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MECHATRONIC HYDRAULIC DRIVE CNARACTERISTICS DURING MANIPULATOR SPATIAL MOTION

The paper proposes a nonlinear mathematical model of spatial motion of the manipulator, based on two individual hydraulic drives with mechatronic control. The developed mathematical model has made it possible to determine the manipulator spatial motion characteristics during simultaneous operation of two hydraulic drives. In particular, the effect of the drives and manipulator parameters on the regulation time and overshooting as well as on the stability of transient processes during the manipulator start-up process is determined and analyzed.

Keywords: *manipulator, mechatronic drive, transient processes, regulation time, overshoot, stability.*

Introduction

Mobile working machines with manipulators are widely used in construction engineering and industry. Manufacturers of such machines produce a variety of replaceable operating members such as various types of grippers, excavation equipment, lifts, hydraulic shears, etc. determine, largely, Functional capabilities of the mobile working machine and its characteristics are determined, mainly, by manipulator design and its drive system. In the process of work the mobile machine manipulator motion is implemented due to simultaneous operation of its drives. This makes it possible to increase productivity of the machine operation. However, when the drives are operated simultaneously, they interact through the manipulator construction. During transients (start-up, changes in the motion direction and speed, braking of the drives) complex dynamic processes, caused by simultaneous operation of the drives and their interaction, occur. This leads to increased oscillation of the drives, reduced response and considerable pressure overshoot and, consequently, to overloading of the manipulator and machine constructions. To date, there are no adequate studies on the peculiarities of a mobile working machine manipulator operation, when its drives are working simultaneously and, therefore, further research is required as to improvement of their dynamic performance. Characteristics and efficiency of mobile machines can be improved by equipping them with mechatronic hydraulic drives, based on variable pumps and controllers [1 – 11].

The paper sets the task to improve quality indicators of controlling mechatronic drives of the mobile machine manipulator during their simultaneous operation.

Main part

Fig. 1 shows the circuit of manipulator with a mechatronic drive. The circuit includes column 1, boom 2, arm 3, grip 4, hydraulic cylinders 5, 6 and swing mechanism 7. The manipulator is mounted on frame 8 of the mobile machine. When working operations are performed, the frame is fixed relative to the support surface by means of outriggers 10, 11. Variable pump 12 supplies working fluid to hydraulic cylinder 5 via hydraulic line 35, directional control valves 19, 20 and hydraulic line 21, actuating boom 2 of the manipulator. Drain of the working fluid from hydraulic cylinder 5 is provided via working hydraulic line 22, directional control valve 20, control hydraulic line 25, brake valve 26 and return hydraulic line 27. Directional control valve includes spring 9 and is controlled by solenoid 31. Variable pump 12 comprises regulator 13, which includes spool 14 with spring 15, throttles 16, 36, valve 17 with solenoid 18. Variable pump 12 provides supply of the working fluid flow to hydraulic cylinder 5, the value of which is determined by the opening of the orifice of directional control valve 20. The value of this flow determines motion speed of rod 24 and, therefore, the motion speed of boom 2 of the manipulator. Hydraulic cylinder 23 of column 1 has an individual pump, which is not shown in the circuit.

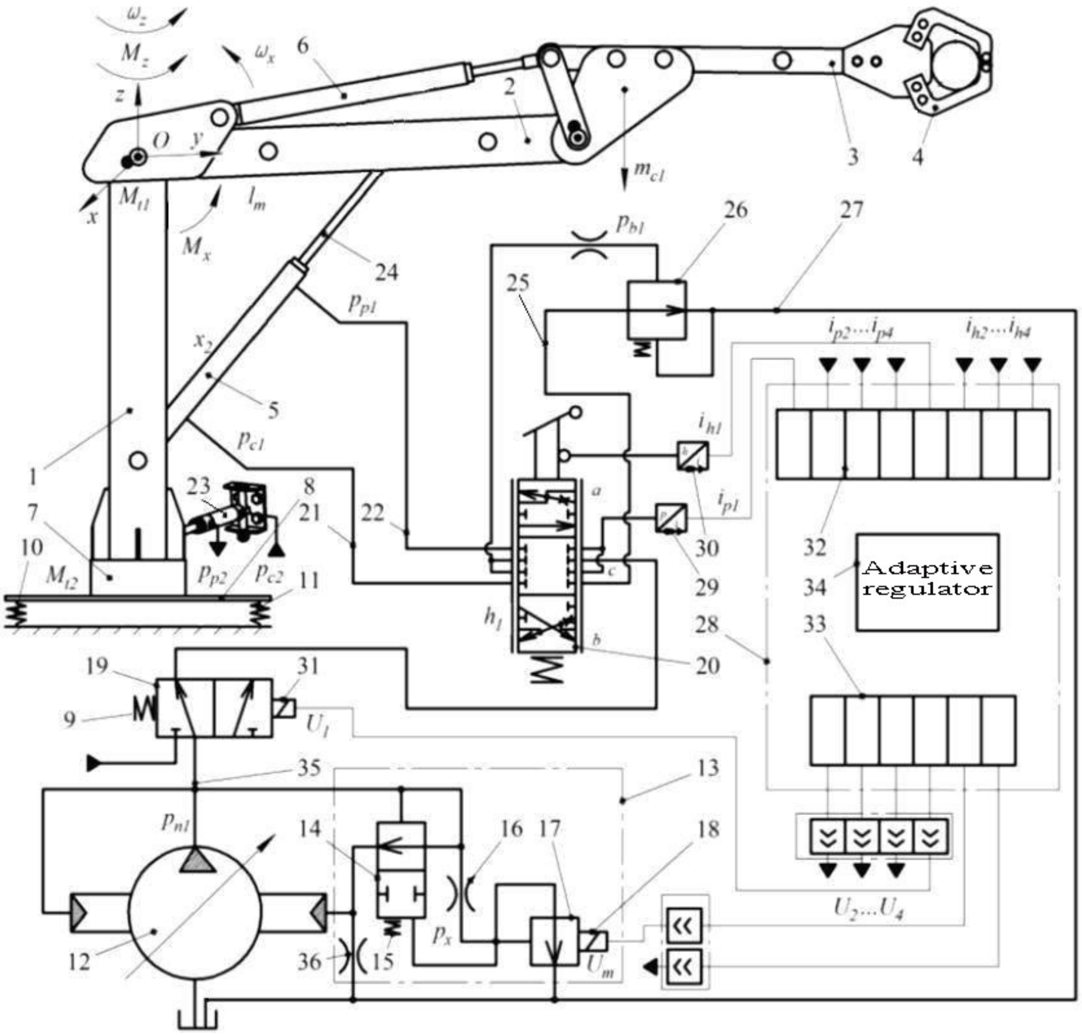


Fig. 1. Circuit of the manipulator with a mechatronic drive

Controller 28 regulates operation of the manipulator drives. Signals from pressure sensor 29 and position sensor 30 are supplied to input board 32 of the controller.

On the basis of signals i_{pi} and i_{hi}, supplied from sensors 29 and 30, in adaptive regulator 34 of controller 28 a signal is generated, which is fed to solenoid 18 of the pump regulator 13. The adaptive regulator operation algorithm provides a decrease in the oscillation amplitude of signal i_{pi} in the transient process, which results in a decrease of oscillation amplitude of pressure p_{n1} at the output of pump 12 and their more intensive damping [3]. This makes it possible to improve the response of the manipulator drives, to reduce pressure overshoot in the manipulator drive by rational choice of the design parameters of the pump regulator 13.

Hydraulic cylinders 5, 23 provide rotation of the manipulator links relative to axes x and z. Projections M_x, M_y, M_z of the main moment of the external forces $\overline{\mathbf{M}}$ act on the manipulator links.The manipulator motion is determined by the projections of angular velocities ω_x, ω_y, ω_z.

Equations of the manipulator spatial motion and angular velocities in the projections on the coordinate axes are given by:

$$\begin{cases} \dfrac{dL_x}{dt} + \omega_y L_z - \omega_z L_y = M_x; \\ \dfrac{dL_y}{dt} + \omega_z L_x - \omega_x L_z = M_y; \\ \dfrac{dL_z}{dt} + \omega_x L_y - \omega_y L_x = M_z; \end{cases} \qquad \begin{cases} \omega_x = \left(L_x + I_{xy} \cdot \omega_y + I_{zx} \cdot \omega_z\right) / I_{xx}; \\ \omega_y = \left(L_y + I_{xy} \cdot \omega_x + I_{yz} \cdot \omega_z\right) / I_{yy}; \\ \omega_z = \left(L_z + I_{zx} \cdot \omega_x + I_{yz} \cdot \omega_y\right) / I_{zz}, \end{cases}$$

where L_x, L_y, L_z – projections of the kinetic moment $\overline{\mathbf{L}}$ of the manipulator movable parts on the coordinate axes; M_x, M_y, M_z – projections of moment $\overline{\mathbf{M}}$ of the external forces acting on the manipulator.

The kinetic moment projections and inertia tensor of the manipulator have the form of

$$L_x = I_{xx} \cdot \omega_x - I_{xy} \cdot \omega_y - I_{zx} \cdot \omega_z;$$

$$L_y = -I_{xy} \cdot \omega_x + I_{yy} \cdot \omega_y - I_{yz} \cdot \omega_z;$$

$$L_z = -I_{zx} \cdot \omega_x - I_{zy} \cdot \omega_y + I_{zz} \cdot \omega_z;$$

$$\left(I_{ij}\right) = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix}.$$

Mathematical model of the manipulator drive, based on the variable pump, is given by:

$$I \frac{d^2\gamma}{dt^2} = p_{n1} \cdot f_5 \cdot l - p_e \cdot f_4 \cdot l - \frac{\pi \cdot \rho \cdot v_k \cdot d_4 \cdot l_4}{\varepsilon_0} \cdot \frac{d\gamma}{dt} \cdot \cos\gamma - M_{v2} + m_0 + m_1 \cdot Q_{n1} +$$
$$+ m_2 \cdot p_{n1} + m_3 \cdot Q_{n1}^2 + m_4 \cdot p_{n1}^2 + m_5 \cdot p_{n1} \cdot Q_{n1} + m_f\left(\omega_n\right);$$

$$m_x \frac{d^2 x}{dt^2} = p_x \cdot \frac{\pi \cdot d_x^2}{4} - k_m \cdot i_{m1} - \left(\frac{\pi \cdot \rho \cdot v_k \cdot d_x \cdot l_x}{\varepsilon_x}\right) \cdot \frac{dx}{dt};$$

$$m_p \frac{d^2 z}{dt^2} = p_{n1} \frac{\pi \cdot d_p^2}{4} - p_x \frac{\pi \cdot d_p^2}{4} - C_p \cdot \left(H_p + z\right) - \frac{\pi \cdot \rho \cdot v_k \cdot d_p \cdot l_p}{\varepsilon_p} \cdot \frac{dz}{dt};$$

$$m_b \frac{d^2 y_1}{dt^2} = p_b \cdot \frac{\pi \cdot d_b^2}{4} - c_b \cdot \left(H_b + y_1\right) - A_g + B_g \cdot p_{p1} - \frac{D_g}{y_1} + \frac{E_g}{y_1^2} -$$
$$- \left(\frac{\pi \cdot \rho \cdot v_k \cdot d_b \cdot l_b}{\varepsilon_b}\right) \cdot \frac{dy_1}{dt};$$

$$F_7 \cdot d_8 \cdot k_1 \cdot n_n \cdot tg\gamma - k_{n1} \cdot p_{n1} = a + b \cdot h_1 + c \cdot \Delta p_1 + d \cdot h_1^2 + e \cdot \Delta p_1^2 + f \cdot h_1 \cdot \Delta p_1 +$$
$$+ \mu \cdot k_z \cdot z \cdot \sqrt{\frac{2 \cdot \left|p_{n1} - p_0\right|}{\rho}} \cdot sign\left(p_{n1} - p_0\right) + \beta_n \cdot W_{n1} \frac{dp_{n1}}{dt};$$

$$a + b \cdot h_1 + c \cdot \Delta p_1 + d \cdot h_1^2 + e \cdot \Delta p_1^2 + f \cdot h_1 \cdot \Delta p_1 =$$
$$= \frac{F_{c1} \cdot l_m \cdot \omega_x}{\cos \alpha_m} + \beta_p \cdot W'_{c1} \frac{dp_{c1}}{dt} + \beta_n \cdot W_{c1} \frac{dp_{c1}}{dt} - \mu \cdot f_b \cdot \sqrt{\frac{2 \cdot |p_{c1} - p_{b1}|}{\rho}} \cdot sign(p_{c1} - p_{b1});$$

$$\frac{F_{p1} \cdot l_m \cdot \omega_x}{\cos \alpha_m} = \mu \cdot k_b \cdot y_1 \cdot \sqrt{\frac{2 \cdot p_{p1}}{\rho}} + \beta_p \cdot W_{p1} \frac{dp_{p1}}{dt};$$

$$\mu \cdot f_b \cdot \sqrt{\frac{2 \cdot |p_{c1} - p_{b1}|}{\rho}} \cdot sign(p_{c1} - p_{b1}) = \frac{\pi \cdot d_b^2}{4} \cdot \frac{dy_1}{dt} + \beta_p \cdot W_b \cdot \frac{dp_b}{dt} -$$
$$- \exp\left(A_b \cdot p_b + B_b \cdot t^\circ + C_b \cdot \varepsilon_b + D_b\right);$$

$$\mu \cdot k_z \cdot z \sqrt{\frac{2 \cdot |p_{n1} - p_0|}{\rho}} \cdot sign(p_{n1} - p_0) =$$
$$= \mu \cdot f_0 \cdot \sqrt{\frac{2 \cdot p_0}{\rho}} + \beta_p \cdot W_0 \frac{dp_0}{dt} + \mu \cdot f_e \cdot \sqrt{\frac{2 \cdot |p_0 - p_e|}{\rho}} \cdot sign(p_0 - p_e);$$

$$\mu \cdot f_x \cdot \sqrt{\frac{2 \cdot |p_{n1} - p_{x1}|}{\rho}} \cdot sign(p_{n1} - p_{x1}) = \mu \cdot \pi \cdot d_x \cdot x \cdot \sin\left(\frac{\alpha_x}{2}\right) \cdot \sqrt{\frac{2 \cdot p_x}{\rho}} + \beta_p \cdot W_x \frac{dp_x}{dt};$$

$$\mu \cdot f_e \cdot \sqrt{\frac{2 \cdot |p_0 - p_e|}{\rho}} \cdot sign(p_0 - p_e) = \beta_p \cdot W_e \frac{dp_e}{dt} - \exp\left(A_e \cdot p_e + B_e \cdot t^\circ + C_e \cdot \varepsilon_e + D_e\right) -$$
$$- f_4 \cdot l \cdot \frac{d\gamma}{dt} \cdot \cos \gamma;$$

$$p_{c1} \cdot k_u \cdot k_c \cdot \left[F_k\left(i_{p1}\right)\right] = L_e \frac{di_{m1}}{dt} + i_{m1} \cdot R_e;$$

$$M_x = p_{c1} \cdot F_{c1} \cdot l_m \cdot cos\alpha_m - m_{c1} \cdot g \cdot l_m - p_{p1} \cdot F_{p1} \cdot l_m \cdot cos\alpha_m - R_1 \cdot \frac{2 \cdot d_{n1}}{\pi} \cdot sign\omega_x -$$
$$- M_{t1} \cdot sign\omega_x - m_g \cdot g \cdot l_g.$$

Equations, describing manipulator swing drive during its operation from the constant pump in the fixed-flow mode, have the following form:

$$M_z = p_{c2} \cdot F_{c2} \cdot l_z - p_{p2} \cdot F_{p2} \cdot l_z - M_{t2} \cdot sign\omega_z - F_{r1} \cdot f_{r1} \cdot \frac{d_{r1}}{2} \cdot sign\omega_z -$$
$$- F_{r2} \cdot f_{r2} \cdot \frac{d_{r2}}{2} \cdot sign\omega_z;$$

$$Q_{n2} = \omega_z \cdot l_T \cdot F_{c2} + \beta_p \cdot W_{c2} \cdot \frac{dp_{c2}}{dt} + \beta_n \cdot W'_{c2} \cdot \frac{dp_{c2}}{dt};$$

$$\beta_n = \frac{1}{E_p} + \frac{d_{mp}}{\delta_{mp} \cdot E_{mp}(p)};$$

$$E_p = \frac{1}{\beta_p} = E_{p0}\frac{W_f / W_a + 1}{W_f / W_a + \left(E_{p0} \cdot p_0\right)/ p^2};$$

where $p_{c1}, p_{p1}, p_e, p_0, p_{b1}$ – pressures at the input and output of hydraulic cylinder 5 (see Fig.1), in the regulator of pump 12, at the input of brake valve 26; z, y_1 – position coordinates of the spool of regulator 14 and of the spool of brake valve 26; ω_x, ω_z – angular rotation velocities of the boom and the manipulator; γ – rotation angle of the swashplate of variable pump 12; f_0– area of throttle 36 in the pump regulator; F_{c1}, F_{p1}, f_4, f_5, f_e, f_b – areas of the piston of hydraulic cylinder 5, servocylinders of the variable pump, the pump pistons, dampers of the pump servocylinder and of the brake valve; D_c, d_p, d_b, d_7, d_8, d_x, d_{mp} – diameters of hydraulic cylinder 5, spool 14 of the regulator, the brake valve spool, pistons of the variable pump and contact circle of the pump pistons with the swashplate, the throttle of the pump regulator, internal diameter of the pipelines; k_q, k_m, k_n, k_c, k_u – coefficients of the specific friction force in hydraulic cylinder 5, proportionality of the solenoid force, leakage flows in pump 12, gains of the pressure sensor and the amplifier; L_e, R_e - inductance and real resistance in the wire of the solenoid valve 18; c_b – stiffness of the brake valve spring; i_{m1}, i_{p1}, i_{h1} – currents in the wires of valve 17, at the output of pressure sensor 29 and position sensor 30; F_n, T_c – reduced forces of load at rod 24 and friction in hydraulic cylinder 5; μ –coefficient of flow through throttle and spool elements;; ρ – working fluid density; l_p, l_4, l_b, l – lengths of contact of the regulator 14 spool, servocylinder of pump 12, spool of the brake valve 26 with the bodies, arm of action of the variable pump12 servocylinders; I – inertia moment of the pump swashplate; m_p, m_b, m_{c1}, m_g – masses of the spools of regulator 14 and brake valve 26, reduced mass of the working mechanism, load mass; W_{n1}, W_0, W_c – volumes of the hydraulic lines between pump 12 and directional control valve 19, between regulator 14 and servocylinder, between directional control valve 20 and hydraulic cylinder 5; n_n – rotation speed of the shaft of pump 12; k_1 – number of pistons in pump 12; q_0 – specific friction force in hydraulic cylinder 5; $\varepsilon_p, \varepsilon_n, \varepsilon_b$ – clearances between the spool of regulator 14, servocylinder of pump 12, the brake valve spool and the bodies; h_1 – opening of the working port of the proportional directional control valve 20; $F_k\left(i_{pi}\right)$ – transfer function implemented by controller 28; H_b – pre-compression of the spring of brake valve 26; m_0, m_1, m_2, m_3 – coefficients of the dependence of the resistance moment at the pump swashplate on the flow rate and the pressure; A_g, B_g, D_g, E_g – coefficients in the formula of dynamic force; A_b, B_b, C_b, D_b – coefficients in the formula of leakage from the control chamber; M_x, M_z – moments developed by the drives of the boom and the manipulator swing mechanism; M_{t1}, M_{t2}– friction moments of the hydraulic cylinders of the boom and swing mechanism; p_{c2}, p_{p2} – pressures at the input and output of the hydraulic cylinder of the swing mechanism; l_z, l_m, l_g – arm of action of the swing mechanism hydraulic cylinder, reduced mass of the manipulator and the load; F_{r1}, F_{r2} – reactions in the bearings of the swing mechanism; f_{r1}, f_{r2} – coefficients of friction in the bearings of the swing mechanism; F_{c2}, F_{p2} – areas of the hydraulic cylinder of the swing mechanism; Q_{n2} – flow rate of the constant pump; W_{c2} – volume of the hydraulic line between the constant pump and hydraulic cylinder; β_p – reduced coefficient of compliance of the gas-liquid mixture; β_n – reduced coefficient of rubber-metal pipelines and gas-liquid mixture; E_{p0}, E_p, $E_{mp}(p)$ – elasticity modulus of the working fluid, reduced elasticity modulus of the gas-liquid mixture and rubber-metal pipelines; δ_{mp} – width of the pipeline wall; W_f – volume of the liquid in the gas-liquid mixture for pressure value p; W_a – volume of gas in the gas-liquid mixture under atmospheric pressure.

Spatial motion of the manipulator is provided by simultaneous motion of column 1 (see Fig. 1) and boom 2 or arm 3. Simultaneous operation of column 1, actuated by hydraulic cylinder 23, and the boom, actuated by hydraulic cylinder 5, is considered. Hydraulic cylinders 23 and 5 are powered by individual pumps. Each of the hydraulic cylinders 23 and 5 has an individual drive and speeds of the pistons depend on the opening of the working ports of the proportional directional control spools, through which hydraulic cylinders are connected to the pumps.

Mathematical model of the manipulator makes it possible to determine characteristics of the spatial motion during simultaneous operation of two hydraulic drives. The influence of the parameters of the drives and the manipulator on the value of regulation time t_p and overshoot σ, at the time when the manipulator is put into operation is determined.

Regulation quality indices during simultaneous operation of two drives are effected significantly by the inertia moment of the manipulator. Fig. 2 shows the effect of the manipulator inertia moment on the regulation time t_p and overshoot σ in the boom lifting drive during simultaneous rotation of the manipulator column for various values of the components I_{xx} and I_{zz}.

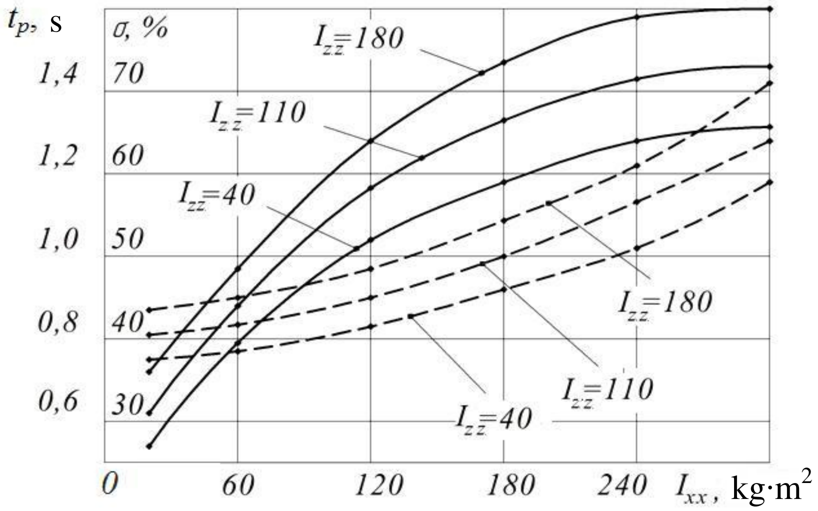


Fig. 2. Dependence of the regulation time t_p (—) and overshoot σ (---) on the values of I_{xx} and I_{zz} when two drives operate simultaneously

Improvement of the quality indicators in the dynamic operating modes, primarily, reduction of overshoot and of regulation time, is achieved in the manipulator drives by rational choice of the pump regulator design parameters. The effect of the main deign parameters of the pump regulator on the control quality indicators in dynamic processes under counter load conditions was investigated.

Fig. 3 shows the influence of the pump regulator parameters, namely, throttle area f_0, area f_e of the servocylinder damper and gain coefficient k_z of the regulator working port on the regulation time. The process of starting up the boom lift hydraulic cylinder with simultaneous rotation of the manipulator column with steady angular velocity of $\omega_z = 0{,}2$ rad / s was simulated.

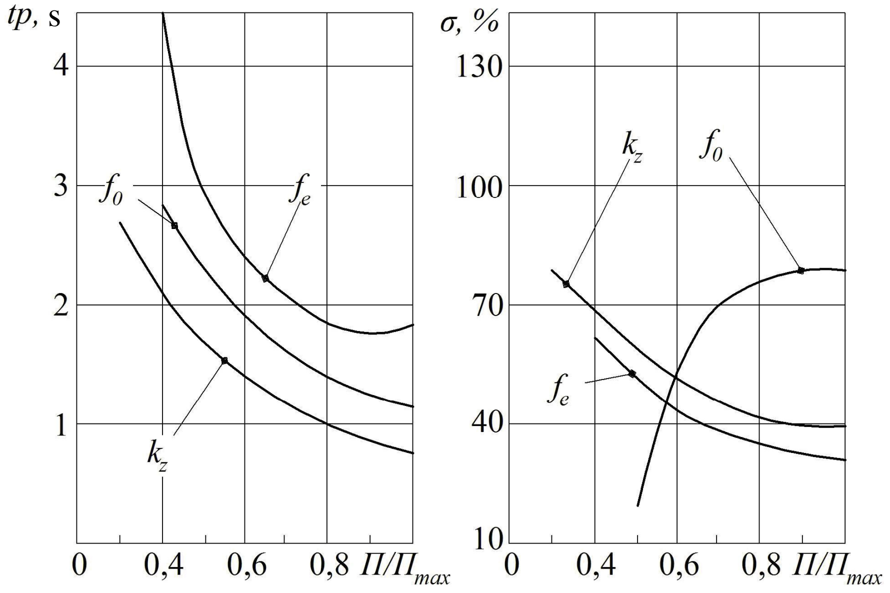
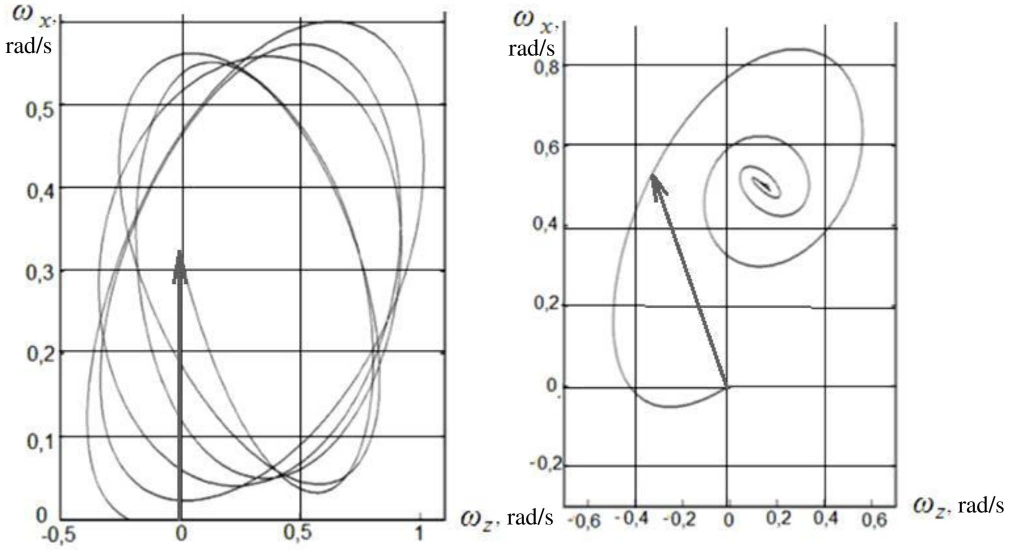


Fig. 3. The influence of the parameters of the damper (f_e), throttle (f_0), pump regulator gain coefficient (k_z) on the regulation time t_p and overshoot σ

Studies were carried out for the opening of working port of the proportional directional control spool $h = 4 \cdot 10^{-3}$ m and counterload on the manipulator boom $M_x = 2{,}8 \cdot 10^4$ N·m, which corresponds to the pressure value at the hydraulic cylinder input in a steady mode $p = 16{,}0$ MPa. The increase of the pump regulator parameters in the range f_0 = (1,5…4,0)·10^{-6} m^2 and k_z = (1,5…6,0)·10^{-3}m results in the regulation time reduction. The area of the servocylinder damper f_e has an ambiguous influence on the regulation time. Variation of f_e in the range of (1,0…2,4)·10^{-6} m^2 decreases the regulation time, while its further growth leads to increased t_p. When k_z and f_e vary in the ranges under consideration, increase of these parameters provides overshoot reduction. Change in the throttle area f_0 from 1,5·10^{-6} m^2 to 3,0·10^{-6} m^2 is accompanied by the growth of overshoot value σ, and further increase to the values of 4,0·10^{-6} m^2 has practically no effect on σ value.

Fig. 4 presents a calculated dependence of the angular velocity of manipulator motion in transient process with simultaneous actuation of the manipulator swing mechanism and the boom lift hydraulic cylinder. When combination of the design parameters of the regulators is f_0 = 1,5·10^{-6} m^2, f_e = 1,0·10^{-6} m^2, k_z = 1,5·10^{-3} m, non-damping self-oscillations with angular rotation velocity range of $\omega_x = (-0{,}05...+6{,}0)$ rad / s and angular velocity range $\omega_z = (-0{,}4...+1{,}0)$ rad / s occur. If the swing and boom lift drives are actuated simultaneously and the combination of the regulator design parameters is f_0 = 3·10^{-6} m^2, f_e = 2,0·10^{-6} m^2, k_z = 3·10^{-3} m, the dependence of the manipulator motion angular velocity has the form presented in Fig. 4, b. Transient process is steady, though it has an oscillatory nature. However, motion speed of the boom is established at the level of $\omega_x = 0{,}5$ rad / s within four oscillations. Motion speed of the manipulator column is stable and has the value of $\omega_z = 0{,}2$ rad / s.



a) b)

Fig. 4. Dependence of the angular velocity of manipulator motion on the operation time:
a – at the boundary of stability; b – at steady motion

Conclusions

It was found that during simultaneous operation of two drives, which interact through the manipulator construction, transient processes occur with intensive oscillations, regulation time and overshoot increase as compared with drives operation in autonomous modes. Improvement of the regulation quality indicators can be achieved by rational choice of the pump regulator design parameters. The following values of the design parameters are recommended: $f_0 = 3 \cdot 10^{-6}$ m^2, $f_e = 2{,}0 \cdot 10^{-6}$ m^2, $k_z = 3 \cdot 10^{-3}$ m. They make it possible to reduce loading in the manipulator construction and operation cycle duration, which improves productivity of the machine and increases its operation life.

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