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DEVELOPMENT OF AN AUTOMATED SYSTEM OF CONTROL OVER A DRILLING MUD PRESSURE AT THE INLET TO A WELL

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This paper addresses control over flushing a well, which belongs to the class of non-stationary dynamic stochastic objects. The object evolves over time and has a large transport delay, which increases with an increase in the well's length. The current work is aimed at solving the tasks on improving a mathematical model of the automated control system taking into consideration a constraint on the capacity of a drilling pumping unit. The normalized transition functions of a pumping unit have been examined, based on which the magnitude of the delay has been determined, and the structures and parameters of typical controllers have been synthesized.

It has been established that the only way to improve control quality is to use a more complex controller, which can reduce the negative impact of the delay.

The closed automated control systems with delay have been investigated, which ensures better indicators of the control process compared to the industrial systems based on PI controllers. It has been shown that the Fuzzy-PID-controllers demonstrate better quality indicators – an overshooting of 0 % and a transition process duration of 15 s in a wide range of changes in the external influences and system parameters.

An issue of the feasibility of applying the PI, PID-controllers with a Smith predictor has been considered. It has been shown that the quality of the control process involving a PID-controller and the Smith predictor is close to the quality indicators of the system with a Fuzzy-PID-controller. The need has been established to build a system that could independently adapt to changes in the geological and technical conditions and the geo-environment that occur in the process of deepening the well. It has been demonstrated that such systems should have a decision support circuit or be adaptive. The obtained data are useful and important because they make it possible to improve the efficiency of the control process of a technical hydraulic system of deep wells flushing during their deepening

Keywords: simulation, wells flushing, controller, pressure at the well inlet, control

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1. Introduction

The world practice of automating the drilling of wells shows that one of the important tasks for oil gas companies is to increase drilling performance and reduce energy consumption. The automation of a wells flushing process occupies a special place in resolving these issues. This is due to the fact that the hydraulic systems of wells flushing belong to the class of complex nonlinear non-stationary dynamic stochastic objects that function under the *a priori* and current uncertainty regarding their structure and parameters. In addition, their pumps' capacity is 600 kW and above and they have a large transport delay that grows linearly as the length of a well increases.

The designed systems that stabilize the pressure of drilling mud at the inlet to a well differ in the structure of controllers, the number of pumps, diesel engines, correcting devices, the types of electric drives. They are implemented by applying specialized PI-controllers at drilling units.

At the same time, programmable controllers have now been widely used to control the continuous technological processes in the oil and gas industry. They make it possible to implement a control system with Fuzzy controllers, Smith predictors, as well as with multiparametric controllers based on the use of a rotation operator with respect to the object of control, or an adequate mathematical model.

The inverse controller application is particularly useful as the well flushing process is characterized by a change, under the influence of perturbations, in the constants of time and a drilling pumping unit's transmission ratio, and the time of delay in a system that transports drilling mud.

In view of the above, it is a relevant task to undertake additional research into the clarification of a mathematical model of the well flushing process and to build the multiparametric inverse controllers, Fuzzy-controllers, and controllers with a Smith predictor for adjusting the operation of drilling pumping units.

2. Literature review and problem statement

Forecasts for the development of advanced technologies in the automation of oil and gas wells drilling are given in works [1, 2]. It is shown that one of the issues related to the general problem of automated control over a well drilling process is the continuous optimization of this process. It should be based on computerized control [3] over the current values of the dynamic parameters [4] for a real-time drilling process [5]. The optimal modes of a well drilling process are achieved by optimizing the axial effort on the bit, the rotational speed of the rock-crushing tool, the hydraulic capacity of the bit [6], and the automated control over a well's trajectory [7]. A maximum of the mechanical velocity of drilling is used as the main optimization criterion in [8], even when the drilling conditions differ by the high pressure and temperature in a well [9].

Paper [10] determined that when drilling at small depths there is a significant difference between the efficiency indicators achieved while applying two criteria – a maximum of the mechanical rate of drilling and a minimum of the run meter cost:

$$\text{prime cost}(x)\xrightarrow[x\in X]{}\min\cup\text{sped}(x)\xrightarrow[x\in X]{}\max, \tag{1}$$

where

$$X=\begin{Bmatrix}(F_i,\Omega_i)_{i=1,2,\dots,N};\ F_{\min}\le F_i\le F_{\max};\\ \Omega_{\min}\le\Omega_i\le\Omega_{\max};\ Q_i=\text{const};\ \sum_{i=1}^{N}l_i=L;\ l_i>0\end{Bmatrix};$$

F_i, Ω_i, Q_i is the axial effort on a bit, the speed of its rotation, and a drilling mud consumption in the *i*-th run of a bit; l_i is the footage per bit in the *i*-th run; L is the well length.

However, at great depths, this difference is very small and can be neglected.

The results of an analysis of theoretical studies in the field of drilling optimization [11] and the practical experience of drilling unit operations [12] have shown that the suboptimal drilling regimes are achieved at the maximum allowable axial efforts on the bit. However, the possibility of maintaining such efforts depends on the purification degree of a drilling area from the products of rock destruction – sludge [13]. This process is carried out using a technical hydraulic well flushing system. Its main element is the drilling pumping unit of large capacity (Table 1) [14–16]. The main task of its functioning is to stabilize the predefined value of a drilling mud pressure at the inlet to a well. Solving it employs a closed system of the automated control over a pumping unit equipped with PI-controllers.

Control problems are compounded by the fact that the dynamics of a well flushing process are often unknown and adjustable processes cannot be considered independent. Measurements are usually highly noisy while the load develops over time. In a general form, the technological process is executed under the conditions of the *a priori* and current uncertainty about the parameters and structures under the influence of interference inaccessible for measurements [17]. Therefore, the characteristics of the controllers are improved by using Fuzzy logic [17, 18], artificial neural networks, and genetic algorithms [19]. Such methods are called "Soft computing", emphasizing their ability to operate with incomplete and inaccurate data. One controller may have a combination of the following methods: Fuzzy-PID, neural-PID, neural-fuzzy-PID-controllers with genetic algorithms [19], etc.

Table 1

Specifications of drilling pumps

Indicator	Pump parameter		
	U8-6M-A2 (UNB-600A)	UNBT-950 and UNBT-1180	NBT-475 and NBT-600-1
1	2	3	4
Pump capcity, kW	600	900/1.180	450/600
Number of cylinders	2	3	3
Number of piston strokes per minute	65	125	140/150
Number of input shaft rotations, min^{-1}	320	556	441/473
Piston run length, mm	400	290	250
Maximal pressure at outlet, MPa	25	32/40	25
Maximal ideal feed, dm^3/s	51.9	46	44.5/47.7
Reducer transmission ratio	4.92	4.448	3.152
Toothed gear type	Helical	Herringbone	Helical
Pulley diameter, mm	1.400. 1.700, 1.800	1.000	1.120
Valve diameter, mm	168	130	130
Hydraulic unit	Cast	Cast/Forged	Cast
Type of pneumatic compensator at outlet	Spherical	Spherical/piston	Spherical
Dimensions, mm:			
length	5.100	5.400	4.842
height	4.040	3.658	2.009
width	3.000	3.398	2.432
Pump weight, kg	25.200–25.700	22.800/24.600	16.520

The main drawback of Fuzzy-controllers and neural network controllers is the complexity of their configuration – compiling a rule base and training an artificial neural network.

In recent years, the systems of automated technological processes employ various means to improve the quality of control, specifically multi-dimensional, multiparametric controllers [20]. Paper [20] proposed a structure of the PIDD2D3- controller based on the principles of combining the multiparametric regulation and Fuzzy-logic. The coefficients of adjusting the controller are formulated based on a database of fuzzy rules. The control system demonstrates better results compared to an analog PID controller: reducing the dynamic error of regulation by more than 10 times, shortening the adjustment time by up to 30 %.

Study [21] investigated closed systems with fractional order of astatism, which, for many technical objects, provide better dynamic and static indicators of the control process compared to systems with the integer order. Based on the analysis of frequency characteristics, transient processes, and the modified criterion of quality estimation, the authors derived an optimum correlation between the parameters of the desirable transfer function. It was shown that fractional integral-differential controllers make it possible to ensure the order of astatism from 1.3 to 1.7, as well as the permissible overshooting from 2.5 to 5.0 % in a wide range of change in external influences.

Paper [22] reports a method to synthesize a cascade Fuzzy controller, which takes into consideration the limitation of the intermediate coordinates of the system state vector and, at the same time, makes it possible to obtain the permanent structure of a Fuzzy-controller. The theory of fuzzy control for the development of a method for the synthesis of Fuzzy regulators of the Takagi-Sugeno type using standard forms of root distribution of a characteristic polynomial was also further developed, which ensured the formation of the desired dynamics of the system.

However, the scientific literature practically does not provide any methodological approaches to the synthesis of systems of automatic control over the processes that evolve over time and possess a large transport delay, in particular, over a well flushing process.

Given this, the issue of constructing an automated control system for the stabilization of drilling mud at the inlet to a well in the context of optimizing the process of drilling deep oil and gas wells is gaining importance and needs detailed research.

The task of managing the performance of pumps in the structure of an adaptive control system is considered in Fig. 1 using an example of the automated control system (ACS) of drilling regimes for conventional drilling units [5].

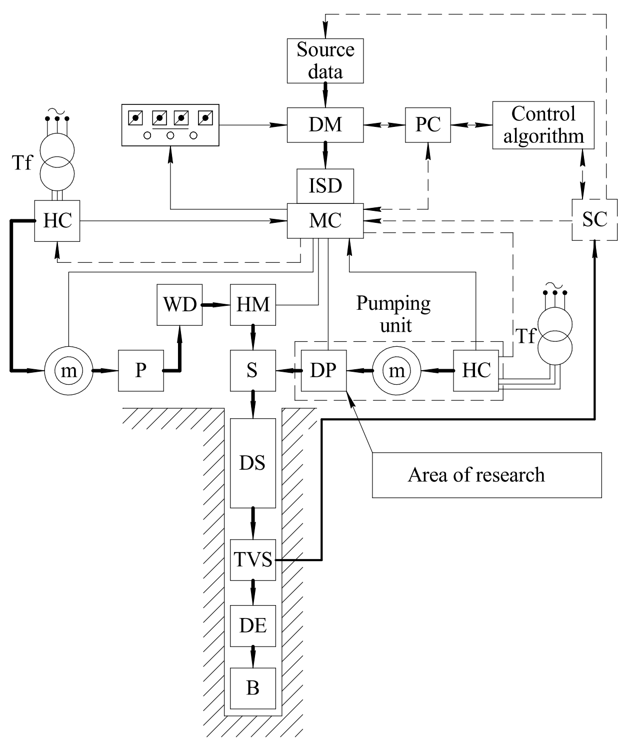

Fig. 1. ASC of drilling regimes for conventional drilling units: DM – decision-maker; Tf – transformer; CP – control panel; MC – microcontroller; ISD – input and setting device; PC – portable computer; SC – stationary computer; P – reducer; WD – winch drum; HM – hoist mechanism; S – swivel; DP – drilling pump; m – electric motor; HC – thyristor converter; DS – drill string; TVS – TV system; DE – downhole engine; B – bit; ⟶ – energy channels; ⟶ – information channels; ----► – control channels [6]

The typical structural diagram of a drilling unit control is characterized by the separate control over a drilling pump unit (DPU) and a bit feed mechanism (BFM). First, the drilling pump is activated from the control panel to set the necessary frequency of its runs; this is followed, from a driller panel, by a transfer to the process of drilling, setting the predefined loading on the bit. A setting parameter accepted is the loading on the hook, which must be determined based on readings from a weight indicator.

Changing the structural scheme of control over the main assemblies of a drilling unit and the transition to automated systems are due to certain reasons. One of them is the inability to maintain the assigned parameters of a drilling mode when developing sloping-directional and horizontal wells with a large hole deviation. This is typical even when using high-precision telemetry networks of downhole parameters control, which compromises the quality and efficiency of wells construction. This is due to the difficult-to-project effect exerted by the friction forces between a drill column and the well walls. It requires changing the adjustment parameter in the main BFM circuit and introducing another, hydraulic control circuit, because the axial hydraulic force from the pressure drop in a downhole engine is dependent on a flushing fluid flow rate. This means that one needs to adopt a dual-circuit control: over the consumption and loading. A given technique can be implemented only by the automated control systems with coordinated DPU and BFM control.

Within a given system, one can use not only typical algorithms but also non-standard algorithms, which include additional parameters. These parameters are the mechanical drilling rate, the frequency of pump runs, which serves for the necessary adjustment of the current job task coordinate and the identification of processes in a dynamic system. In addition, such algorithms make it possible to realize adaptive control in the functions of several parameters; therefore, there is a transition to the intelligent control systems of new generation with flexible decision-making procedures. This transition makes it possible to overcome the difficulties that arise in the development of ASC over drilling regimes, to identify and eliminate the impact of perturbing factors.

The main difficulties that result from the development of algorithms for drilling mode control are associated with the fact that the object of control is a system with unknown, time-variable dynamic characteristics. Since the controlling and perturbing influences are transmitted with a significant delay along extended waveguides, it is necessary to use forecasting estimations [25, 27].

During the performance adjustment of drilling pumps, various ways of connection to each other are used, different ways of changing the parameters of the characteristics of both pumps and systems for which they work. These techniques have a common basis for consideration and understanding – the use of the characteristics of pumps, the characteristics of the systems, obtaining the working points of pumps working in conjunction with systems [14–16].

At automatic regulation, it is important to maintain a strong flow of liquid and low pressure in the well. This can be achieved by using an adequate pump and the power of a cleaning plant. It is necessary to ensure that the number and size of the nozzles correspond to the pumped volume of the liquid.

In order to determine the flow of the drilling mud supplied by the drilling pump, it is necessary to use a stationary flow meter; however, small units are not equipped with such counters. Liquid flow indicators, which count the strokes of a pump piston or rotations, cannot detect a lack of liquid, cannot take into consideration the inefficiency caused by the viscosity of the drilling mud and the action of atmospheric pressure.

3. The aim and objectives of the study

The aim of this study is to develop an automated control system for drilling mud pressure at the inlet to the well in the context of improving the quality indicators of the process of deepening oil and gas wells in real time.

To accomplish the aim, the following tasks have been set:

– to develop an algorithmic structure of the improved controller to improve the efficiency of a drilling mud pressure stabilization system at the inlet to the well;

– to synthesize the system of automated control, which ensures the stabilization of drilling mud pressure at the well inlet in real time, without overshooting;

– to investigate the quality indicators of the transition process of a drilling mud pressure stabilization system at the inlet to the well, which is based on different types of controllers.

4. Materials and methods to study an automated control system

The methodological basis of the current work is formed by the following research methods:

– the fundamental provisions of the classical theory of automatic control – to analyze the stability of the system and quality indicators;

– the methods of analysis and synthesis of automated control systems with random input influences – to synthesize the optimal control laws;

– simulation – to confirm the probability of the obtained theoretical results and the effectiveness of the proposed control system.

The methodological apparatus is a systematic approach and the methods of mathematical analysis, based on which we modeled the system of automated control over the stabilization of drilling mud pressure at the inlet to a borehole with the inverse multiparametric Fuzzy-controller.

The following set of methods and techniques has been used:

– a Taylor's series and a pade function to approximate the sheer delay by a rational transfer function;

– Ziegler-Nichols method – to adjust the parameters of the controller;

– graphic method – for the visual representation of the theoretical and practical material.

The main research toolset was the software packages MATLAB, Mathcad.

5. Substantiating the problem of control over drilling pumping units' operation modes as the system elements

The results of studying the drilling automation issues [2, 6, 11, 13] suggest that the mechanical drilling velocity V_m grows linearly with an increase in the axial effort F on a bit under certain conditions. That requires the stability of the hydraulic power N_H=const at a downhole and the coefficient of rock drill. This pattern is disrupted when sludge is removed completely from a borehole. In this case, the mechanical drilling velocity reaches its maximum value $(\partial V_m/\partial F)=0$ and decreases with a further increase in the axial effort on a bit $(\partial V_m/\partial F)<0$. The violation of linearity along with the loss of the mechanical drilling rate leads to the accumulation of sludge in a downhole and its subsequent dispersion (grinding). This phenomenon is the cause of additional energy costs and can cause accidents.

The linear dependence zone $V_m(F)$ can be increased by increasing the hydraulic capacity of drilling mud. However, this increase is limited to the power of a drilling pump's drive, the geometry of a bit and downhole. Thus, a quasi-optimal drilling regime at the maximum mechanical velocity would only be set at the maximum permissible efforts on the bit $F\rightarrow$max and the maximum possible hydraulic capacity of drilling mud at a well downhole $N_r\rightarrow$max.

Fig. 2 shows the diagrams of the quasi-optimum dependence of the mechanical drilling velocity $V_{mo}(F)$ at Q=const, Ω_i=const for rocks with different drill coefficients.

The curves are built under the condition $F\Omega$=const. In this case, there is a sufficient reserve of hydraulic power of drilling mud on the bit, which makes it possible to execute the drilling process under a quasi-optimum mode [23].

The absence of control systems over the operation modes of the drives in the pumps for drilling mud leads to that the diesel engines work all the time under a maximum power mode. Under such an operation mode of the diesel engines, the overspending of fuel is possible, as well as supplying a well downhole with unacceptably high energy of the hydraulic flow. It actively washes out the wells' walls. If one uses an electric drive, the large amount of electricity is unproductively consumed.

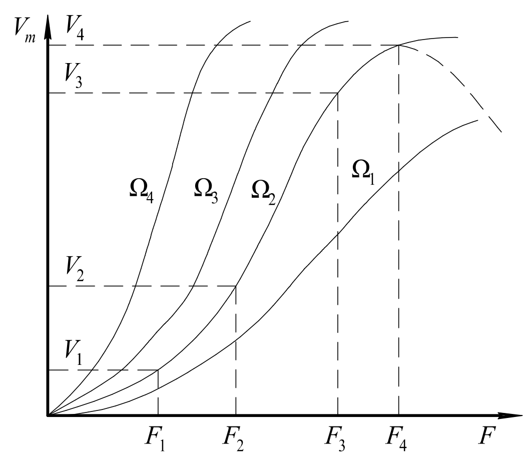

Fig. 2. Static characteristics $V_m(F)$ at Q=const and Ω_i=const: $\Omega_1<\Omega_2<\Omega_3<\Omega_4$

The average power consumed by a pump unit is determined from the following formula [24]:

$$N_N = 9{,}8\cdot 10^2 \frac{1}{\eta_{NP}} Qp, \ \text{kW}, \qquad (2)$$

where $\eta_{NP}=\eta_N\cdot\eta_P$ is the product of pump efficiency η_P; and its electric drive η_N Q is the average value of pump performance, m^3/s; p is the average value of drilling mud pressure at the outlet from the pump, MPa.

The Q and p values are set by a geological and technical order or a project to drill the well different for different trunk lengths. Therefore, we consider the way the power consumed by the pump unit changes under different conditions of well drilling. As an example, we shall consider three wells with a trunk length of l=4,700 m (well No. 20-SL in Prykarpattya, Ukraine), l=2,256 m (well No. 522 HS at

Dolinske field, Ukraine), l=2,500 m (Western Siberia, Russia) (Table 2).

Table 2

Results of calculating the required power of pumping units for different wells

Well trunk length l, m	Drilling mud flow rate Q, m^3/s	Pressure p, MPa	Pump efficiency η_N	Drive efficiency η_P	Pumping unit power N_N, kW
Prykarpattya well No. 20-SL					
600	0.042	9.5	0.81	0.92	524.85
780	0.042	10.0	0.81	0.92	552.48
1.500	0.042	11.3	0.81	0.92	624.3
1.900	0.042	12.0	0.81	0.92	662.97
2.350	0.042	13.4	0.81	0.92	740.32
3.000	0.042	16.5	0.81	0.92	911.59
3.600	0.037	10	0.81	0.92	486.7
3.630	0.037	11.5	0.81	0.92	552.72
4.700	0.03	10.3	0.81	0.92	409.22
Dolinske field well No. 522GS					
1.065	0.0288	7.22	0.82	0.94	264.64
1.466	0.0288	8.68	0.82	0.94	318.59
1.700	0.0288	8.90	0.82	0.94	326.22
2.256	0.0183	9.53	0.82	0.94	221.96
Western Siberia					
2.010	0.02	15.0	0.80	0.93	395.16
$1.5\cdot10^3$	0.015	15.0	0.80	0.93	296.37
$2.5\cdot10^3$	0.025	15.0	0.80	0.93	493.95

If one takes the data on well Np. 20-SL at a depth of 600 m, Q=0,042 m^3/s, p=9.5 MPa, η_N=0.81, η_P=0.92, and fit these values to formula (2), then one obtains N_N=524.85, kW.

At a depth of 3,000 m, the power of the pumping unit should be increased to 911.6 kW, that is, by 1.73 times more than at a depth of 600 m. A similar situation is observed at well No. 5 22GS (by 1.47 times) and at wells in Western Siberia – by 1.66 times.

The task of managing the drilling mud flow can be solved by the application of pumps with an adjustable drive, which ensures control over the desired range.

The controlled drive of the pumping unit is needed because different drilling conditions may require different drilling mud consumption, which is needed to remove the rock and optimize a drilling regime. The need to replace the pumping plugs is eliminated at the same time. For some circuits of the adjustable drive, it is advisable to adjust the value Q towards an increase at the lowered pressure p, which may be needed during the drilling of the upper sections of the trunk.

In addition, the required condition is the failure-free operation of pumping units over time, which corresponds to the longest duration of drilling or several drillings.

However, there are pumps designed to continuously work at the pressure $p\approx16$ MPa over time t=20÷30 hours. Constructing an automated control system for the pumping drilling units' drives as an element of a technical hydraulic system makes it possible to eliminate the specified shortcomings.

6. Development of an algorithmic structure for the improved controller

It should be noted that the technological hydraulic system (THS) for well flushing (WF) operates on the principle of an open circuit.

The well flushing process at its deepening acquires the properties of a stochastic dynamic system, functioning under the *a priori* and current uncertainty conditions about its parameters and structure. In this case, it can be set by using the following representation [29]:

$$x(k)=\varphi\begin{bmatrix} x(k-1),x(k-2),...,x(k-q), \\ y(k-1),y(k-2),...,y(k-q),w \end{bmatrix}+z(k), \quad (3)$$

where $x(k)$ is the m-dimensional vector of the output variables of the system at a discrete time point k=0, 1, 2, ..., N; ϕ is the non-linear unknown operator to be defined; $y(k)=(y_1(k), y_2(k), ..., y_n(k))^T$ is the n-dimensional input variable vector; q is the maximum order of delay; $w=(w_1, w_2, ..., w_n)^T$ is the vector of unknown coefficients to be defined; $z(k)$ is the disturbance vector, which is a random obstacle with zero mathematical expectation and an unknown distribution density function.

Control actions are produced depending on the results of measuring the disturbances – a well's length, the characteristics of the layers' hydrodynamic parameters, the characteristics of pumps and other elements in a hydraulic system. At this stage, the main problem of THS WF control is the complexity of determining the dependence of the hydraulic parameters of the system on the technical parameters of individual elements of THS without a real change in their indicators. It is possible to estimate the results of such changes only when using an adequate mathematical model of THS WF built on the basis of system theory and the systems analysis.

Analysis of the THS WF structural diagram by decomposing it into separate elements makes it possible to adequately model the hydraulic system of well flushing as an open hydraulic circuit (Fig. 3).

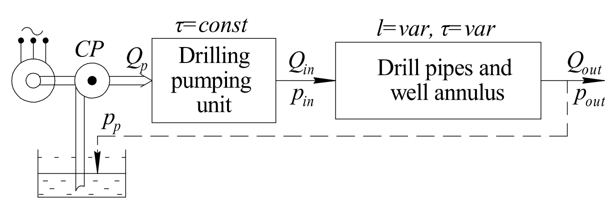

Fig. 3. The structure of a well flushing hydraulic system at drilling: Q_p, p_p — flow rate and pressure generated by the supporting centrifugal pump; CP — supporting centrifugal pump; l — well length; τ — transport delay

The flow rate Q_{in} and pressure p_{in} at the inlet to a well are formed by a drilling pumping unit according to a geological and technical order (GTO). These parameters characterize the mode of well drilling. They are formed according to the depth of the well, the stratigraphic and lithological sections, the strength of rocks, oil and gas manifestations, the gradient of a layer's pressure and temperature, possible complications during drilling, the parameters of drilling mud, and other factors.

These parameters are different for each well (Tables 3, 4). To visually represent the patterns of change in Q_{in} and p_{in} due to the length L of a well, Fig. 4 and Fig. 5 show the diagrams of change in $Q_{in}(L)$ and $p_{in}(L)$ due to the length of wells 522 GS and No. 20-SL.

Given that the length of a drill pipe string grows all the time with the deepening of the well, this element of THS WF is the link with a sheer delay τ=var. For example, for well No. 522GS at depth L=1,655 m, when using the TBE-139.7 pipes with a wall thickness of 10 mm at flow rate Q=49.2 dm^3/s, the sheer delay time equals τ=12.56 min; with an increase in the length of the well, τ grows and reaches several tens of minutes.

Table 3

Information on the flow rate and pressure of drilling mud at the inlet to well No. 20-SL according to a geological and technical order

Well length, m	Drilling mud flow rate at inlet, dm^3/s	Inlet pressure, MPa	Pumps number n, bushings diameter Ø, piston strokes per minute n_x
0–200	59.5	9.9	n=2; Ø=170; n_x=55
200–600	42.1	9.5	n=2; Ø=150; n_x=52
600–980	42.1	10.0	n=2; Ø=150; n_x=52
980–1,500	42.1	11.3	n=2; Ø=150; n_x=52
1.500–1.900	42.1	12	n=2; Ø=150; n_x=52
1.900–2.350	42.1	13.4	n=2; Ø=150; n_x=52
2.350–2.550	42.1	14.6	n=2; Ø=150; n_x=52
2.550–3.000	42.1	16.5	n=2; Ø=150; n_x=52
3.000–3.600	37.1	10.0	n=2; Ø=140; n_x=54
3.600–3.700	37.1	10.6	n=2; Ø=140; n_x=54
3.700–3.950	37.1	11.5	n=2; Ø=140; n_x=54
3.950–4.150	22.7	8.0	n=1; Ø=150; n_x=66
4.150–4.350	22.7	8.6	n=1; Ø=150; n_x=66
4.350–4.550	22.7	9.1	n=1; Ø=150; n_x=66
4.550–4.700	22.7	9.3	n=1; Ø=150; n_x=66

Table 4

Information on the flow rate and pressure of drilling mud at the inlet to well No. 522GS according to a geological and technical order

Well length, m	Drilling mud flow rate at inlet, dm^3/s	Inlet pressure, MPa	Pumps number n, bushings diameter Ø, piston strokes per minute n_x
20–150	49.2	1.91	n=2; Ø=180; n_x=50
150–950	28.8	7.22	n=1; Ø=170; n_x=65
950–1.250	28.8	8.68	n=1; Ø=170; n_x=65
1.250–1.495	28.8	8.93	n=1; Ø=170; n_x=65
1.495–2.020	18.3	9.55	n=1; Ø=150; n_x=58

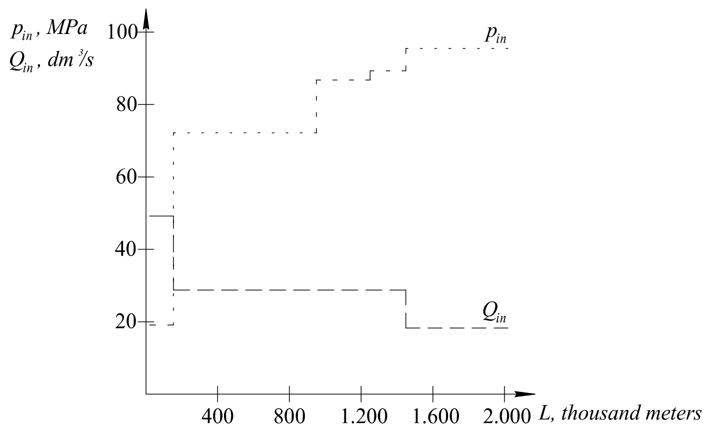

Fig. 4. Diagrams of change in $Q_{in}(L)$ and $p_{in}(L)$ due to the length of well 522GS

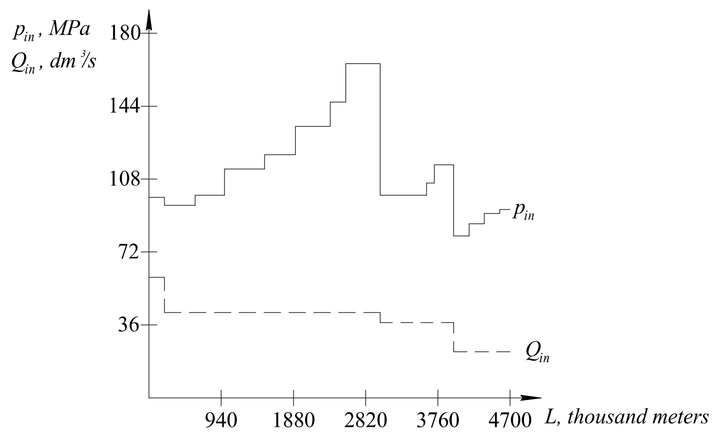

Fig. 5. Diagrams of change in $Q_{in}(L)$ and $p_{in}(L)$ due to the length of well No. 20-SL

The time delays lead to that the information on a well downhole flushing process enters the operator's control panel later than it is required. This can lead to certain complications, that is, the impaired stability of the hydraulic well flushing system. The complexity of control over such an object with a great delay is usually characterized [26] by the ratio of the magnitude of delay to the time constant of the control object. The larger the ratio, the harder it is to achieve the necessary quality of control. Theoretically [26], it is possible to improve the quality of control in such cases either by reducing the delay in the object through modifying its design or by applying a more complex structure of the control system, which reduces the negative impact of the delay.

The first technique is not fundamentally suitable for use in the control of drilling wells since the increase in transport delay is the essence of the drilling technology. Therefore, we shall consider only those techniques that are based on the use of more complex structures of control systems.

We take into consideration that the drill pipes of fixed length and well annulus of a hydraulic system are typically decomposed as a link with delay, which is described by the following equation [26]:

$$p_{out}(t) = kp_{in}(t-\tau), \quad (4)$$

and has a transfer function:

$$W(s)=\frac{p_{out}}{p_{in}}=ke^{-\tau s}, \tag{5}$$

the transient characteristic:

$$\mathrm{A}(\omega)=|W(\omega)|=k, \tag{6}$$

and the phase-frequency characteristic:

$$\varphi(\omega)=-\omega\tau, \tag{7}$$

where τ=var is the delay time; k is the transfer ratio; p_{in} is the input value of pressure; p_{out} is the output value of pressure; s is the Laplace operator; ω is frequency.

Since the analytical synthesis of the investigation of controllers for such an object leads to transcendental equations, we shall conduct its approximation by the rational transfer functions.

One way of approximation is the expansion of e^{-x} exponent into a Taylor series:

$$e^{-x}=1-\frac{x}{1!}+\frac{x^2}{2!}-\frac{x^3}{3!}+\ldots+\frac{x^n}{n!}+\ldots, \tag{8}$$

or

$$e^{-x}=\frac{1}{1+\frac{x}{1!}+\frac{x^2}{2!}+\frac{x^3}{3!}+\ldots+\frac{x^n}{n!}}. \tag{9}$$

Then the sheer delay can be represented as an aperiodic link of the first order

$$e^{-\tau s}\approx\frac{1}{\tau s+1},$$

or the second-order link

$$e^{-\tau s}\approx\frac{1}{0.5\tau^2 s^2+\tau s+1}.$$

At the same time, some error is allowed, which equals:

$$R=e^{-x}-\left[1-\frac{x}{1!}+\frac{x^2}{2!}-\frac{x^3}{3!}+\ldots+\frac{x^n}{n!}\right]. \tag{10}$$

Because this method has a large error, it is used only for those control objects whose sheer delay does not exceed 10 % of the time constant of the control object. This condition is not met for THS WF. Therefore, a more precise method of approximation is used. To transform the transfer function to the form where the numerator and denominator take the form of algebraic polynomials, we applied the approximation of $e^{-\tau s}$ by using a pade function (Fig. 6) [25].

Assuming that τ=1 s and one needs to obtain the approximation that corresponds to the order of approximation n=2, the application of a pade function yields the following result:

$$e^{-s}\approx\frac{s^2-6s+12}{s^2+6s+12}, \tag{11}$$

or

$$e^{-\tau s}\approx\frac{\frac{\tau^2}{12}s^2-0.5\tau s+1}{\frac{\tau^2}{12}s^2+0.5\tau s+1}, \tag{12}$$

where $\tau\neq 1$.

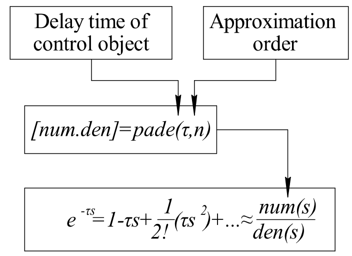

Fig. 6. A pade function

Typically, the polynomials to the fourth order inclusive are used. When using the order of approximation n=1, a pade function produces the following result:

$$e^{-\tau s}\approx\frac{-0.5\tau s+1}{+0.5\tau s+1}. \tag{13}$$

Note that the drill pipes with annulus are the object in which a time delay is significantly larger than the duration of the transition process. Since in this object the offset of phases $\phi=-\omega\tau$ indefinitely increases with an increase in the delay magnitude τ, the ratio $\tau/(\tau+T)$, where T is the time constant, characterizes the difficulty of managing such an object. The closer this ratio to unity, the harder it is to achieve the required quality of control.

If the length of a well is insignificant and the following condition is met:

$$\frac{\tau}{\tau+T}\geq 0.2\div 0.5, \tag{14}$$

where T is the time constant of the control object, a Smith anticipator (predictor) can be used [28].

A controlling action in the control system employing a Smith predictor is calculated from the following formula [28]:

$$y=k\varepsilon(t)+\frac{k}{T_i}\int\varepsilon(t)\mathrm{d}t-\frac{1}{T_i}\int\big(y(t)-y(t-\tau)\big)\mathrm{d}t, \tag{15}$$

where k is the amplification factor; T_i is the integration time constant; $\varepsilon(t)$ is the discrepancy; τ is the delay.

The algorithmic structure of an ASC with a Smith predictor is shown in Fig. 7.

At the input to the simulation unit, the $X_m(s)$ signal is formed, which would subsequently reach the control system's input. It is sent to the controller's input until the signal from the primary feedback $X(s)$ is received.

This signal for equivalent control systems' structures with a Smith predictor can be determined from the following formula [26]:

$$X(s)=\left[\frac{W_{reg}(s)W_{co}(s)}{1+W_{reg}(s)+W_{mco}(s)+W_{reg}(s)(W_{co}(s)-W_{mco}(s))e^{-\tau s}}X_Z(s)\right]e^{-\tau s}. \tag{16}$$

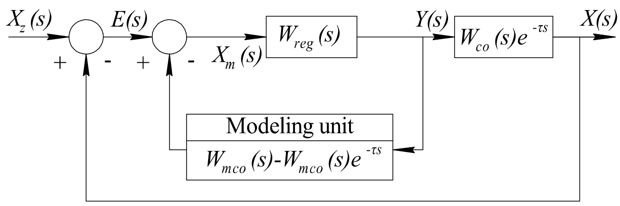

Fig. 7. The algorithmic structure of an ACS with a Smith predictor: $X_z(s)$ – task; $E(s)$ – discrepancy; $Y(s)$ – controlling operation; $X(s)$ – the managed magnitude value; $W_{reg}(s)$ – a controller's transfer function; $W_{co}(s)e^{-\tau s}$ – a transfer function of the control object; $W_{mco}(s)$ – a transfer function of the control object's model

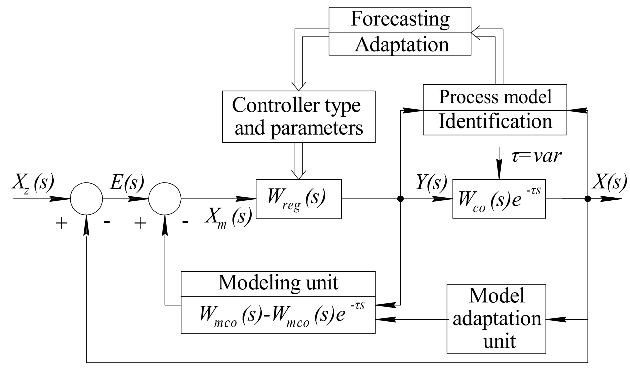

Fig. 8. The structure of an adaptive control system with a Smith predictor and decision-making support (forecasting)

Fig. 7 shows that with an increase in the accuracy of the model the difference ($W_{co}(s)$–$W_{mco}(s)$) in the denominator approaches zero and the system's transfer function excludes a transport delay, which is only added to the already obtained result of control – in brackets (16).

Systems with a Smith predictor have not been widely applied as their implementation is more complex than an ACS with a PID-controller and requires accurate identification of the transfer function of the control object, which is impossible for the object being investigated. It is proved [26] that the highest quality of control is achieved at the identical transfer functions of the model, contained in a Smith predictor and an actual control object at the ratio $\tau=(0.2–0.5)(\tau–T)$.

Changing the real-time delay in the control object, compared to that contained in a Smith predictor's model, results in a substantial deterioration in the quality of control, the occurrence of fluctuations, and could compromise the stability of the system.

In addition to that, configuring the Smith predictor's settings is more complex than those of a PID-controller, because five parameters need to be configured – the K, T parameters of a PI-controller, and the K_{co}, T_{co}, and τ parameters of the mathematical model of the control object.

Since the quality of control with a Smith predictor is significantly dependent on the accuracy of determining the parameters of the control object, there is a need to build a system that could independently, or with limited participation of the operator, adapt to changing the current conditions of drilling. These systems are the systems with the circuits of decision-making support or forecasting.

Therefore, for certain intervals of drilling of wells, it is expedient to use adaptive systems of the automated control over THS WF that include an adaptation unit for automatically determining the time of delay and introducing a corresponding correction to the model of the control object. For a system of control over the entire THS WF, it is necessary, along with the adaptive system, to use a decision support system (Fig. 8).

The purpose of building an adaptive THS WF control system is to provide for the necessary indicators of quality control when changing the dynamic parameters of the object in the process of drilling a well, as well as to accelerate and ensure the required accuracy in setting the controller of a pumping unit.

7. The synthesis and study of quality indicators

The systems of automated control in the oil and gas industry are built mainly on the typical P- and PI–the algorithms of control. This is due to the simplicity of their configuration. They provide, in many cases, for the sufficient dynamic accuracy of adjustment systems but their main advantage is their robustness. The robust P- or PI-algorithm can operate at the inevitable variation in the characteristics of the control object and deviations from the optimum values of the controller's adjustment parameters while maintaining sufficient quality of the control system [28].

One way to improve the quality indicators of the transition process in a control system of drilling pump units is to complicate the control algorithm. Because this is a task associated with the dynamic properties of the control object, we shall consider an example of the transitional characteristic $p=f(U)$ of the pumping unit U8-6M-A2, shown in Fig. 9, and determine a transfer function (Fig. 10).

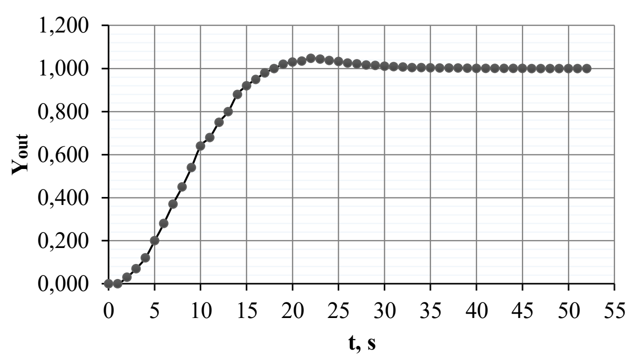

Fig. 9. The transitional characteristic of a drilling pump unit with the pump U8-6M-A2 $p=f(U)$: $Y_{out}\rightarrow p$

The result is the following derived transfer function of a drilling pump unit:

$$W(s)=\frac{1}{21.749s^2+6.739s+1}e^{-\tau s}, \tag{17}$$

where τ=1 s is the time of delay.

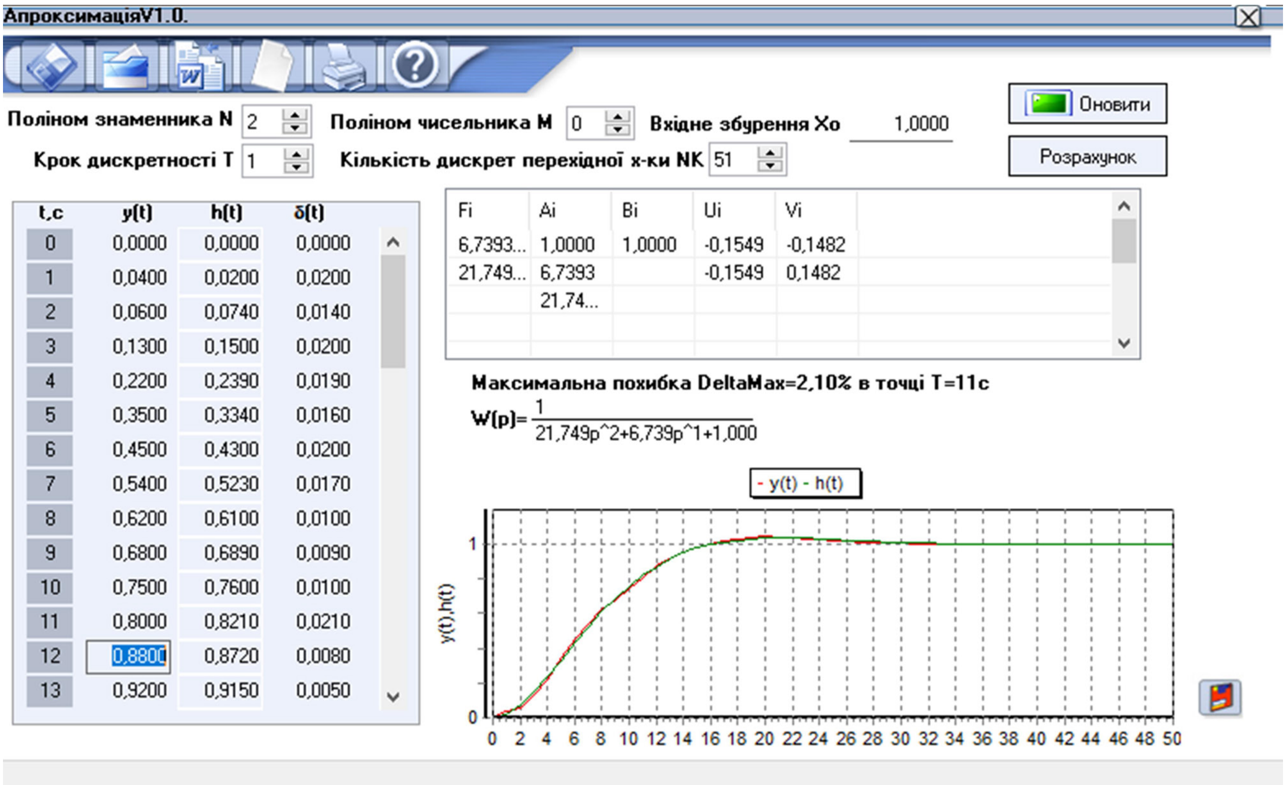

Fig. 10. Determining a transfer function of a drilling pump unit with the pump U8-6M-A2

To analyze the quality indicators of the system of automated control over a drilling mud pressure at the inlet to a well, we built a simulation model in the MATLAB–Simulink programming environment. The quality indicators of transitional processes in ACS with different types of controllers were investigated.

For comparison, Fig. 11–16 show the ACS models and transitional characteristics for three types of controllers. Research results are given in Table 5.

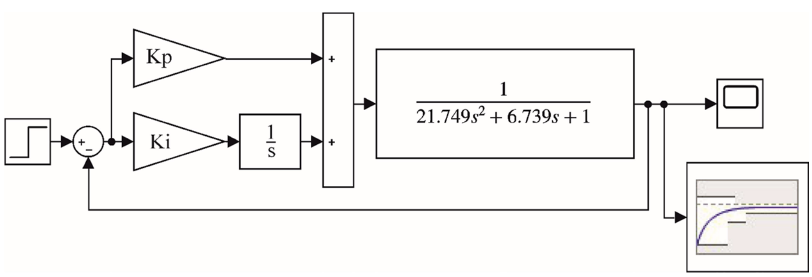

Fig. 11. Structural diagram an ACS with a PI-controller

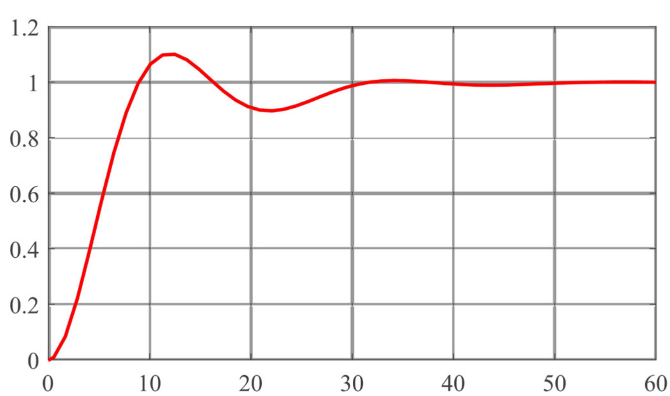

Fig. 12. Transitional characteristic an ACS with a PI-controller

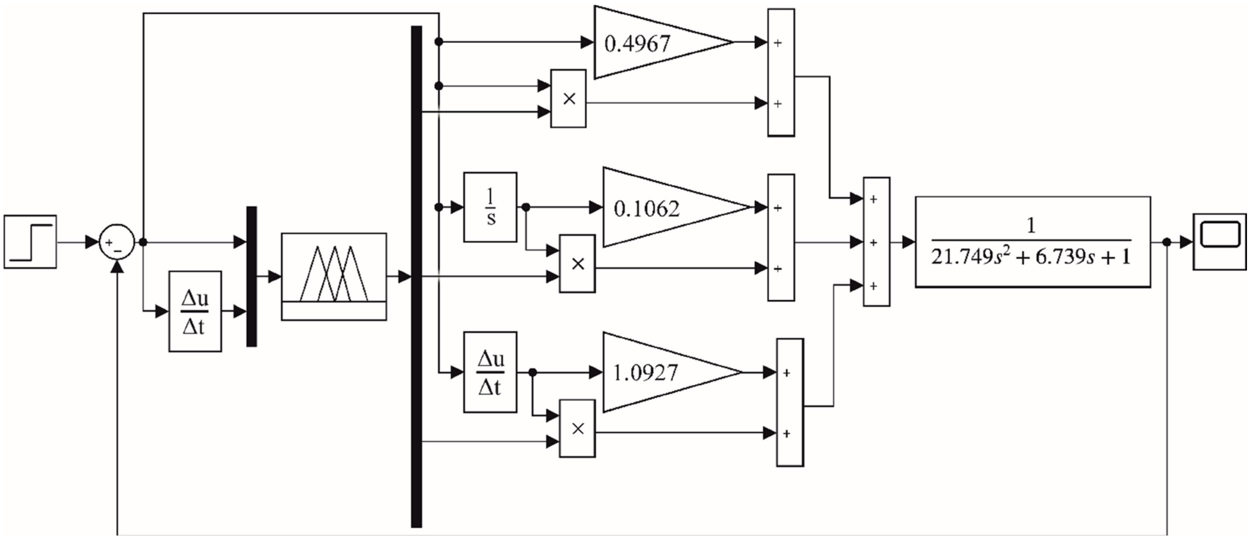

Fig. 13. Structural diagram an ACS with a Fuzzy-PID-controller

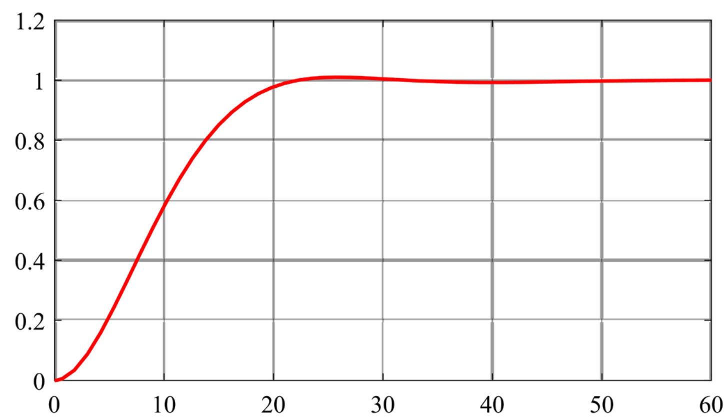

Fig. 14. Transitional characteristic an ACS with a Fuzzy-PID-controller

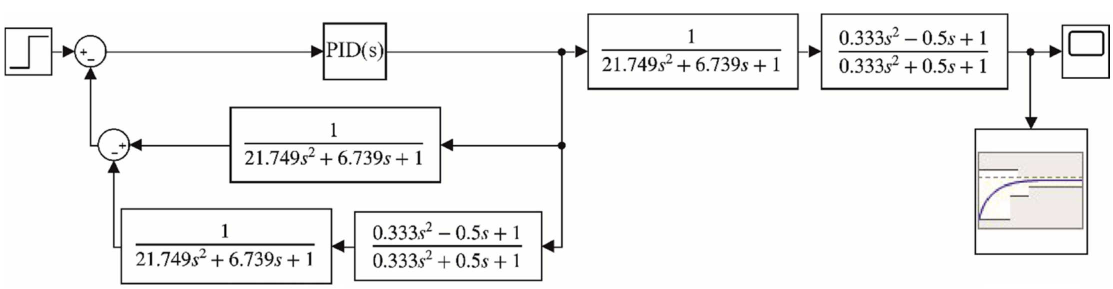

Fig. 15. Structural diagram an ACS with a Smith predictor-based PID-controller

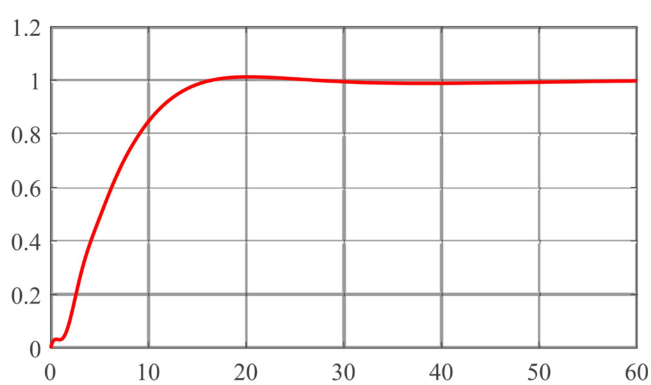

Fig. 16. Transitional characteristic an ACS with a Smith predictor-based PID-controller

Table 5

The quality indicators of ACS of a pumping unit with different types of controllers

Controller type	Controller configuration coefficients	Transition process quality indicators	
		Control time	Overshooting
PI-controller	K_p=0.297 K_i=0.092	31	10
PID-controller	K_p=0.496 K_i=0.106 K_d=1.092	21	0
Fuzzy-PID-controller	K_p=0.496 K_i=0.106 K_d=1.092	20	0
PI-controller+a Taylor series $e^{-s\tau}=\frac{1}{2s+1}$	K_p=0.224 K_i=0.069	30	1.0
PI-controller+a Taylor series $e^{-s\tau}=\frac{1}{2s^2+2s+1}$	K_p=0.214 K_i=0.068	30	0
PI-controller+a Pud series $e^{-s\tau}=\frac{-s+1}{s+1}$	K_p=0.257 K_i=0.072	30	0
PI-controller+a Pud series $e^{-s\tau}=\frac{0.333s^2-0.5s+1}{0.333s^2+0.5s+1}$	K_p=0.261 K_i=0.077	30	0
PID-controller+a Taylor series $e^{-s\tau}=\frac{1}{2s+1}$	K_p=0.253 K_i=0.123 K_d=1.913	20	0
PID-controller+a Taylor series $e^{-s\tau}=\frac{1}{2s^2+2s+1}$	K_p=0.753 K_i=0.123 K_d=1.913	20	0
PID-controller+a Pud series $e^{-s\tau}=\frac{-s+1}{s+1}$	K_p=0.423 K_i=0.088 K_d=0.968	25	0
PI-controller+a Pud series $e^{-s\tau}=\frac{0.333s^2-0.5s+1}{0.333s^2+0.5s+1}$	K_p=0.593 K_i=0.116 K_d=0=1.201	20	0
PID-controller+a Smith predictor $e^{-s\tau}=\frac{0.333s^2-0.5s+1}{0.333s^2+0.5s+1}$	K_p=1.005 K_i=–1.6587 e-04	22	0
PID-controller+a Smith predictor+a Pud series $e^{-s\tau}=\frac{0.333s^2-0.5s+1}{0.333s^2+0.5s+1}$	K_p=0.975 K_i=4.4869 e-04 K_d=3.357	16	0

An analysis of our results makes it possible to assert that the significant complication of the automated control system of drilling pump units does not lead to a substantial improvement of the dynamic characteristics of the system.

The application of a Fuzzy controller with a PID-controller theoretically enables to obtain the system of control over a drilling mud pressure at the inlet to a well with new properties, in particular, to form transitional regimes for the assigned values of the system's output coordinates – pressure and productivity, and also to significantly improve the technical and economic performance of a well flushing system.

8. Discussion of results of modeling a control system

The advantages of our study are the designed automated control system for a drilling mud pressure at the inlet to a well, which ensures the formation of the necessary dynamic characteristics of the control object.

During the research, we developed an algorithmic structure (Fig. 7) and the structure of an adaptive control system with a Smith predictor and decision-making support (Fig. 8) for the advanced controller aimed at improving the efficiency of the system for stabilizing the pressure of drilling mud at the inlet to a well.

Based on the structures shown in Fig. 7, 8, a model of the system of automated control (Fig. 13) has been synthesized that ensures the stabilization of a drilling mud pressure at the inlet to a well in real time without overshooting and with a transition process duration of 16 s.

In order to study the quality indicators of the transition process of the system of automated control over a drilling mud pressure at the well inlet, we have developed an entire series of simulation models in the MATLAB–Simulink programming environment. Several of these models are shown in Fig. 11–16. The results of studying the transitional characteristics are given in Table 5.

Based on the results given in Table 5, we can conclude that the use of a PID-controller+a Smith predictor+a Pud series gives an opportunity to significantly improve the dynamic characteristics of the system. A given controller provides an increase in the system performance by 15 seconds compared to the applied PI-controller.

The application of compensation based on a Smith technique makes it possible to exclude a delay from the closed circuit of the system and apply for synthesis the methods similar to those for an object without delay. However, the system with a Smith controller is more stable when the delays in a control object and in a model coincide. This requirement is met only for a pumping unit.

The main limitation is that a given scientific-applied problem considers only a drilling pumping unit with a single drilling pump. However, in the process of well construction, whose length is 5 to 7 thousand meters, they use drilling pump units with two and three pumps operating in parallel. Further research is therefore may address the construction of an adaptive control system that should improve the quality of control over a well flushing process when using two and three drilling pumps. Resolving this issue requires not only a preliminary estimation of the perturbing actions but also tackling the task of managing a group of pumping units.

9. Conclusions

1. To improve the efficiency of a drilling mud pressure stabilization system at the inlet to a well, we have developed

an algorithmic structure of the adaptive control system with a Smith predictor.

2. Based on the algorithmic structure of the adaptive control system with a Smith predictor, a model of the automated control system has been synthesized, ensuring the stabilization of a drilling mud pressure at the inlet to a well in real time without overshooting and with a transitional process duration of 16 s.

3. The result of the simulation is the established quality indicators of transitional processes in a drilling mud pressure stabilization system at the inlet to a well, built on the basis of different types of controllers. Our results make it possible to assert that the use of a PID-controller+a Smith predictor+a Pud series makes it possible to significantly improve the dynamic characteristics of the system. Compared to the used PI-controller, the performance of the system increased by 15 seconds.

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