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Investigation of Energy-Power Parameters of Manipulator Drive for Addition of Shut-Off Elements in Basic-Oxygen Converter Outlet

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Theoretical and experimental investigation of kinematics and dynamics of electromechanical drive of device for addition of shut-off elements in the basic-oxygen converter outlet is carried out in order to prevent entering of considerable amount of slag into ladle.

Keywords: CONVERTER, MANIPULATOR, DRIVE, STATIC LOADING, INERTIA MOMENT, ACCELERATION, DYNAMIC MOMENT

Introduction

Various systems of slag melt cut-off are developed and introduced into production as a result of long-term investigations devoted to issues of enter of considerable amount of final slag in teeming ladle when steel tapping from basic oxygen furnace.

Method of nonslagging steel teeming which involves blocking of steelmaking vessel outlet by a special float-type element added by means of mechanical manipulator is considered the most perspective based on technical-and-economic indices which enable to estimate efficiency of known methods of nonslagging steel teeming in oxygen-steelmaking process.

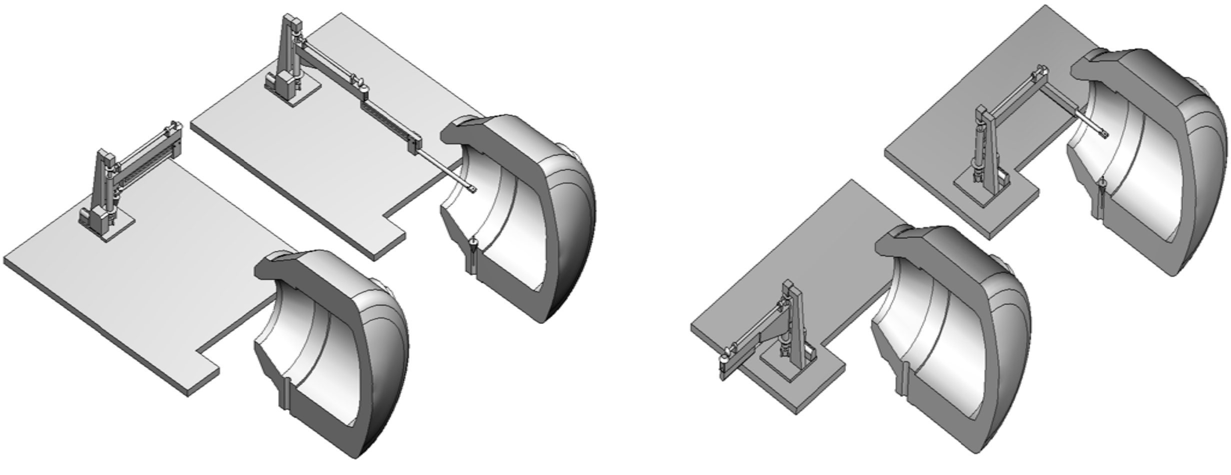
In turn, the extent of response of such slag cut-off system is 80-90 %. Now, development of reliable manipulator systems which design in the greatest measure satisfies production conditions of converter plants is underway. First of all, the kinematic scheme of manipulator should provide its lay-out in relation to LD furnace not disturbing operation of supporting machines and mechanisms used during service and repair of steelmaking vessel. And strength properties of the most critical parts and power parameters of manipulating system drive should correspond to extreme thermal and considerable technological loadings [1].

In this relation, the problem of creation of competitive equipment for implementation of highly effective converter slag cut-off is actual and needs searching for the optimum solutions that enable to implement such construction which would be featured by possibly more considerable advantages at minimized deficiencies [2].

Results and Discussion

Employees of Department of Mechanical Equipment of Iron and Steel Plants of Donetsk National Technical University designed and patented the construction design of multiple-purpose manipulator which kinematic scheme allows compact lay-out in any zone of operating floor near LD furnace and also putting into action of required motion law and necessary accuracy of positioning of shut-off element in relation to outlet (**Figure 1**).

The manipulator is shown in **Figure 2**. It includes column 3 fixed in the bottom 2 and upper 5 fixed bearing assemblies. The column is turned by drive 1 and connected with console 4 on which bearing unit with vertical shaft 12 is built. Supporting bracket 13 is rigidly fixed on the bottom end of this shaft and equipped with two long carriages in which rollers 14 carry the hollow rod 15. Shut-off element 16 is kept on the fast-head end of the rod with the use of spring-loaded lock. Tilting gear of supporting bracket 13 in relation to console 4 consists of conic gear set 11 connecting the vertical shaft 12 with trailing edge of horizontal shaft 9 bearing cone gear 7 on the fast-head end with possibility of burnishing on a conic gear wheel 6 rigidly fixed on the fixed upper support 5 of rotary column [3]. Calculation and designing of production prototype of suggested manipulating system required preliminary estimation of loadings that can appear in the elements of this mechanism during its functioning. Considering extreme service conditions of manipulator which do not enable to carry out full-scale experiments, theory of calculation of its power parameters was worked out on the basis of construction diagrams and mathematical description of operation of mechanical and power-driven systems of the mechanism and using modeling methods and laboratory testing [4].



a b

Figure 1. Lay-out of segments of manipulator mechanical system in initial and working positions at coaxial (*a*) and side (*b*) location on the working floor in relation to LD converter

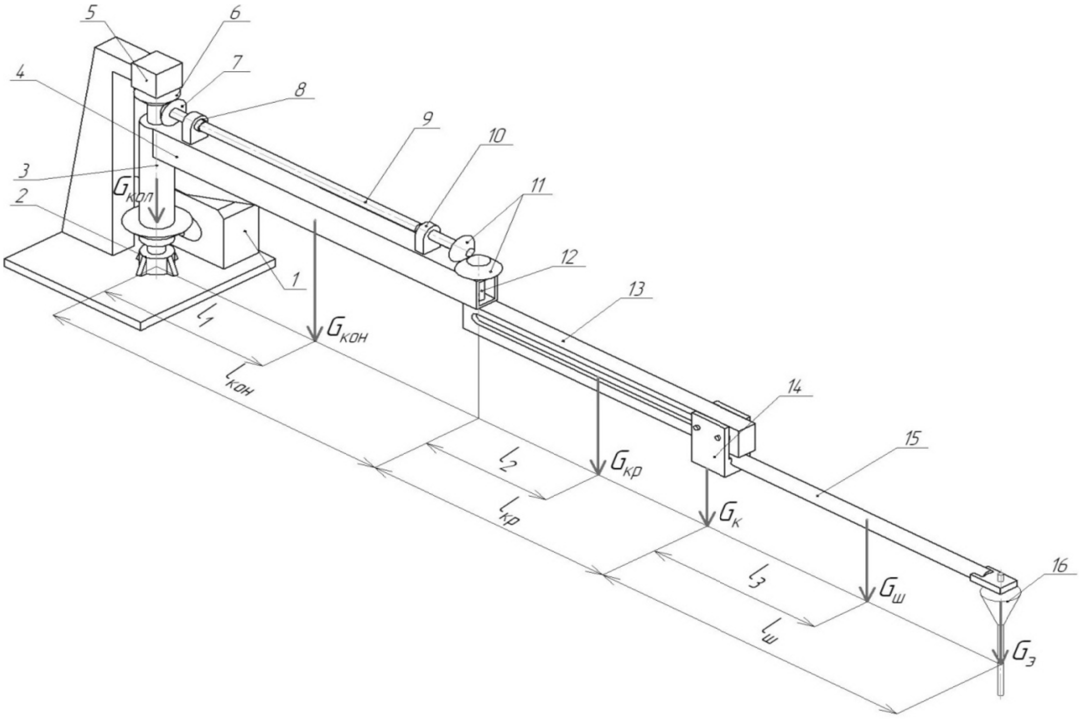


Figure 2. Manipulator for calculation of weights and sizes of basic elements

According to the standard rules of design theory and estimation of reliability, the formulated problem was solved as follows: sizes and weights of mechanism`s details were defined preliminary according to working capacity criteria; stress-strain state in the most loaded cross-sections was estimated. Strength of manipulator elements was assessed by means of comparison of forces in them from acting mechanical and thermal loadings [5]. Weights of shut-off element and hollow rod were accepted as initial data for subsequent calculations.Weight of shut-off element was counted taking into account its shape and sizes that correspond to outlet diameter of LD converter. Weight of hollow rod depends on its length and cross-sectional area. The rod length l_{rod} is defined by distance from the edge of working floor of the steelmaking vessel outlet at the moment of addition of shut-off element. Cross-section of the rod should be set taking into account thermal deformations and admissible stress induced by joint action of mechanical loadings and heating. Across-sectional dimensions of the rod of specified length are defined by numerical method with application of ANSYS.

Results of calculation of time history of temperature and equivalent stresses in the most loaded cross-section of the hollow rod are indicative of that in 40 seconds after rod feeding into converter its surface heats up to 600 °C, and stresses in dangerous cross-section have critical values. In that case, external and internal diameters of cross-section should be not less than 220 and 160 mm respectively taking into account time of stay in high-temperature zone not exceeding 45 seconds [6].

According to presented scheme the following static loadings act on the elements: gravity of column $G_{col,}$ console G_{con}, supporting bracket G_{sb}, chariot G_{char}, hollow rod G_{rod}, shut-off element G_e.

For power calculation of the mechanism we used D'Alembert principle according to which each moment of the time a movable system of bodies is in balance under the action of applied forces including inertial force. Thus we will break up the mechanism in two structural groups (**Figure 3**) and start calculation with the latter.

We choose frame of axes with axis Y_1 parallel longitudinal axis of console symmetry. Preliminary we find co-ordinates of gravitational center of system $S_1(x_{C_1}, y_{C_1}, z_{C_1})$ in which the total gravity is applied $G_1 = G_{sb} + G_{char} + G_{rod} + G_e$. We define inertial forces that appear at rotation of vertical shaft round axis Z_1 with angle acceleration ε_1 and rotary speed ω_1.

At rotational motion tangential F_{it_1} and normal F_{in_1} of inertial force are:

$$F_{it_1} = \frac{G_1}{g} \cdot \varepsilon_1 \cdot r_{C_1} \quad \text{(Eq. 1)}$$

$$F_{in_1} = \frac{G_1}{g} \cdot \omega_1^2 \cdot r_{C_1} \quad \text{(Eq. 2)}$$

where r_{C_1} – distance from axis of rotation to gravitational center of system C_1,

$$r_{C_1} = \sqrt{x_{C_1}^2 + y_{C_1}^2} \quad \text{(Eq. 3)}$$

Centre-of-gravity position C_1 in the plane $X_1 O_1 Y_1$ is expressed in terms of angle φ_1:

$$\mathrm{tg}\varphi_1 = \frac{y_{C_1}}{x_{C_1}} \quad \text{(Eq. 4)}$$

$$\sin\varphi_1 = \frac{y_{C_1}}{r_{C_1}} \quad \text{(Eq. 5)}$$

$$\cos\varphi_1 = \frac{x_{C_1}}{r_{C_1}} \quad \text{(Eq. 6)}$$

Inertial forces F_{it_1} and F_{in_1} are applied to point K_1 which position is defined by formula 7:

$$K_1C_1 = \frac{\rho_{C_1}^2}{r_{C_1}} \quad \text{(Eq. 7)}$$

where ρ_{C_1} – radius of inertia of system in relation to axis over-the-center-of-gravity C_1 that is parallel axis of rotation. We will put forces F_{it_1} and F_{in_1} in point C_1. Force F_{in_1} is relocated in the line of action. Force F_{it_1} is relocated parallely in point C_1 with addition of couple which moment is:

$$M_{j_1} = F_{it_1} \cdot K_1C_1 \qquad \text{(Eq. 8)}$$

Having substituted values F_{it_1} and K_1C_1 in equation 8 we will obtain:

$$M_{j_1} = \frac{G_1}{g} \cdot \rho^2_{C_1} \cdot \varepsilon_1 = I_{C_1} \cdot \varepsilon_1 \qquad \text{(Eq. 9)}$$

where $I_{C_1} = \frac{G_1}{g} \cdot \rho^2_{C_1}$ – inertia moment of rotation system relating to vertical axis over-the-center-of-gravity C_1.

Moment M_{j_1} is directed opposite to direction of rotating direction of elements of system. All inertial forces acting on the rotation system are in one plane perpendicular axis of rotation of vertical shaft Z_1. The following forces and moments are applied to system: P_1 - peripheral force on conic gear wheel; M_E, M_D - the moments of friction forces in bearings E and D; X_D, Y_D, X_E, Y_E, Z_E components of reactions in these bearings.

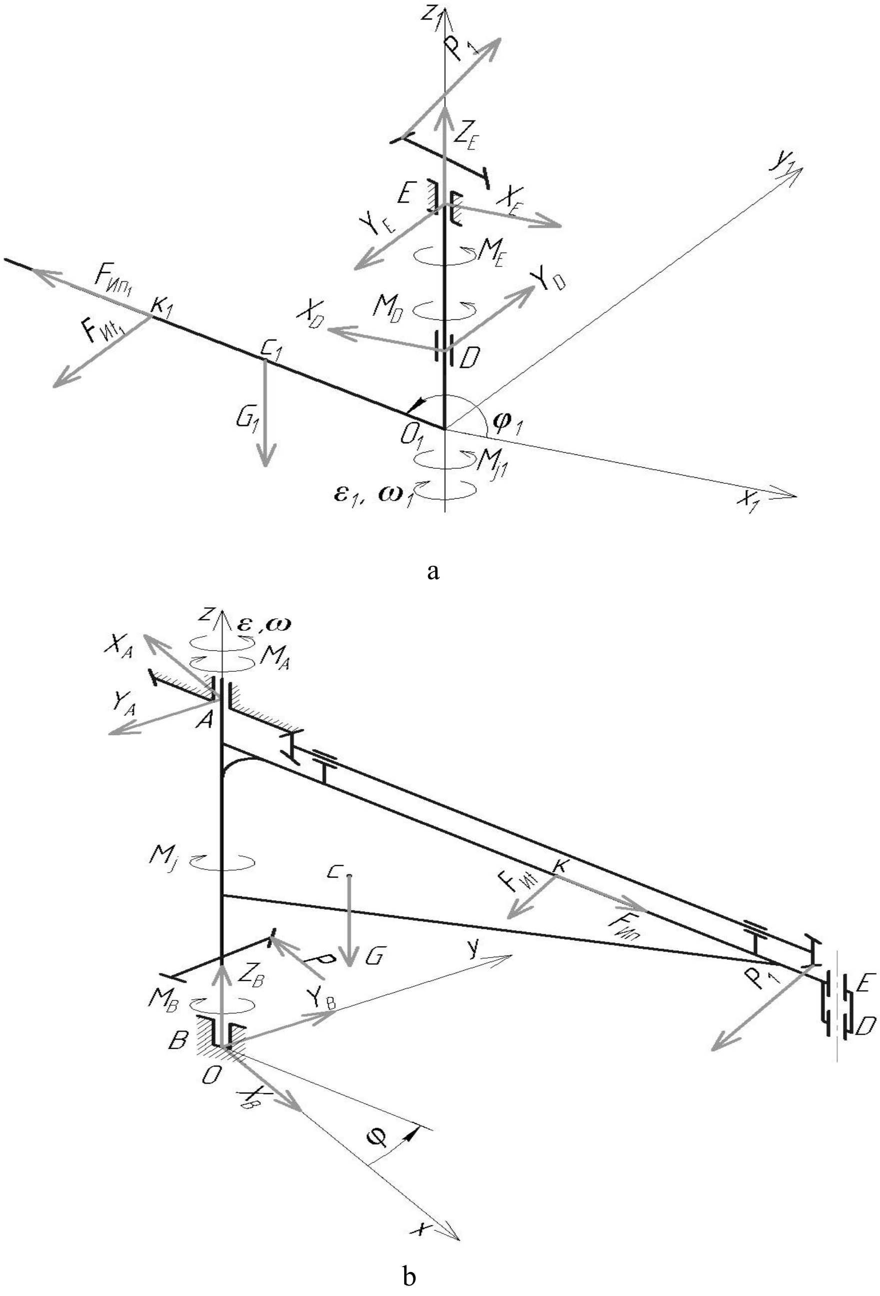


Figure 3. Design model of manipulator column rotator

$$\left.\begin{aligned}
&\Sigma F_{ix_1} = -F_{in_1}\cdot\cos\varphi_1 - X_D + X_E - F_{it_1}\cdot\sin\varphi_1 = 0;\\
&\Sigma F_{iy_1} = Y_D - Y_{1E_1} - F_{it_1}\cdot\cos\varphi_1 + F_{in_1}\cdot\sin\varphi_1 + P_1 = 0;\\
&\Sigma F_{iz_1} = Z_E - G_1 = 0;\\
&\Sigma M_{x_1}(F_i) = -Y_E\cdot z_E + Y_D\cdot z_D + G_1\cdot y_{C_1} + P_1\cdot z_{P_1};\\
&\Sigma M_{y_1}(F_i) = X_D\cdot z_D - X_E\cdot z_E + G_1\cdot x_{C_1} = 0;\\
&\Sigma M_{z_1}(F_i) = P_1\cdot\frac{d}{2} - M_E - M_D - F_{it_1}\cdot\cos\varphi_1\cdot x_{C_1} - F_{it_1}\cdot\sin\varphi_1\cdot y_{C_1} - M_{j_1} = 0.
\end{aligned}\right\} \quad \text{(Eq. 10)}$$

Moments of friction in vertical shaft bearings are:

$$M_D = \mu_1\cdot R_1\cdot\sqrt{X_D^2 + Y_D^2} \qquad \text{(Eq. 11)}$$

$$M_E = \mu_1\cdot R_1\cdot\sqrt{X_E^2 + Y_E^2} + Z_E\cdot\mu_2\cdot\frac{d_{1c}}{2} \qquad \text{(Eq. 12)}$$

where h, x_{C_1}, y_{C_1}, z_E, z_D - arms of forces; R_1 - radius of bearings E and D; μ_1 - friction coefficient in bearings E and D; d_{1c} - diameter of axial bearing E; μ_2 - friction coefficient in axial bearing E. We will solve system of equations 10 and find constituents of reaction of bearings X_D, Y_D, X_E, Y_E, Z_E and peripheral force P_1 applied to power-driven conic wheel of vertical shaft for overcoming of static and dynamic loads at rotation of supporting bracket.

When calculating forces of the first group, we use peripheral force P_1 including rotary column and console. We apply force P_1 to console and change its direction on opposite (**Figure 3b**). At the same time, the following forces act on system elements: gravity of column and console; friction resistance forces in bearing assemblies caused by forces of reactions; inertial forces; peripheral force P applied to gear wheel of column and necessary for overcoming of specified forces.

We will find co-ordinates of gravity centre C (x_C, y_C, z_C) in which total force is applied $G = G_{col} + G_{con}$ and count inertial forces that appear at rotation of column with console round Z-axis with angular acceleration ε and rotary speed ω.

At rotational motion tangential F_{it} and normal F_{in} of inertial force are:

$$F_{it} = \frac{G}{g}\cdot\varepsilon\cdot r_C \qquad \text{(Eq. 13)}$$

$$F_{in} = \frac{G}{g}\cdot\omega^2\cdot r_C \qquad \text{(Eq. 14)}$$

where r_C – distance from axis of rotation to gravitational center of system C:

$$r_C = \sqrt{x_C^2 + y_C^2} \qquad \text{(Eq. 15)}$$

Centre-of-gravity position C in plane XOY is expressed in terms of angle φ:

$$\mathrm{tg}\varphi = \frac{y_C}{x_C} \qquad \text{(Eq. 16)}$$

$$\sin\varphi = \frac{y_C}{r_C} \qquad \text{(Eq. 17)}$$

$$\cos\varphi = \frac{x_C}{r_C} \qquad \text{(Eq. 18)}$$

Inertial forces F_{it} and F_{in} are applied to point K which position is defined by equation 19:

$$KC = \frac{\rho_C^2}{r_C} \qquad \text{(Eq. 19)}$$

where ρ_C – radius of inertia of system relating to axis over-the-center-of-gravity C that is parallel axis of rotation. We will put forces F_{it} and F_{in} in point C. Force F_{in} is relocated in the line of action. Force F_{it} is relocated parallely in point C_1 with addition of force couple.

Moment of added force couple is:

$$M_j = F_{it} \cdot KC = I_C \cdot \varepsilon \qquad \text{(Eq. 20)}$$

where $I_C = \frac{G}{g} \cdot \rho_C^2$ – inertia moment of rotation system relating to vertical axis over-the-center-of-gravity C.

Moment M_j is directed opposite to rotating direction of specified system. All inertial forces acting on the rotation system are in one plane perpendicular Z-axis of rotation. The following forces and moments are applied to system: P - peripheral force on conic gear wheel; M_A, M_B- moments of friction forces in bearings A and B; X_A, Y_A, X_B, Y_B, Z_B components of reactions in these bearings. We will set up equilibrium equations by laws of statics:

$$\left.\begin{aligned}
&\Sigma F_{ix} = X_B - X_A + F_{it} \cdot \sin\varphi + F_{in} \cdot \cos\varphi - P + P_1 \cdot \sin\varphi = 0;\\
&\Sigma F_{iy} = Y_B - Y_A - F_{it} \cdot \cos\varphi + F_{in} \cdot \sin\varphi - P \cdot \cos\varphi = 0;\\
&\Sigma F_{iz} = Z_B - G = 0;\\
&\Sigma M_x(F_i) = -Y_A \cdot z_A - F_{it} \cdot \cos\varphi \cdot z_C + F_{in} \cdot \sin\varphi \cdot z_C + G \cdot y_C -\\
&- P_1 \cdot \cos\varphi \cdot z_{P_1} = 0;\\
&\Sigma M_y(F_i) = X_A \cdot z_A - G \cdot x_C - F_{it} \cdot \sin\varphi \cdot z_C - F_{in} \cdot \cos\varphi \cdot z_C -\\
&- P_1 \cdot \sin\varphi \cdot z_{P_1} = 0;\\
&\Sigma M_z(F_i) = M_B + M_A + M_j - P \cdot \frac{d_w}{2} + F_{it} \cdot \cos\varphi \cdot x_C + F_{it} \cdot \sin\varphi \cdot y_C +\\
&+ P_1 \cdot \cos\varphi \cdot x_{P_1} + P_1 \cdot \sin\varphi \cdot y_{P_1} = 0.
\end{aligned}\right\} \qquad \text{(Eq. 21)}$$

Moments of friction in vertical shaft bearings are as follows:

$$M_A = \mu_1 \cdot R \cdot \sqrt{X_A^2 + Y_A^2} \qquad \text{(Eq. 22)}$$

$$M_B = \mu_1 \cdot R \cdot \sqrt{X_B^2 + Y_B^2} + Z_B \cdot \mu_2 \cdot \frac{d_c}{2} \qquad \text{(Eq. 23)}$$

where x_C, x_E, x_D, y_C, y_E, y_D, z_A, z_C, z_D, z_E – arms of forces; R – radius of bearings A and B; μ_1 – friction coefficient in bearings A and B; d_c – diameter of axial bearing B; μ_2 – friction coefficient in axial bearing B.

We will solve system of equations 21 and find bearing reaction A and B as well as peripheral force P applied to power-driven wheel for overcoming of static and dynamic loads at rotation of column with console.

Maximum rotational moment from resistance in column bearings and inertial loadings in the moment of mechanism start-up are as follows:

$$M_r = P \cdot \frac{d_w}{2} \qquad \text{(Eq. 24)}$$

where d_w – initial diameter of driven wheel. Than calculated power of drive of manipulator rotator is:

$$N = \frac{M_r \cdot \omega}{\eta} \qquad \text{(Eq. 25)}$$

where ω – set rotary speed of column rotation; η – drive efficiency.

Power parameters were calculated, experimental model of manipulator was designed and fabricated (**Figure 4**) to check accepted technical solutions and obtained dependences. The task of laboratory testing is to define values of really acting loadings in the elements of manipulating system for their subsequent comparison with computation data. A conversion device was installed between corresponding shafts of high-speed and low-speed reducers of manipulator electromechanical drive during trial testing of experimental model of manipulator. This conversion device helped control current values of rotational moment surpassed by drive motor in final and intermediate positions of investigated kinematic system.

Figure 5 illustrates dependence obtained according to calculation data. It follows from presented diagrams that results obtained by theoretical and experimental methods correlate well (disarrangement does not exceed 15 %), therefore the developed technique was used for engineering calculations of constructive and power parameters of commercial machine of suggested manipulating system [7]. Thus, data of theoretical and experimental investigations can be used when designing mechanical manipulators intended for nonslagging steel tapping from LD converters at steel plants of Ukrainian iron & steel works and capable to compete with known foreign analogues.

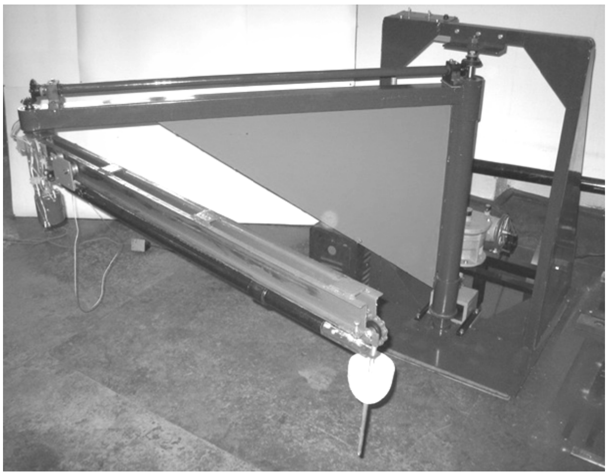


Figure 4. Experimental model of manipulator

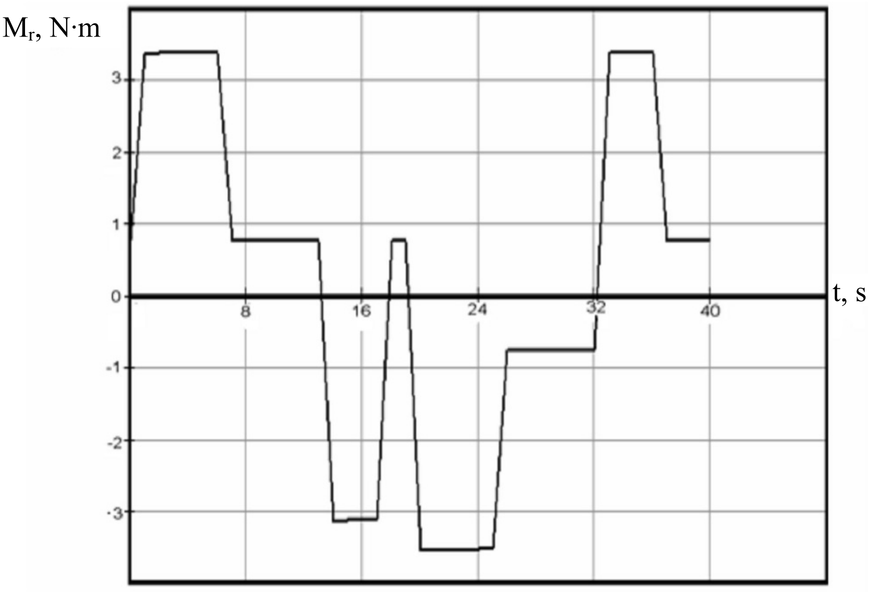


Figure 5. Diagram of rotational moment change on the transmission shaft of manipulator drive obtained via calculation

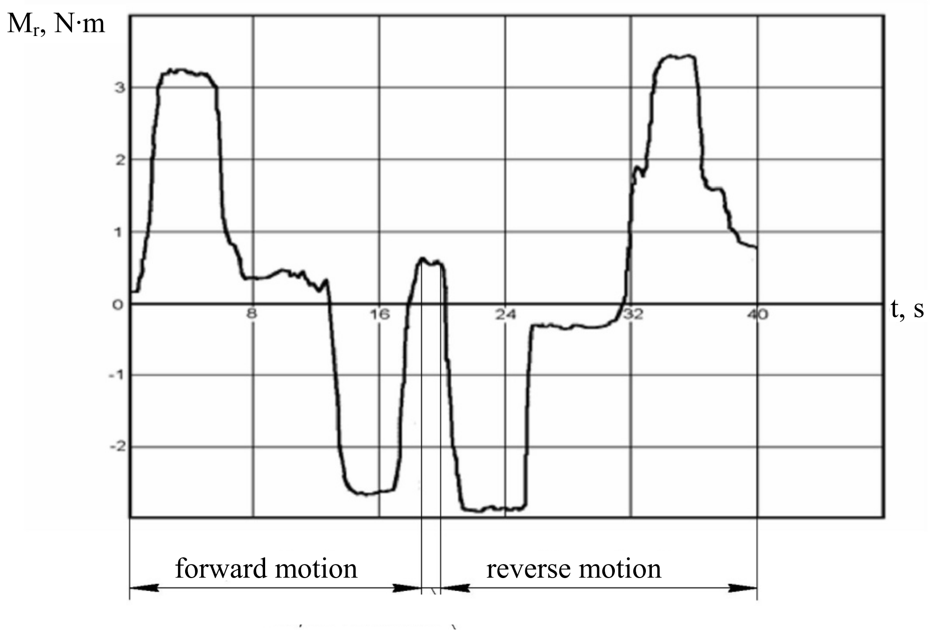


Figure 5. Diagram of rotational moment change on the transmission shaft of manipulator drive obtained via experiment

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Исследование энергосиловых параметров привода манипулятора для ввода отсечных элементов в выпускной канал кислородного конвертера

Еронько С.П., Ошовская Е.В.,
Бедарев С.А., Мечик С.В.

Выполнены теоретические и экспериментальные исследования кинематики и динамики электромеханического привода устройства, обеспечивающего введение отсечных элементов в выпускной канал кислородного конвертера с целью предотвращения попадания большого количества шлака в сталеразливочный ковш.