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ВОПРОСЫ ПРОЕКТИРОВАНИЯ БУРОВЫХ ДОЛОТ НОВОГО ПОКОЛЕНИЯ С ОПТИМАЛЬНЫМ МЕЖОСЕВЫМ ЭКСЦЕНТРИСИТЕТОМ

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Аннотация: Технико-экономические показатели процесса бурения скважины во многом зависят от конструкции бурового инструмента. Несоответствие конструкции бурового долота горнотехническим условиям приводит к снижению скорости бурения и уменьшению срока службы самого инструмента, что в свою очередь связано с увеличением эксплуатационных расходов и потребления электроэнергии. Для дальнейшего повышения производительности и технико-экономических показателей бурового инструмента необходимы новые конструктивные решения. Рассмотрено конструктивное решение для разработки нового бурового долота, а также лабораторный стенд для изучения процесса метода режуще-абразивного бурения. Показаны пути совершенствования работы и производительности буровых долот с одинаковыми значениями нагрузки и износа зубьев новой конструкции долота. Затронуты вопросы выбора оптимальных значений траектории движения зубьев долота, а также методы определения сетки перекрытия забоя скважины с использованием лабораторного стенда новой конструкции долота. Новая конструкция имеет ряд достоинств: равномерный износ зубьев, определенное число передаточных отношений, равные числа контактных и объемных работ по зубьям долота, при увеличении осевой нагрузки на долото равномерно по рабочей площади увеличиваются все показатели долота, не требует вычислений для определения наиболее эффективного количества зубьев.

Ключевые слова: буровое долото, парное вращение, режуще-абразивное бурение, лабораторный стенд, траектория, рабочая матрица, равномерная работа зубьев, параллельная ось вращения.

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Designing new generation drill bits with optimal axial eccentricity

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Abstract: The technical and economic performance of well drilling largely depends on the design of a drilling tool. Inconsistency of the drill bit design with the geotechnical conditions decreases the rate of drilling and shortens the service life of the tool, which, in turn, increases the drilling cost and electrical energy consumption. For enhancing the productivity and performance of drilling tools, new design solutions are required. This article presents the structure of the lab-scale bench tester for studying the process of cutting–abrasive drilling with a drill bit. The authors discuss the ways of improving performance of the new-design drill bits by ensuring uniform loading and wear of the bit teeth on the novel bench tester to practice the mechanism of rock destruction at well bottom. Optimization of the bit teeth paths and well bottom coverage is addressed. The new-generation drill bits designed with assistance of the new bench tester will be advantageous for the uniform wear of teeth, certain number of gear ratios, as well as for the equal contact and volumetric destruction per drill bit teeth. Furthermore, with increase in the axial load on the bit, the drill performance will increase evenly over the well bottom area, and no computational formulas are required for determining the most effective number of teeth.

Key words: drill bit, turning pair, cutting–abrasive drilling, bench tester, trajectory, working matrix, uniform work of teeth, parallel rotation axis.

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Introduction

The scope of engineering, design and manufacturing of rock drilling tools encompasses a huge number of standard sizes and modifications. Generally, two kinds of tools are in use in drilling: roller cone bits and drag bits. Roller cone bits destruct rocks by impacts while drag bits operate in the mode of shearing both in soft and medium-strength rocks [1].

Drilling modes naturally depend on the drilling conditions, and the size and type of drill bits are governed by the design various-purpose wells in mineral exploration and mining, and in oil and gas industries [2].

At this stage of development, a theoretical framework is required to design more efficient drilling tools. At first, the theoretical search was limited to the physical and mechanical properties of rocks. Then, the parameters of the drilling modes were involved to some extent. Generally, the studies had no positive results, and researchers tried to attempt deterministic modeling of efficiency criteria of drill bits at well bottom. The theoretical studies showed the task was not easy as it was necessary to construct a theoretical deterministic model of interaction of drill bits. That involved certain difficulties associated with both the methodology of the deterministic modeling and the calculatabilty of objective serviceability criteria of drill bits. The latter, as practice has shown, is connected with the most complex computational algorithms and sophisticated computers.

Finally, such model was built in the 1970s in Uzbekistan and made it possible to optimize dynamics of roller cone bits on a deterministic basis. This technique was implemented at the design bureaus of all four drill factories in the former CIS countries.

Optimization of cutting structure of three-cone and single-cone bits have yielded significant and positive results. They included elimination of uneven loading exerted on legs of cones of three-cone bits, levelling of volumetric destruction per cones of three-cone bits, as well as reduction and equalization of abrasive wear of the top and side rims of cones with regard to steppedness of single cone bits.

Despite the successful equipment optimization, the causes of vibration of drill bits at well bottom remained unknown, and geometrization of drill legs was complicated, while those issues were important and of interest to find the causes of packing.

In other words, the issues of the dynamics of drill bits remained a stumbling block in the way of finding universal and general assessment criteria for the performance of drill bits.

The difficulties and impossibility of finding the causes of the above-listed phenomena at well bottoms and of designing bearing units for cones lasted until B.L. Steklyanov discovered the so-called 'mechanism of energy consumption versus travel resistance in dynamic systems' [3]. Therefore, this study pays much attention to the physics of this mechanism. This mechanism has made it possible to determine the causes of the above-listed phenomena, and, consequently, to find the ways to eliminating them. As a result, the drill bit design efficiency can be improved on an objective scientific basis.

The goal of this study is to test experimental designs of drill bits, such that all of the above negative reasons are eliminated to a fairly complete extent. Therefore, we focus optimization on design variables of a single-cone bit and a bit which operates as a turning pair.

Regarding the drill bits operating as turning pair, we are going to present both the theoretical design framework for such bits and a testing plant to practice the mechanism of rock destruction at well bottom.

The new type design used the operation principles of the tricone drill bit. The roller cone bit with steel teeth is used in softer incoherent rocks. Teeth on the rollers are large and sharp, so they can penetrate deeply into soft rock and crush it, after which drill cuttings are removed [4].

Our theory of a new the type drill bit includes uniform loading and strict motion trajectory of the bit teeth.

Materials and methods

Nowadays, it is already clear to everyone, and especially to specialists, that drilling is a very complex dynamic process involving phenomena that are difficult to comprehend and, even more so, to model mathematically. In order to make it clear what we are talking about, there are two illustrative examples of such drilling phenomena below.

First, until very recently, such phenomenon as the multifaceted shaping of cross-sections in wells was not understood. And only now it has become clear that the essence of this unordinary phenomenon lies in the classical principle of the least energy consumption during functioning of dynamic systems. This principle was known back in the 18th century, while the multifaceted shaping of cross-sections in well drilling has become explicable only now [3]. This phenomenon was also observed when drilling holes in metals, which forced calibration of the holes drilled.

Secondly, in drilling wells with drill bits of any design, the phenomenon of packing is known [5]. Packing leads to a drop in the drilling speeds and, accordingly, to a jump in the drilling cost.

For instance, when drilling wells in clay layers with tricone bits, the penetration rate was limited to 1.5 meters per hour regardless of operating conditions. In the same conditions, the penetration rate of drilling with a one cone bit was even lower – less than one meter per hour. This phenomenon is paradoxical but it is already taken for granted in the drilling practice. And the reason is that people do not fully understand many processes taking place around them, and do not understand the natural essence of the dynamic processes but take it for granted.

For example, packing of drill bits in sticky clay is self-evident as the draught of sugar particles to the center of the swirl made in a cup of liquid (water, tea).

But it has now been proven that the cause for such unusual phenomena lies, ultimately, in the same mechanism of energy consumption subject to travel resistance in dynamic systems. The point is that heavy streamlined particles move according to the least energy input principle and find their place on the axis of swirling flows [6].

Nowadays, everyone understands how complex the process of drilling is, and especially the process of rock destruction at well bottom. And everyone realizes the role of the rock drilling tool model in this process, with all its constituents, namely, dynamics of bits, dynamics of chucks and dynamics of chip removal from well bottom. The correct formulation and effective solution of the associated problems can provide quite definite economic benefits.

Well bottom coverage grid determination using bench tester

We would like to notify right away that our design of the rock drilling tool has no analogues in world practice. As a matter of fact, the Maupertuis–Lagrange principle has always been interpreted as a limit in a limited framework, that is, it is limited to a breakaway point, to a preset time moment, etc. That was true for the same principles of other researchers, which disabled analysis of a dynamic system in time and space. Ultimately, that limited general understanding of the nature of functioning of dynamic systems and, thus, constrained optimization of even the simplest technical problems.

After all, it is quite clear that the paradoxical effect observed with an increase in velocities and forces on dynamic systems should somehow be explained using exact theories and, first of all, on the basis of the aforementioned Maupertuis–Lagrange principle.

Certainly, at low speeds and under low loads, many technical structures have been modeled, manufactured and successfully operated.

At the same time, a question arose: If a dynamic system, under certain conditions, functions obeying the Maupertuis–Lagrange principle, then where does it head and finally come?

In order to answer this questions, the authors chose an experimental model in the form of a symmetric disk with rubbing protrusions and, at the fixed time interval of one revolution around an immobile center, calculated energy consumption in all possible modes of functioning: centric, eccentric and bicentric.

Moreover, the contact paths to have no influence on the model performance were assumed. It was shown that the phenomena of the Maupertuis–Lagrange principle were inherent to technical, hydrodynamic and aerodynamic systems.

These comments are to back the research into operation of a dynamic system represented by a rock drilling tool in the mode of a turning pair.

Thus, it is necessary to demonstrate experimentally feasibility of designing higher effective drilling tools operating in the mode of turning pairs. To this end, we have built a device, or more precisely, an experimental bench tester, to offer a new way of designing drilling equipment. First of all, this is connected with simple and more reliable engineering solutions on the dynamics optimization of all constituents of drilling process: dynamics of the matrix tools; dynamics of stability of the matrix relative to the axes of drilling tools, dynamics of support units (bearings) of the matrix in the bodies of drill bits, and, what is particularly important to us, dynamics of well bottom cleaning from drill cuttings [7].

To pass to these practice-focused tasks, we want to prove theoretical feasibility of designing such drilling tools so that to convince even strong sceptics. To this effect, we have invented, designed and manufactured an installation with a work matrix operating in the mode of a turning pair (Fig. 1).

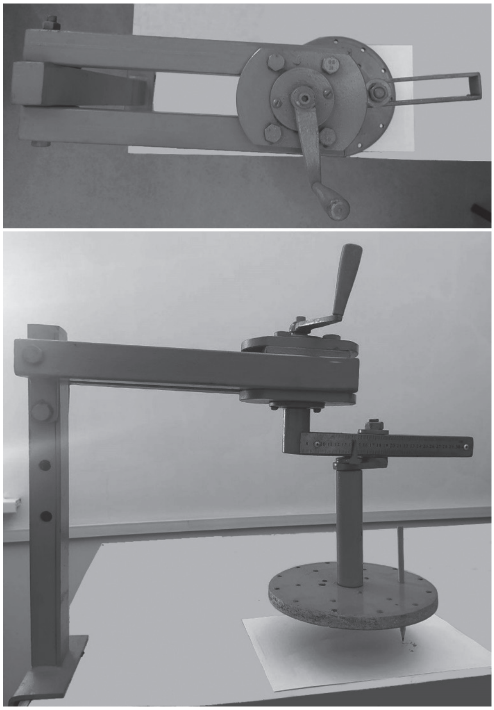

Fig. 1. General view of bench tester
Рис. 1. Общий вид стенда

First, we consider the theoretical proofs of motion trajectories of the work matrix protrusions in operation in the mode of a turning pair.

Development and improvement of drilling tool designs is based on the optimization of rock destruction at well bottom subject to abrasion resistance and strength of the drill bit components as against the rock being cut and using the drilling efficiency criterion represented by the drilling cost [8].

The layout of the bench tester consists of (Fig. 2):

- vertical leg *1* made fast on some surface, for example, on a table;
- T-shaped suspension *2* fast-fixed on leg *1* with parallel recess *3* on its bottom;
- holding element *4* to accommodate axle *5* with bearings *6* with handle *7* arranged above and with ability to move in parallel to T- bar *8*;
- axle *9* fastened to bar *8* in parallel to axle *5*;
- disk-shaped work matrix *10* to accommodate bearing for axle *11* and holes *12*.

Results and discussions

Practice shows that the dynamics of all types of drill bits in wells is unstable. They always try to escape from the rotation pattern around the well axis and minimize inter-axis eccentricity after acquiring it jump-wise [9]. When a drill bit operates with a variable inter-axis eccentricity, i.e. in the mode of non-fixed rotation axis, the chaotic process finally stabilizes. This produces multi-faceted well cross-sections [10]. The nature of this phenomenon is currently theoretically substantiated by the revealed dependence of energy consumption on travel resistance [11]. When drill bit operates in the non-fixed rotation axis mode, the penetration rate increases [12], and when it operates in the mode of a turning pair, the wear of drill bits becomes uniform.

The main objective in engineering of new generation rock cutting tools is to calculate the limits of variation of the inter-axis eccentricities such that operation of drill bits in the modes of turning pairs is stable.

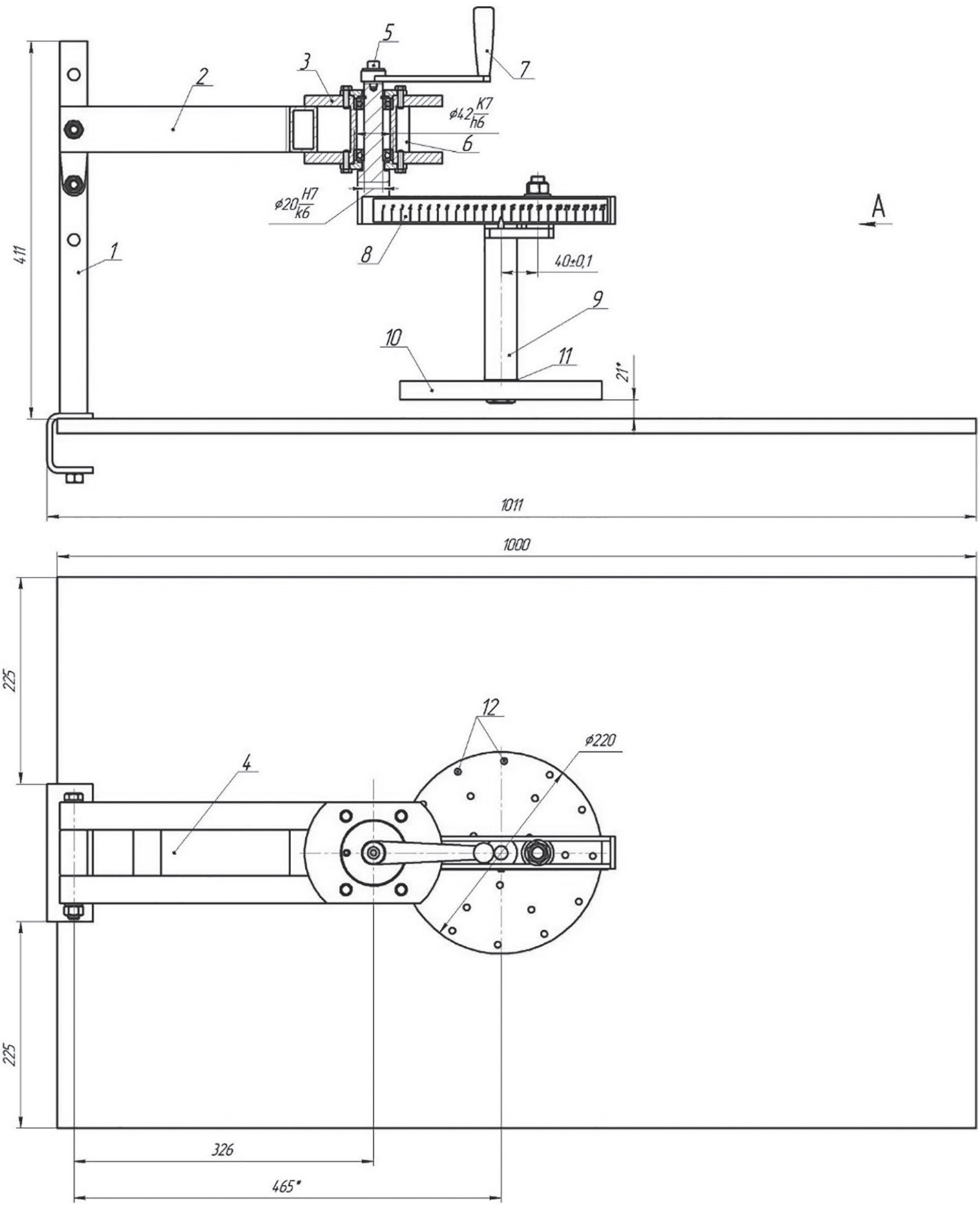

Fig. 2. Layout of work matrix operating in mode of turning pair
Рис. 2. Стенд с рабочей матрицей, функционирующей в режиме пар вращения

Let us prove that any face of the bit has a range of inter-axis eccentricities for self-sustaining and stable operation in the mode of a turning pair, and that it linearly depends on geometric values.

To solve the set tasks, we compare energies of the work matrix protrusions per unit time (one revolution) in the mode of rotation around one given center and in the mode of a turning pair. Let the travel

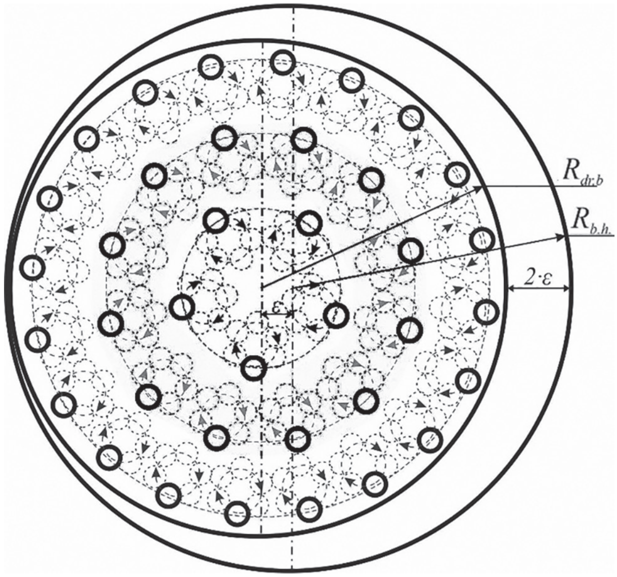

Fig. 3. Path of teeth and bit on well bottom
Рис. 3. Траектория движения зубьев и долота на забое скважины

resistances at each point of trajectories and the contact areas of the working protrusions be constant, and let the number of points of the lines be defined by the lengths of the lines. In this case, the comparative analysis of energy consumptions versus travel resistances in different modes of rotation of the bit tip is performed with respect to the values of the contact paths of the working protrusions.

We choose a system of n points that are in contact during rotation at the distances $R_1 < R_2 < ... < R_n$ from the center of rotation. The sum of the contact paths:

$$\sum_{j=1}^{n} S_{1,j} = 2\pi R_1 + 2\pi R_2 + ... + 2\pi R_n = 2\pi \sum_{j=1}^{n} R_j . \quad (1)$$

In the mode of a turning pair for the same system of points:

$$\sum_{j=1}^{n} S_{2,j} = 2\pi\varepsilon + 2\pi\varepsilon + ... + 2\pi\varepsilon = n2\pi\varepsilon \quad (2)$$

where ε is the inter-axis eccentricity, mm.

If $\varepsilon = R_J$, then

$$\sum_{j=1}^{n} S_{2,j} < \sum_{j=1}^{n} S_{1,j} , \quad (3)$$

if $\varepsilon = R_n$, then

$$\sum_{j=1}^{n} S_{2,j} > \sum_{j=1}^{n} S_{1,j} . \quad (4)$$

It is natural to suppose that there exists such inter-axis eccentricity when

$$\sum_{j=1}^{n} S_{2,j} = \sum_{j=1}^{n} S_{1,j} . \quad (5)$$

Consequently, for a system of points rigidly connected with the given center of rotation, there is such inter-axis eccentricity, at which the energies versus travel resistances in the modes of rotation around the center and in the mode of a turning pair are equal. We call this value balancing eccentricity. An eccentricity greater than the balancing value gives stable rotation around a preset center, the smaller eccentricity produces the mode of a turning pair.

Since no restrictions are imposed on the coordinates of the selected system of points, it can be stated that for any surface in contact there is a whole domain of inter-axis eccentricities that provide a stable mode of a turning pair.

The designed tool is capable to work in the mode of a turning pair owing to introduction of the second parallel axis of rotation into the tool structure. In this case, the inter-axis eccentricity never goes beyond the radius of the circumscribed circle of the tool surface in plan, and the preset surface of the well bottom is completely covered (Fig. 3).

Alongside with the existing rock drilling tools with a solid bottom and core drills, it is possible to create core bits for coring at any cross section, with natural wedge formation in directional and exploration drilling, etc.

Conclusions

A drill bit made according to the presented structural scheme will work as follows:

- when the body rotates, the working part will begin to rotate at the gear ratio $i = -1$, i.e., in the mode of a turning pair [13, 14];
- in this case, obviously, each point of any circular matrix will perform a circular motion along a circle with the radius $r = \varepsilon$. This will contribute to both uniform wear of teeth and uniform destruction of rock, and drill cuttings will be removed through the inlet and outlet holes (channels) onto top surface. The working surface with annular matrices and flushing channels provided in proportion to the areas of the annular matrices ensures the effective operation of such designs of drill bits both in rock destruction at well bottom and in removal of drill cuttings from the well, with uniform and structurally specified wear of the circular matrix structure;
- possible designs for various conditions at the well bottom, depending on the physical and mechanical properties of rocks, are implementable through variation of eccentricities ε, strength characteristics and abrasive properties of the matrix tools made of bit steel or diamond elements.

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