eISSN 2500-0632
https://mst.misis.ru/

MINING MACHINERY, TRANSPORT, AND MECHANICAL ENGINEERING

Research paper

https://doi.org/10.17073/2500-0632-2022-3-231-239
UDC 622.23.051.78

Theoretical studies on the nature and conditions of interaction of heel and peripheral nose cones of offset roller cone bits with a bottom hole

D.A. Boreiko[1] ✉, A.A. Lyutoev[1], D.Yu. Serikov[2]

[1] *Ukhta State Technical University, Ukhta, Russian Federation*

[2] *Gubkin Russian State University of Oil and Gas (National Research University), Moscow, Russian Federation*

✉ *diacont_dboreyko@mail.ru*

Abstract

An offset of roller cone rotation centerlines is used to increase the mechanical penetration rate while drilling in soft rocks. This enables increasing the area of a cutting structure teeth contact with a bottom hole. The analysis of offset cone drill bit (cutting structure) teeth wear showed that particularly significant wear is characteristic of the transition zone from the heel cone to the nose cone, which leads to significant reduction in the mechanical rate of penetration and a rapid decrease in the hole diameter. The purpose of this paper is to conduct a theoretical research on the nature and conditions of interaction between heel and peripheral nose cones of offset roller cone bits with a bottom hole, which is aimed at improving the efficiency of rock cutting by offset roller cone bits. To achieve the purpose, the authors analyzed data on the nature and causes of wear of existing offset roller cone bit cutting structure (teeth); developed a mathematical model in a cylindrical coordinate system allowing to determine the location and geometric parameters of the gage cone contact area with the hole wall for different roller cone bits sizes; developed a computer solid model for checking the adequacy of the mathematical model by comparing these two models; prepared recommendations for further improvement of the design of existing offset roller cone bit cutting structure (teeth). The research was carried out by the method of mathematical simulation of geometric figures and bodies corresponding to roller cones and a hole. The research has revealed that significant adjustments need to be made to the geometry of the roller cone teeth (currently being patented). This would allow decreasing the areas of cone heel blunting by 15–20 % as well as providing more prolonged contact of base and gage cones with bottom hole and wall surfaces. This allows to reduce wear of teeth in the transition zone of the generatrix from the peripheral nose cone to the gage (heel) cone of the roller cone and to maintain the required specific pressure on the cut rock for a longer period of time and, as a result, to increase both the mechanical penetration rate and the service life of the drilling tools.

Keywords

drill bit, roller cone, hole, roller-bit drilling, mathematical simulation, rock destruction, tool

For citations

Boreiko D.A., Lutoev A.A., Serikov D.Yu. Theoretical studies on the nature and conditions of interaction of heel and peripheral nose cones of offset roller cone bits with a bottom hole. *Mining Science and Technology (Russia)*. 2022;7(3):231–239. https://doi.org/10.17073/2500-0632-2022-3-231-239

ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Теоретические исследования характера и условий взаимодействия с забоем тыльных и периферийных конусов шарошек бурового долота со смещенными осями вращения

Д.А. Борейко[1] ✉, А.А. Лютоев[1], Д.Ю. Сериков[2]

[1] *Ухтинский государственный технический университет, г. Ухта, Российская Федерация*

[2] *Российский государственный технический университет (национальный исследовательский университет) имени И.М. Губкина, г. Москва, Российская Федерация*

✉ *diacont_dboreyko@mail.ru*

Аннотация

Для увеличения механической скорости бурения при бурении мягких пород используют смещение осей вращения шарошек, которое позволяет увеличить проскальзывание зубьев вооружения по всей площади забоя. Анализ износа зубчатого вооружения бурового инструмента со смещёнными осями вращения шарошек показал, что происходит существенное изнашивание («зализывание») переходной зоны от тыльного конуса к основному, и это приводит к существенному снижению механической скорости бурения и быстрому уменьшению диаметра скважины. Целью работы является проведение теоретических исследований характера и условий взаимодействия с забоем тыльных и периферийных конусов шарошек данного вида бурового инструмента для повышения эффективности разрушения породы забоя шарошечным буровым инструментом со смещенными осями вращения шарошек. Для достижения поставленной цели в работе проведён анализ характера износа зубчатого вооружения и причин его возникновения у существующих конструкций шарошечного бурового инструмента; разработана математическая модель в цилиндрической системе координат, позволяющая определять расположение и геометрические параметры зоны контакта калибрующего конуса со стенкой скважины для различных типоразмеров шарошечных буровых долот; разработана компьютерная твердотельная модель для проверки адекватности работы математической модели путём их сравнения; разработаны рекомендации по дальнейшему совершенствованию конструкции зубчатого вооружения шарошечного бурового инструмента со смещёнными осями вращения шарошек. Исследования были проведены методом математического моделирования геометрических фигур и тел, соответствующих шарошкам и скважине. В результате исследований определено, что необходимо внести существенные коррективы в геометрию зубчатого вооружения шарошек (на данный момент патентуется), позволяющие на 15–20 % уменьшить площади площадок притупления периферийных венцов шарошек, а также обеспечить более длительный контакт основных и калибрующих конусов шарошек с поверхностью забоя и стенки скважины. Это позволит снизить повышенный износ зубьев вооружения в зоне перехода образующей от периферийного основного к калибрующему конусу шарошек и даст возможность зубчатому вооружению шарошек более длительный период времени сохранять требуемое удельное давление на разрушаемую породу, диаметр долота и, как следствие, обеспечит увеличение как механической скорости бурения, так и ресурса бурового инструмента.

Ключевые слова
буровое долото, шарошка, скважина, шарошечное бурение, математическое моделирование, разрушение породы, инструмент

Для цитирования
Boreiko D.A., Lutoev A.A., Serikov D.Yu. Theoretical studies on the nature and conditions of interaction of heel and peripheral nose cones of offset roller cone bits with a bottom hole. *Mining Science and Technology* (*Russia*). 2022;7(3):231–239. https://doi.org/10.17073/2500-0632-2022-3-231-239

Introduction

At present, different approaches are known for estimating the drilling efficiency of a roller-bit, which depends on a large number of diverse factors. They can be divided into process and design ones.

In terms of design, a roller cone bit is a rock destruction tool equipped with toothed wheels (roller cones or cones) capable of rotating around their own centerlines [1, 2]. In most cases, the bit designs do not provide for offset of a roller cone rotation centerline relative to a bit rotation centerline. This allows reducing the wear of the bits when drilling hard rocks (of high and medium hardness), as well as rocks of increased abrasiveness [3]. Figure 1 shows examples of tricone and two-cone drill bits without the cone rotation centerline offset. Particular emphasis in the Figure is made on the transition of a cone generatrix from peripheral nose teeth rows to heel cones (teeth rows), which are gage cones and form a hole diameter and walls.

But such bits cannot provide the highest mechanical penetration rate and specific penetration rate (per bit) when drilling through soft rocks. To increase mechanical penetration rate while drilling soft rocks, parallel offset of roller cones rotation centerlines is applied, allowing to increase the area of roller cone teeth contact with a bottom hole [4]. In contrast, most foreign companies primarily use angular offset of roller cone centerlines, which results in a smaller teeth contact area but allows to increase the size of roller cones [5–7].

However, the analysis of offset roller cone bit wear after running in the field drilling of oil and gas holes allowed establishing some important features of this process [8]. The main feature is the “licking” (wear) of the angle formed by the intersection of a peripheral nose cone (teeth row) and a gage cone of a roller cone (Fig. 2). This leads to an increase in the area of the peripheral nose teeth rows “blunting area” that inevitably leads to the reduction of the specific pressure on a bottom hole surface and, as a consequence, to a reduction in the destructive capacity of the roller cone [9].

Analysis of drill bit cutting structure (teeth) wear in the case, when the rotation centerlines of roller cones are offset relatively to the rotation centerline of the drill bit, showed that the wear of the transition zone from a heel cone to a nose cone was rather intensive. An intensive wear of this surface leads to increasing the “blunting area” of the roller cone peripheral teeth, the most energy-consuming zone working simultaneously both for gauging and destruction of the peripheral area of a bottom hole, since this part of a roller cone comprises the largest teeth forming the hole diameter and, respectively, experiencing the highest impact and abrasion loads [10]. Moreover, this leads to a rapid loss in the bit diameter and, correspondingly, in the diameter of the hole itself.

As a rule, an increase in the performance of a roller cone drilling tool derives from reduced energy consumption during the drilling by aligning the geometry of the roller cone with the operating conditions of each of the roller cone teeth rows in the annular sections of the bottom hole and the physical and mechanical properties of the drilled rock. Thus, the task of improving the design of roller cone drilling tools is still quite urgent at present [11, 12]. Therefore, it is necessary to examine the reasons for the aforementioned adverse processes occurring during drilling with offset roller cone bits.

Research tasks and objectives

The main objective of this study is to increase the performance of bottom hole rock destruction using offset roller cone bits by means of theoretical research of the nature and conditions of interaction between the roller cone heel and peripheral nose cones with the bottom hole.

a *b*

Fig. 1. Options of new (unused) bit designs: *a* – tricone bit; *b* – two-cone bit

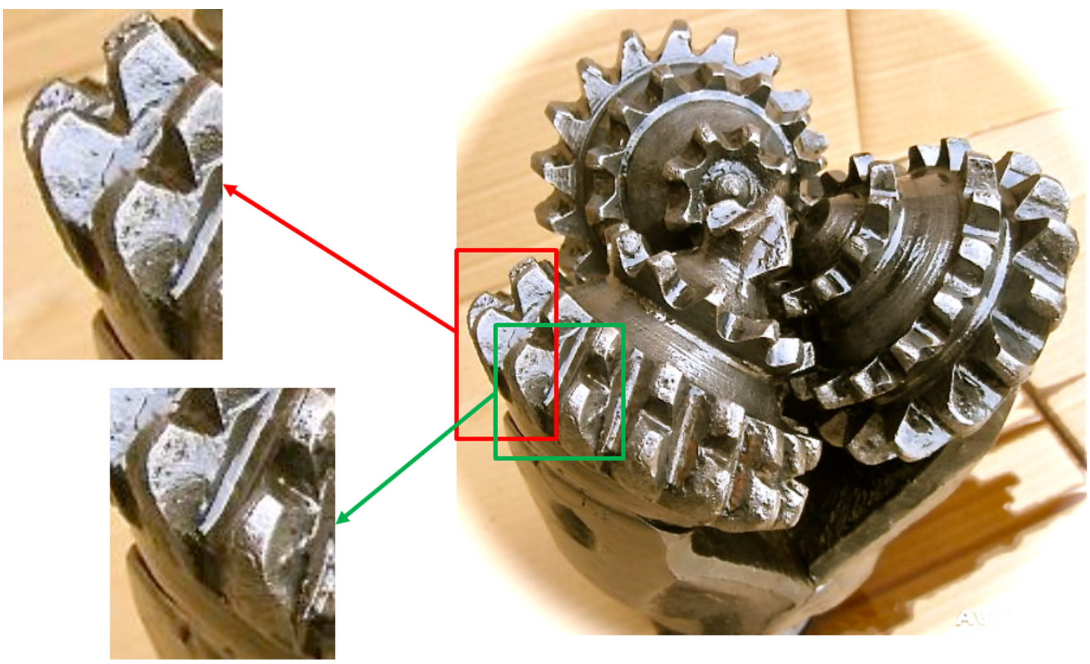

Fig. 2. Wear (“licking”) of peripheral nose and heel cone teeth rows of offset roller cones

In order to achieve this objective, the study addressed the following tasks:

1. Analysis of the nature of existing roller cone cutting structure (teeth) wear and its causes.
2. Development of a mathematical model in cylindrical coordinate system, allowing to determine the location and the geometry of the contact area of a gage cone with a hole wall for different types of roller cone bits.
3. Development of a computer-assisted solid model to check the adequacy of the mathematical model by comparing these models.
4. Development of recommendations on further improvement of the design of teeth of offset roller cone bits.

Research techniques

The studies on determining the position of the contact area between the large base of a gage cone and a hole wall were performed by the method of mathematical simulation of geometric figures and bodies, corresponding to the roller cones and the hole, taking into account a number of simplifications and assumptions [13]. For example, it is known that structurally all drill bit roller cones consist of a roller cone body and the cutting structure, which are milled or tungsten carbide teeth. In its turn, a roller cone body consists of several interconnected cones, which in general can be split into two bodies: the nose cone and the gage cone, as shown in Fig. 3. Thus, structurally, a standard roller cone design is a twin cone (nose cone + gage cone). An important feature of this design is that the transition zone is formed at an angle of $\gamma = 90°$ between the generatrixes of the base and gage cones.

Another simplification in the model is the form of the modeled body itself – it is the nose cone and the transition plane θ, which is common to both the nose cone and the gage cone. This plane is of particular scientific interest for the research since the contact area with a hole wall belongs to it.

The mathematical simulation was based on the methods of coordinate transformation, the system of equations of the cylinder, the inclined cone and the transition plane θ passing through their contact point (Fig. 4). For this purpose, at the first stage, we have created a geometric description of the examined bodies in the cylindrical coordinate system for a roller cone without its centerline offset relative to a hole centerline.

As can be seen from Fig. 4, the point M of the contact of the cone and the hole belongs to both the hole cylinder wall and the base (bottom) of the hole. This position provides perfect contact of lateral surface of a gage cone with hole wall allowing minimizing the wear of peripheral teeth rows. Fig. 2 demonstrates unfavorable position and contact.

Then, the centerline of the cone geometric model is offset along *X* and *Y* axes relative to the centerline of geometric model of the hole by distances *dx* and *dy*, respectively. At this offset of the cone centerline, the point *M* changes its spatial position, moving up the wall of the hole cylinder, and "overhanging" over the bottom hole, losing contact with it. In this position, sharp indentation of the peripheral teeth rows

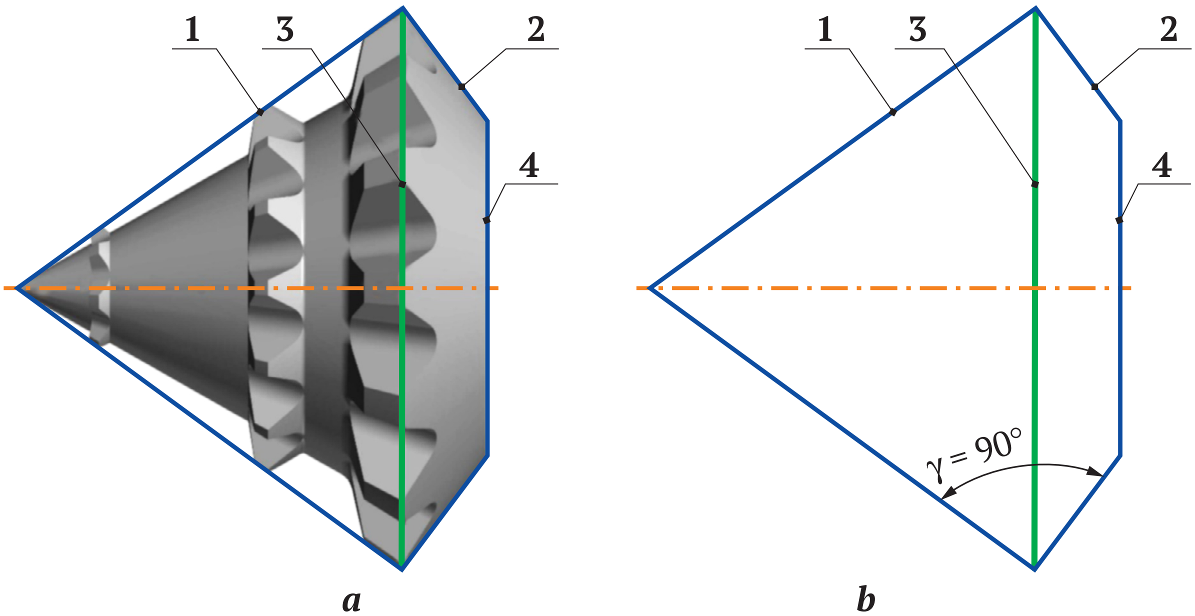

Fig. 3. Simplification of roller cone geometry before simulation:
a – model of a roller cone with milled teeth; *b* – sketch of a longitudinal section of cones of a roller cone; *1* – nose cone; *2* – gage cone; *3* – rib of transition surface θ (large base of gage cone); *4* – rib of small base of gage cone; γ – angle between the generatrixes of the nose and gage cones

into a rock takes place, resulting in their increased wear and formation of a rounded transition zone. Let us introduce two coordinate systems *OXYZ* and *O'X'Y'Z'* (Fig. 5) in the considered geometrical model to define the equation of cone and the equation of cylinder.

Taking into account the parallel translation of *dx* and *dy* and the rotation of the system *O'X'Y'Z'* relative to *OXYZ* through the angle β, we obtain:

$$\begin{cases} x' = (x - dx)\cos\beta + z\sin\beta; \\ y' = y - dy; \\ z' = z\cos\beta - x\sin\beta. \end{cases} \tag{1}$$

The problem of finding the coordinates of point *M* was converted to finding the point of contact of a cylinder given by the corresponding equation and a cone “angled” at the angle β with the base given by the plane θ.

The equation of cylinder has the following form:

$$x^2 + y^2 = R^2. \tag{2}$$

The equation of cone in canonical form in the *O'X'Y'Z'* coordinate system is written as follows:

$$x'^2 + y'^2 = \frac{z'^2}{c^2}, \tag{3}$$

where *c* is a cone constant (angular coefficient).

The section of a cone by the plane *OY'Z'* is given by the following equation: $z = \pm cy$. Then the angular coefficient of the straight line of section c (Fig. 6, *a*) is written as follows:

$$c = \operatorname{tg}(90 - \alpha) = \operatorname{ctg}\alpha. \tag{4}$$

Equation (3) will take the following form:

$$x'^2 + y'^2 = \frac{z'^2}{\operatorname{ctg}^2\alpha}. \tag{5}$$

Bearing in mind that:

$$\frac{1}{\operatorname{ctg}\alpha} = \operatorname{tg}\alpha, \tag{6}$$

$$\alpha = 90^\circ - \beta \Rightarrow \operatorname{tg}(90^\circ - \beta) = \operatorname{ctg}\beta, \tag{7}$$

and the transformation (1) of translation and rotation, we obtained the equation of cone in the *OXYZ* coordinate system:

$$\begin{aligned} &((x - dx)\cos\beta + z\sin\beta)^2 + (y - dy)^2 = \\ &= (z\cos\beta - x\sin\beta)^2 \operatorname{ctg}^2\beta. \end{aligned} \tag{8}$$

The plane θ passing through point M_0 perpendicularly to the normal vector $\bar{N}(A;B;C)$, in a general way, is given by the following equation:

$$A(x - x_0) + B(y - y_0) + C(z - z_0) = 0. \tag{9}$$

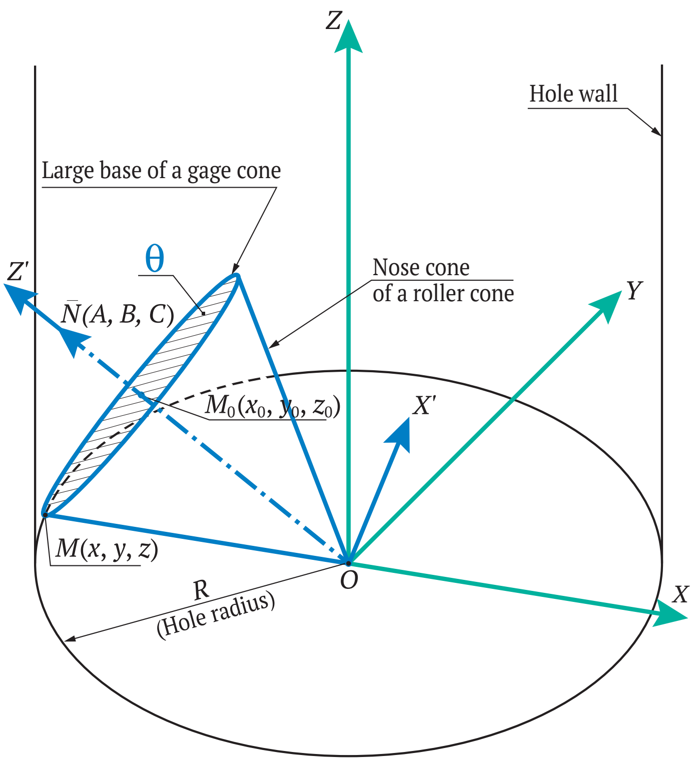

Fig. 4. Geometric model of a roller cone without centerline offset:
M – point of contact of the large base of a cone and a hole;
M_0 – center of the large (transitional) base of the cone

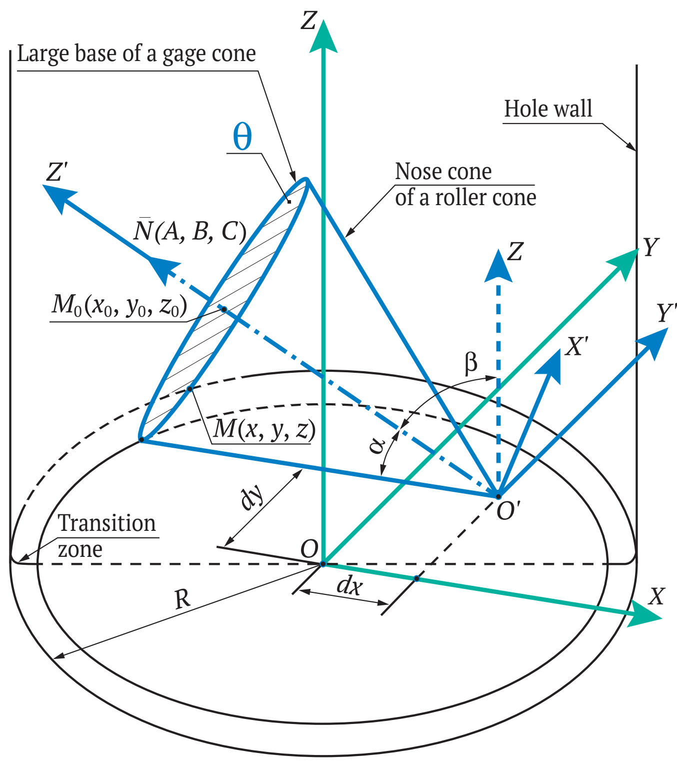

Fig. 5. Geometric model of offset roller cone:
α – angle between *O'Z'* and cone generatrix;
β – angle of cone centerline rotation relative to *OZ*;
dx – offset of cone centerline relative to *OX*;
dy – offset of cone centerline relative to *OY*

eISSN 2500-0632
https://mst.misis.ru/

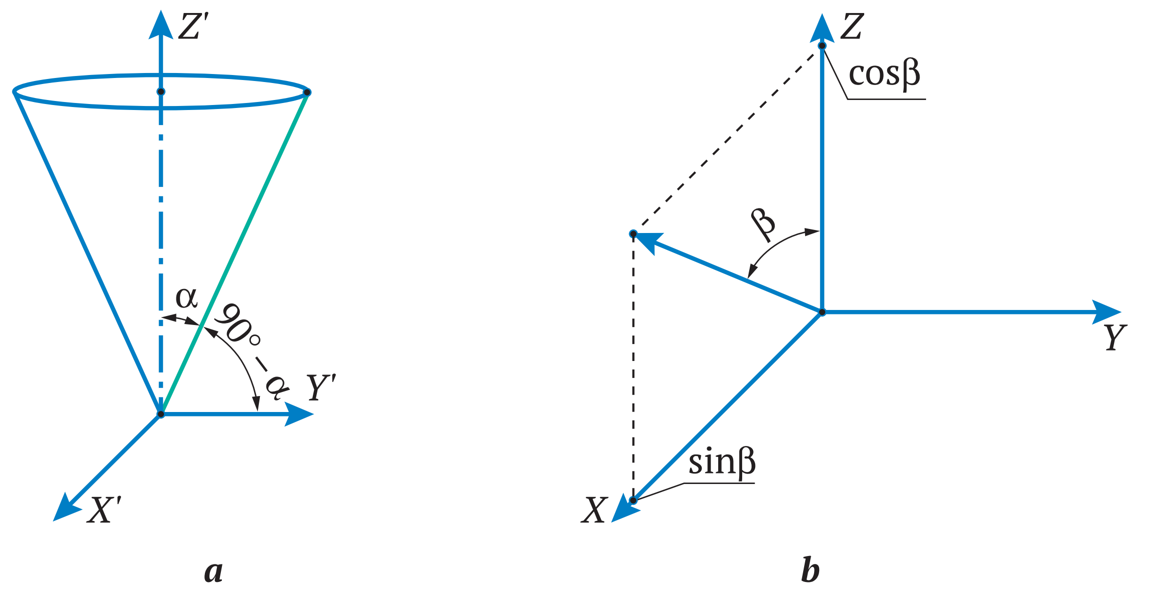

Fig. 6. $O'X'Y'Z'$cone geometric model:
a – $O'X'Y'Z'$ cone geometric model; *б* – determination of the coordinates of the plane θ normal vector; α – cone angle

Taking into account that the normal vector of the plane θ is the centerline of cone obtained by the rotation relative to *OY* axis by the angle β (Fig. 6, *b*), we obtain $\bar{N}(\sin\beta;\, 0;\, \cos\beta)$.

Then the equation of the plane θ is written as follows:

$$\sin\beta(x - x_0) + \cos\beta(z - z_0) = 0. \quad (10)$$

Research Findings

Thus, to find the point *M*, it is necessary to solve a system of nonlinear equations:

$$\begin{cases} x^2 + y^2 = R^2; \\ (x - dx)(\cos\beta + z\sin\beta)^2 + (y - dy)^2 = \\ = (z\cos\beta - x\sin\beta)^2 \operatorname{ctg}^2\beta; \\ \sin\beta(x - x_0) + \cos\beta(z - z_0) = 0. \end{cases} \quad (11)$$

The resulting system of equations (11) will make it possible to determine the coordinates of point *M* for different bit sizes when drilling holes of different diameters.

After mathematic simulation, a computer-generated solid model of the roller cone, similar to its geometric model, and a model of a hole cylinder were built to check the coincidence of the results and visualise the desired contact area. Fig. 7 shows the models of roller cones and a hole created in the domestic computer-aided design system KOMPAS-3D.

The Figure shows that in the solid model, the gage cone contact area is defined in the same area as in the mathematical model. This testifies to the adequacy of both models and the correctness of the obtained results.

To minimize fast wear and formation of "blunting area" in an offset roller cone bit, it is necessary to achieve full contact of lateral surface of a gage cone with a hole wall, as is the case in standard bits with no offset [14]. To ensure such contact, it is necessary to increase the angle γ between the generatrixes of the nose and gage cones until the small base of the gage cone touches the hole wall in the same way and simultaneously with its transition plane θ. We obtained such position iteratively in the computer-assisted solid model presented in Fig. 7, *d*.

To achieve this result, several successive iterations were simulated to increase the angle γ to a value that ended up being 97.7913°. The longitudinal dx and transverse dy offsets according to the scheme (Fig. 7, *b*) amounted to +5.4839 mm and +11.8789 mm, respectively, and were also determined iteratively. According to the simulation result, the required geometry of the gage cone can be determined mathematically, similarly to the mathematical model of the transition plane contact area with the hole wall.

Due to this roller cone design, it will be possible to maintain the required specific contact pressure for the efficient destruction of a rock for a longer period of time [15]. This all will allow increasing mechanical penetration rate and keeping hole diameter for the whole period of the drilling tool operation.

Areas of further research

To finally meet the purpose of this research, it is necessary to determine the full geometry of a gage cone, at which the contact of its surface with a hole wall will be along the line connecting the point *M* belonging to the transition plane θ and a similar point

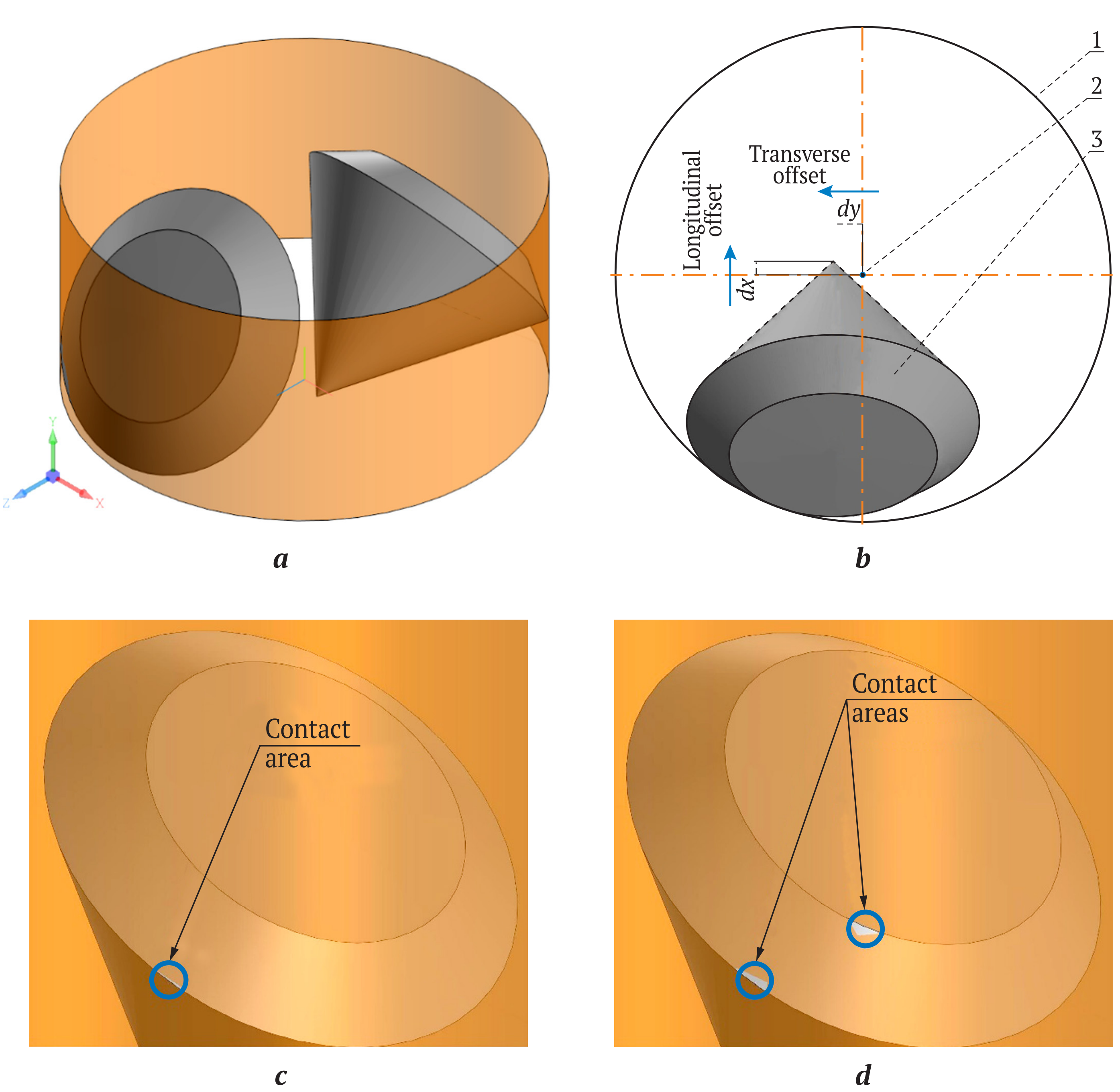

Fig. 7. The result of 3D simulation of the contact area of plane θ with a hole:
a is a model of the location of the cone models inside the hole cylinder model; *b* is a scheme of the offset of the roller cone model rotation centerline; *c* is the result of the contact area simulation; *d* is the result of 3D simulation of the areas of simultaneous contact of the gage cone two bases with the hole wall; *1* – hole model wall; *2* – hole model centerline; *3* – roller cone model

belonging to the small base, the coordinates of which are determined on the basis of the developed mathematical model, taking into account the angle of inclination γ. For this purpose, a mathematical model will be developed describing the specified line, which belongs to both the inner side surface of the hole cylinder and the lateral surface of the gage cone, which provides a uniform "contact spot" (this model is currently being patented).

Conclusion

1. The performed theoretical studies made it possible to establish the causes of uneven wear of cutting structures (teeth) of offset roller cone bits: this is an inconsistency between the geometry/position of the cutting structures (teeth) and the curvature of a hole wall in the transition zone of the generatrix of a nose cone to a gage one, as well as the kinematic features of offset roller cone bits.

2. A mathematical model of the intersection of the plane θ of the roller cone model transitional base in the area of its contact with the cylinder of a hole model was developed. The model provides the possibility of creating the geometry of roller cone cutting structure (teeth) which can significantly reduce the uneven wear of the cone heel teeth and their gauging surfaces in such a way that when the teeth are subject to wear, the teeth "blunting area" is 15–20% smaller than that of similar standard roller cones. The mathematical model was verified by its comparison with the results of solid-state computer simulations, which showed good correlation of the model and simulation results.

3. The researches showed that it is necessary to make significant adjustment to the geometry of roller cone cutting structure (teeth) (at the moment they are being patented). This would allow decreasing the areas of cone heel blunting by 15–20% as well as providing more prolonged contact of nose and gage cones with bottom hole and wall surfaces. This allows reducing the teeth wear in the area of the transition of generatrix from a peripheral nose cone to a gage cone of a roller cone and enables keeping the required specific pressure on the cut rock for a longer time and as a result increasing both the mechanical penetration rate and the life time of the drilling tools.

References

1. Paliy P.A., Korneev K.E. *Drill bits*. Handbook. 3rd Ed., Moscow: Nedra Publ.; 1971. 445 p. (In Russ.)

2. Maslennikov I.K., Matveev G.I. *Tools for drilling boreholes*. Reference manual. Moscow: Nedra Publ.; 1981. 335 p. (In Russ.)

3. Shigin A.O., Gilev A.V., Shigina A.A. Stresses and stability of rolling cutter bits in complex-structure rock masses. *Mining Informational and Analytical Bulletin*. 2013;(4):325–333. (In Russ.)

4. Serikov D.Yu., Pikanov K.A. Some methodology of determining location of momentary rotational axis of a drill bit cutter. *Construction of Oil and Gas Wells on Land and Sea*. 2014;(5):20–22. (In Russ.)

5. Warran T.M. Penetration-rate performance of roller-cone bits. *SPE Drilling & Completion*. 1987;2(01):9–18. https://doi.org/10.2118/13259-PA

6. Hamrick T.R. *Optimization of operating parameters for minimum mechanical specific energy in drilling*. [Dissertation of Doctor of Philosophy.] Morgantown, West Virginia. 2011. 147 p.

7. Hea W., Chen Y., He J., Xiong W., Tang T., OuYang H. Spherical contact mechanical analysis of roller cone drill bits journal bearing. *Petroleum*. 2016;2(2):208–214. https://doi.org/10.1016/j.petlm.2016.03.002

8. Agoshashvili T.G. Qualitative analysis of teeth slippage values in offset roller cone bits. In: *Scientific works VNIIBT Publ. "Theory and technique of drilling"*. 1967. Rel. 17. Pp. 144–154. (In Russ.)

9. Bliznyukov V.Yu., Serikov D.Yu. A drill bit with sphero-conical rolling-cutter drill bits. *Construction of Oil and Gas Wells on Land and Sea*. 2020;(5):28–32. (In Russ.) https://doi.org/10.33285/0130-3872-2020-5(329)-28-32

10. Bogomolov R.M. *Methods to increase the efficiency of rock destruction when drilling with roller cone bits*. [Doctoral thesis in Engineering Science]. Moscow: NPO "Drilling Technics"; 2001. 434 p. (In Russ.)

11. Steklyanov B.L. *Increasing the performance of rock destruction drilling tools based on a comparative analysis of the kinetic characteristics of their cutting structures*. [Doctoral thesis in Engineering Science]. Moscow; 1988. 393 p. (In Russ.)

12. Povalihin A.S., Bliznyukov V.Yu. Learning to use novel technologies for well construction on the basis of key well drilling. *Inzhener-Neftyanik*. 2014;(2):5–9. (In Russ.) URL: http://www.ids-corp.ru/files/oil_engineer/pdf/in2014-2.pdf

13. Bykov I.J., Smirnov A.L., Borejjko D.A. Stress-deformed state of cylindrical specimen with artificial defects: computer modeling. *Inzhener-Neftyanik*. 2013;(1):40–43. (In Russ.) URL: http://www.ids-corp.ru/files/oil_engineer/pdf/in2013-1.pdf

14. Bogomolov R.M., Nosov N.V. *Drilling tools. Encyclopedia of Inventions*. (In 2 parts). Moscow: Innovatsionnoe Mashinostroenie Publ.; 2015. 826 p. (In Russ.)

15. Bogomolov R.M., Serikov D.Yu. Improvement of the cutting structures of the rolling cutter drill bits. *Equipment and Technologies for Oil and Gas Complex*. 2018;(5):24–28. (In Russ.) https://doi.org/10.30713/1999-6934-2018-5-24-28

Information about the authors

Dmitry A. Boreiko – Cand. Sci. (Eng.), Head of the Department of Machines and Equipment of Oil and Gas Industry, Ukhta State Technical University, Ukhta, Russian Federation; ORCID 0000-0002-0248-4526, Scopus ID 56912272500; e-mail diacont_dboreyko@mail.ru

Alexander A. Lutoev – Cand. Sci. (Eng.), Associate Professor of the Department of Advanced Mathematics, Ukhta State Technical University, Ukhta, Russian Federation; Scopus ID 57208719323; e-mail allyutoev@yandex.ru

Dmitry Yu. Serikov – Dr. Sci. (Eng.), Associate Professor of the Department of Standardization, Certification and Quality Management of Oil and Gas Equipment Manufacturing, National University of Oil and Gas "Gubkin University", Moscow, Russian Federation; ORCID 0000-0003-3256-580X, Scopus ID 6506405788; e-mail serrico@yandex.ru

Received 23.03.2022
Revised 28.08.2022
Accepted 01.09.2022