Adaptive model of the control of roller bit drilling process

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Abstract. The article is devoted to research of the features of roller-bit drilling process control under incomplete information caused by random variation of the drilled rocks properties. It is proposed to optimize control model of the roller-bit drilling process parameters that uses the correction values of axial force and rotational speed of drill bit. The optimization method of operating parameters of roller-bit drilling process is developed and based on the correcting values of axial force and bit rotational speed depending on the technical characteristics of the drilling unit and physic and mechanical rocks properties. The proposed method allows determining the maximum headway per drill bit, drilling speed and its ratio corresponding to the optimum efficiency of the roller-bit drilling process, required for adaptive control of process parameters. The structure of intelligent automated control system of roller-bit drilling process with an adaptive element is developed and this system can adjust and maintain the values of operating parameters correspondingly actual rocks properties for effective process control.

1. Introduction

Optimization problems, regulation of the roller drilling process parameters and accounting for uncontrolled factors are often associated with information uncertainty [1]. This problem is especially acute during drilling wells for various applications, when it is not possible to foresee in advance a change in the structure and strength of rocks. To study the influence of operational parameters on the drilling process and determine the most significant controlled factors, foreign authors suggest using the analysis-of-variance method, neural network methods [2], and algorithms for the drilling rate optimization [3].

The choice of the mode control strategy is the most complicated task in the drilling process automation [4]. Various strategies of control and optimization of drilling are known [5-7]: with the drilling model and searching for an extremum; with the identification of rocks; with a searchless extreme tuning; with the vibration parameter control, etc. The current state of research in the area shows that the influences of many regime parameters and uncontrolled factors on the technological process are not taken into account. The irrational and untimely selection of drilling operating parameters, which do not adapt to the optimal values, is the reason for the low resource, unanticipated failure of drilling bits and significantly undercapacity productivity [8]. Existing control systems, in order to avoid frequent failure of the drilling bit, operate with non-critical values of the regime parameters that provide significantly underestimated performance. The landmark for the operating parameters setting is their optimal values that are timely to the current rock characteristics, which are determined using the optimization model. Optimization of the roller drilling process is possible only if there is a mathematical model based on a united universal criterion [9].

2. Materials and methods

An optimization model is proposed to improve the quality of the drilling process control under unpredictable change conditions of the rocks properties. This model uses correcting quantity of axial load P_{ax} and bit rotation frequency n_{rot}. The task is to find the extremum of the efficiency function, which allows determining the optimal values of the parameters of the studied process under incomplete information about the rock properties' change Provided that the input control actions for the drilling machine are corrected values of the $P_{ax.cor}$ и $n_{rot.cor}$ [1], the multidimensional function will be as follows:

$$y = f(P_{ax.cor}, n_{rot.cor}) = max,$$

where $P_{ax.cor}$, is the corrected value of axial force, $P_{ax.cor} = P_{ax} + \Delta P_{ax}$; $n_{rot..cor}$, is the corrected value of frequency of rotation, $n_{rot..cor}=n_{rot}+\Delta nr_{ot}$. Here ΔP_{ax}, Δnr_{ot}. – correction values of axial force, frequency of rotation.

These values are obtained in the controller by using calculation methods that assess drilling tool resource and economic efficiency of the drilling process and the procedure for determining of settlement firmness of drill bits with complex loads, depending on the rock characteristics and drilling modes. The goal is to maximize productivity under the existing conditions of the roller bit drilling process (the optimality criterion is efficiency) and minimize cost during the productivity (the optimality criterion is cost). The maximization of the productivity is possible by maximizing axial load and optimization of the bit rotation frequency in combination with maximization of a resource.

The optimal value of the drilling bit rotation frequency [n_{rot}] when drilling a rock massif [1] is proposed to be determined by the formula:

$$\left[n_{rot}\right] = \frac{0{,}94 \cdot N}{10^8 \cdot \pi \cdot D_1^3 \cdot I_d \cdot h} \cdot \frac{2I_d^1 + 2\Delta I_d}{2I_d^1 + \Delta I_d} \cdot k_{ind}, \tag{1}$$

where N – the power transmitted to rock-breaking, W; D_1 – rolling drilling bit diameter, m; h – tooth height protruding beyond the profile of the tooth rim, m; I_d – drillability index; I_d^1 – the value of the drillability index before change the rock property; k_{ind} – indenter form factor.

As it can be seen from expression (1), the rotation frequency of roller bit n_{rot} depends on the strength characteristics change, discontinuity and homogeneity of the rock massif. Herewith, with a gradient increase of the strength characteristics, fracturing, stratification, the optimum rotation frequency increases, reducing the overall load on the individual rolling elements of the rolling drilling bit.

The maximum allowable axial force is determined from the allowable loads on the rolling elements of rolling drilling bit. The allowable maximum axial force [P_{ax}] of the drilling machine working part is determined from the allowable loads on the rolling elements of rolling drilling bit [1]:

$$\left[P_{ax}\right] = 6 \cdot z \cdot D_r \cdot L_r \cdot \left(\frac{\left[\sigma_{i.l.r}\right]}{600 \dfrac{2\left(v_d + v_s/2\right)}{2\left(v_d + v_s/2\right) - v_s/2} \cdot \dfrac{2I_d^1 + 2\Delta I_d}{2I_d^1 + \Delta I_d} \cdot k_{ind}} \right)^3, \tag{2}$$

where D_r – roller diameter, mm; L_r – roller length, mm; [$\sigma_{i.l.r}$] – allowable stress for rolling drilling bit bearings, MPa; v_{d} – drilling speed, m/s; v_s – tooth lowering speed, m/sec.

From the analysis of expression (2), it follows that the optimization criterion the maximum axial force depends on the strength of the bit bearing material, strength and structural rock properties. The maximum value of the axial force as operating parameter under any conditions should not exceed the value of the criterion of the expression (2). Prime cost minimization is possible if the optimality criteria are met - rotation frequency and axial force in accordance with expressions (2) and (3), which will result in an optimal ratio of performance and resource.

3. Formation and implementation of the model in the intelligent automated control system of the roller bit drilling process

On the basis of the proposed model, drilling process adaptive control under uncertainty is implemented. Figure 1 shows the developed block diagram of the intelligent automated control system (ACS) of the drilling process.

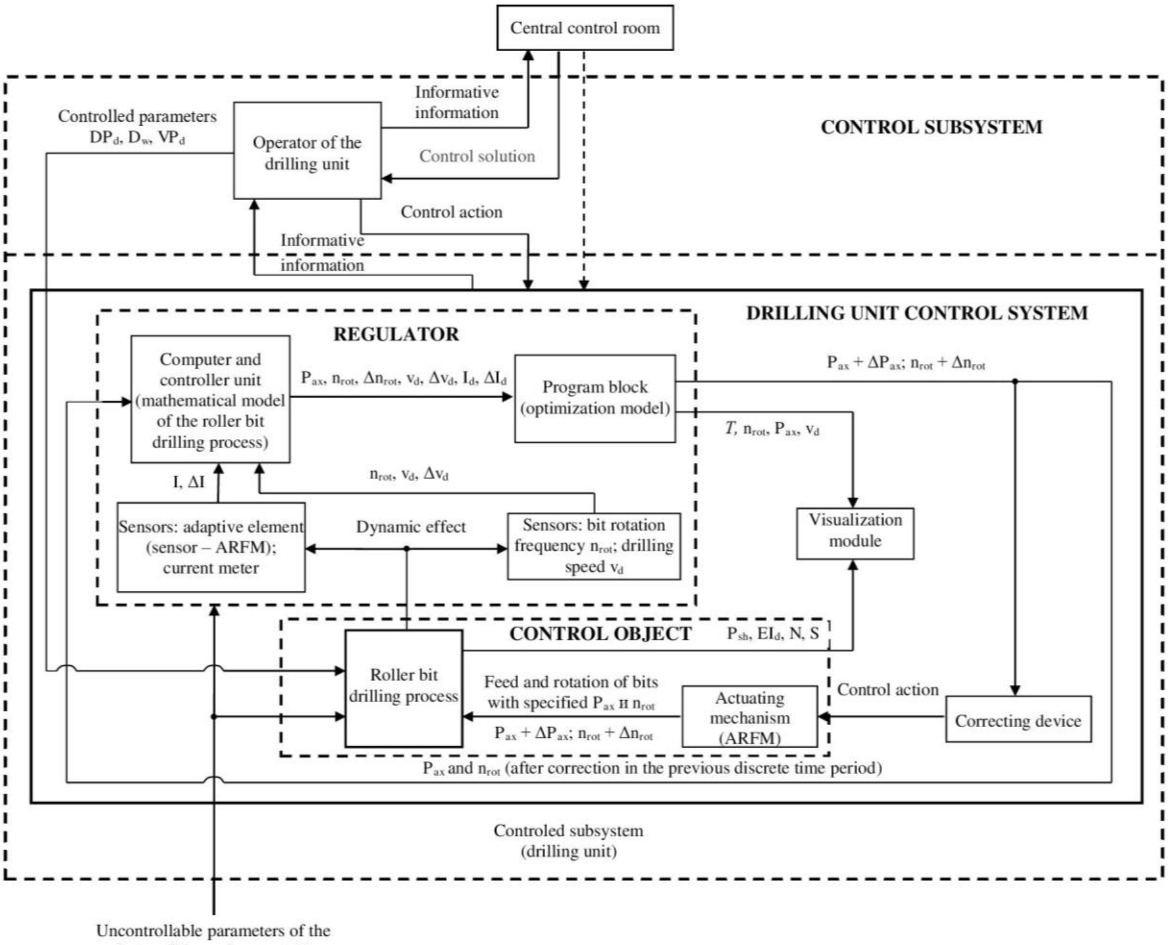

Figure 1. Structural diagram of the intelligent ACS of roller bit drilling process.

In this scheme ARFM – adaptive rotary feed mechanism, DP_d – design parameters of the drilling unit; D_w – the diameter and the depth of the well; VP_d – the vibration parameters of the drilling unit; P_{ax} – axial force, kN; n_{rot} – drilling bit rotation frequency, rev/sec; v_d – drilling speed, m/s; I_d – drillability index; T – bit resource, m; I – current, Amp; P_{sh} – the productivity of the drilling unit per shift, m/shift; EI_d – energy intensity of drilling, kWh/m; N – the power transmitted to rock-breaking, W; S – the cost of the drilling process, rub/m.

The deviation of the current value of controlled parameter from the required value is used to form the control action. In the control process it is possible to measure the main disturbance. The intellectual ACS of nonlinear feedbacks based on the combination of control principles in the perturbation and the deviation (combined control) to improve the control accuracy.

The control system and the roller bit drilling process (the control object) are influenced by external disturbing effects – uncontrolled parameters of the destructible environment D_e (properties of drill rocks and their accidental change). This system contains a regulator, a corrective device and an actuator [4]. The role of the executive mechanism supports adaptive rotationally-feeding mechanism (ARFM). The regulator includes: a computer containing the developed mathematical model of the roller bit drilling process, and a block of controllers; a software unit including the developed optimization model; sensors: an adaptive element, a current meter; sensors of drilling speed v_d, bit rotation frequency n_{rot}.

Input information about the change of rock properties obtained from the control object enters the controller to the sensors by means of dynamic action [1, 4]. The computer from the sensors receives information signals about the current value I, its changes ΔI in the stator ARFM and signals about the drilling speed values v_d, its change Δv_d and bit rotation frequency n_{rot}. The current meter is a current transformer or ammeter. As a speed sensor, a standard electromechanical counter is used, located in the block of the rope-polispast mechanism. The bit rotation frequency sensor is a tachometer mounted on the rotator. The value I_d characterizing the rock massif properties is a current function in the stator of the motor or coupling of the drilling rig ARFM. The value ΔI_d characterizes the change in properties, the presence of structural inhomogeneities in the rock mass and is a function dependent on the change in current. The measured bit rotation frequency as kinematic characteristics, combined with readings of the current sensors and drilling speed, allows obtaining the numerical values of axial forces P_{ax}, indicator of drillability I_d and ΔI_d in the drilling process. These signals are then converted into control signals by means of a controller block that detect and eliminate the deviation (implementation of the control process). Next, the signals are sent to the program block, which calculates the optimal values of the regime parameters P_{ax} and n_{rot}, the drilling speed v_d, the predicted bit resource T (output observed parameters).

The program block contains an optimization model using the correction values of the axial force ΔP_{ax} and the bit rotation frequency Δn_{rot}. To improve the quality characteristics of the system, the actual values of the operating parameters are compared with the optimal ones and are automatically changed by means of a corrective device. The roller bit drilling process is influenced by the actuator in accordance with the received command information from the regulator. Next, the process is carried out with the newly specified values of the operating parameters $P_{ax.cor}$ and $n_{rot.cor}$. The visualization module reflects quickly calculated the output values of the drilling unit productivity in the shift P_{sh}, the energy intensity of the roller bit drilling process EI_d, the power transmitted for the rock destruction N, the specific cost of drilling S.

Feedback is used to transmit information about the current values of the operating parameters P_{ax} and n_{rot} established after correction in the previous discrete time period. The calculated values of all output parameters are displayed on the dashboard through the visualization module for control. The information about the values of these parameters comes from the control system to the drilling unit operator and then to the central control room.

4. Results and Discussion

The developed optimization model makes it possible to calculate the criteria of optimality, the drilling speed and the rolling drilling bit resource for various rock properties. Figure 2 shows the calculated functions dependences of the drilling bit resource T on the drilling speed v_d and the axial force P_{ax}, obtained using a developed mathematical model of a roller bit drilling process [1].

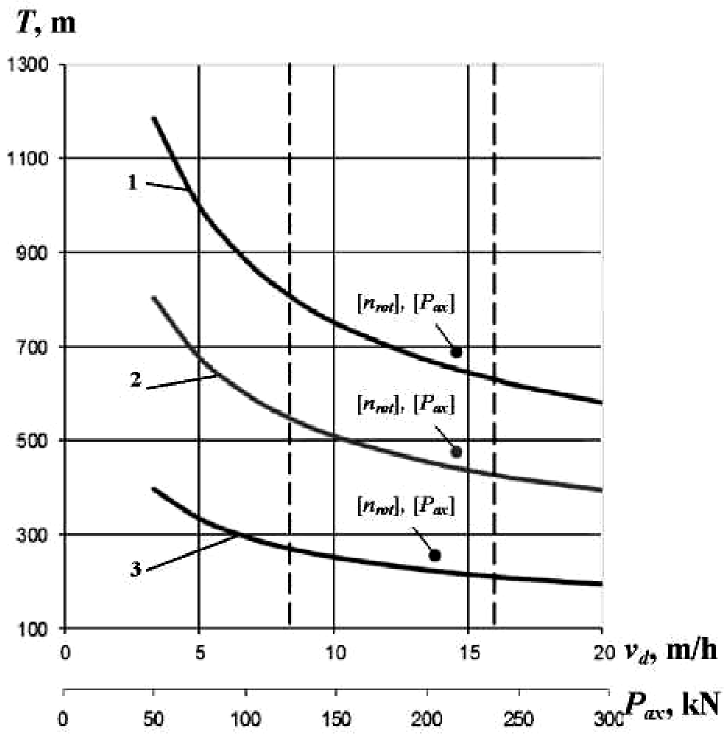

Figure 2. Dependencies of rolling drilling bit resource *T*, drilling speed v_d and axial force P_{ax} at n_{rot} = 1,5 rot/sec and I_d=15.

The dots indicate the modes at the optimal values of the parameters [P_{ax}] and [n_{rot}]. Rock characteristics for curves are indicated by the corresponding numbers (figure 2): 1 - the number of boundaries between rock layers with different physic and mechanical properties per linear meter ($n_{r.l}$ = 10), ΔI_d = 2, the number of cracks in the rock per linear meter (n_{cr} = 0); 2 – $n_{r.l}$ = 20, ΔI_d = 2, n_{cr} = 10; 3 – $n_{r.l}$ = 20, ΔI_d = 4, n_{cr} = 20. Curves 1, 2 and 3 show the corresponding points of the optimal modes for the indicated rock characteristics. For the rock properties, corresponding to curves 1 and 2, the optimal values of the operating parameters were determined: [n_{rot}] = 1,79 rev/sec, [P_{ax}] = 185 kN; the drilling bit resource *T* is for curve 1: *T* = 692 m, for curve 2: *T* = 469 m. For the rock properties corresponding to curve 3, the optimum values of the operating parameters are determined: [n_{rot}] = 1,88 rev/sec, [P_{ax}] = 158 kN; the drilling bit resource for curve 3: *T* = 246 m. The analysis shows that at the optimal mode there is increase of the drilling speed and bit resource. In this case, the optimal modes are in the range of acceptable values set by the producer factory, which proves the adequacy of the optimization model (curved line in figure 2, delimited by vertical lines).

Taking into account the expressions for determining the optimal values of the operating parameters (1) and (2), the drilling speed with optimal control v_d using the adaptive element is proposed to be determined by the following formula [1]:

$$v_d = \frac{40\,[P_{ax}]\cdot[n_{rot}]}{I_d \cdot D_1^2}.$$

5. Conclusion

The developed adaptive model of the process control allows correcting the values of the operational parameters when the changes in rock properties are unpredictable. Efficiency estimation of the roller bit drilling process control with considering the optimization criteria when using the proposed intelligent control system makes it possible to determine the minimum cost of the roller drilling process with the maintaining optimal values of the operating parameters.

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References

[1] Shigina A A, Shigin A O, Stupina A A, Antipina S M and Dzhioeva N N 2018 *Proc. IOP Conf. Series: Mater. Sci. Eng.* **450** 1-6

[2] Wang Y, Salehi S 2015 *J. of Energy Resources Technology-transactions of the ASME* 13 **137 (6)** p 9

[3] Chapman C D, Sanchez J L, Perez R [et al.] 2012 *SPE-151736-MS, IADC/SPE Drilling Conf. and Exhibition*

[4] Shigin A O, Gilyov A V, Shigina A A 2017 *Gornyi Zhurnal* **2** 79-82

[5] Mehaysen A 2017 *International J. of Oil, Gas and Coal Engineering* **5** 13-8

[6] Hankins D, Salehi S and Saleh F K 2015 *J. of Petroleum Engineering* **2015** p 12

[7] Yilmaz M, Mujeeba S and Dhansria N R 2011 *Procedia Computer Science* **6** 106-111

[8] Dushaishi M, Nygaard R, Andersen M, Jeffery C, Hellvik S, Saasen A and Hareland G 2016 *Proc. IADC/SPE Drilling Conf. and Exhibition* (Texas, USA) IADC/SPE-178834-MS

[9] Hou B, Chen M and Yuan J 2014 *Research J. of Applied Sciences, Engineering and Technology* **8** 179-87