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# AN ADJUSTABLE ELECTRIC DRIVE OF COORDINATE SYSTEMS OF LASER INSTALLATIONS: SIMULATION MODELING IN THE MATLAB SIMULINK PACKAGE

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**Keywords:** adjustable electric drive; circuit flaw; coordinate system; information-measuring and control system; laser installations; over adjusting; position circuit; velocity control range.

**Abstract:** The paper describes the relevant course of the native machine-tool industry development – the implementation of laser technological installations. The features of designing the coordinate systems of laser installations are considered. An original block diagram of an adjustable electric drive with an information-measuring and control system, which is characterized by increased efficiency indicators, is presented. A simulation model of the coordinate system of a laser facility in the Matlab Simulink program is presented.

## Introduction

Equipping Russian enterprises with modern high-tech equipment is one of the primary tasks due to the need of replacement and modernization of the main stock of the native industry.

Restrictive measures of a political and economic nature, introduced by various countries of the world in response to the foreign policy of the Russian Federation, lead to the need to restructure the state economy and production policy. The main directions of the domestic industry development are import substitution and import advance [1, 2].

The policy of import substitution and import advance should be aimed not only at import substitution in quantitative terms, but also at promoting the development of new and modernization of existing technologies.

The relevant development direction of machine-tool enterprises of private and public economic sectors is the creation of the material and technical enterprise independence, specifically the production of the necessary components on the enterprise basis.

A promising direction in the development of machine tools is the development and production of precision and ultra-precise laser proceeding centers (hereinafter referred to as laser installations). Modern laser installations are complex automated systems, which can be divided into two large groups by their functions [3, 4].

Laser installations included in the first group traditionally use laser radiation sources. The average power of a laser tool used in such installations is units of kilowatts. The main field of application of laser systems is the machine-building, instrument-making and machine-tool industries. Laser systems can be used for welding parts, cutting sheet metal of special strength, drilling, etc.

Modern developments of high-power technological lasers and systems for automated control and management of technological processes have made it possible to use laser welding in tasks that were previously considered unpromising for laser technologies. For example, welding of car body panels, fabrication and joining of building frames, welding of spatial structures, etc.

The next group includes installations with less powerful lasers, where, in addition to the energy capabilities of the laser beam, other properties of laser radiation are often used, such as spectral selectivity, energy distribution over time, etc.

The application area of such laser systems is extremely diverse, for example, artistic cutting of sheet material (wood, metal, plastic), engraving and marking of finished products, scribing, spot hardening, dimensional processing, etc.

Compared to traditional cutting methods, the use of laser systems is due to a number of significant advantages: absence of mechanical impact on the processed material; performing complex circuit cutting with materials of any hardness and thickness (no need for additional heat treatment of the material); cleanliness of the workpiece cut and absence of internal mechanical strain; high cutting accuracy (positioning); non-waste and high productivity.

When designing and manufacturing laser systems, the most time-consuming and expensive part is the coordinate system, which consists of a set of electric drives that move the laser tool, a kinematic scheme, sensors, and an optical system [3].

An important direction in the development of laser installations is to increase the efficiency of information-measuring and control systems (**IMCS**) of an adjustable electric drive. For adjustable electric drives applicable as part of the coordinate systems of laser systems, the main technical and economic indicators are: control range, velocity, reliability and cost.

As part of the research activities of the department KB-6 "Instruments and information-measuring systems" (MIREA – Russian Technological University), the authors developed the original structure of the electric drive IMCS of increased efficiency [5].

The developed IMCS of the electric drive is characterized by increased velocity, simplified tuning algorithm, reduced product price and increased reliability while maintaining all the necessary technical characteristics [5, 6].

According to practical and theoretical tests, the electric drive of the coordinate system of the laser installation with the developed IMCS of increased efficiency has a velocity control range of 10000 and a frequency bandwidth (of the velocity circuit) of 123 Hz. The obtained technical characteristics of the electric drive with the developed IMCS are not inferior to systems based on scalar control, but have higher reliability indicators and reduced cost [6].

The experience in the development of electric drives has shown that the preliminary synthesis of controllers and the analysis of transient processes of the system are a necessary, but not a sufficient step in the design of technological machines. To refine the parameters of the increased efficiency electric drive of the developed IMCS as part of the coordinate system, it becomes necessary to study interconnected electric drives. The accuracy of processing of a given trajectory of movement on a plane by a laser installation is one of the main indicators of the quality and performance of the entire system.

In accordance with the technical requirements of laser systems and GOST 27803–91 “Controlled electric drives for metal-cutting equipment and industrial robots”, the main quality criteria for tracking electric drives of coordinate systems are the frequency bandwidth of the position circuit, the absence of overregulation in the position circuit and the magnitude of the circuit error.

## Simulation model of the coordinate system

According to the study of simulation models of machine tool coordinate systems [4, 7, 8], the simulation model of interconnected electric drives includes an electric motor model, an IMCS model, and sources of position setting signals.

The disadvantages of existing models include the lack of consideration of the kinematic scheme (linear displacement transducer), the absence of the influence of the quantization effect in the position sensor model, the use of the model of a magnetoelectric DC motor (**MMDC**) as an object of regulation. Given these flaws, we will develop a simulation model of a coordinate system with an IMCS of an electric drive of increased efficiency.

In laser installations, the executive body is a set of technical means that form a coordinate system, the task of which is to move the laser tool relative to the surface of the work piece. The executive instruments of laser systems are ball screws and linear electric motors.

In this report, we will study the developed IMCS of increased efficiency as part of the coordinate system of a laser installation with a simulation model of the ball screw type executive mechanism.

The simulation model of a ball screw is often presented as a two-mass system with elastic links [9, 10]. The mathematical description of the longitudinal feed drive with elastic links is based on Newton's second law for rotating masses (1):

$$\begin{cases} M_1 - M_{c1} - M_{12} = J_1 \dfrac{dw_1}{dt}; \\ M_{12} = C(\varphi_1 - \varphi_2); \\ M_{12} - M_{c2} = J_2 \dfrac{dw_2}{dt}, \end{cases} \tag{1}$$

where $J_1$, $J_2$ are the moments of inertia of the first and second masses; $C$ is the coefficient of rigidity; $w_1$, $w_2$ are the angular velocity of rotation of the first and second masses; $M_{c1}$, $M_{c2}$ are the static moments due to friction and load on the second mass; $M_{12}$ is the moment of elastic interaction; $\varphi_1$, $\varphi_2$ are the rotation angles of the first and second masses.

To increase reliability and accuracy, and improve dynamic and operational characteristics, the leading international and domestic manufacturers use permanent magnet synchronous motors (**PMSM**) as part of the coordinate systems of laser systems. The use of PMSM is the most promising in the range of low and medium powers, which brings its characteristics closer to a DC motor (**DCM**), which is considered referential [11].

According to [6, 11, 12], the PMSM mathematical model consists of general differential equations describing the physical processes occurring in the engine (2):

$$\begin{cases} U_A \sin(\theta) = RI_A(\theta) + L\dfrac{dI_A(\theta)}{dt} + \Phi_0 \omega k_{\text{EMF}} \sin(\theta); \\ U_B \sin\left(\theta - \dfrac{2\pi}{3}\right) = RI_B(\theta) + L\dfrac{dI_B(\theta)}{dt} + \Phi_0 \omega k_{\text{EMF}} \sin\left(\theta - \dfrac{2\pi}{3}\right); \\ U_C \sin\left(\theta - \dfrac{4\pi}{3}\right) = RI_C(\theta) + L\dfrac{dI_C(\theta)}{dt} + \Phi_0 \omega k_{\text{EMF}} \sin\left(\theta - \dfrac{4\pi}{3}\right); \\ M_\Sigma = \left[ I_A(\theta)\Phi_0 \sin(\theta) + I_B(\theta)\Phi_0 \sin\left(\theta - \dfrac{2\pi}{3}\right) + I_C(\theta)\Phi_0 \sin\left(\theta - \dfrac{4\pi}{3}\right)\right] k; \\ J\dfrac{d\omega}{dt} = M_\Sigma - M; \qquad \theta = \theta_0 + n\displaystyle\int_0^t \omega\, dt, \end{cases} \tag{2}$$

where $U_A$, $U_B$, $U_C$ are the voltage on the stator windings of a 3-phase machine; $R$, $L$ are the resistance and inductance of the windings; ω is the angular velocity of rotation of the engine; $M_\Sigma$ is total electromagnetic moment; $M$ is the reduced moment; $\Phi_0$ is magnetic flux; θ is the angle of rotation of the motor rotor; $\theta_0$ is the initial angle of the motor shaft; $k$ is the electromechanical transmission coefficient; $k_{\text{EMF}}$ is the EMF transfer coefficient; $J$ is the moment of inertia on the motor shaft; $n$ is the number of pairs of poles. $I_A$, $I_B$, $I_C$ are the currents in the stator windings.

Based on the system of differential equations (2), which describes the electromechanical processes in a 3-phase machine, we will compose a general simulation model of the PMSM (Fig. 1).

We will develop a simulation model of the tracking electric drive with an increased efficiency IMCS. According to [5, 6], the simulation model of the tracking electric drive should include the following blocks: current regulators, velocity and position controllers, module selection block, multiplication block, pulse-width modulator, power converter, feedback sensors (current, velocity, position) and etc.

From the general theory of the electric drive [13], conventionally approximated the power converter circuit (transistor unit), PWM and logic switch by a first-order aperiodic link, the transfer function of which has the form:

$$W_{\text{PC}}(s) = \frac{k_{\text{PC}}}{1 + T_{\text{PC}} s} = \frac{k_{\text{PC}}}{1 + 2T_{\text{PWM}} s}, \tag{3}$$

where $k_{\text{PC}}$ is the transmission coefficient of the power converter; $T_{\text{PC}}$ is the time constant of the power converter ($T_{\text{PC}} = 2T_{\text{PWM}}$); $T_{\text{PWM}}$ is the period of the output pulses of the saw oscillator.

The transfer coefficient of the power converter $k_{\text{PC}}$ is calculated according to the equation

$$k_{\text{PC}} = \frac{U_{\text{sup}}}{U_{y\max}}, \tag{4}$$

where $U_{\text{sup}}$ is the maximum supply voltage of the power converter; $U_{y\max}$ is the maximum control voltage.

The transfer function of the current sensor can be represented as an amplifying link

$$W_{\text{CS}}(s) = k_{\text{CS}}, \tag{5}$$

where $k_{\text{CS}}$ is the current sensor transfer coefficient.

The transfer coefficient of the current sensor $k_{\text{CS}}$ is calculated according to the equation

$$k_{\text{CS}} = \frac{U_{\text{CR}}}{2 i_{\text{a}}^{\text{r}}}, \tag{6}$$

where $U_{\text{CR}}$ is the maximum output voltage of the current regulator; $i_{\text{a}}^{\text{r}}$ is the rated current of the motor armature.

The transfer function of the velocity sensor (tachogenerator) without taking into account the rigidity of the clutch with the rotor and the time constant of the switching circuit can be represented as an amplifying link of the form

$$W_{\text{VC}}(s) = k_{\text{VS}}, \tag{7}$$

where $k_{\text{VS}}$ is the transmission coefficient of the velocity sensor;

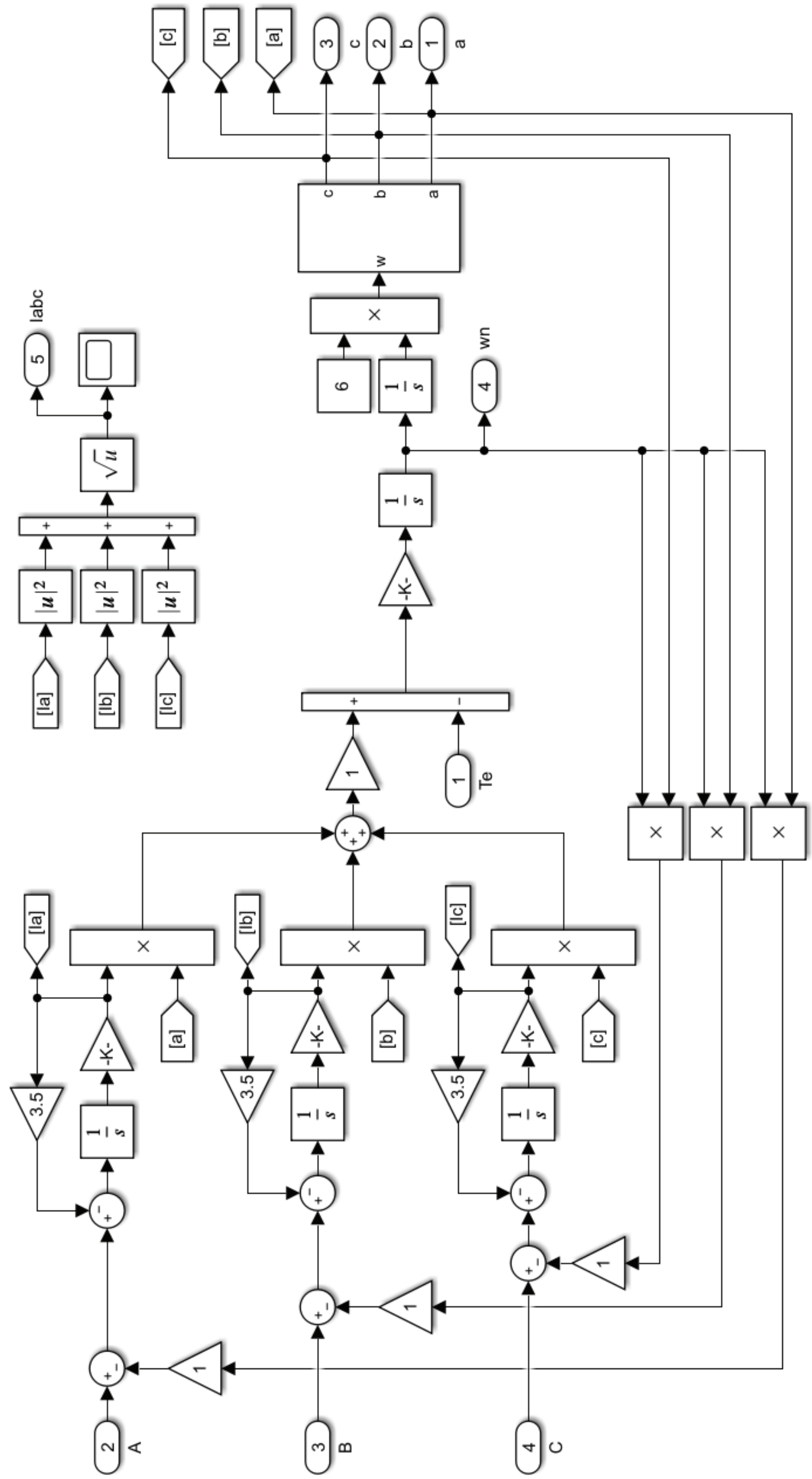



**Fig. 1. PMSM simulation model (Matlab Simulink)**

$$k_{CS} = \frac{U_{VC}}{\omega_{max}}, \quad (8)$$

where $U_{VC}$ is the maximum output voltage of the velocity controller; $\omega_{max}$ is the maximum angular velocity of the engine.

According to [6, 14, 15], the current and position controllers are adjusted to the technical optimum, and the velocity controller to the symmetrical optimum.

Based on experimental studies of electric drives, it was revealed that electric drives have the best velocity, the current controller in which has the transfer function of the amplifying link (proportional controller). Then the desired transfer function of the torque controller will take the form:

$$W_{CS}(s) = \frac{R\, i_a^r\, U_{y\max}}{T_{PC} U_{sup} U_{CR}} = k_{CR}\,. \quad (9)$$

In accordance with the setting of the velocity controller for a symmetrical optimum, its transfer function is determined by the equation

$$W_{VS}(s) = \frac{J\, k_{CS}(8T_{PC}s + 1)}{32kT_{PC}^2 k_{VS} s}. \quad (10)$$

According to the condition of the technical optimum, the transfer function of the position controller defined as

$$W_{PC}(s) = \frac{k_{CS}}{8k_{PS}T_{PC}}, \quad (11)$$

where $k_{PS}$ is the transfer coefficient of the position sensor.

The developed simulation model of a tracing electric drive with an electric motor KM-090-32-02 and an increased efficiency IMCS is shown in Fig. 2.

The simulation is carried out with the following parameters: $R = 3.5$ Ohm, $L = 3.4$ mH, $k_v = 1$ V·s/rad; $k_m = 1$ N·m/A; $k_{EMF} = 1$ V·s/rad; $J_1 = 0.00079$ kg·m$^2$; $U_{sup} = \pm 150$ V; $k_{CS} = 2$ V/A; $k_{VS} = 0.066$ V·s/rad; $k_{PS} = 1\,000\,000$ dis/μm; $k_{PC} = 0.055$; $k_{VS} = 25\,000$; $T_{VS1} = 0.05$ s; $T_{VS2} = 10$ s; $k_{PC} = 50$; $C = 510$ N·m$^2$; $\beta = 0.23$ N·m·s/rad; $J_2 = 0.00035$ kg·m$^2$; $k_r = 0.00066$ m·s/rad. Bogatsky–Champin integration method with a step $5 \cdot 10^{-6}$.

We study the simulation model (Fig. 2) relatively to the frequency bandwidth. According to clause 2.5.6 of GOST 27803–91, the frequency bandwidth of the position curcuit must be at least 5 Hz for thyristor and at least 10 Hz for transistor electric drives. We determine the frequency bandwidth of the position curcuit of the electric drive with a sinusoidal input signal for setting the position with an amplitude of 1000Δ (0.1 mm) and frequencies of 1, 5, 10 and 11 Hz (Fig. 3). The REB bandwidth is determined in the linear zone of the regulators and without additional moment of inertia.

Based on the simulation results (see Fig. 3), it can be affirmed that the bandwidth of the tracing electric drive of a laser system with an increased efficiency IMCS will be 11 Hz, which satisfies clause 2.5.6 of GOST 27803–91.

Next, we study the system with respect to the conditions of c. 2.5.7, 2.5.9 GOST 27803–91. The simulation results are shown in the form of graphs of position transients (Fig. 4) with input 1000Δ, $1 \cdot 10^4$Δ, $1 \cdot 10^5$Δ, $1 \cdot 10^6$Δ.

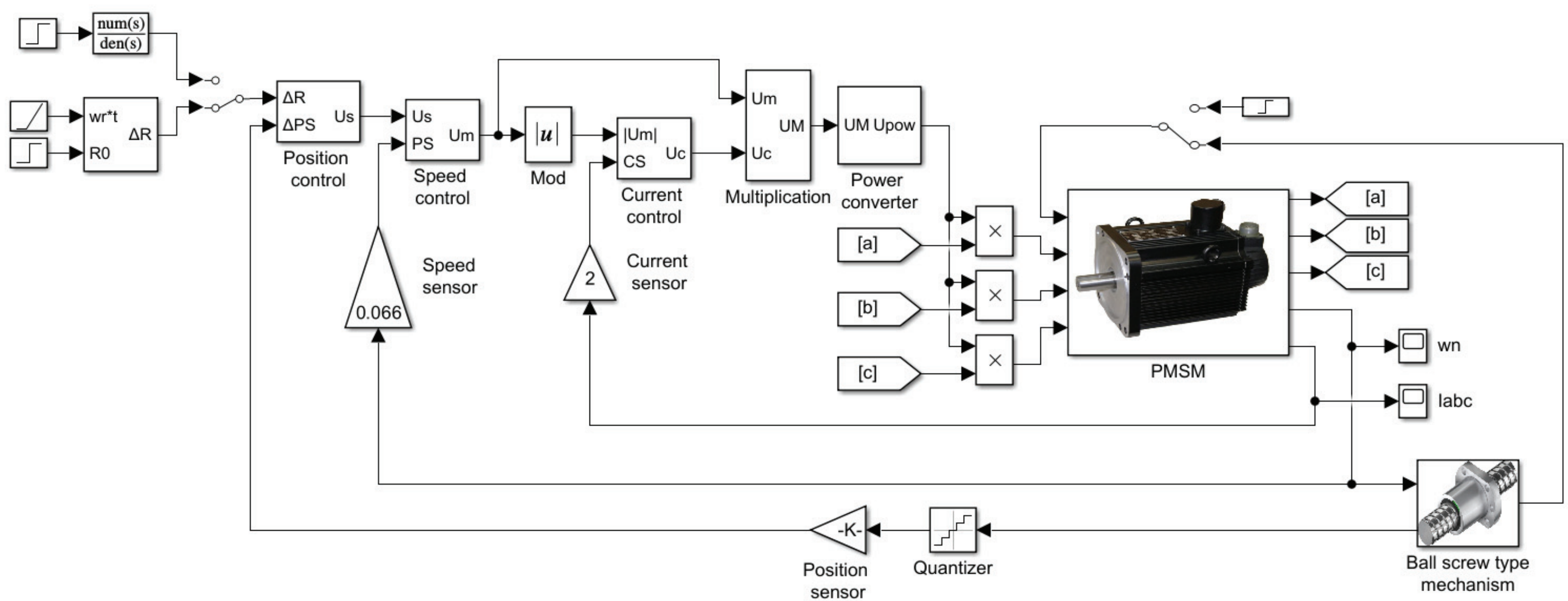



Fig. 2. Simulation model of the electric drive (Matlab Simulink)

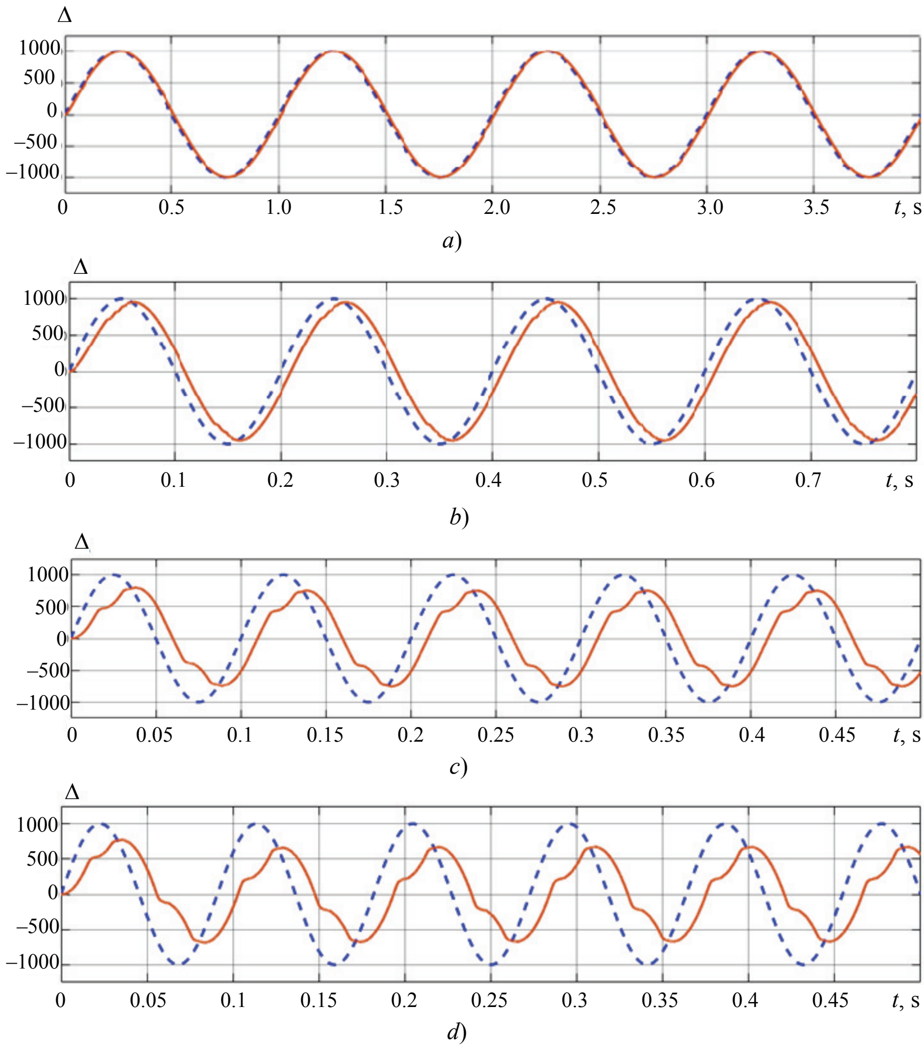


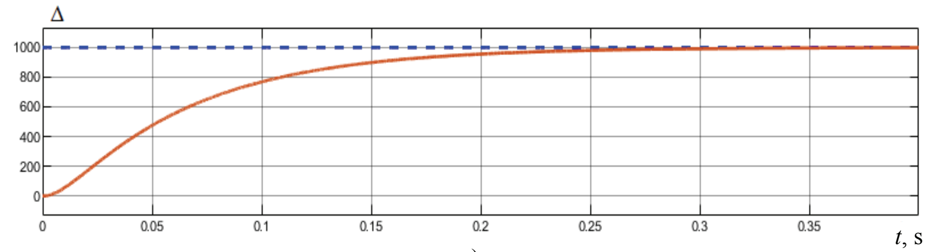

**Fig. 3. System response to a sinusoidal signal with an amplitude of 1000Δ and a frequency of 1 (*a*), 5 (*b*), 10 (*c*), 11 (*d*) Hz**
(shows the intermittent line that indicates the input signal of the setting position, the solid line indicates the output signal of the position sensor)

The resulting graphs of transient processes (Fig. 4) have no overregulation, which satisfies the conditions of c. 2.5.7, 2.5.9 GOST 27803–91 and indicates the correctness of the calculations.

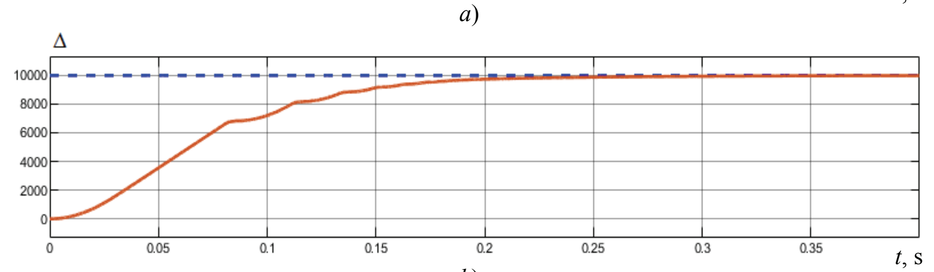
According to the considered methods [4, 7, 8] for assessing the quality of coordinate systems, we will develop a simulation model of interconnected electric drives with the developed IMCS of increased efficiency and an actuator of the ballscrew type mechanism (Fig. 5).

Let us study the developed simulation model of the coordinate system (Fig. 5) relatively to the circuit error $\Delta_c$ .

It is known that the main trajectories of motion in laser systems are straight and complex trajectories, which can be approximated by a set of straight lines and circles of different diameters [4, 15, 16].




*a*)

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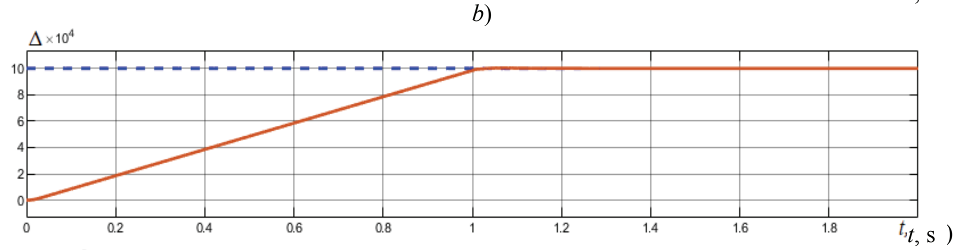
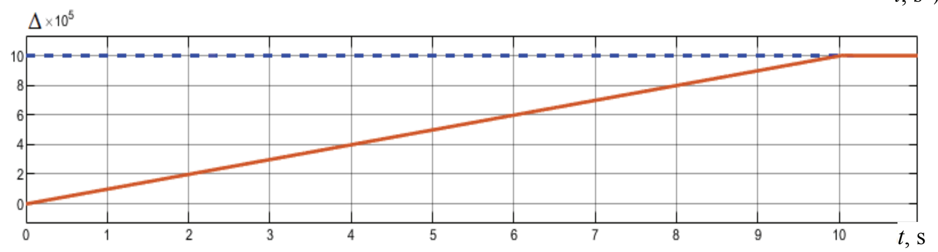



*d*)

**Fig. 4. System response to impulse impact**
**with an amplitudes of 1000Δ (*a*), 1·10^4Δ (*b*), 1·10^5Δ (*c*), 1·10^6Δ (*d*)**
(shows the intermittent line that indicates the input signal of the setting position,
the solid line indicates the output signal of the position sensor)

The circle processed by the laser beam during circular interpolation is given by the following parametric equations [4, 16]:

$$x_{\text{giv}}(t) = R_0 \sin(\omega_c t); \quad y_{\text{giv}}(t) = R_0 \cos(\omega_c t), \tag{12}$$

where $\omega_c$ is the circuit velocity of movement along the circle radius $R_0$.

A simplified equation for determining the circuit error $\Delta_c$ when processing a circle can be determined from the expression [4, 8]

$$\Delta_c = R_0 \left[ 1 - \sqrt{1 + \left( \frac{V_c}{R_0 K_V} \right)^2} \right], \tag{13}$$

where $V_c$ is the circuit velocity of the circular trajectory of the laser spot; $K_V$ is the quality factor of tracing electric drives ( $K_V = K_{Vx} = K_{Vy}$ ).

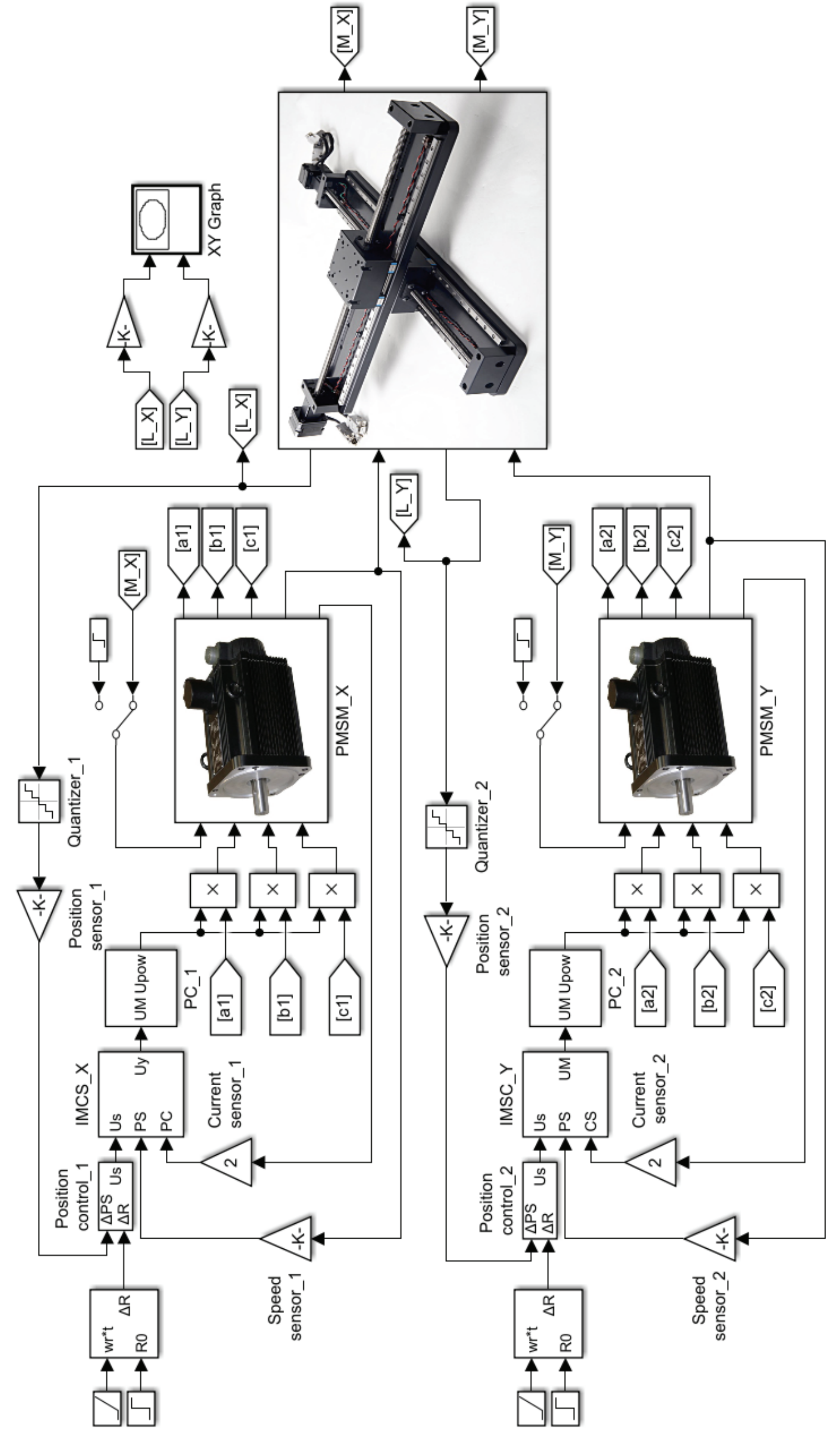



**Fig. 5. Simulation model of the coordinate system of the laser machine (Matlab Simulink)**

We represent the circuit velocity $V_c$ as the product of the circle radius $R_0$ and the angular velocity $\omega_c$, then

$$V_c = \omega_c R_0 . \quad (14)$$

We transform the expression (14) with respect to the circuit velocity $V_c$

$$V_{c.adm} = R_0 K_V \sqrt{\left(1 - \frac{\Delta_c}{R_0}\right)^2 - 1} .$$

It follows from equation (14) that the circuit error increases with an increase in the circuit velocity and decreases with an increase in the radius of the circle and the quality factor of the electric drive.

We calculate the admissible circuit velocity $V_{c.adm}$ at $\Delta_c = \pm 5$ μm and a circle radius of 5000 μm (5 mm)

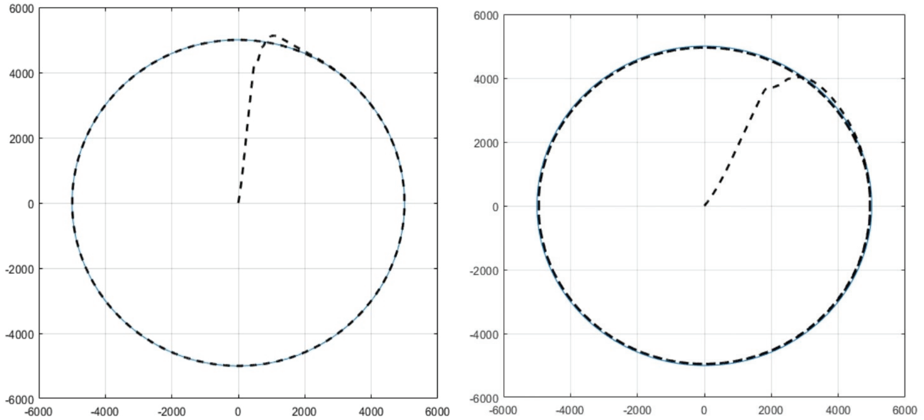
$$V_{c.adm} = 5000 \cdot 50 \sqrt{\left(1 - \frac{5}{5000}\right)^2 - 1} \approx 11000 \ \text{μm/s}.$$

Then the admissible angular velocity

$$\omega_c = \frac{11000}{5000} = 2.2 \ \text{rad/s}.$$

Using the built-in tools of Matlab Simulink, we will plot the trajectory of the laser spot (circle) by points (Fig. 6). On the *X* and *Y* axes, we apply the obtained data of the linear displacement sensor and the block for setting the position signal. Signals corresponding to parametric equations (12) are applied to the system input.

Analyzing the motion trajectories (Fig. 6), it can be seen that the contour error $\Delta_c$ will be the smallest at the input signal frequency ω = 2.2 rad/s and is less than 2 μm (this error is acceptable). At an input signal frequency ω = 10 rad/s, the contour error is more than 6 μm. In most laser systems, the circuit error should not exceed ±5 μm.




*a*) *b*)

**Fig. 6. Graphs of the trajectory of the laser spot:**
*a* – trajectories of movement at frequency ω = 2.2 rad/s;
*b* – movement trajectories at frequency ω = 10 rad/s

Based on the simulation results, it can be concluded that the theoretical adjustment of the current, velocity and position controllers of the developed increased efficiency electric drive IMCS is correct. The simulation results meet the requirements of c. 2.5.6, 2.5.7, 2.5.9 GOST 27803–91 and can be used when adjusting the coordinate system of a real laser facility.

## Conclusion

A comprehensive study of the simulation model of the coordinate system of the laser installation with the original IMCS of the electric drive with increased efficiency indicators, has been carried out. The basic expressions for calculating current, velocity and position controllers are given. The simulation was carried out in accordance with the conditions of clauses 2.5.6, 2.5.7, 2.5.9 of GOST 27803–91. The obtained results satisfy the conditions of GOST 27803–91, which indicates the accuracy of the calculations performed and the adequacy of the developed simulation model.

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## Регулируемый электропривод координатных систем лазерных установок: имитационное моделирование в пакете Matlab Simulink

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**Ключевые слова:** диапазон регулирования скорости; информационно-измерительная и управляющая система; контурная ошибка; контур положения; координатная система; лазерные установки; перерегулирование; регулируемый электропривод.

**Аннотация:** Дано описание актуального направления развития отечественного станкостроения – внедрения лазерных технологических установок. Рассмотрены особенности проектирования координатных систем лазерных установок. Приведена оригинальная структурная схема регулируемого электропривода с информационно-измерительной и управляющей системой, отличающейся повышенными показателями эффективности. Представлена имитационная модель координатной системы лазерной установки в программе Matlab Simulink.

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## Einstellbarer elektrischer Antrieb für Koordinatensysteme der Laser-Anlagen: Simulationsmodellieren im Matlab Simulink-Paket

**Zusammenfassung:** Es ist die aktuelle Entwicklungsrichtung der heimischen Werkzeugmaschinenindustrie beschrieben – die Einführung der lasertechnologischen Anlagen. Die Besonderheiten der Projektierung der Koordinatensysteme von Laseranlagen sind betrachtet. Angegeben ist das Original-Blockschaltbild des verstellbaren Elektroantriebs mit einem Informations-, Mess- und Steuerungssystem, das sich durch erhöhte Effizienzindikatoren auszeichnet. Es ist ein Simulationsmodell des Koordinatensystems einer Laseranlage im Programm Matlab Simulink vorgestellt.

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## Entraînement électrique réglable des systèmes des coordonnées laser: simulation d'imitation dans le package MATLAB Simulink

**Résumé:** Est donnée une description de la direction actuelle du développement de la construction de machines–outils nationales – l'introduction d'installations technologiques laser. Sont examinées les caractéristiques de la conception des systèmes de coordonnées des installations laser. Est cité le schéma structurel original de l'entraînement électrique réglable avec un système d'information, de mesure et de contrôle caractérisé par des indicateurs de performance améliorés. Est présenté un modèle de simulation du système de coordonnées de l'installation laser dans le programme Matlab Simulink.

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