

DIGITAL PD CONTROLLER WITH DYNAMIC CORRECTION OF THE DIFFERENTIAL COMPONENT COEFFICIENT FOR A MECHATRONIC HYDRAULIC SYSTEM

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Abstract: *The paper presents a circuit of the mechatronic control system developed in Vinnitsa National Technical University (Ukraine). The mechatronic hydraulic system operation has been investigated according to the non-linear mathematical model processed using MATLAB-Simulink software package. Dependence of the differential component coefficient of PD-controller on the value of pressure in the mechatronic control system has been found and used for dynamic adjustment of the controller. Application of the proposed correction of the PD controller differential component has made it possible to reduce the time of transient process in the mechatronic hydraulic system by 25 – 75 % depending on the pressure variations in the system in the range of $p_c=(20\dots150)\cdot 10^5$ N/m².*

Keywords: *mechatronic system, mathematical model, PD controller, dynamic correction, transient process time.*

1. Introduction

A tendency of the development of working mobile machines (harvesters, excavators, tractors, loaders, crane-manipulator installations) is transition to hydraulic systems with electrohydraulic control and free-programmable controllers. They were named mechatronic hydraulic systems. Application of mechatronic hydraulic systems makes it possible to improve economic efficiency, productivity and operation quality of mobile working machines [1].

In mechatronic hydraulic systems regulators are used, the role of which is performed by free-programmable controllers.

In mechatronic hydraulic systems digital controllers implement control algorithms (based on PID, fuzzy and neural technologies).

At present extensive research is carried out on searching optimal structures of digital controllers, determination of their parameters and methods of adjustment depending on the purpose and dynamic performance of regulated objects.

One of the methods for improving the operation quality of PID controllers is dynamic

correction of their coefficients depending on the changes of regulated object operation modes [2, 3].

In Vinnitsa National Technical University a mechatronic hydraulic system has been developed (Fig. 1). It includes a free-programmable controller 6 that implements a control algorithm on the basis of PD controller [4].

A mobile machine operation is characterized, by constant changes in the directions of the working fluid flow in the hydraulic lines and hydraulic units as well as by changes in the directions and value of technological loads at the actuators. Dynamic modes are characteristic of a mobile working machine operation.

To provide the required dynamic characteristics of the mechatronic hydraulic system, a free-programmable controller realizes the function of PD controller for controlling pump 1.

PD controller used in a mechatronic hydraulic system must be appropriately adjusted, otherwise deterioration of dynamic characteristics may

occur with the change of mechatronic hydraulic system operation modes.

PD controller adjustment depends directly on the dynamic performance of the mechatronic hydraulic system and its operation modes. In order to adjust PD controller taking into account dynamic properties of the mechatronic hydraulic system, a non-linear mathematical model has been developed.

2. Mathematical model

The hydraulic system (Fig. 1) includes pump 1 with regulator 2 which is connected with hydraulic cylinder 3 via directional control valve 4. According to the signal of pressure sensor 12, controller 6 regulates electromagnet 8 of the pump 1 regulator.

The mathematical model includes the equation of torques on the swashplate of pump 1 (Fig. 1), the equation of forces on the piston of hydraulic cylinder 3 and spool 7 of regulator 2, the equation of the continuity of flows in the hydraulic lines between pump 1, directional control valve 4 and regulator 2 of pump 1, between directional control valve 4 and hydraulic cylinder 3, between regulator 2 and servo-cylinder 10 of pump 1, equation of the voltage drop in the circuit of electromagnet 8, the equation that determines the law of the signal change at PD controller output and dependence of the force at electromagnet output on the voltage value.

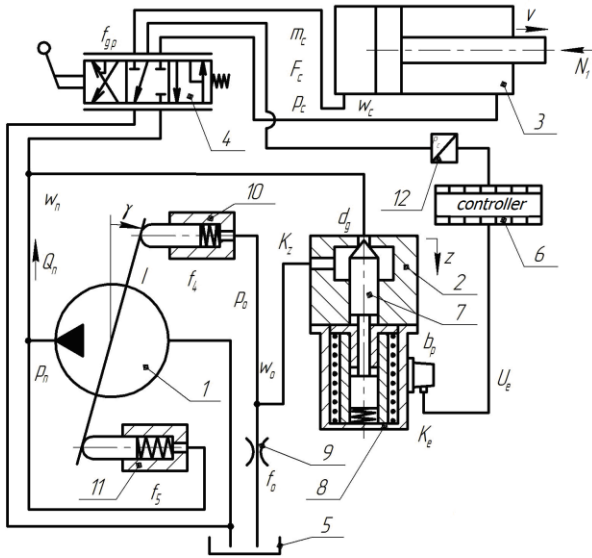


Figure 1: – Design circuit of the hydraulic system.

$$I \frac{d^2 \gamma}{dt^2} = p_n \cdot f_5 \cdot \ell - p_0 \cdot f_4 \cdot \ell - b_\gamma \frac{d\gamma}{dt} + 26,41 - 3,17 \left(\frac{p_n - 9 \cdot 10^6}{7 \cdot 10^6} \right) - 9,86 \left(\frac{Q_n - 0,657 \cdot 10^{-3}}{0,5 \cdot 10^{-3}} \right) - 2,2 \left(\frac{p_n - 9 \cdot 10^6}{7 \cdot 10^6} \right) \left(\frac{Q_n - 0,657 \cdot 10^{-3}}{0,5 \cdot 10^{-3}} \right); \quad (1)$$

$$m_c \frac{dv}{dt} = p_c \cdot F_c - N_1 - b_c \cdot v - T_c \cdot \text{sign } v; \quad (2)$$

$$b_p \frac{dz}{dt} = p_n \cdot \frac{\pi \cdot d_g^2}{4} - K_e \cdot i - T_p \cdot \text{sign} \frac{dz}{dt}; \quad (3)$$

$$\frac{\pi \cdot d_7^2}{4} \cdot d_8 \cdot k \cdot n \cdot \text{tg} \gamma = C_1 + C_2 \cdot f_{gp} + C_3 \cdot f_{gp}^2 + C_4 \cdot p_c + \mu \cdot k_z \cdot z \cdot \sqrt{\frac{2|p_n - p_0|}{\rho}} \cdot \text{sign}(p_n - p_0) + \beta_n \cdot W_n \frac{dp_n}{dt}; \quad (4)$$

$$C_1 + C_2 \cdot f_{gp} + C_3 \cdot f_{gp}^2 + C_4 \cdot p_c = F_c \cdot v + \beta_c \cdot W_c \frac{dp_c}{dt}; \quad (5)$$

$$\mu \cdot k_z \cdot z \cdot \sqrt{\frac{2|p_n - p_0|}{\rho}} \cdot \text{sign}(p_n - p_0) = \mu \cdot f_0 \sqrt{\frac{2p_0}{\rho}} + \beta_n \cdot W_n \frac{dp_n}{dt}; \quad (6)$$

$$p_1 = K_p \cdot p_c + (A - B \cdot p_c) \frac{dv}{dt}; \quad (7)$$

$$U_e = K_u \cdot p_1; \quad (8)$$

$$U_e = L_e \frac{di}{dt} + i \cdot R + C_e \frac{dz}{dt}; \quad (9)$$

$$\beta_n = \begin{cases} 2 \cdot 10^{-9} \left(1 - 0,03 \frac{p_n}{10^5} \right) & p_n \leq 23 \cdot 10^5 \\ 0,6 \cdot 10^{-9} & 23 \cdot 10^5 < p_n \leq 300 \cdot 10^5 \end{cases} \quad (10)$$

In the mathematical model the following designations are used:

Q_n – flow rate of pump 1;
 p_n – pressure at the output of pump 1;
 p_c – pressure at the output of directional control valve 4;
 p_1 – signal at PD controller output;
 p_0 – pressure in servo-cylinder 10 of variable pump 1;
 z – location coordinate of spool 7;
 v – motion speed of hydraulic cylinder 3;
 γ – rotation angle of the swash plate of variable pump 1;
 f_{gp}, f_0 – areas of the working ports of directional control valve 4 and throttle 9;
 F_c, f_4, f_5 – areas of pistons of hydraulic cylinder 3 and servo-cylinders of the variable pump;
 d_7, d_8, d_g – diameters of the pistons of the variable pump and contact area of the pump pistons with the swashplate, of the pump regulator throttle;
 K_z, K_e, K_w, K_p, K_g – gain coefficients of the working port of regulator 2, of the electromagnet of controller, PD controller proportional and differential components;
 L_e, R, C_e – inductance, active resistance and counter-EMF of the electromagnet windings;
 A, B – coefficients of PD controller differential component;
 C_1, C_2, C_3, C_4 – coefficients of the flow rate characteristic of the directional control valve;
 L – current in the electromagnet windings;
 U_e – voltage supplied to the electromagnet windings;
 N_1, T_c, T_p – forces of the reduced load at the rod, of friction in hydraulic cylinder 3 and regulator 2;
 b_p, b_c – coefficients of viscous friction in hydraulic cylinder 3 and regulator 2;
 μ – flow coefficient at the throttling and spool elements;
 ρ – working fluid density;
 ℓ – arm of action of the servo-cylinders in variable pump 2;
 $\beta_n, \beta_C, \beta_0$ – coefficients that take into account total deformation of the working fluid and rubber-metal sleeves;
 I – inertia moment of the pump swashplate;
 m_c – reduced mass of the working mechanism;
 W_m, W_o, W_c – volumes of the hydraulic lines between pump 1 and directional control valve 4, between regulator 2 and servo-cylinder 10, between directional control valve 4 and hydraulic cylinder 3;
 n – rotation speed of the shaft of pump 1.

3. Dynamic correction of PD controller

The mathematical model was processed in *MATLAB* – Simulink environment.

In static and transient modes the digital controller receives a signal proportional to the value of pressure p_c and generates signal U_e which controls electromagnet 8 in regulator 2 of pump 1.

Block-diagram of the digital controller is presented in Fig. 2.

The digital controller generates a signal

$$p_1 = K_p \cdot p_c - K_g \frac{dp_c}{dt} \quad (11)$$

This signal consists of a proportional component $K_p \cdot p_c$ and differential component

$K_g \frac{dp_c}{dt}$. In the process of investigation the proportional component coefficient was not changed and adopted $K_p=1$. Differential component coefficient K_g varied during transient process depending on the value of signal p_c .

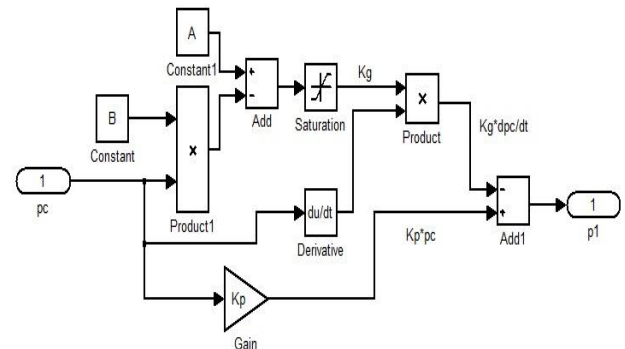


Figure 2: – Block-diagram of the digital PD controller with dynamic correction of the differential component coefficient.

$$K_g = A - B \cdot p_c \quad (12)$$

Differential component of PD controller signal was limited to the range of $K_g \frac{dp_c}{dt} = (-5 \dots +5) \cdot 10^{-5}$. In static modes of the mechatronic hydraulic system operation the digital controller output signal has only a proportional component $p_1 = K_p \cdot p_c$ because $\frac{dp_c}{dt} = 0$.

For finding A and B coefficients numerical experiments were conducted in order to determine transient process in the mechatronic hydraulic system during stepwise variation of load N_1 at the hydraulic cylinder rod.

Transient processes were determined in three series of the experiments for different values of maximal load N_1 that took maximal values equal to 2000 N; 15000 N; 35000 N corresponding to the following values of pressure p_c : $20 \cdot 10^5$ N/m²; $80 \cdot 10^5$ N/m²; $150 \cdot 10^5$ N/m².

In each series of experiments with a fixed maximal value of load N_1 the value of coefficient K_g varied in the range from $20 \cdot 10^{-5}$ to $800 \cdot 10^{-5}$ and the transient process time was determined.

The results of numerical experiments are presented in Fig. 3.

As a result of investigation, range K_g that provides the change of the transient process time not exceeding $\pm 2,5$ % was found for different values of maximal load N_1 at the hydraulic cylinder rod.

On the experimental results dependence of the differential component coefficient K_g on the value of pressure p_c was approximated by the dependence $K_g = A - B \cdot p_c$, for values $A = 980 \cdot 10^{-5}$, $B = 6 \cdot 10^{-10}$.

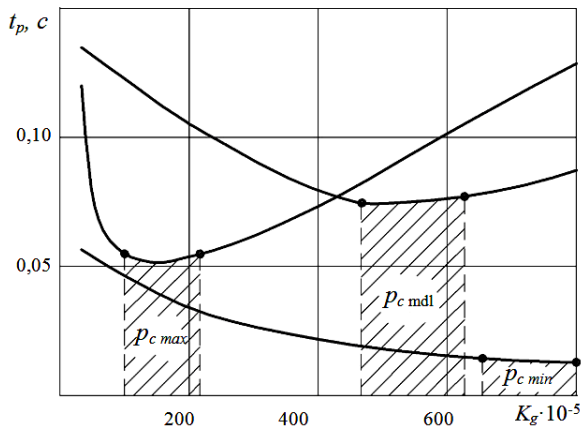


Figure 3: –Dependence of the transient process time on the value of differential component coefficient K_g of PD controller signal.

Fig. 4 presents dependences of the value of pressure p_c at the hydraulic cylinder input for a stepwise change of load N_1 from 0 to 25000 N without correction of PD controller coefficient (a) and for PD controller that has dynamic correction of the differential component coefficient (b).

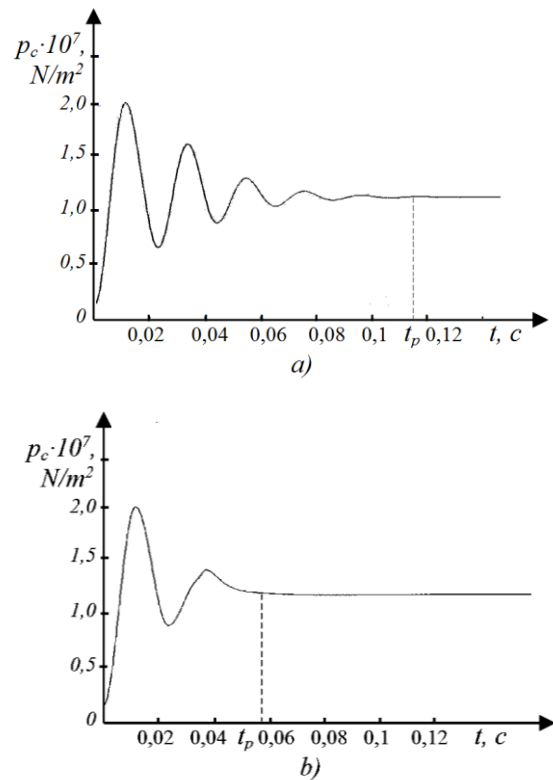


Figure 4: –Transient processes in the mechatronic hydraulic system:
a) without correction of PD controller coefficients;
b) with dynamic correction of PD controller differential component coefficient.

The presence of digital PD controller with dynamic correction of the differential component coefficient makes it possible to reduce the time of transient process in the mechatronic hydraulic system by the value from 25% to 75% when the value of pressure at the hydraulic cylinder input changes in the range from $p_c=20 \cdot 10^5$ N/m² to $p_c=150 \cdot 10^5$ N/m².

4. Conclusions

1. Application of a digital PD controller in the mechatronic hydraulic system makes it possible to improve dynamic characteristics for the case of pressure value change at the hydraulic cylinder input.
2. Adjustment of the digital PD controller depends on the pressure value at the input of the hydraulic cylinder of the mechatronic hydraulic system.
3. The proposed correction of the differential component coefficient makes it possible to reduce the time of transient process in the mechatronic hydraulic system by the value from 25% to 75% depending on the operation mode, which is

characterized by the value of pressure at the hydraulic cylinder input in the range of $p_c=(20...150) \cdot 10^5 \text{ N/m}^2$.

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