Optimization model controlling parameters of a roller drilling process based on energy criterion

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Abstract. The article is concerned with development and research of an optimization model controlling parameters of a roller drilling process using correcting values of operating parameters. The optimization model proposes the use of an energy criterion that provides the ratio of performance and drilling bit resource, corresponding to the minimum cost of a roller drilling process. The proposed model allows to determine the optimal values of the technological process operating parameters, as also the maximum values of the drilling bit resource and performance under the information uncertainty associated with an unpredictable change in the properties of drilled rocks, which is necessary for the effective control of the process parameters under research.

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 [2]. 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 [3]. The landmark for the operating parameters setting are 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 [4, 5].

To improve the quality of the drilling process control under unpredictable change conditions of the rocks properties, an optimization model is proposed based on an energy criterion that contains the condition for the optimal course of rock destruction by the roller bit teeth, which provides a ratio of performance and drilling bit resource corresponding to the minimum prime cost. This model uses correcting quantity of axial load $P_{ax}$ and bit rotation frequency $n_{rot}$ [6]. The extreme goal is to minimize the prime cost with a known performance (the optimality criterion is the prime cost). Performance maximization is possible by the way of maximization axial force and optimization bit rotation frequency in combination with maximization of resource.

The actuating part of the drilling machine has a certain power with which it is necessary to influence the rock volume for a certain period of time in order to destroy it, having done the work [7]:

$$A_{cut} = N \cdot t_{cut}$$
where \( N \) – is the power transmitted for rock destruction, Watt;
\( t_{cut} \) – the time required for the destruction of a certain rock volume by means of roller bit one tooth.

Thus, the time required for the work of the rock destruction by one tooth of the roller bit is determined by the formula:

\[
t_{cut} = 7.2 \times 10^8 \frac{k_{rol.\ bit} \cdot I_d \cdot V_{cut}}{N} \quad \text{or} \quad t_{cut} = 7.2 \times 10^8 \frac{k_{rol.\ bit} \cdot I_d \cdot V_{cut}}{v_d \cdot P_{ax}},
\]

where \( k_{rol.\ bit} \) – coefficient of proportionality;
\( I_d \) – drillability index;
\( V_{cut} \) – volume of destroyed rock by one tooth, m³;
\( v_d \) – drilling speed, m/sec;
\( P_{ax} \) – axial force, kN.

It is necessary to compare the destruction time of rock volume with the time of tooth contact with the rock given the kinematic laws of motion taking into account the diameter of the rollers and the teeth number in rows to determine the rotation frequency of the roller bit at which the time of teeth contact will be sufficient to transfer energy leading to the destruction of a given rock volume.

From the effective functioning condition of roller bits, the contact time of individual teeth with the rock is determined according to the following formula:

\[
t_{xc} = \frac{1}{1.7 \cdot n_{rot} \cdot k},
\]

where \( n_{rot} \) – rotation frequency of the roller bit, rotation/sec;
\( k \) – teeth number of all rows of roller bit.

The essence of the energetic optimization criterion (1) is the equality of the contact time of individual teeth with the rock and the time of rock destruction by one tooth of the roller. This equality corresponds to the maximum destruction efficiency of the rock massif:

\[
t_{xc} = t_{cut}
\]

If \( t_{xc} > t_{cut} \), then the operating time of the drilling machine is inefficiently consumed and it is necessary to increase the rotation frequency of drill bit. If \( t_{xc} < t_{cut} \), then the drilling bit resource is used inefficiently and it is necessary to lower the rotation frequency.

The optimal value of the drilling bit rotation frequency \([n_{rot}]\) when drilling a rock massif [8] is proposed to be determined by the formula:

\[
[n_{rot}] = \frac{0.94 \cdot N}{10^8 \cdot \pi \cdot D_1^3 \cdot I_d \cdot h \cdot \frac{2I_1 + 2\Delta I_d}{2I_1 + \Delta I_d} \cdot k_{ind}},
\]

where \( I_1 \) – the value of the drillability index before change the rock property;
\( D_1 \) – rolling drilling bit diameter, m;
\( h \) – tooth height protruding beyond the profile of the tooth rim, m;
\( \Delta I_d \) – change of drillability index;
\( k_{ind} \) – indenter form factor.

As it can be seen from expression (2), 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:

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

where 
- \( z \) – the number of rolling elements in the bit bearing;
- \( D_r \) – roller diameter, mm;
- \( L_r \) – roller length, mm;
- \( \sigma_{i,l,r} \) – allowable stress for rolling drilling bit bearings, MPa;
- \( v_s \) – tooth lowering speed, m/sec.

From the analysis of expression (3), it follows that the energy 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 specified criterion [9]. 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.

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 1 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 mathematical model of a roller bit drilling process [7].

![Dependence of rolling drilling bit resource](image)

**Figure 1.** Dependences 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 1): 1 - the number of boundaries between rock layers with different physicomechanical properties per linear meter \( n_{r,l} = 10 \), \( \Delta I_d = 2 \), the number of cracks in the rock per linear meter \( n_{cr} = 0 \); 2 – \( n_{r,l} = 20 \), \( \Delta I_d = 2 \), \( n_{cr} = 10 \); 3 – \( n_{r,l} = 20 \), \( \Delta I_d = 4 \), \( n_{cr} = 20 \). 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: \( n_{\text{opt}} \) = 1.79 rev/sec, \( P_{\text{ax}} \) = 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: \( n_{\text{opt}} \) = 1.88 rev/sec, \( P_{\text{ax}} \) = 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 1, delimited by vertical lines).

Taking into account the expressions for determining the optimal values of the operating parameters (2) and (3), the drilling speed with optimal control \( v_d \) using the adaptive element is proposed to be determined by the following formula:

\[
v_d = \frac{40 | P_{\text{ax}} | \cdot | n_{\text{rot}} |}{I_d \cdot D_i^2}.
\]

As an integral criterion for evaluating the control efficiency of the roller bit drilling process (including operating parameters), the are taken operating costs \( S \) for drilling 1 m of the well taking into account with regard to the increase in productivity and drilling bit resource when optimal control [7]. The developed optimization control model the roller drilling process parameters using correcting quantities of operating parameters (axial force and drilling bit rotation frequency) allows determining their optimal values as well as maximum values of drilling bit resource and productivity (drilling speed) under conditions of rock properties unpredictable changes. Evaluation of the effectiveness upon integrated index taking into account with regard to the energy optimization criterion allows you to determine the minimum prime cost of the roller bit drilling process with the condition to maintain the optimal values of operating parameters under conditions of information uncertainty associated with unpredictable changes the drilled rocks properties and impact loads.

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