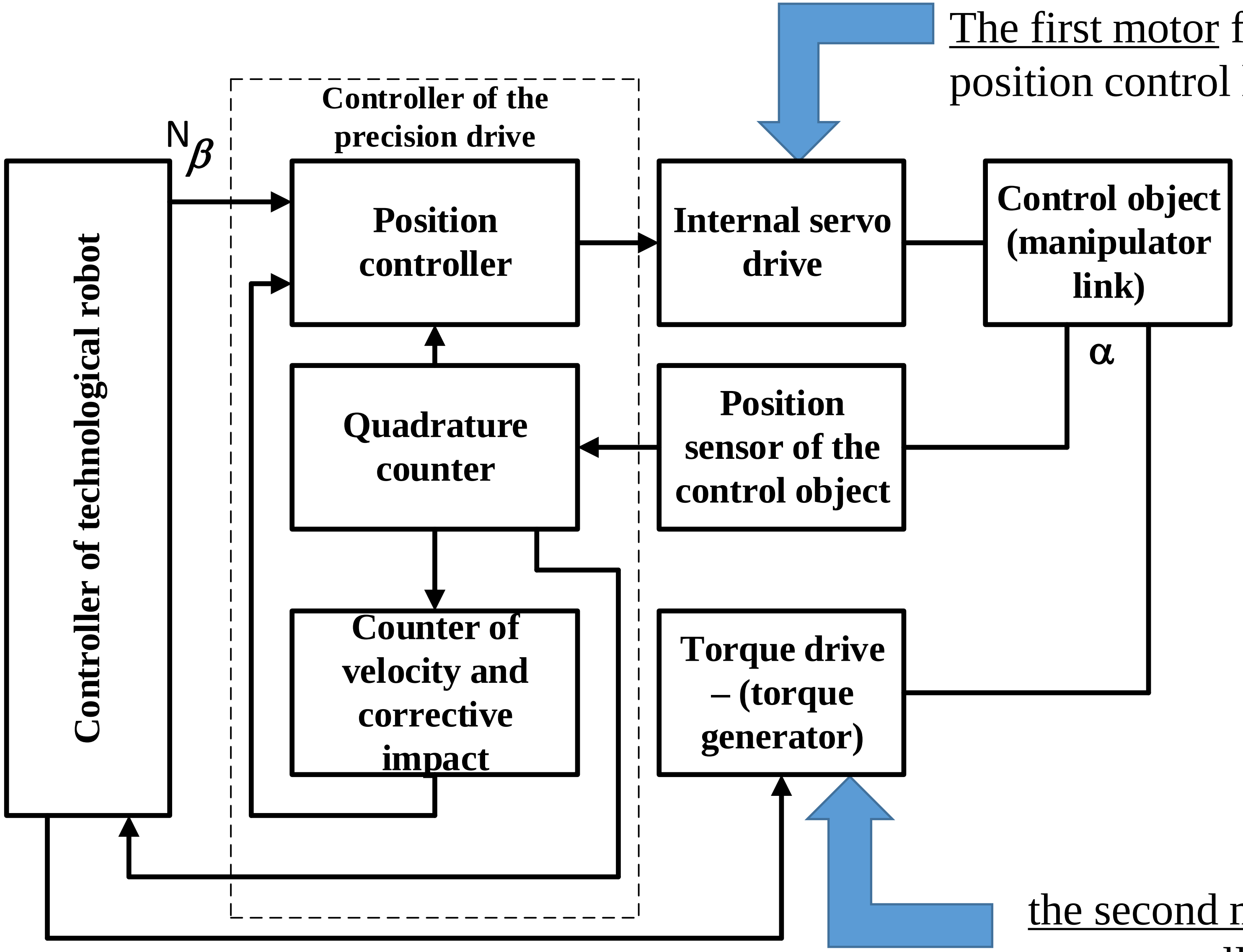
- **elasticity** of mechanical gears of drives
- **backlash** of mechanical gears of drives

Two types of geared servo drives, which can be used in manipulators construction:

The first type. Servo drive with traditional structure, which has one actuating motor, built as a system with inner control loops, closed by feedback position control loop of the motors shaft. Its main particularity is of the fact that control object and mechanical transmission are not included into position control loop. Elasticity and backlash of mechanical gears significantly decrease accuracy of manipulator motion.

The second type. Servo drive with two actuating motors and feedback position control loop of the control object. Its main particularity is in potentially higher accuracy, caused by direct control of control object position, also in backlash and gear elasticity active elimination and in usage of position sensor with high resolution.

Structure of precision dual-motor servo drive, closed by feedback position control loop of the control object.



The first motor forms servo drive, closed by feedback position control loop of the manipulator link.

So, the structure of precision drive contains:

- 2 actuating motors
- 2 position sensors
- 5 control loops

the second motor forms a torque loader, which acts as a controlled backlash eliminating device.

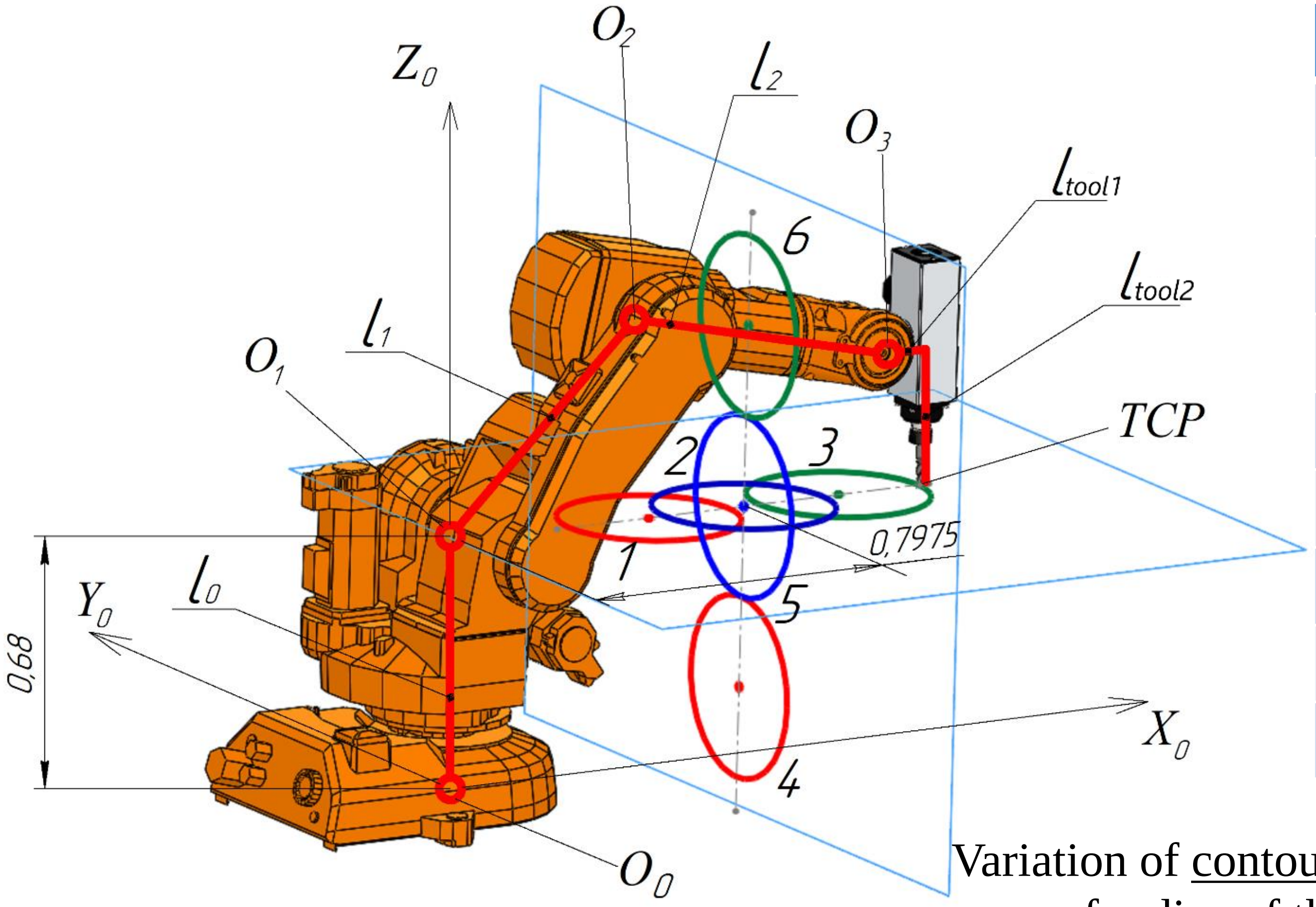
Research objective and tasks

Research objective – creation of procedure of evaluating motion accuracy of technological robots, built on traditional drives with one motor and on precision dual-motor drives.

Research tasks:
1. Definition of type and parameters of manipulator mechanism, used in research;
2. Definition of test trajectories and movement modes for implementing research of motion accuracy of technological robots, built on traditional drives with one motor and precision dual-motor drives;
2. Development of evaluation criteria of motion accuracy;
3. Development of mathematical model and program for computer simulation;
4. Computer simulation and detection of error dependencies on contour velocity, radius and position of the desired circular trajectory in space;
5. Accuracy comparison of manipulators with drives with one motor and dual-motor drives.

Conditions of the computer experiment, aimed at comparison between the errors of the manipulator, built on drives with one motor, and on dual-motor drives at motion along circular trajectories.

Circular trajectories, realised by manipulator in horizontal (1-3) and vertical (4-6) planes

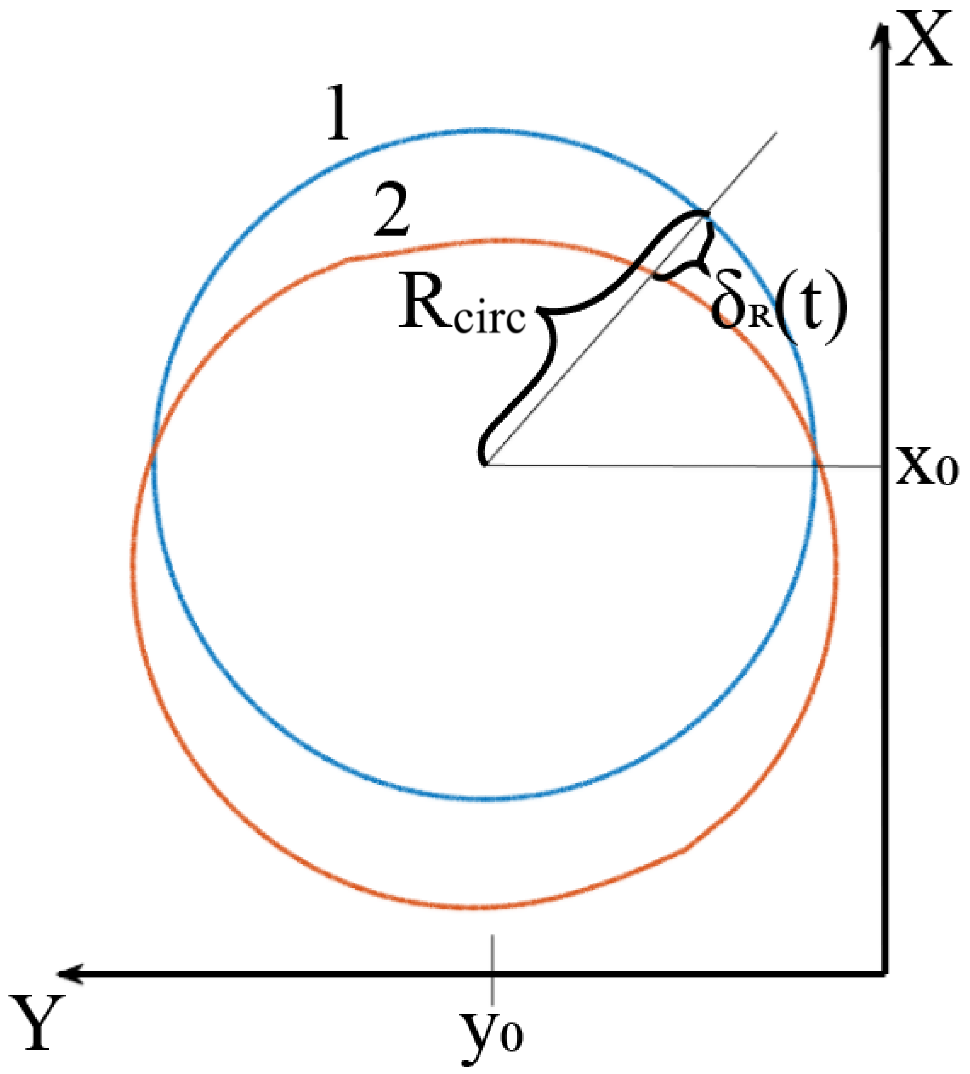


Principal manipulators parameters

Parameter	Value
Column weight, m_0, kg	55
Column length, l_0, m	0.68
Weight of shoulder link, m_1, kg	38
Length of shoulder link, l_1, m	0.68
Weight of elbow link, m_2, kg	35
Length of elbow link, l_2, m	0.68
Weight off « hand» link, m_3, kg	16
Length of hand link along OY axis, l_{tool1}, m	0.235
Length of hand link along OZ axis, l_{tool2}, m	0.3

Variation of <u>contour velocity within a range from 5 to 25 mm/s;</u>
<u>of radius of the desired circular trajectory within a range from 10 to 150 mm.</u>

Criteria of accuracy evaluation at motion along circular trajectory in horizontal plane



1 – desired trajectory
2 – actual trajectory

$$x_{circ} = x_0 + R\cos\Omega t$$
$$y_{circ} = y_0 + R\sin\Omega t$$
$$z_{circ} = z_0$$

Radial mean-square deviations

$$|R|_{avr} = \sqrt{\frac{1}{T}\int_0^T |\delta_R(t)|^2\, dt}$$

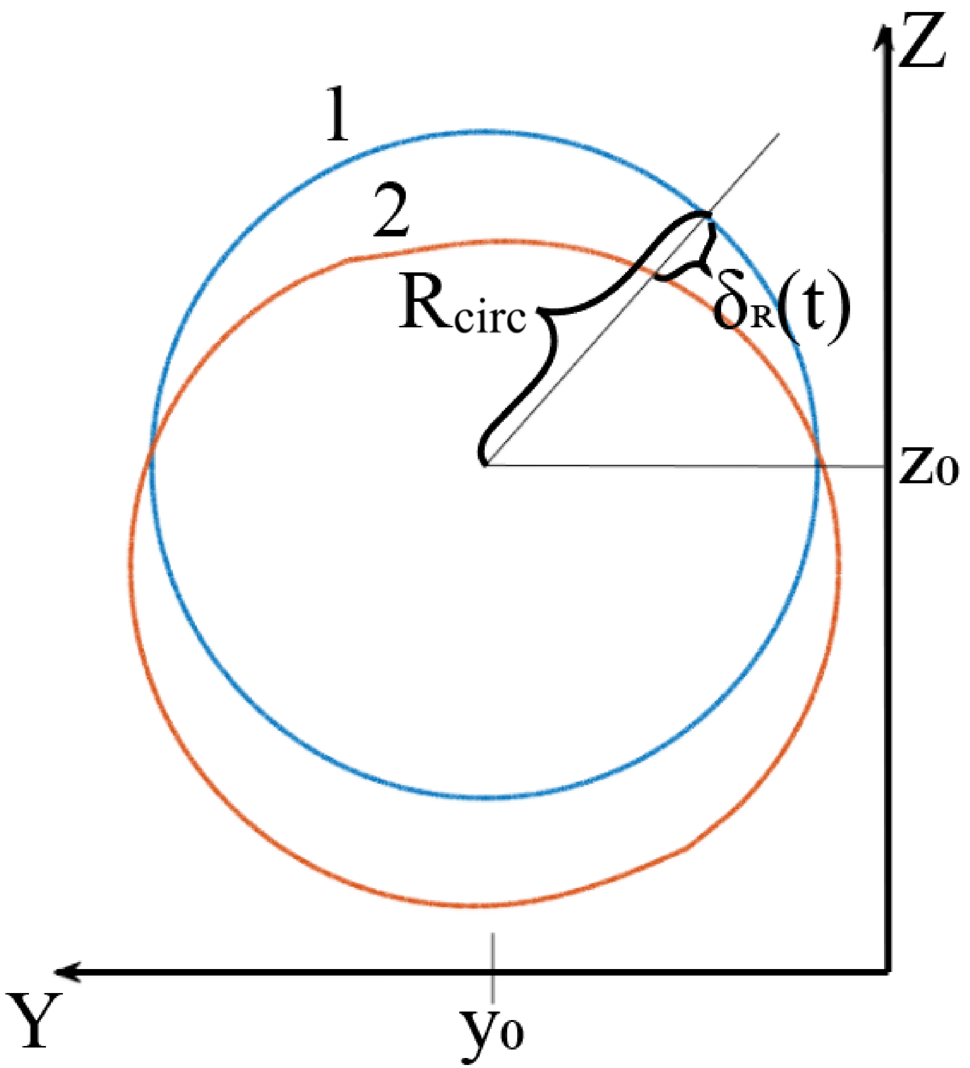
$$\delta_R(t) = R_{circ} - \sqrt{(x_{rob}(t) - x_0)^2 + (y_{rob}(t) - y_0)^2}$$

Axial mean-square deviations

$$|Z|_{avr} = \sqrt{\frac{1}{T}\int_0^T |\delta_z(t)|^2\, dt}$$

$$\delta_z(t) = z_{circ} - z_{rob}(t)$$

Criteria of accuracy evaluation at motion along circular trajectory in vertical plane



1 – desired trajectory
2 – actual trajectory

$$y_{circ} = y_0 + R\cos\Omega t$$
$$z_{circ} = z_0 + R\sin\Omega t$$
$$x_{circ} = x_0$$

Radial mean-square deviations

$$|R|_{avr} = \sqrt{\frac{1}{T}\int_0^T |\delta_R(t)|^2 dt}$$

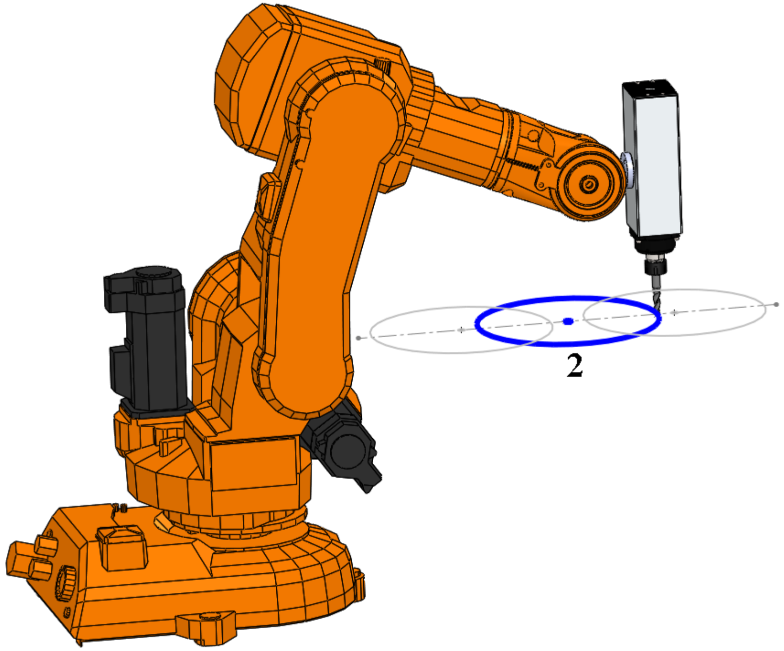
$$\delta_R(t) = R_{circ} - \sqrt{(z_{rob}(t) - z_0)^2 + (y_{rob}(t) - y_0)^2}$$

Axial mean-square deviations

$$|X|_{avr} = \sqrt{\frac{1}{T}\int_0^T |\delta_x(t)|^2 dt}$$

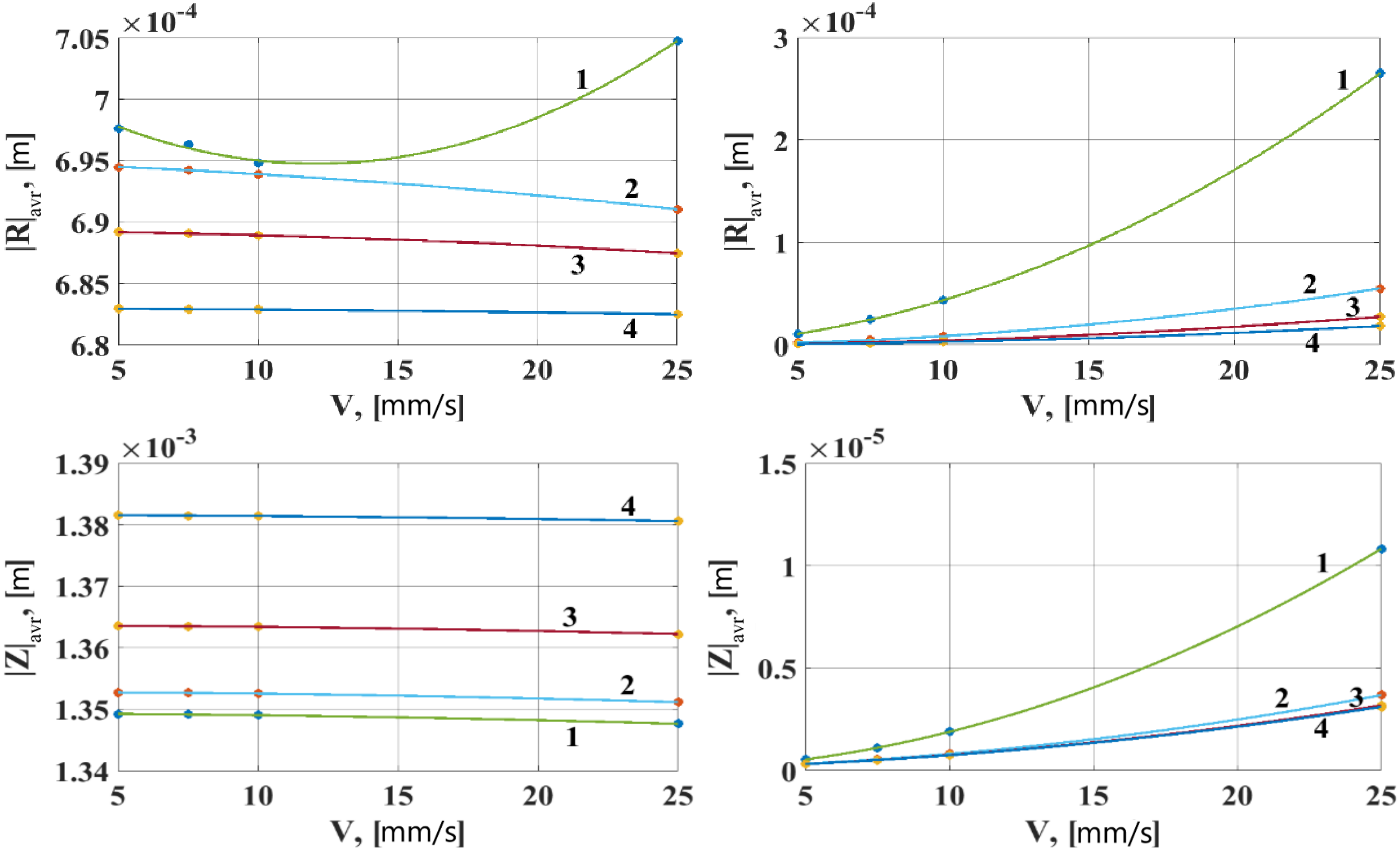
$$\delta_x(t) = x_{circ} - x_{rob}(t)$$

Radial and axial mean-square deviations of manipulator at motion along circular trajectory №2 in horizontal plane



for manipulator with drives with one motor

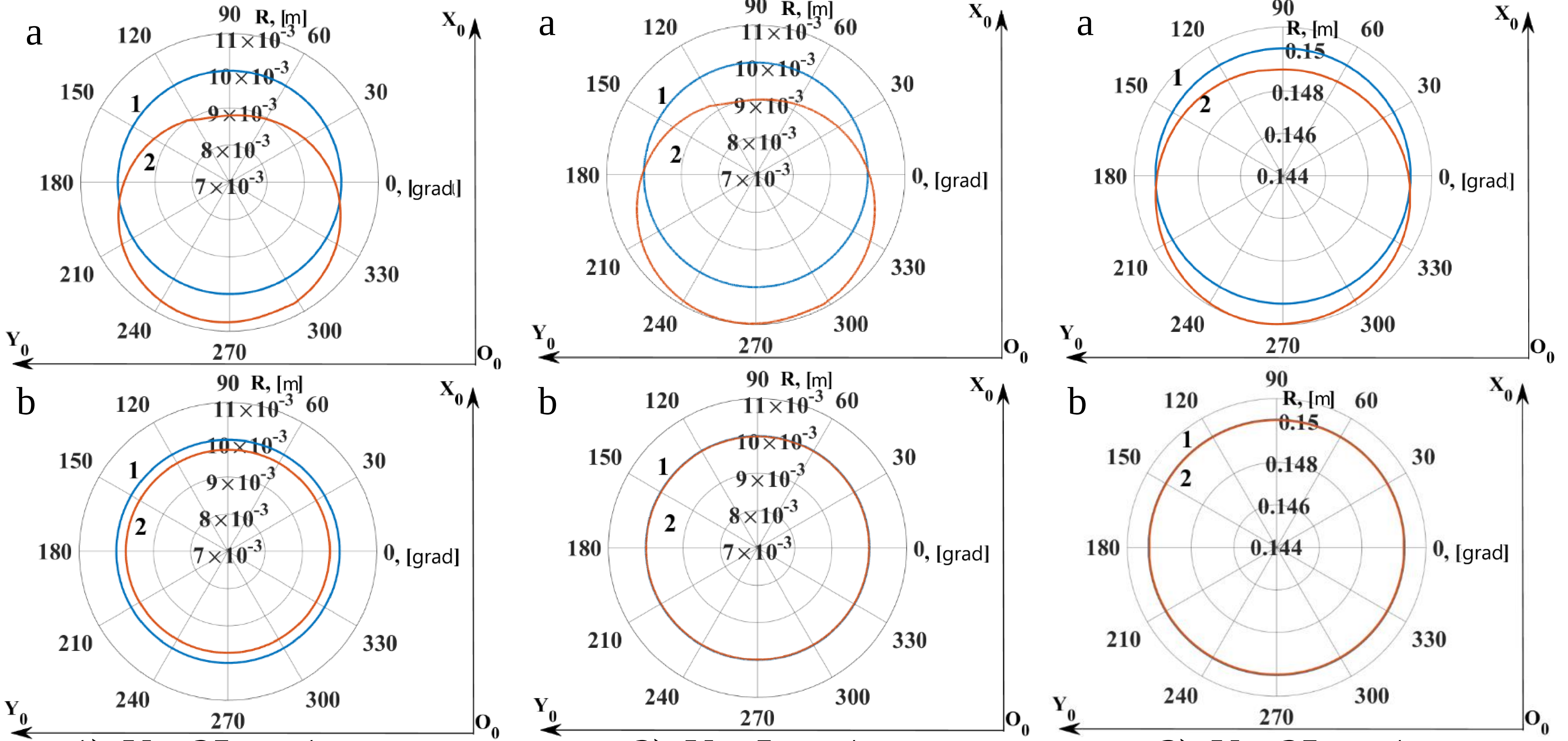
for manipulator with dual-motor drives



1 – at radius equal to 10 mm; 2 – 50 mm; 3 – 100 mm; 4 – 150 mm.

<u>Conclusion</u>: in these cases manipulator with precision dual-motor drives possesses significantly higher accuracy than manipulator with drives with one motor.

Comparison between the desired (1) and the actual (2) trajectories



1) V = 25 mm/s R = 10 mm

2) V = 5 mm/s R = 10 mm

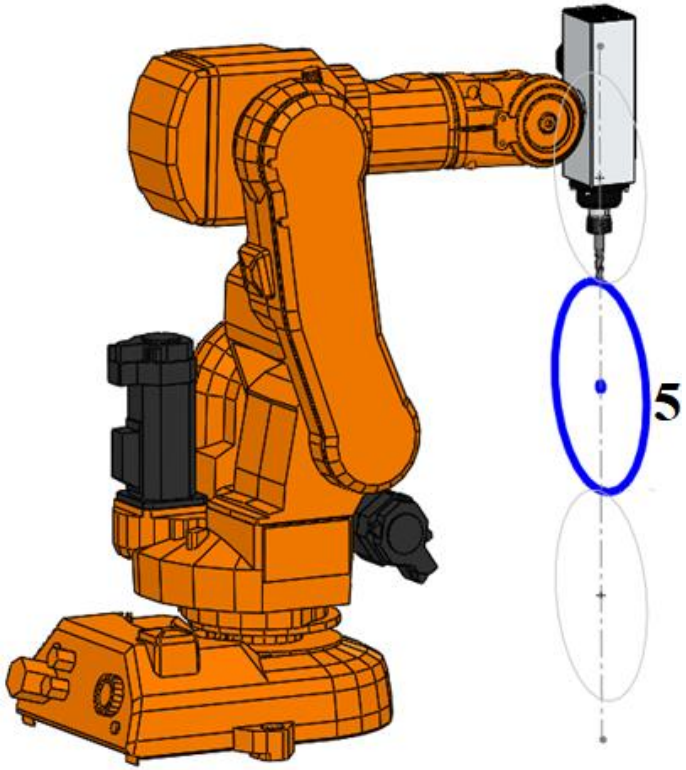
3) V = 25 mm/s R = 150 mm

Accuracy comparison between manipulators built on drives with one motor and dual-motor drives at motion along circular trajectory №2 in horizontal plane

Contour velocity, mm/s	Radius, mm	Radial mean-square deviations of manipulator		Accuracy gain coefficient
		with drives with one motor, µm	with dual-motor drives, µm	
25	10	705	265	3
5	10	698	11	63
25	150	683	19	36

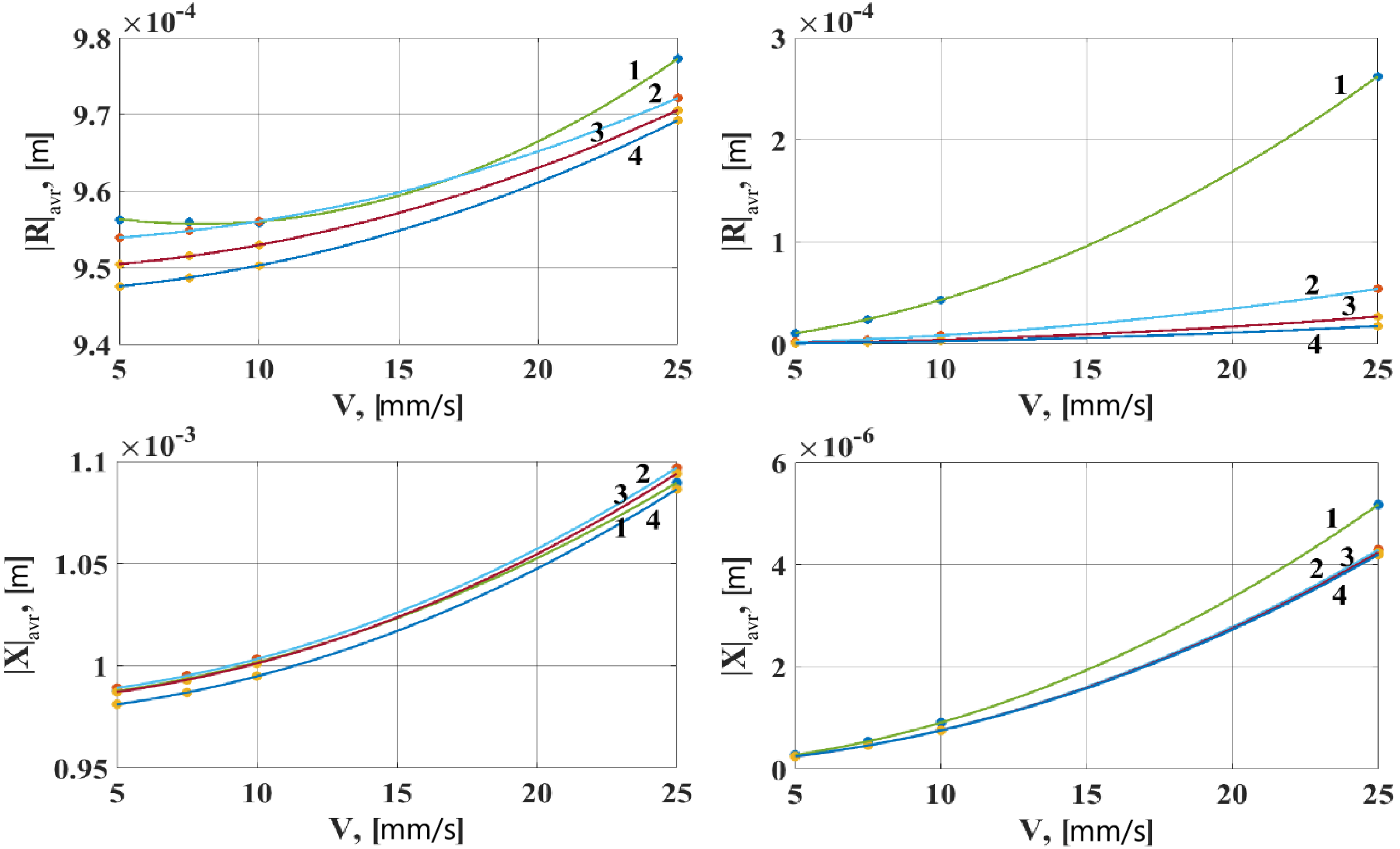
Conclusion: accuracy gain at the usage of manipulator with dual-motor drives at motion along circular trajectory in horizontal plane has achieved a range from almost 3 to 63 times.

Radial and axial mean-square deviations of manipulator at motion along circular trajectory №5 in vertical plane



for manipulator with drives with one motor

for manipulator with dual-motor drives



1 – at radius equal to 10 mm; 2 – 50 mm; 3 – 100 mm; 4 – 150 mm.

Conclusion: type of dependencies of radial and axial mean-square deviations of manipulator with drives with one motor and dual-motor drives at motion along circular trajectories in vertical plane is reserved.

Accuracy comparison between manipulators built on drives with one motor and dual-motor drives at motion along circular trajectory №5 in vertical plane

Contour velocity, mm/s	Radius, mm	Radial mean-square deviations of manipulator		Accuracy gain coefficient
		with drives with one motor, μm	with dual-motor drives, μm	
25	10	977	262	3.7
5	10	956	11	87
25	150	969	18	54

Conclusion: accuracy gain at the usage of manipulator with dual-motor drives at motion along circular trajectory in vertical plane has achieved a range from almost 4 to 87 times.

Comparison of variations of radial and axial deviations of manipulators with drives with one motor and dual-motor drives at different positions of the desired circular trajectory in space at contour velocity equal to 25 mm/s and radius 10 mm.

	Radial mean-square deviations of manipulator		**Axial mean-square deviations of manipulator**	
	with drives with one motor, μm	with dual-motor drives, μm	with drives with one motor, μm	with dual-motor drives, μm
Motion in horizontal plane				
Circular trajectory №1	702	264	1184	10
Circular trajectory №2	705	265	1348	11
Circular trajectory №3	699	266	1648	12
Difference between deviations for circular trajectories №1-3	3.7	1.6	464	2
Motion in vertical plane				
Circular trajectory №4	731	257	1154	7
Circular trajectory №5	977	262	1089	5
Circular trajectory №6	1063	268	543	4
Difference between deviations for circular trajectories №4-6	332	11	611	3

Conclusion: Parameters stability of manipulator with dual-motor drives within its workspace is higher than of manipulator with drives with one motor.

Principal results and conclusions

- The obtained estimation of motion accuracy along desired circular trajectories of technological robots with considered two types of servo drives confirms the fact that manipulators with precision dual-motor drives possess an advantage.
- In all of the considered cases of the desired trajectories radial and axial mean-square deviations from the desired trajectory of manipulator with dual-motor drives are less than of manipulator with drives with one motor.
- For example, at contour velocity 5 mm/s and radius of the circular trajectory 10 mm accuracy is increased up to 87 times.
- Variations of the desired circular trajectory position in space weakly influence deviation of manipulator with dual-motor drives from its desired trajectory both along the radius of the circular trajectory and along the normal direction to the plane of motion.
- The results of the provided research allow recommending to construct manipulators of technological robots at their analytical programming at technological operations, which require high motion accuracy, on precision dual-motor servo drives

Thank you for your attention!

The main factors, which reduce motion accuracy of technological robots-manipulators and limit their implementation:

- Imperfection of mathematical models, used for kinematic control of manipulator, discrepancy between them and real manipulators;
- Errors, caused by inaccurate “referencing” of manipulator coordinate system to coordinate system of the processed part;
- Errors of position sensors of manipulator links;
- Elastic compliance of manipulator links, defined by material properties of manipulator links and of the base, and by their geometrical properties;
- Dynamic imperfection of servo drives, low dynamic stiffness and accuracy due to kinematic errors and elastic compliance of mechanical transmissions;

<u>The major factors, which reduce the motion accuracy of technological manipulators and which limit their implementation:</u>

- Imperfection of mathematical models, used for kinematic control of manipulator motion, discrepancy between them and real manipulators;
- Errors, caused by inaccurate “referencing” of manipulator coordinate system to coordinate system of the processed part;
- Errors of position sensors of manipulator links;
- Elastic compliance of manipulator links, defined by material properties of manipulator links and of the base, and by their geometrical properties;
- Dynamic imperfection of servo drives, low dynamic stiffness and accuracy due to kinematic errors and elastic compliance of mechanical transmissions;

<u>The ways of reducing factors, which decrease robots accuracy</u>

Increase in accuracy of calibration process

Increase in sensors accuracy, usage of precision photoelectrical sensors

Increase in quantity of metal of manipulation mechanism

Increase in accuracy and stiffness of robot drives

Increase in accuracy and stiffness of robot drives:

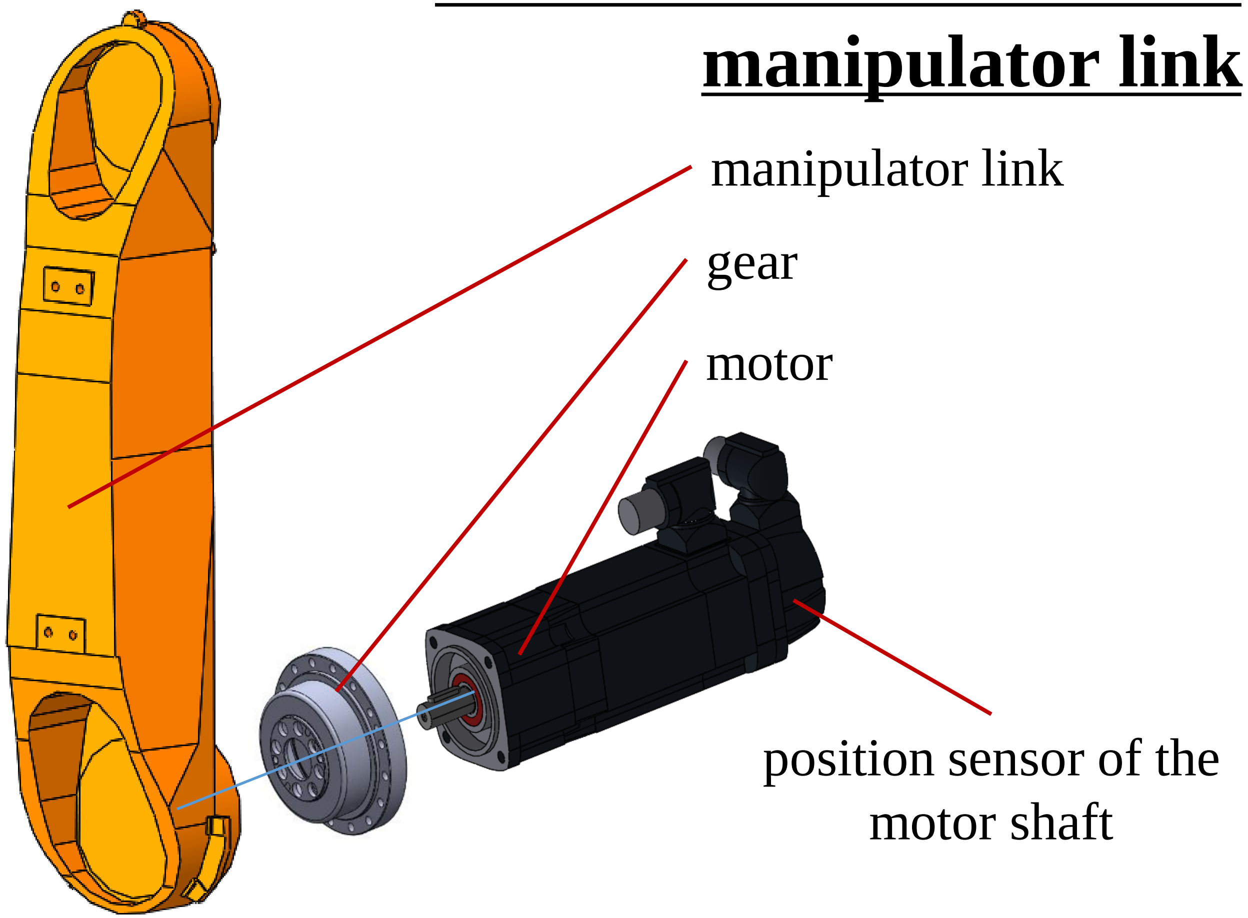
- the usage of gearless drives

- Introduction of corrective and compensative control links and loops

- Correction of reference impacts, set by CNC devices
- Creation of adaptive velocity (feed) control system of tool motion taking into consideration cutting forces and deviations from the desired trajectory

Angular manipulator

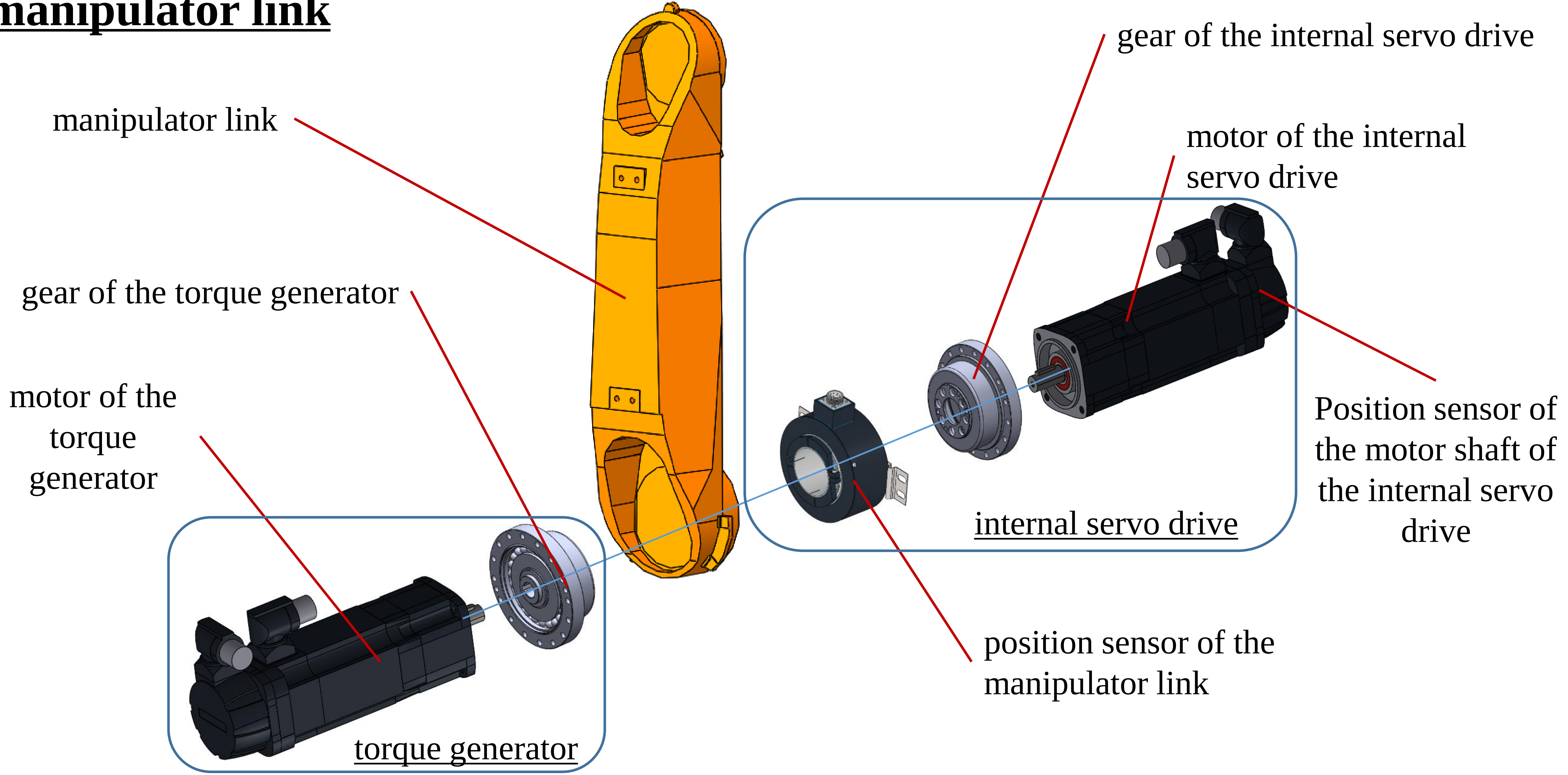
Geared servo drive of the manipulator link



The major factors, which provoke deviations of TCP of angular manipulator with geared servo drives from a desired position, set by control program:

- **elasticity** of mechanical gears of drives
- **backlash** of mechanical gears of drives

Component composition of precision dual-motor geared servo drive of manipulator link



Parameters of dual-motor drives of manipulator links

Parameters of dual-motor drive	column, «shoulder» link	«elbow» link	«hand» link
Motor of the internal servo drive and torque generator	KEB 44.SM.203-34B5	KEB 42.SM.203-34B5	KEB 33.SM.203-34B5
Rated power, kW	2,67	1.44	0.68
Rated torque, Nm	**8.5**	**4.6**	**2.15**
Rated rotation frequency, min^{-1}	3000	3000	3000
Gear of the internal servo drive and torque generator	Harmonic Drive HFUC-58-2A-GR	Harmonic Drive HFUC-45-2A-GR	Harmonic Drive HFUC-20-2A-GR
Gear ratio coefficient	**120**	**120**	**80**
Stiffness coefficient of gear, Nm/rad	710000	330000	29000
Backlash, arc. min.	**1**	**1**	**1**
PWM frequency, kHz	**16**	**16**	**16**
Resolver resolution (on motor shaft), discrete/rev.	**2047**	**2047**	**2047**
Encoder resolution (on link shaft), discrete/rev.	**250000**	**250000**	**250000**
Torque of the torque generator, Nm	20.7	9.6	0.8

Parameters of drives with one motor of manipulator links

Parameters of drive with one motor	column, «shoulder» link	«elbow» link	«hand» link
Motor of the internal servo drive	KEB 44.SM.203-34B5	KEB 44.SM.203-34B5	KEB 33.SM.203-34B5
Gear of the internal servo drive	Harmonic Drive HFUC-58-2A-GR	Harmonic Drive HFUC-40-2A-GR	Harmonic Drive HFUC-20-2A-GR

R_{rad} – summary radial deviation of manipulator

R_1 – deviations, caused by dynamics of drive

R_2 – deviations, caused by backlash and elasticity of gears

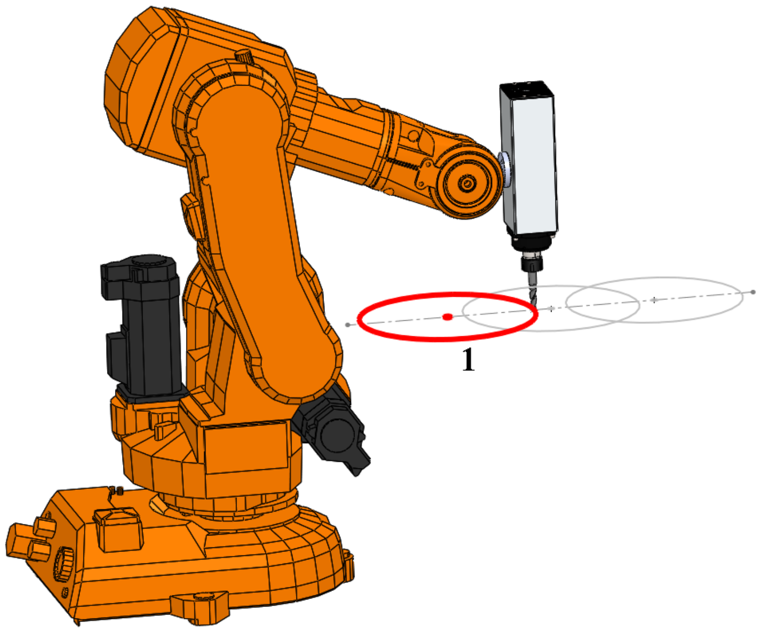
<u>Summary radial deviation of manipulator with drives with one motor</u>

$$R_{rad} = -R_1 + R_2$$

<u>Summary radial deviation of manipulator with dual-motor drives</u>

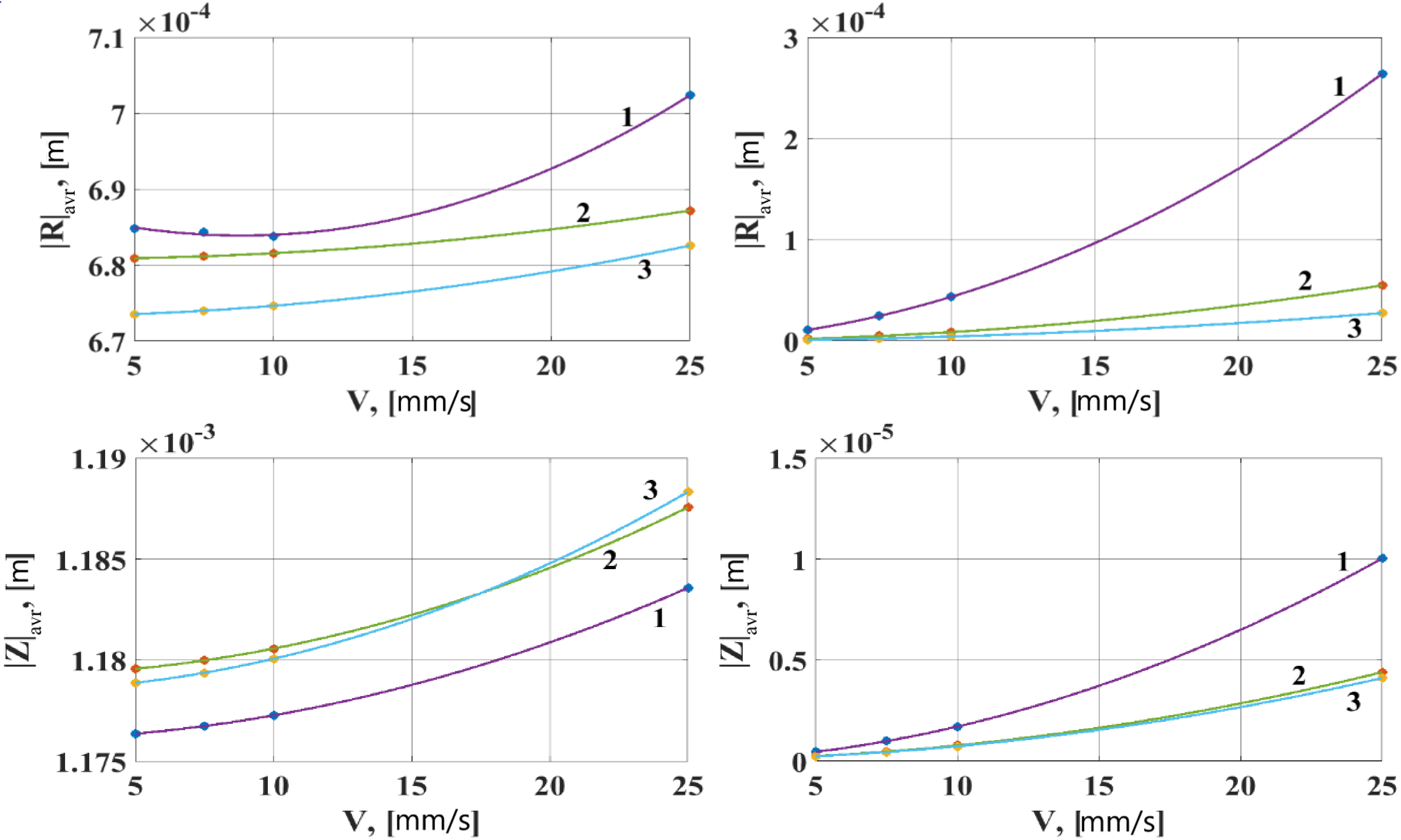
$$R_{rad} = -R_1$$

Radial and axial mean-square deviations of manipulator at motion along circular trajectory №1 in horizontal plane



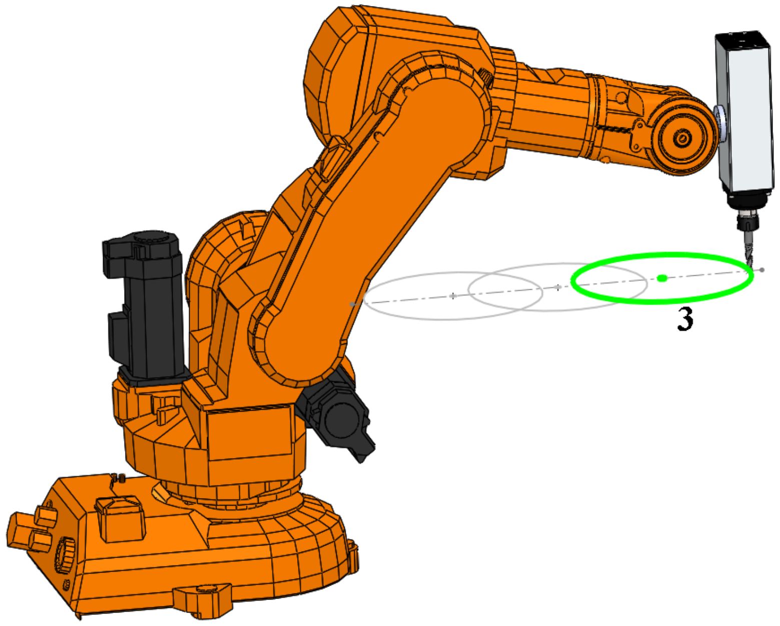
for manipulator with drives with one motor

for manipulator with dual-motor drives

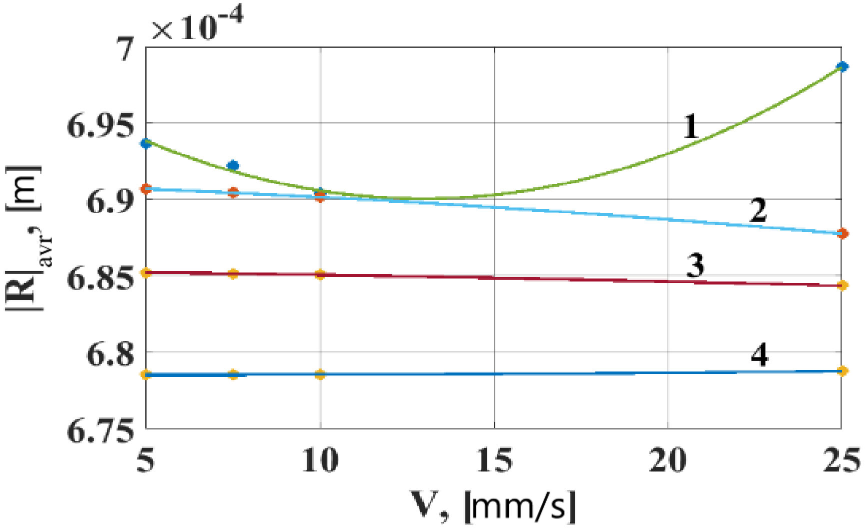


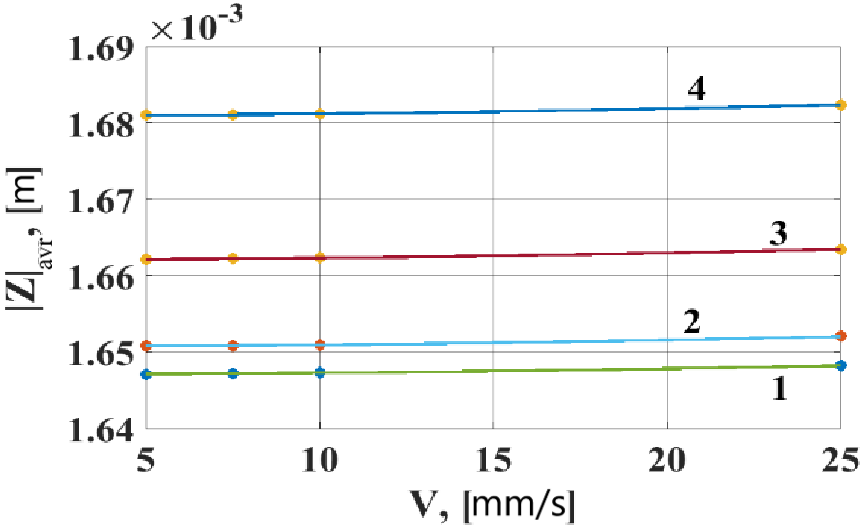
1 – at radius equal to 10 mm; 2 – 50 mm; 3 – 100 mm.

Radial and axial mean-square deviations of manipulator at motion along circular trajectory №3 in horizontal plane

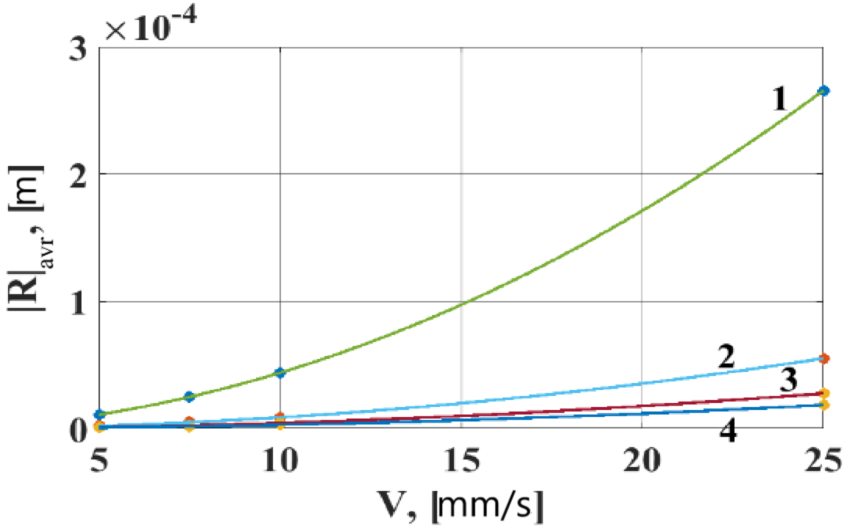


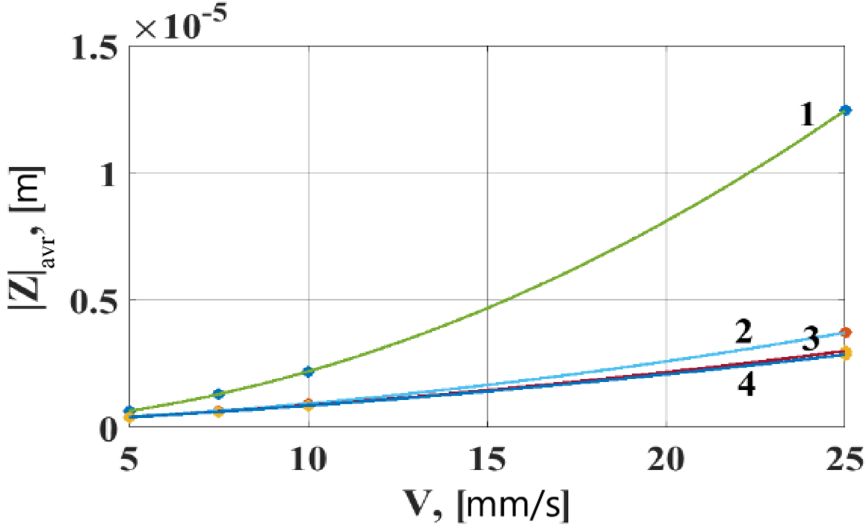
for manipulator with drives with one motor





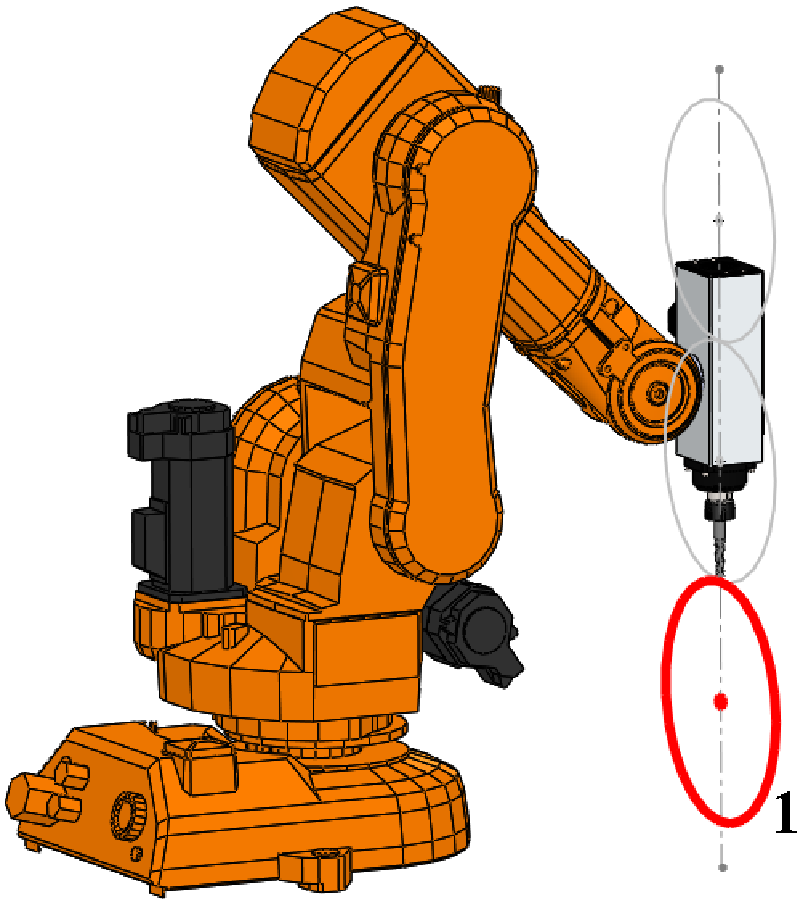
for manipulator with dual-motor drives





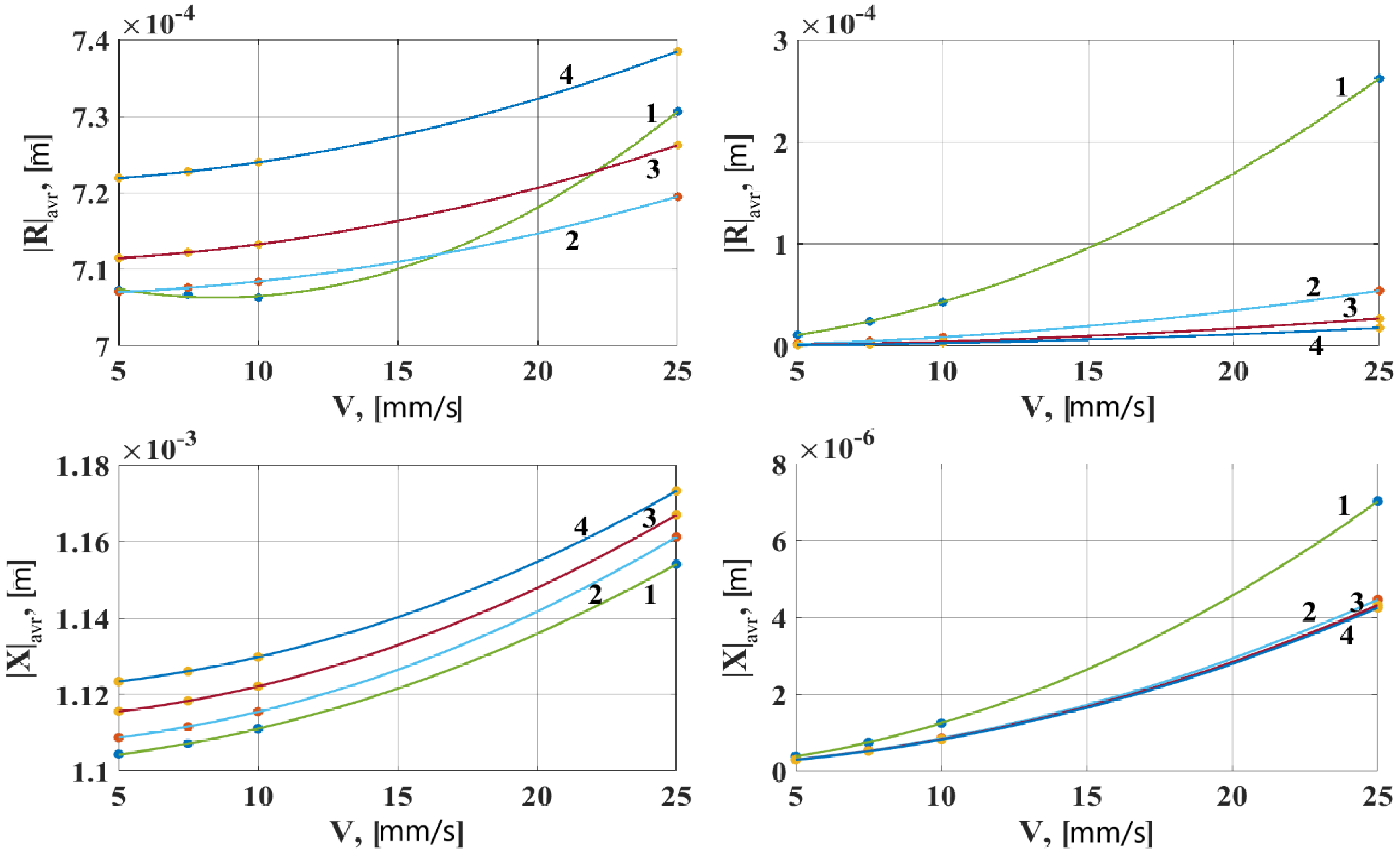
1 – at radius equal to 10 mm; 2 – 50 mm; 3 – 100 mm ; 4 – 150 mm.

Radial and axial mean-square deviations of manipulator at motion along circular trajectory №4 in vertical plane



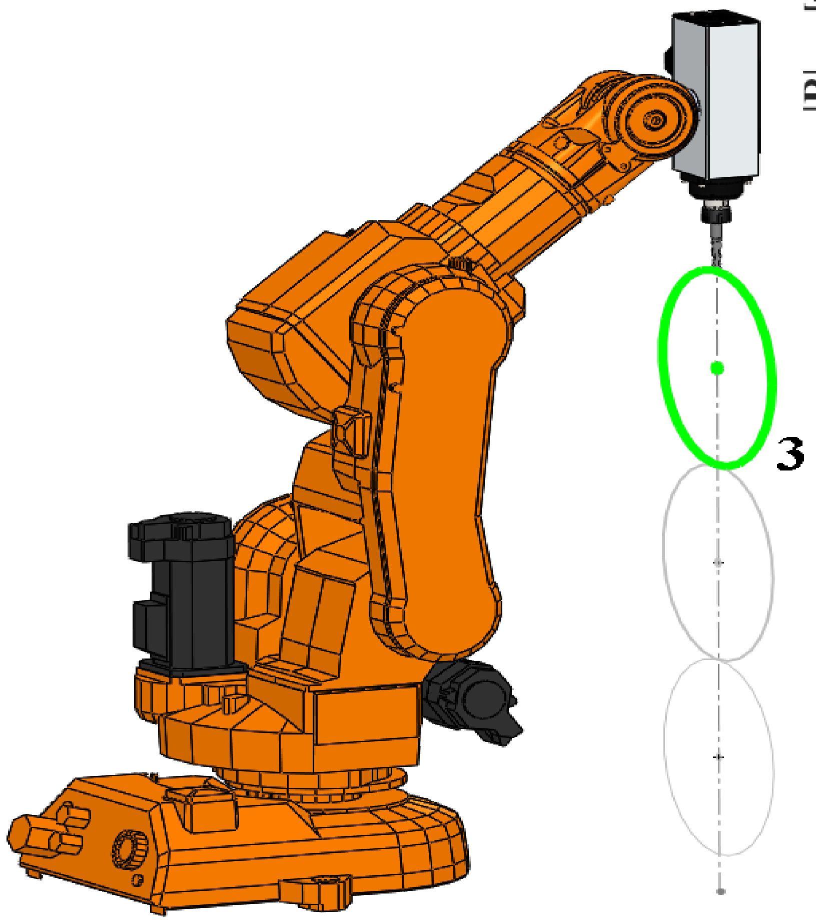
for manipulator with drives with one motor

for manipulator with dual-motor drives



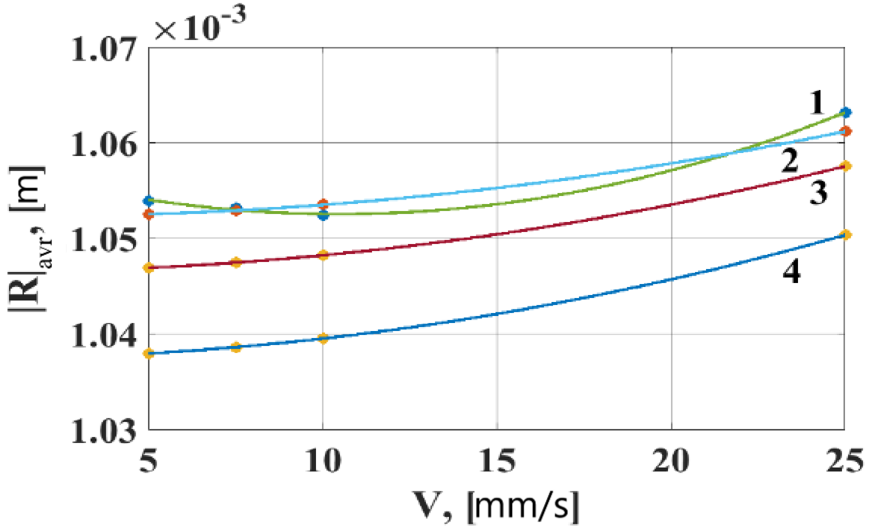
1 – at radius equal to 10 mm; 2 – 50 mm; 3 – 100 mm ; 4 – 150 mm.

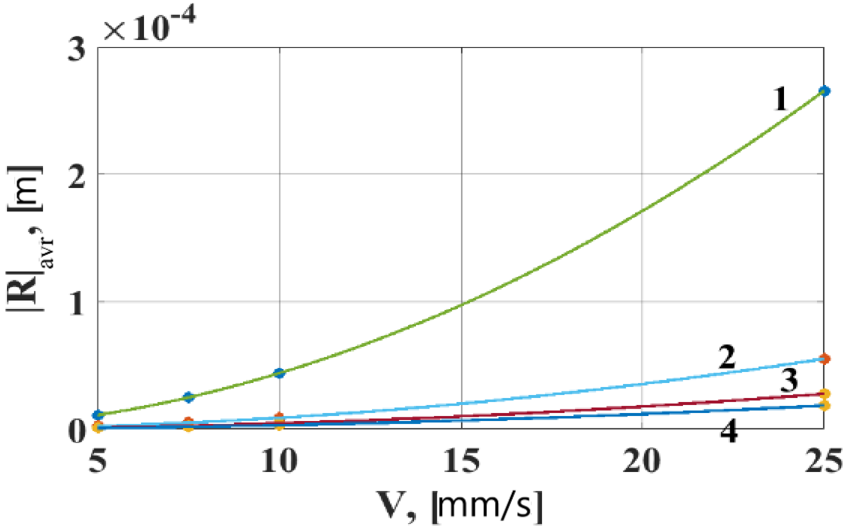
Radial and axial mean-square deviations of manipulator at motion along circular trajectory №6 in vertical plane

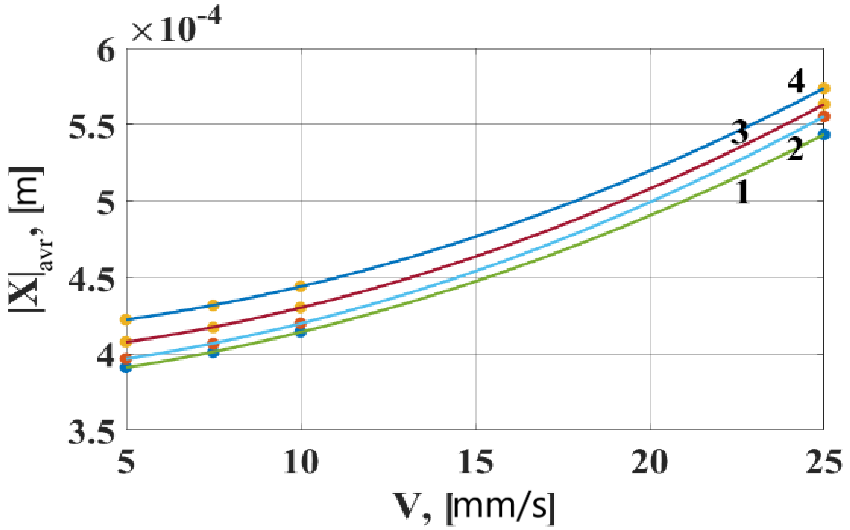


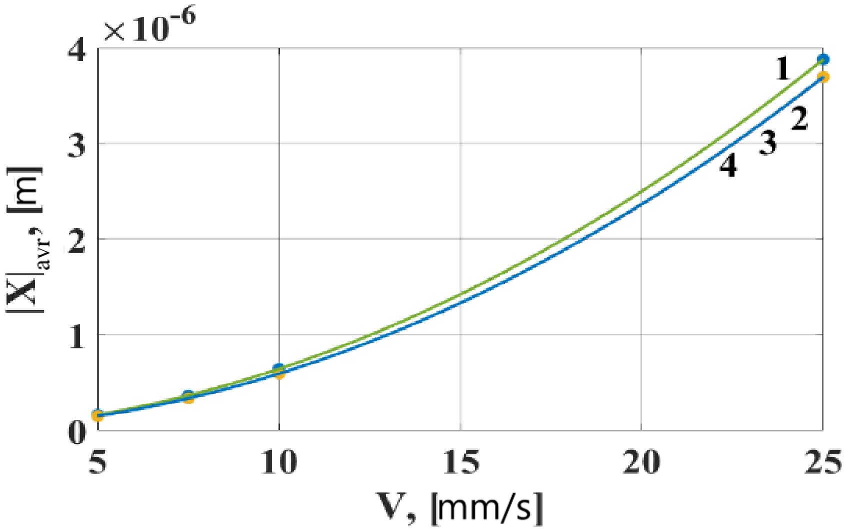
for manipulator with drives with one motor

for manipulator with dual-motor drives









1 – at radius equal to 10 mm; 2 – 50 mm; 3 – 100 mm ; 4 – 150 mm.

An increase in accuracy and performance of robotic milling

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The advantages of robotic milling

- Large workspace of manipulators
- The processed part may have complex surface shape
- The equipment costs are significantly less than for processing parts by machine tools
- Less volume of metal for the equipment is required as compared with machine tools
- High levels of flexibility, adaptability and programmability of robotic system
- It is easy to introduce additional axes in the system in order to increase the workspace

Major problems of robotic milling

- Low stiffness of manipulator mechanism
- Low accuracy of manipulator mechanism
- A reduction in feed velocity promotes increase in accuracy, but leads to decrease in performance
- Chatter and vibrations, which arise during the milling process

Accuracy and performance requirements to robotic milling

The performance of robotic milling is

$$Q = BhS$$

where h – cutting depth; B – width of the removed layer; S – velocity of longitudinal feed of tool (contour velocity).

The cutting force F_P is often calculated by empirical formulas:

$$F_P = k_F B^{n1} h^{n2} S^{n3}$$

where k_F – proportional coefficient, which takes into account material properties of the workpiece and the tool, diameter D, number of teeth z, rotation frequency n and coefficient of wear of the milling cutter; $n1, n5, n3$ – power exponents.

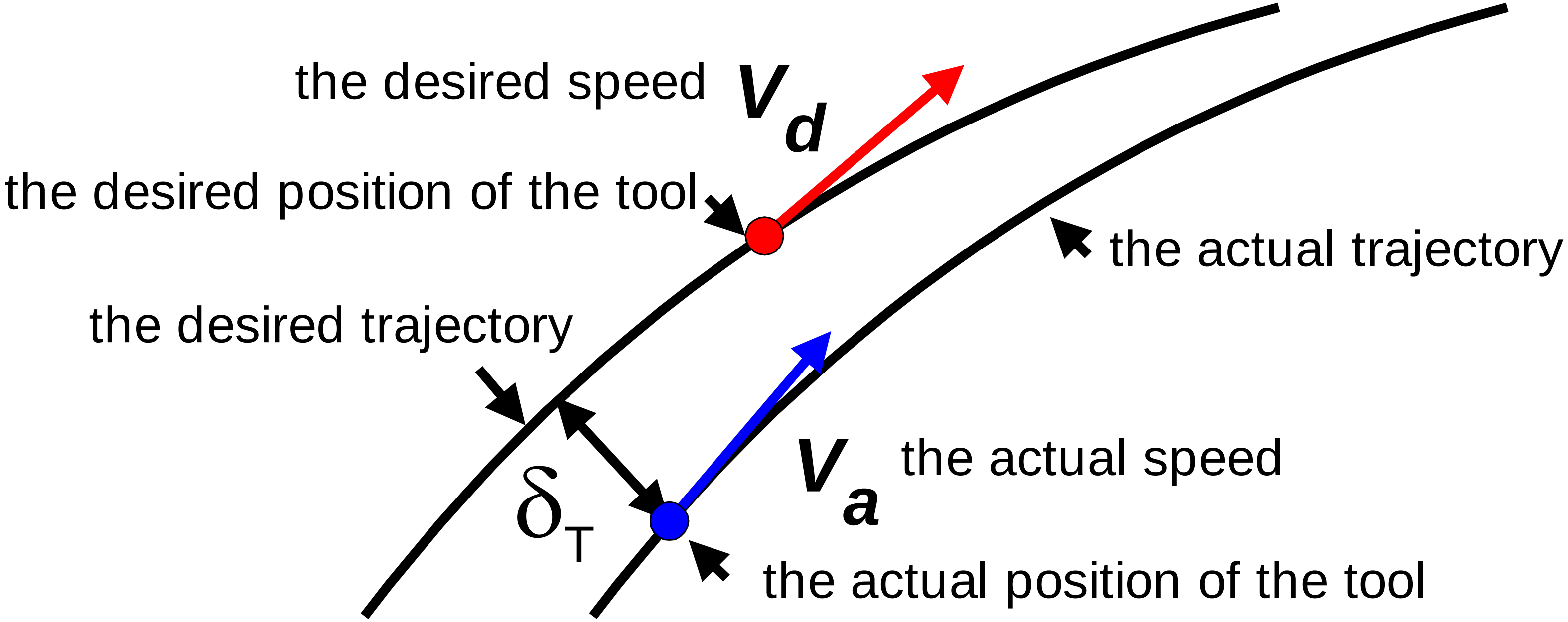
Accuracy and performance requirements to robotic milling

Accuracy and performance of milling process are interconnected.
An increase in performance is possible until the accuracy requirement of milling is met

$$|\delta_T| \leq \delta_{T.ADM},$$

δ_T – deviation of tool, measured normal to the desired trajectory of its movement;

$\delta_{T.ADM}$ – admissible deviation of tool.



The major factors, which reduce the accuracy of movements of technological manipulators and which limit their implementation:

- Imperfection of mathematical models, used for kinematic control of manipulator movements, discrepancy between them and real manipulators;
- Elastic compliance of manipulator links, defined by material properties of manipulator links and its base, and also by their geometrical features
- Dynamic imperfection of servo drives, low dynamic stiffness and accuracy due to kinematic errors and elastic compliance of gears;
- Dynamic stiffness, provided by position control system of manipulator;
- Errors of position sensors of manipulator links;
- Errors, caused by inaccurate linkage of manipulator coordinate system to coordinate system of the part which is being processed.

The ways of reducing factors, which decrease robots accuracy

Increase in accuracy of calibration process;

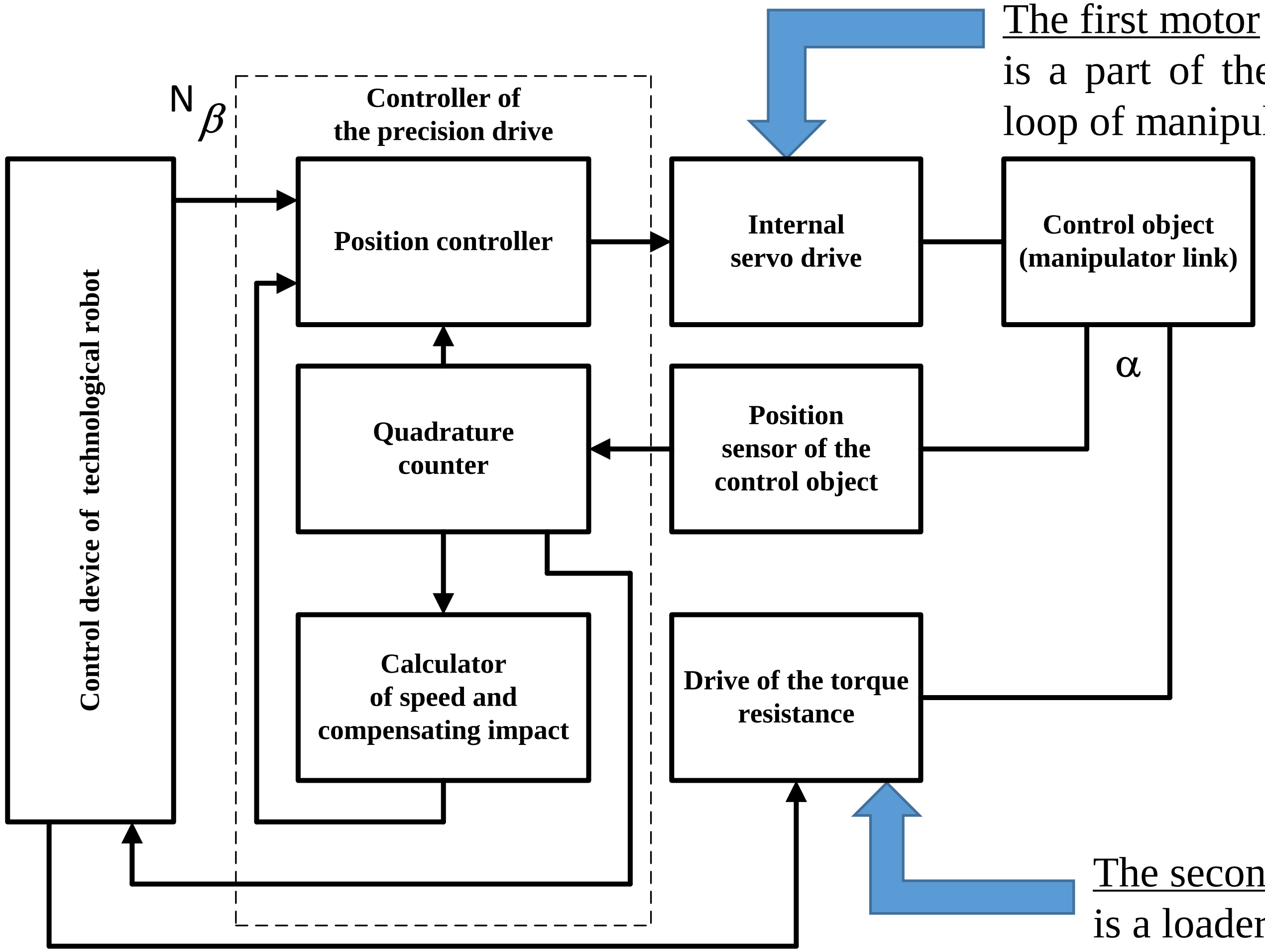
Variations in mechanical components of robot. Increase in quantity of metal of manipulation mechanism and application of other technological and design solutions, which may cause significant increase in costs of robotic system;

Increase in accuracy and stiffness of robot drives by the following methods:

- the usage of gearless drives (machine tool industry);
- Introduction of corrective and compensative control links and loops;
- Correction of reference impacts, set by CNC devices (machine tool industry).

An idea of constructing manipulator, which realizes robotic milling, on dual motor servo drives

Structure of precision servo drive with two interactively controlled motors:



The first motor

is a part of the primary servo drive, closed by a position control loop of manipulator link.

The structure of precision drive contains:

- 2 motors
- 2 position sensors
- 5 control loops

The second motor

is a loader, which generates torque, counteracting the primary motor.

The application of drives with such structure is accompanied by the following factors:

\+ increase in accuracy of robot motion along the desired trajectory

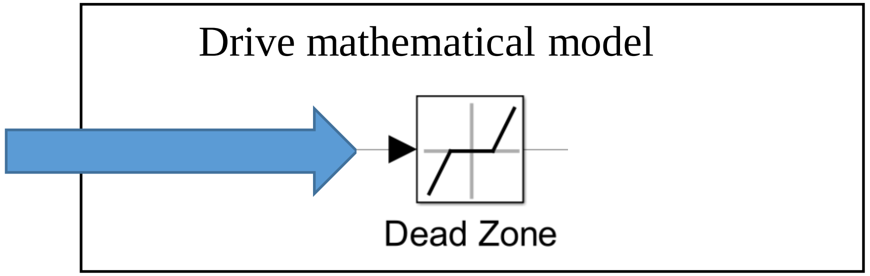
\+ significant increase in stiffness

\- appearance of intensive self-oscillations due to elastic gear with backlash, which is included into control loop

\- appearance of relatively low-frequent low damped oscillations in electromechanical subsystems

The condition of appearance of self-oscillations

Backlash of gear



Linearized equation of mechanical transmission:

$$M_{Tr} = C_{Eq}(1+T_G s)\left(\frac{\alpha_{in}}{i} - \alpha_{out}\right)$$

where $C_{Eq} = C_G q(A)_{MIN};\ T_G = \chi_G / C_G$

$$q(A)_{MIN} = f\left\{\frac{M_{Ex}}{C_G \sigma}\right\} = f\left\{\frac{\varphi}{\sigma}\right\}$$ varies from 0 to 1

when $M_{Ex} = 0, \quad q(A)_{MIN} = 0$ There are no structures and control algorithms which can guarantee the absence of self-oscillations without the loader

if $q(A)_{MIN} > 0,$ it is possible to get a drive with no self-oscillations

The influence of the external moment impact

The first task consists in selecting the torque of the drive of the loader so that variations of the coefficient q(A) are limited. So,

$$M_{load} \approx q(A)_{MIN}\,\sigma C_G$$

When $q(A)_{MIN} = 1$ the external moment impact results in the fact that the properties of the mechanical transmission with backlash approach the properties of the backlash-free transmission

- the drive has no static error, caused by elasticity and backlash of mechanical transmission
- High accuracy of movements of control object
- Static stiffness of the drive tends to infinity at the constant external torque.

The dynamic stiffness of the servo drive at the action of the varying moment of external forces can be increased as a result of the rational choice of the structure and the values of the controllers parameters.

The danger of appearance of low-damped oscillations.

Mechanical subsystem of the drive

$$W_0(s) = \frac{1+T_G s}{\omega_0^{-2} s^2 + 2\xi_0 \omega_0^{-1} s + 1}$$

$$\omega_0 = \sqrt{C_G / J_0} \qquad \xi_0 = 0.5 T_G \omega_0 = 0.05 \ldots 0.2$$

Electromechanical subsystem of the drive

The internal digital servo drive and the mechanical subsystem are dynamically interconnected and they form a unified dynamical electromechanical subsystem of the precision drive. The motor shaft of the internal drive is shifted under the action of the moment of reaction forces from the elastic gear side. Therefore, the value of the resulting stiffness of the electromechanical subsystem is reduced, and this fact causes the reduction in the resonant frequency of the electromechanical subsystem.

$$W_{EM}(s) = \frac{\alpha(s)}{U_2(s)} = \frac{1}{i \cdot k_{ps2}} \frac{1+T_G s}{(\omega_1^{-2} s^2 + 2\xi_1 \omega_1^{-1} s + 1)(1+T_{sd2} s)}$$

$$\omega_1 << \omega_0 = \sqrt{\frac{C_G}{J_0}} \qquad \xi_1 \approx 0.05 \ldots 0.2$$

Low-damped oscillations may appear

Taking measures for damping oscillations in order to increase performance and accuracy of the servo drive

Introduction of corrective velocity feedback loops of manipulator links to the inputs of internal servo drives

This fact leads to:

$$\xi_1 \rightarrow \xi_2 = 0.7...1$$

And the cutoff frequency of the opened precision drive

$$\omega_C \leq \omega_{1.}\xi_2 \quad > \quad \omega_C \leq \omega_{1.}\xi_1$$

It is advisable to adjust controllers of the internal drive so that their cutoff frequency in the opened position control loop is close to the minimum value of the frequency of natural oscillations of the mechanical subsystem:

$$\omega_{0.MIN} = \sqrt{C_P / J_{0.MAX}}$$

In order to increase dynamic stiffness and accuracy of the drive it is also feasible to increase the following parameters:

$\omega_C \uparrow$ $\omega_0 \uparrow$ $C_G \uparrow$ $i \uparrow$

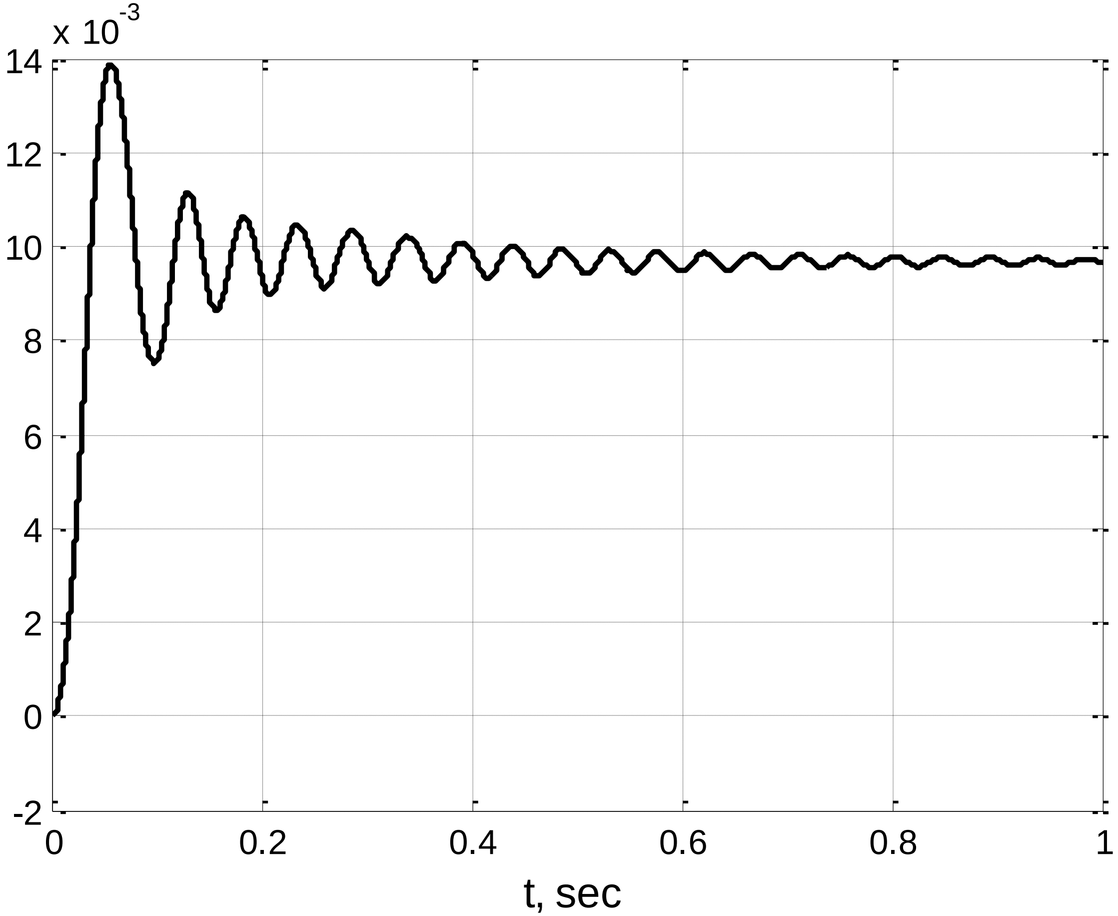
Parameter of drive	Parameter value	Размерность
Rated speed	4000	rpm
Rated torque	2	N*m
Inertia moment of the rotor	$5.7*10^{-5}$	$kg*m^2$
EMF coefficient of motor	0.577	Vs
Electromagnetic time constant	3.2	ms
Winding resistance	9.2	Ohm
Gear ratio	100	
Stiffness coefficient of gear	250000	Nm/rad
Backlash	1	arc min
Coefficient of viscous friction in gear	500	Nms/rad
Constant moment of the loader	45	N*m
Division value of the binary code LSB of the position sensor of the control object	$1.75*10^{-6}$	rad
PWM frequency in power converter	20	kHz
Resolution of the position sensor of the motor shaft	5000	discrete per revolution
Cutoff frequency of the internal servo drive opened by position control loop	105	rad/s
Inertia moment of the control object	10	$kg*m^2$

Motor B3.SM.000-4400 by KEB

Precision waveform gear HFUC-2A-50 by Harmonic Drive

The results of the computer simulation of the precision drive

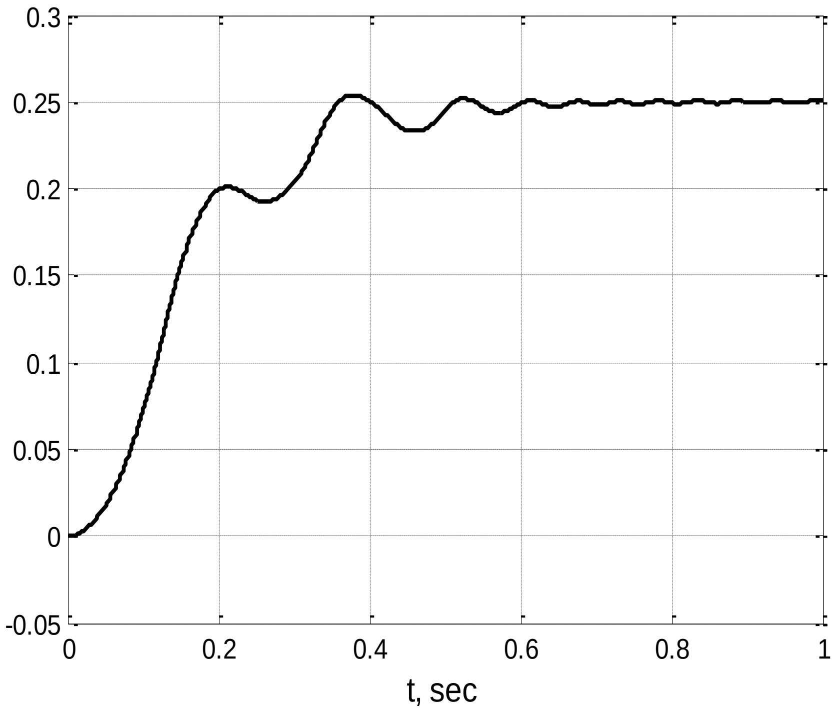
1) <u>The object is driven only by the internal drive, closed by a position control loop of the motor shaft</u>



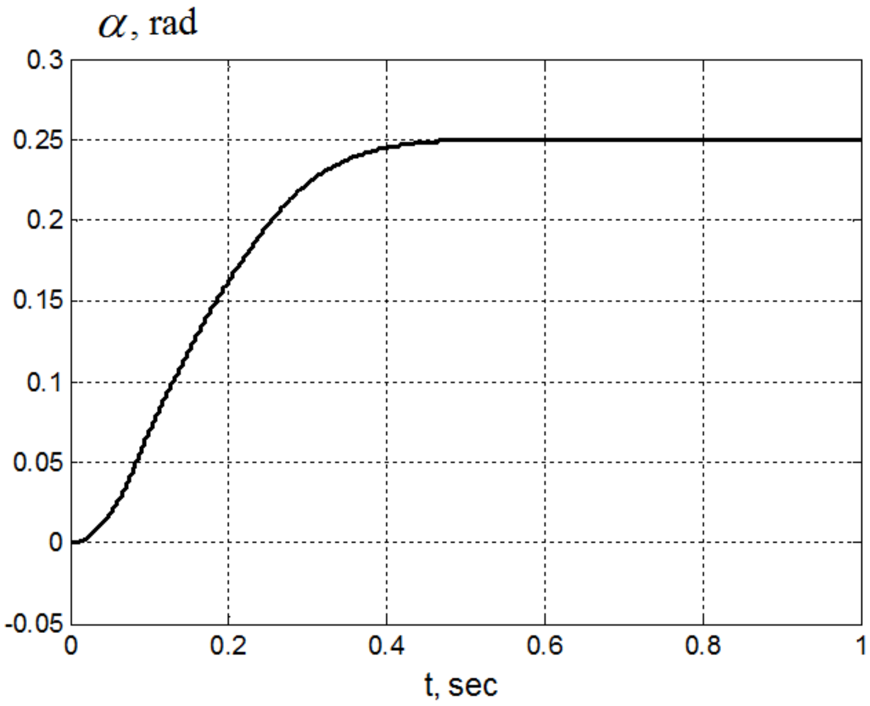
The transient process of position control of the control object by the internal drive without the corrective loop

<u>Conclusion</u>: low-damped electromechanical subsystem does not allow us to significantly increase accuracy of the servo drive, as it obliges us to limit its cutoff frequency.

2) <u>System response to the reference impact $\beta = 0.25$ rad of the control object angle at consideration of the precision servo drive closed by position control loop</u>



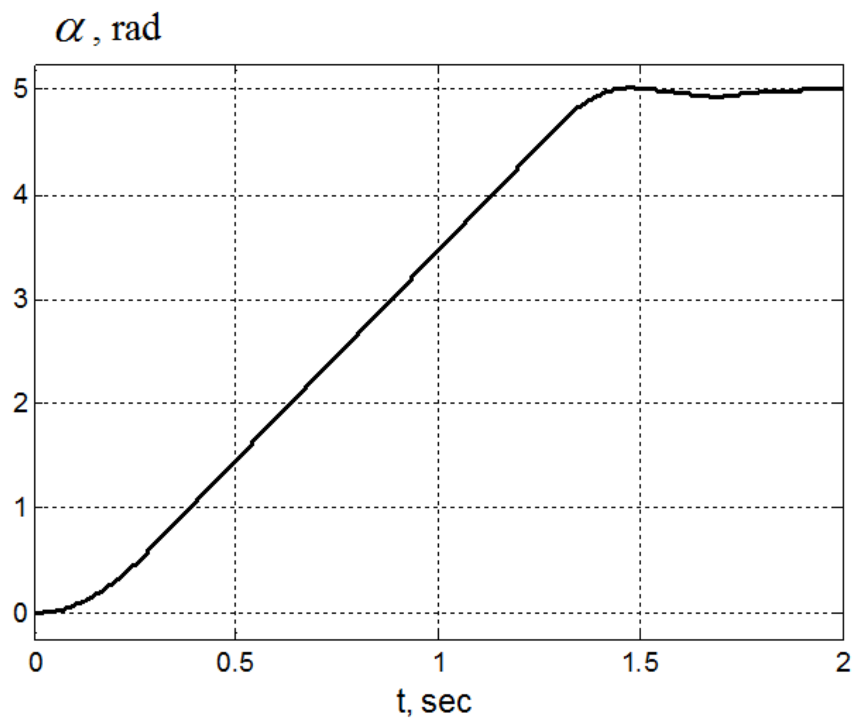
The transient process of position control of the control object by the precision drive without the corrective loop



The transient process of position control of the control object by the precision drive with the velocity corrective loop ($k_{OCC} = 9000$ c).

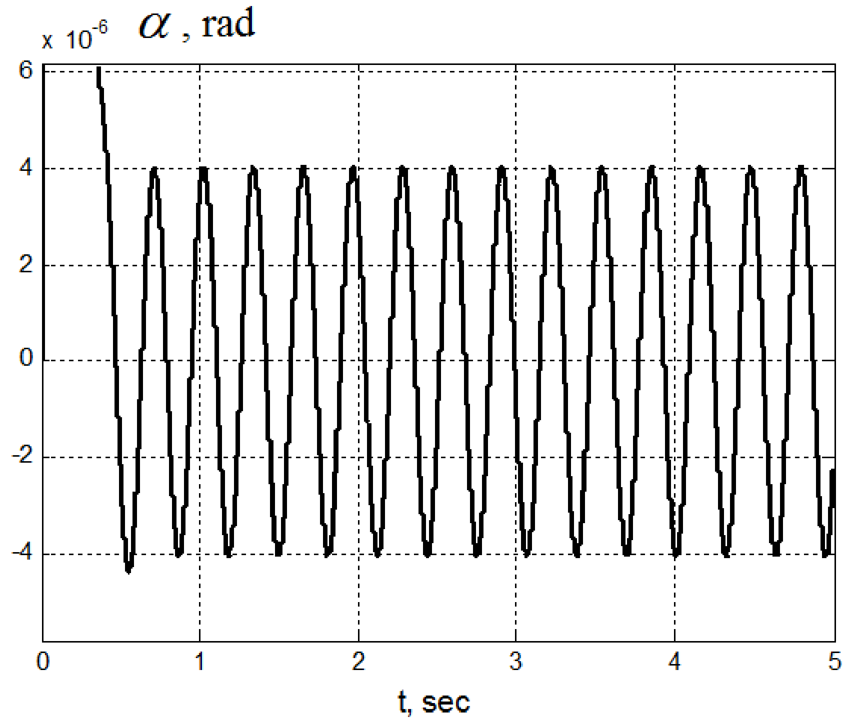
<u>Conclusion</u>: introduction of corrective velocity feedback loop of the control object allows us to completely damp oscillations, caused by elasticity of the gear.

3) System response to the step impact



A response of the precision drive to large initial error, when there is a velocity corrective feedback control loop of the control object and a nonlinear correction of the input impact of the position controller

4) System response to the harmonic disturbance impact

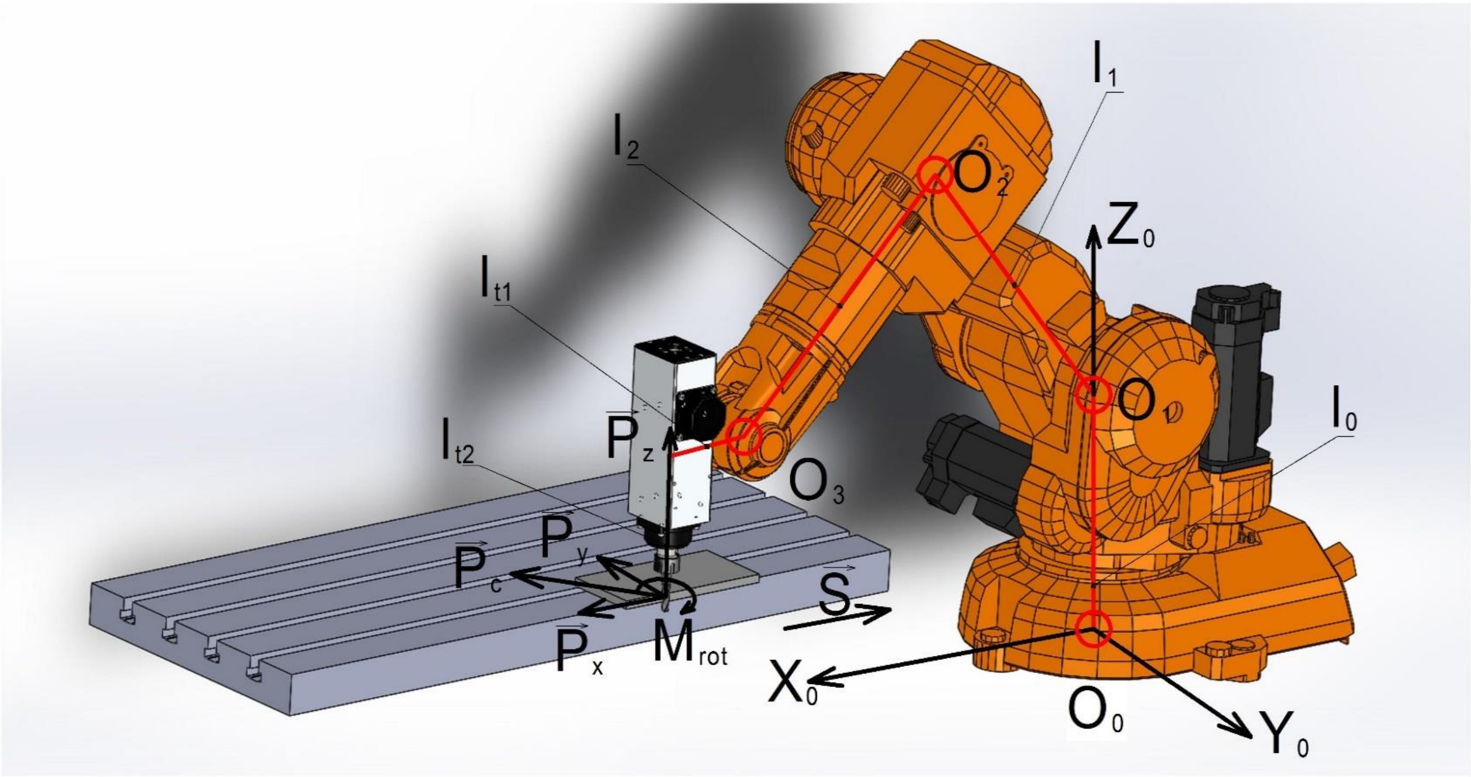


The error of the drive at harmonic variation of the moment of external forces with magnitude 1 Nm and frequency 20 rad/s

Conclusion: the suggested structure of servo drive allows us to significantly increase dynamic stiffness and controlled damping of control object oscillations. This kind of drive can be related to the class of high precision servo drives and it can be recommended for constructing technological robots.

The conditions of the computing experiment on comparison of the errors arising at robotic milling process implemented by manipulator, built on dual motor drives and manipulator, built on traditional drives with one motor

1. Dynamic model of the manipulator, designed to perform cylindrical up-milling of the lateral surface of the workpiece



Manipulator parameters

Parameter	Value
Mass of the «shoulder» link, m_1, kg	38
Length of the «shoulder» link, l_1, m	0.68
Mass of the «elbow» link with load, m_2, kg	35
Length of the «elbow» link, l_2, m	0.68
l_0, m	0.68
l_{t1}, m	0.1
l_{t2}, m	0.2

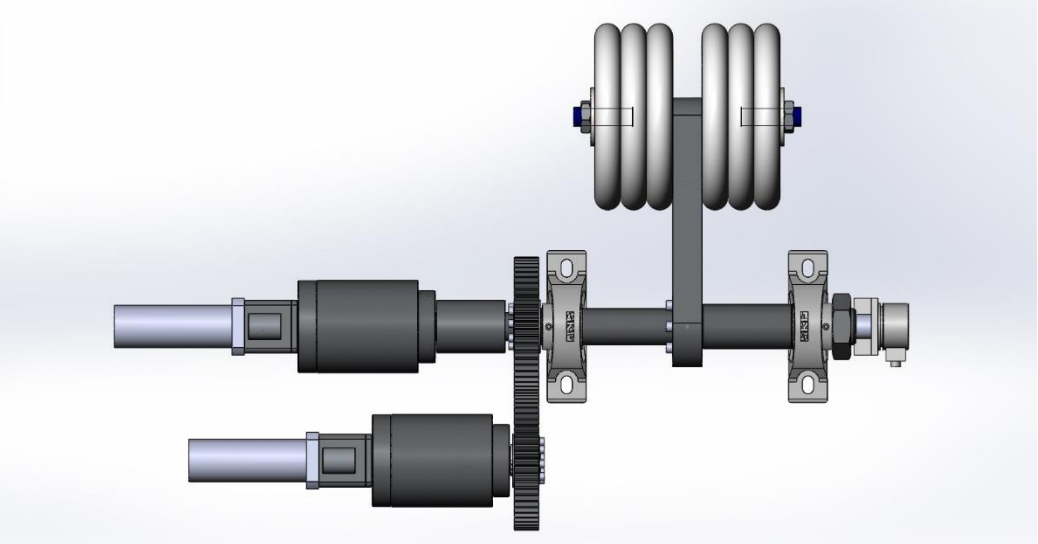
There is an admission that the links of manipulator mechanism are absolutely rigid. The milling process occurs when the configuration of the manipulator, characterized by the angle between the "shoulder" and "elbow" links, is approximately equal to 45°.

2. Parameters of dual-motor drives (motors and gears) of the «shoulder», the «elbow» and the column links of robot.

Parameters of dual motor drive	The drive of the «shoulder» and column links		The drive of the «elbow» link	
	The value of the parameter	Dimension	The value of the parameter	Dimension
Model of the motor of internal servodrive	KEB 44.SM.203-34B5	-	KEB 42.SM.203-34B5	-
Rated power	2,67	kW	1.44	kW
Rated torque	8.5	Nm	4.6	Nm
Rated speed	3000	min^{-1}	3000	min^{-1}
Model of the gear of internal servodrive	Harmonic Drive HFUC-50-2A-GR	-	Harmonic Drive HFUC-40-2A-GR	-
Gear ratio	120	-	120	-
Stiffness coefficient of gear	400000	Nm/rad	130000	Nm/rad
Natural frequency of mechanical subsystem	43	Rad/s	69	Rad/s
Backlash	1	arc min	1	arc min
PWM frequency of the power converter	16	kHz	16	kHz
Resolution of the resolver (of the motor shaft)	2047	discrete/rev.	2047	discrete/rev.
Resolution of the encoder (of the manipulator link)	250000	discrete/rev.	250000	discrete/rev.

Loader parameters

	The drive of the «shoulder» and column links	The drive of the «elbow» link
Model of the motor of internal servodrive	KEB 44.SM.203-34B5	KEB 42.SM.203-34B5
Model of the gear of internal servodrive	Harmonic Drive HFUC-50-2A-GR	Harmonic Drive HFUC-40-2A-GR
Gear ratio	120	120
The moment, generated by the loaders, Nm	11.6	3.8



3. Parameters of drives with one motors (motors and gears) of the «shoulder» and the «elbow» links of robot.

Parameters of drive with one motor	The drive of the «shoulder» and column links		The drive of the «elbow» link	
	The value of the parameter	Dimension	The value of the parameter	Dimension
Model of the motor of internal servodrive	KEB 44.SM.203-34B5	-	KEB 42.SM.203-34B5	-
Model of the gear of internal servodrive	Harmonic Drive HFUC-50-2A-GR	-	Harmonic Drive HFUC-40-2A-GR	-

4. Cutting parameters

Parameters	designation	Value
Material of the part	-	D16T / 2024 (AlCu4Mg1)
Number of teeth of the milling cutter	z	5
Diameter of the milling cutter, mm	D	6
Length of the working part of the cutter, mm	B	12
Angle of the helical chip grooves	ω	20°
Rotation frequency of the tool, rpm	n	10000
Cutting width, mm	-	12
Trajectory length, mm	-	200

The empirical formula for determining the peripheral cutting force

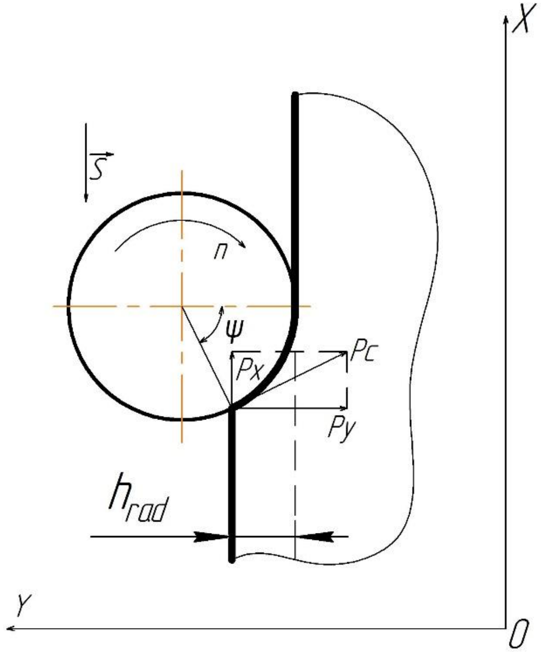
$$P_c = \frac{2.5 \cdot C_p B \cdot z^{0.25} \cdot K_{mp}}{D^{0.73} n^{0.62}} h^{0.85} S^{0.75}$$

$$\Psi = \arccos\left(\frac{D}{2} - h\frac{2}{D}\right)$$

$$P_x = P_c \cos\Psi$$

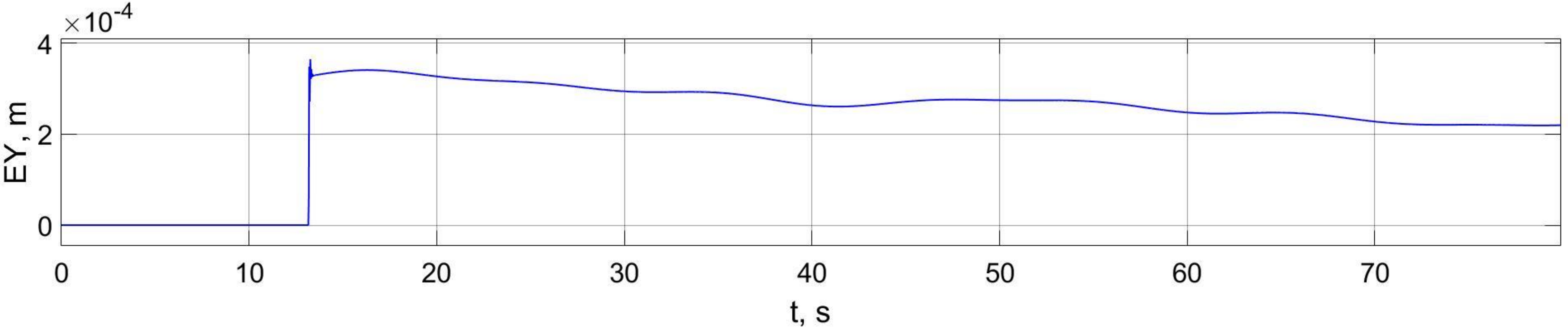
$$P_y = -P_c \sin\Psi$$

$$P_z = 0.4 \tan\left(\omega \frac{\pi}{180}\right)$$

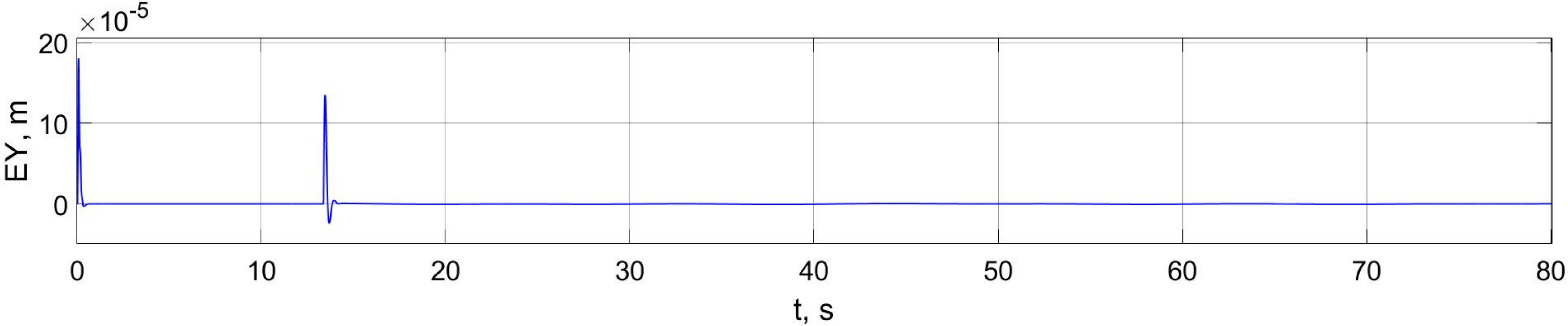


Cp – empirical coefficient, which is chosen depending on the type of milling cutter and the material of the cutting tool;
Kmp – the correction factor which takes into account the influence of the quality of aluminum alloys on the force dependence;
h – depth of cutting, mm;
S – feed velocity, m/s.

4. The results of the computing experiment (simulation). The transient processes.

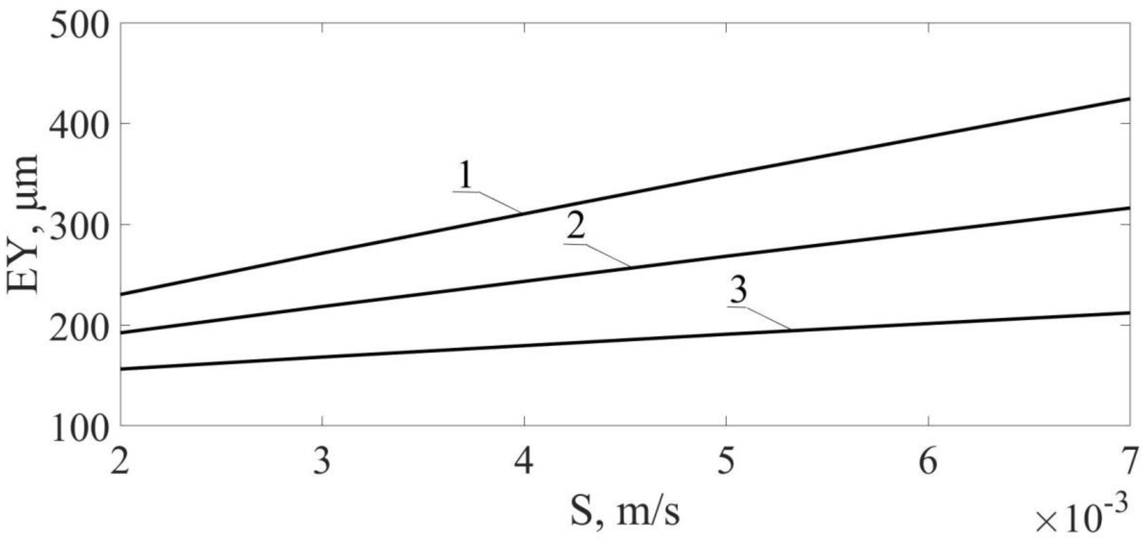


The error of the manipulator with drives with one motor, measured along OY axis, taking into account surface roughness of the workpiece.

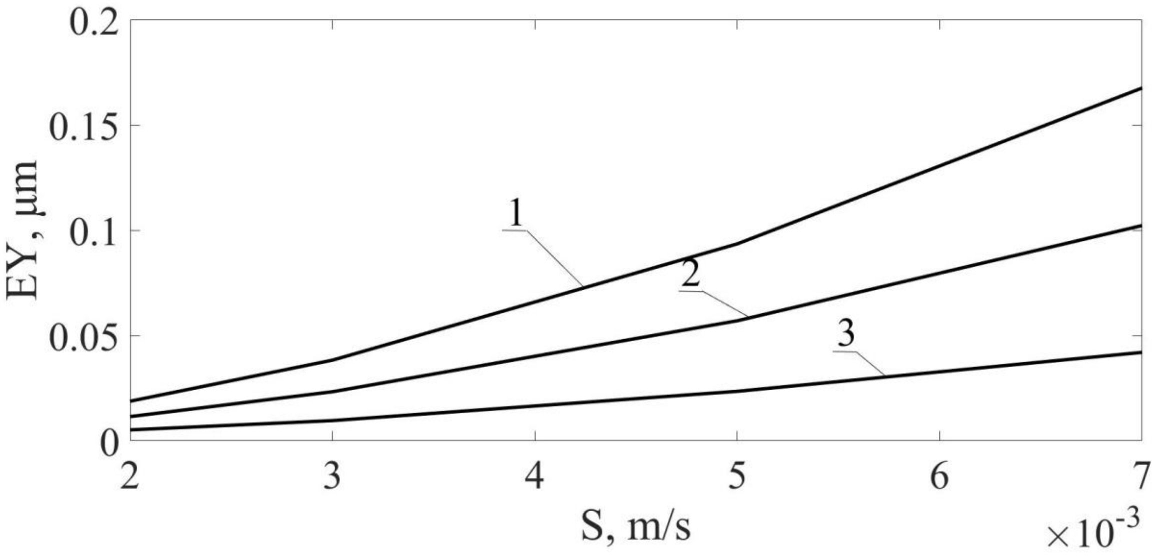


The error of the manipulator with dual motor drives, measured along OY axis, taking into account surface roughness of the workpiece.

<u>5. Changes of manipulator deviation from the trajectory at different cutting parameters</u>



The dependence of the deviation from the trajectory of the manipulator built on drives with one motor at different values of the cutting depth and feed velocity:
1 – at h = 1.5 mm,
2 – ath = 1 mm, 3 – at h = 0.5 mm.



The dependence of the deviation from the trajectory of the manipulator built on dual motor drives at different values of the cutting depth and feed velocity :
1 – at h = 1.5 mm,
2 – ath = 1 mm, 3 – at h = 0.5 mm.

$$\left|\delta_T\right|_{avrg} = \frac{1}{T}\int_0^T \left|\delta_T(t)\right| dt$$

The average value of the absolute value of the deviation of tool from the trajectory, measured along the normal direction to the processed surface.

6. Variations of the linear stiffness value of manipulator, measured along the normal direction to the processed surface, at different cutting parameters and at system nonlinearities

$$C_y = \frac{F_y}{\Delta_y}$$

F_y – cutting force component, acting along the direction normal to the processed surface;

Δ_y – deviation of the manipulator tool from its desired position measured along the direction normal to the processed surface.

S, m/s	**Linear stiffness of the manipulator along OY axis, N/m**					
	at h = 0.5 mm		at h = 1 mm		at h = 1.5 mm	
	manipulator with dual motor drives	manipulator with one motor drive	manipulator with dual motor drives	manipulator with one motor drive	manipulator with dual motor drives	manipulator with one motor drive
0.002	141330000	101840	288370000	175270	452550000	227900
0.003	95870000	131000	195530000	214580	306420000	269240
0.005	58380000	176100	119020000	268690	186300000	321740
0.007	41020000	210810	83840000	305760	131360000	355180

Conclusions of the simulation results

1. In order to increase accuracy and performance of robotic milling technological robots based on dual motor servo drives, closed by position control loops of the manipulator links, can be used.
2. In order to improve the dynamic parameters of such robots it is advisable to apply impedance control, implemented at the introduction of velocity corrective control loops of manipulator links.
3. The proposed solution allows us to significantly increase the static and dynamic stiffness of the robot by control means without any changes in mechanical robot components. This fact gives an opportunity to weaken the influence of cutting forces on tool deviation from the desired trajectory, and to improve the performance of robotic milling on this basis.
4. The results of computing experiments have shown a considerable increment of accuracy and tenfold gain in performance of the suggested solution in comparison with the robot with traditional structure of servo drives, closed by position control loops of their motor shafts.