Increasing the Efficiency of Underground Short-Hole Drilling by Combined Action of Axial and Moment Pulses

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Abstract. The article substantiates the possibility of improving the efficiency of short-hole drilling by combining axial and moment pulses with a rotating drill cutter. The control of regime parameters of drilling, including parameters of axial and moment pulses, in order to establish rational ratios of parameters can be carried out by boring machines of the mechatronic class directly in the process of short-hole drilling. A methodology has been developed for conducting experimental studies in accordance with which experiments have been carried out and dependencies obtained that reflect the effect of the combined effect of axial and moment pulses on the penetration rate. The stress-strain state of the rock in the undercutter zone of the short-hole with the combined effect of axial and momentum pulses on the drilling tool is investigated using the method of finite element analysis.

1. Introduction
Improving the efficiency of the tunneling equipment and reducing the cost of mine workings in modern economic conditions plays a significant role. During the construction of mining enterprises, the volume of mining works is from 30 to 50% of the total amount of work, and at existing enterprises from 10 to 30%. With such a proportion of mining works, an increase in drilling efficiency can significantly reduce the cost of work and will have a significant economic effect.

Mining works are carried out in two most common ways: combine and drilling and blasting. Combine method is used if the bottom is composed of rocks with a strength of less than 6 units on a scale of prof. M.M. Protodyakonov, if the strength of rocks exceeds 6 units, then mining works are carried out mainly by drilling and blasting. The use of drilling and blasting method of mining works is widely used due to the large distribution of the corresponding mining and technical conditions. In addition, during drilling, short-hole drilling is used for the construction of roof bolting, and in the construction of tunnels and other underground utilities - to strengthen the arches and adjacent layers of rock. Given that in the drilling cycle, the proportion of time for direct drilling prevails over other components, an increase in the efficiency of short-hole drilling can significantly increase the rate of tunneling.

2. Review and analysis of methods for improving the efficiency of short-hole drilling
Short-hole drilling as a technological process has a history of more than 350 years [1]. Until about the second half of the 19th century, short-hole were manually drilled. Since the advent of mechanization
tools, there has been a constant effort to improve the efficiency of the drilling process of short-holes by improving machines and rock-cutting tools. The efficiency of short-hole drilling was proposed to be raised in various ways, which can be divided into two categories: ways to increase drilling efficiency by improving the design of rock-cutting tools and methods implemented by improving the designs of rock-drilling machines, including the introduction of automation tools.

Mining tools, as design objects, must satisfy the requirements of reliability (have high wear resistance and the necessary margin of safety), ensure the destruction of rocks with minimal energy, have low material consumption, high adaptability in manufacturing and operation [2]. The task of creating and upgrading mining tools was solved at the Platov South-Russian State Polytechnic University (NPI) earlier [3,4,5], which allowed the creation of a serial cutter for short-holes drilling RP-42, as well as being solved today at the modern technical level using modern computer simulation tools [6,7].

The drilling equipment was first of all modernized by increasing its power supply. The designs of rotary, rotary-percussive drilling and percussive drilling machines have been developed. However, over time, the increase in drive power reached certain technical limitations and, in a further increase in drilling efficiency, was achieved by controlling the mode parameters of drilling (tool rotation frequency, axial force value, and, in the case of rotational percussion drilling, impact frequency), as well as maintaining them at a rational level throughout the time of short-hole drilling.

Short-holes drilling is a complex multi-factorial process, the management of which, as practice has shown, with enough accuracy is difficult to carry out in manual mode. This circumstance has created the prerequisites for the development and implementation of automation tools for managing operational parameters of drilling. Such scientists as Professor V.T. Zagorodnyuk [8,9], Professor G.M. Vodyanik [10], Associate professor V.A. Yatskevich, Associate Professor E.V. Rylev and a number of other scientists [11,12]. Most of the proposed systems for automating the short-holes drilling were based on the use of various force-moment connections between the drill-rod and the whim. Attempts were also made to create a control system using a cutter-face sensor, however, due to the complexity of the implementation of the idea of creating such a sensor, no expected results were obtained.

In modern conditions, the control system of regime parameters of drilling can be implemented on the basis of mechatronic modules, which combine electromechanical components with power electronics and are controlled using a microcontroller or an onboard computer.

The analysis performed allows us to conclude that the greatest effect in increasing the productivity of short-holes drilling can be achieved by further improving the rock-breaking tool and using modern control systems for operating drilling parameters based on mechatronic modules. Such a control system will allow, by periodically adjusting various operating parameters over the drill cutter durability period or during the short-hole drilling time, to achieve a reduction in specific tool wear and an increase in the theoretical penetration rate [13, 14].

3. Formulation of the problem
To drill the short-hole in a rotational way, an axial force (\(P_a\)) and moment force (\(M_m\)) (Fig.1) must be applied to the tool, which create at the cutting edge of the tool a force \(P_y\) and a cutting force \(P_z\), sufficient to form large chips. Improved drilling efficiency can be achieved through additional shock effects. It is obvious that the combination of the values of the number of chips and the impact frequency theoretically should coincide in phase, that is, the addition of the vectors of cutting forces, feed and impact load will have a decisive role in increasing the efficiency of rock destruction by the cutting edge of the cutter. However, this process is stochastic and cannot be directly controlled. At the same time, it is obvious that by controlling the direction of the vector \(P\) and its value, it is possible to increase the efficiency of rock formations and, as a result, increase the penetration rate. In addition to imposing on the instrument additional pulses of the axial force \(P_{a_{inc}}\), it is also possible to superimpose the moment pulses \(P_{m_{inc}}\), which allows not only increasing the force \(P\) but also ensuring its targeted impact on the rock to be destroyed.
Adding an additional impact on the drilling tool will entail a complication of the algorithm for controlling the regime parameters of drilling and, as a consequence, the cost of the rock-drilling machine, but ultimately will increase the efficiency of rock destruction at the face. To improve the efficiency of drilling, it is proposed to additionally influence the drill cutter with axial and moment pulses in various combinations.

In this regard, there is a need for an experimental study of the combined effect on the drilling tool of axial and moment pulses, as well as the study of the stress-strain state of the rock mass in the undercut zone caused by such an impact on the drilling tool.

![Figure 1. Scheme of operating forces when applying moment and axial pulses: $P_y$ – axial force; $P_z$ – cutting force; $P$ – resultant on the tool; $P_{ax}$ – axial impulse; $P_{mu}$ – moment impulse; $R_y$ – resistance of the rock to introduction; $R_z$ – resistance of the rock to cutting; $R$ - resultant rock; $\tau$ - possible area of change in the direction of the resultant $P$.](image)

4. Theoretical part

To carry out experimental studies of the combined effect of the axial and moment pulses on the drilling tool, the original design of the drilling stand was used [15]. Previous studies have shown a nonlinear dependence of the penetration rate on such operating parameters as rotational speed [16,17,18], frequency and energy of axial pulses, therefore, when developing a methodology for conducting experimental studies, a second order plan was chosen. As a plan for the experiment, a rotatable central compositional plan (RSCP) was chosen, which allows predicting the response function values with the same accuracy in all directions at the same distance from the center of the experiment plan [19]. Experimental studies were conducted on cement-sand samples with a diameter of 70 mm. The contact strength of rock samples was determined by the method L.I. Baron and L.B. Glatman on the hydraulic press PSU-10. A short-hole was drilled using the BI-741 model with a coal cutter with a scale factor of 4 on the modes corresponding to this scale factor [20]. The study of the stress-strain state of the rock mass in the undercut zone was carried out using a finite element analysis.

5. Results of experimental studies

The study of the effect of the combined effect of axial and moment pulses on the drilling tool was carried out in the range of rotation frequency of 200-360 min$^{-1}$ and the frequency of axial and moment pulses in the range of 2200-4000 pulse/min. These ranges of values were selected based on the known recommendations on the speed and rational angle of rotation of the tool between the axial pulses [17]. 3 groups of rocks with contact strength $P_{k1} = 500$ MPa, $P_{k2} = 600$ MPa and $P_{k3} = 700$ MPa were selected for the experiment.
As a result of the experiment and data processing, regression models were obtained, reflecting the effect of the combined effect of axial and moment pulses on the penetration rate of the short-hole:

- rocks with contact strength $P_{k1} = 500$ MPa
  \[ V_{k1} = -1,02 \cdot 10^{-6} \cdot n_u^2 + 9,48 \cdot 10^{-3} \cdot n_u - 8,77 \cdot 10^{-9} \cdot n_o^2 + 5,75 \cdot 10^{-5} \cdot n_o - 1,48 \cdot 10^{-5} \cdot n_m + + 9,85 \cdot 10^{-9} \cdot n_m \cdot n_o - 0,036 \]

- rocks with contact strength $P_{k2} = 600$ MPa
  \[ V_{k2} = -9,59 \cdot 10^{-7} \cdot n_u^2 + 8,5 \cdot 10^{-4} \cdot n_u - 8,35 \cdot 10^{-9} \cdot n_o^2 + 4,95 \cdot 10^{-5} \cdot n_o - 1,31 \cdot 10^{-5} \cdot n_m + + 9,19 \cdot 10^{-9} \cdot n_m \cdot n_o - 0,006 \]

- rocks with contact strength $P_{k3} = 700$ MPa
  \[ V_{k3} = -9,24 \cdot 10^{-7} \cdot n_u^2 + 7,89 \cdot 10^{-4} \cdot n_u - 7,83 \cdot 10^{-9} \cdot n_o^2 + 4,34 \cdot 10^{-5} \cdot n_o - 1,24 \cdot 10^{-5} \cdot n_m + + 8,87 \cdot 10^{-9} \cdot n_m \cdot n_o - 0,014 \]

where $n_u$ – the tool rotation frequency, min$^{-1}$; $n_m$ - is the frequency of the moment pulses, pulse/min; $n_0$ - frequency axial pulse, pulse/min;

![Figure 2](image_url)

**Figure 2.** The response surface of the regression model for rock samples with contact strength $P_{k3} = 700$ MPa at tool rotation frequencies: a - 200 rpm; b - 360 rpm.

![Figure 3](image_url)

**Figure 3.** Comparative characteristics of the rotational method of drilling with a method with a combined effect on the drill cutter: 1-rotary drilling; 2,3,4-drilling with a combined effect of axial and moment pulses with a frequency of 2200/2200, 3100/3100, 4000/4000 imp / min, respectively.
Evaluation of the statistical significance of the coefficients and the adequacy of the regression equations was carried out by the criterion of Student and Fisher, respectively. As a result of the verification of the regression equations at a significance level of $\alpha = 0.05$, it was determined that the resulting regression models with a probability of at least 95% adequately describe the phenomenon under study.

For the regression equation obtained by drilling rocks with a rock strength of $P_{k3} = 700$ MPa with a combined effect of axial and moment impulses, graphical dependencies were constructed (Fig. 2).

A comparative characteristic of the rotational method of drilling with a method with a combined effect on the drill cutter in the form of axial and moment pulses is shown in Fig. 3.

The study of the stress-strain state of the rock mass in the undercutter zone while drilling with the combined action of axial and moment pulses on the drill cutter was carried out using the finite element analysis method. As a result of modeling a section of the cutting edge of the drill cutter, 1 mm wide, in the drilling mode with a combined effect of axial and moment pulses on the rock with a Young's modulus of $E = 1 \cdot 10^9$ Pa and a Poisson coefficient $\mu = 0.3$, a picture of the stress-strain state of the rock was obtained in the undercutter zone shown in fig. 4.

From figure 4.a it can be seen that when drilling in a rotational mode, approximately the same stress and strain fields occur in front face of the tool and under the cutting edge. With an additional impact on the drill cutter axial pulses, the tool is additionally introduced into the rock, which ensures the volume destruction of the rock, albeit with increased specific energy costs. This is indirectly indicated by the picture of the stress-strain state of the rock massif, shown in Figure 4.b. In the case when, during rotational drilling, the drill cutter is combined with axial and moment pulses in the rock mass, additional shear stresses occur, which ensures a less energy-intensive fracture process, reduces the friction forces between the rock and the tool [21] and, therefore, provides a higher penetration rate. From figure 4.c it is clear that the stress and strain fields in the rock mass in front edge of the cutter appear to a greater extent than in other cases.

6. Conclusions
As a result of studies of short-holes drilling with a combined effect of axial and moment pulses on the drilling tool, the following conclusions were made.

1. Improving the drilling efficiency can be achieved by further improving the rock-breaking tool and using modern control systems for operating drilling parameters based on mechatronic control modules.
2. Experimental studies of the combined effect of axial and moment pulses on a drill cutter have established that in the rotation frequency ranges of 200-360 min⁻¹ and pulse frequencies of 2200-4000 pulses/min, the penetration rate increases 1.78 - 3.14 times, depending on selected modes.

3. By the method of the finite element analysis, it has been established that the combined effect of axial and momentum pulses on the drilling cutter allows to increase the efficiency of drilling due to the additional shear stresses in the rock mass in front edge of the drilling tool.

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