A Method for Calculating The Values of Forces Acting on The Roller-cone Bit Teeth

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Abstract*: The results of an analytical study of the loading of elements of a roller-cone bit cutting structure are given. For an analytical assessment of the magnitude of the forces acting on the bit teeth, the bit is fixed in a static state in a string of drill pipes or a drill assembly, with each roller cone resting on a flat bottom with one tooth on which axial force acts from the bottom. For the disclosure of static indefinability, the equations of deformation of the system are compiled. Calculation of the loads acting on the cone rows was carried out in relation to the cutting structure layout for the Sh215,9K-PV bit cones. To determine the values of the forces acting on the teeth, the dependencies between the magnitude of the load acting on the roller cone and the vertical movement of this tooth, previously obtained analytically and experimentally, were used. It is established that the maximum load acts on the rows located in the middle part of the bit radius. The calculation results are confirmed experimentally. The results obtained can be used to optimize the design of the cutting structures and supports of roller-cone bits at the design stage.

***Keywords* : bit, cone cutting structure, drilling, load, roller cone, support.**

I. INTRODUCTION

The key indicators of the efficiency of the drilling process largely depend on the durability of the cutting structure of cones directly destroying the rock and the support assemblies. Therefore, there is a significant number of studies on the performance criteria of roller bits. The issues of durability of bits with a milled cutting structure [1,2,3,4] are most fully investigated. Hard-alloy insert drill bits have significant differences in the nature of destruction and damage to the teeth, the material of which resists abrasive wear well [2,5,6], but having a relatively low impact strength and low resistance to tensile stresses, has a tendency to brittle fracture [5,6,7,8]. Many researchers have also found uneven wear and destruction of elements of the cutting structure and support assemblies of cones. Uneven wear is observed both during milled drill bit run and during hard-alloy insert drill bit run. During the commercial run of the first design of hard-alloy roller bits, their uneven wear was noted. The bits failed mainly due to the wear of the apex of the first cone, the splitting of the teeth in the peripheral tooth rows and the jamming of the supports of the cones [9]. In subsequent designs of bits, by changing the geometric shape of the cones, increasing the diameters of the teeth and making vertices on all three cones, it was possible to reduce the uneven wear and destruction of hard-alloy inserts and to increase the efficiency of the bits. However, it is not possible to completely eliminate uneven wear and destruction of hard-alloy inserts. In [10], it is noted that the teeth located on the peripheral rows are most susceptible to destruction. Unfortunately, quantitative data on the destruction of teeth on the bit rows and cones are not presented in the work. Lysenko V.N. [11] also points to the uneven nature of the destruction of hard-alloy inserts noting that the most frequent cause of bit failure is wear and destruction of the cutting structure on the vertex rows. But here are only summarized data for several types of bits, from which it is very difficult to obtain any particular patterns. The results of a survey of 105 spent 7R-190 OKP bits equipped with hard-alloy teeth, given in [10], found that the main cause of uneven wear of bit supports across sections is the unequal height of the cones, causing uneven distribution of axial load across sections. There are also a number of studies showing the negative effect of varying height on the wear resistance of supports and the efficiency of roller-cone bits.

II. METHODS

To obtain a comprehensive qualitative and quantitative picture of wear and destruction of hard-alloy inserts of roller bits, we examined 250 bits of type Sh215,9TKZ-TsV-3 and 100 bits of type Sh215,9K-PV, spent in field conditions. It is established that the main cause of failure of hard-alloy inserts are chipping and breakage of teeth (Fig.1, Fig.2)

Fig.1: A characteristic type of destruction of the cutting structure of spent Sh215,9K-PV bits

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Fig. 2: A characteristic type of destruction of the cutting structure of spent Sh215,9TKZ-TsV-3 bits

The research established a significant unevenness of wear and destruction of hard-alloy bit inserts, both along the tooth rows and cones, and of the support assemblies along the sections. In Sh215,9K-PV bits, the largest number of teeth is destroyed in the middle rows of all the cones. In Sh215,9TKZ-TsV-3 bits, the greatest amount of damage occurs in the middle and peripheral rows. In general, for cones, the largest share of damage to the teeth for bits of both types falls on the first cone. Support assemblies of the first roller cones fail most frequently. Our results do not coincide with known results from other studies. Most researchers believe that the greatest amount of damage to the teeth of the insert bits and the greatest abrasive wear are observed in the peripheral rows of the bits. In some studies, it is argued that the destruction and wear of the teeth occur more frequently in the vertex rows. The reason for such contradictions in our opinion is that in most cases bits designed for drilling soft and medium-hard rocks were investigated which have a significant extension of teeth from the cone and greater displacement of the axes of the cones. Such bits cause significant slippage of the peripheral and vertex tooth rows on the bottom hole, as a result of which large tangential forces act on the teeth, resulting in breakages and intensive abrasive wear. The unevenness of the destruction and wear of the bit inserts along the tooth rows of the cones and supports along the sections can be explained by their different workloads. The investigated bits are designed for drilling hard rock and have a small extension of teeth from the body of the cones. Therefore, the teeth mainly experience axial loads that create compressive stresses in them. Since the largest share of destroyed teeth falls on the middle rows, it can be assumed that these rows experience a larger proportion of the axial load. A significant number of both analytical and experimental work is devoted to the study of the patterns of interaction between the roller bit inserts and the bottom hole.

The works of Steklyanov B.L. [l2,13] offer a kinematic model of a roller bit, which takes into account the penetration of teeth into the rock. A method has been developed for estimating the relative abrasive wear of the roller-cone cutting structure and the relative effect of rock destruction at the bottom of the well on specific contact and specific volume destruction work done by the teeth of the roller cones on their contact with the rock. However, this technique, like all the others, does not take into account the real nature of the distribution of the bottom-hole reaction along the generated cone. It assumes that the penetration depth of the teeth of different rows is the same, i.e. the bottom-hole reaction is distributed evenly along the generatrix of the roller cone. In [14,15], either a uniform distribution of the bottom-hole reaction along the generatrix of the roller cone or a varying one according to the trapezoidal or parabolic law with a maximum at the peripheral row is also taken a priori. In the work of Abdulzade A.M. [16] on a theoretical study of the effect of the arrangement of tooth rows on the surface of the cones on the distribution of the axial load between them, it is concluded that the load is unevenly distributed both along the rows and various cones, the peripheral rows being more loaded than the vertex. This result was obtained when considering the rolling of a smooth cone with an intermittent generatrix along a deformable bottom hole, the deformation of which obeys the laws of visco-plastic flow of matter and is explained by the difference in strain rates with distance from the center of the bottom hole. A completely opposite conclusion about the nature of the distribution of the axial load along the tooth rows of the cones was made in the work of Popov A. I. and Spivak A.I. [17]. Considering the possible depths of penetration of the teeth of various rows into the rock in one act of their interaction with the rock, the authors of this work assume that the greatest penetration depth and, consequently, the greatest contact pressure is observed at the teeth of the vertex rows, and the less effective the destruction of the rock, the greater the degree of uneven distribution of specific pressure on the teeth of various rows. However, the conclusions made, as rightly noted in [11], are not confirmed either experimentally or analytically. When analyzing the nature of the distribution of the axial load between bit cones, Lysenko V.N. [11] proposes a method for calculating the magnitude of the forces acting on each roller cone for one of the variants of static interaction of bit cones with the bottom hole. The case is considered when each roller cone of the bit rests on the bottom with only one tooth. Replacing the bit with the earth rod driver system, and considering the equilibrium conditions of this system (Fig. 3), the author comes to the conclusion that the cone resting on the vertex row takes the greatest axial load.

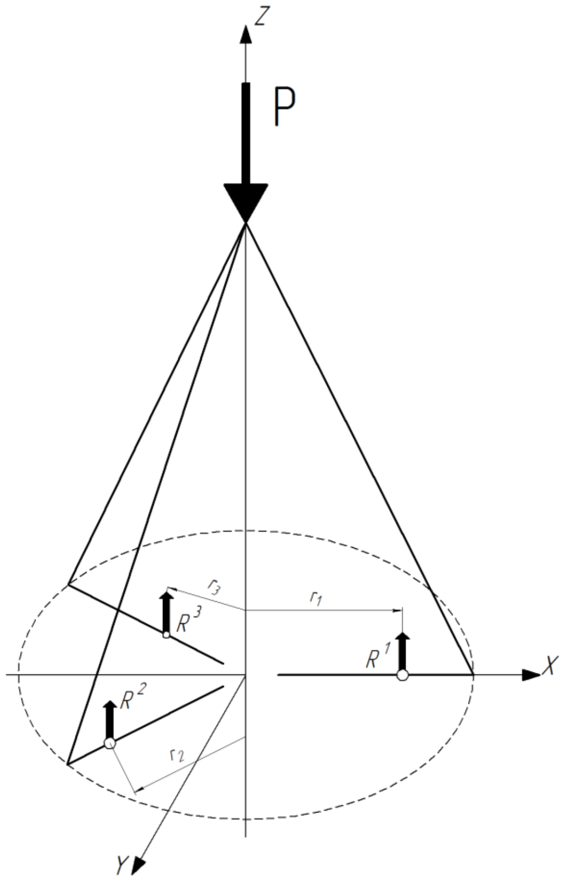

Fig.3: A calculation scheme for determining the axial forces acting on the bit sections

However, the validity of the proposed solution method and the result obtained are doubtful. The bit resting on three teeth is proposed to be considered as a statically definable system. In fact, the bit, fixed in the drilling assembly or in the drill string, and supported by three teeth is not a statically definable system, since in the place where it is fixed, unknown reaction moments of the embedding occur. In addition, the replacement of the bit with the earth rod driver system is not, in our opinion, justified, since it oversimplifies the design scheme. In the works of Langleben M.A. [18] and Postash S.A. [19] attempts were made to determine analytically the forces acting on the bearings of the roller bit. It is assumed that the axial load is distributed evenly between all the cones, and the bottom-hole reactions are proportional to the width of the teeth. Considering the equilibrium conditions of the roller cone and leg, as well as additional deformation conditions, the required forces are determined. In this case, if in [17] the deformations of the trunnion and the body of the cone are taken into account, and the contact deformations and gaps in the supports are neglected, in [19], on the contrary, only the contact deformations and the gaps in the bearings are taken into account. Accordingly, the results of the calculations were different. So, according to [17], the ball bearing perceives the largest radial load, and according to [19], on the contrary, the radial load acting on this bearing is minimal. In the proposed work of Stepanyuk A.I. [20], the method for calculating the strength of the elements of the roller bit support is determined by the forces acting on the elements of the radial roller bearing. But it is assumed that the retaining ball bearing does not experience the radial load.

The process of interaction of the roller bit with the bottom is very complicated, depending on a large number of factors. Each roller cone, rolling over the bottom, makes a complex movement, consisting of the rotation of the roller cone around the axle of the trunnion, rotation around the vertical axis of the bit, and vertical translational motion as the rock breaks. Since the cones are not kinematically interconnected, the number of teeth that are simultaneously in contact with the bottom is a random value, and accordingly, the number of interactions of the bit with the bottom will also be a variable value. The maximum axial force acts on the tooth at the moment of its transition through the vertical position. And since the teeth of the tooth rows of the roller cone are displaced relative to each other along the generatrices, it can be assumed that most often each roller cone will come into contact with the bottom with only one tooth in an upright position. This assumption is especially true when drilling hard and extremely hard rocks. Proceeding from this assumption, for an analytical assessment of the magnitude of the forces acting on the bit teeth, we consider the bit fixed in the static state in the string of drill pipes or drill stem, each roller cone of which rests on the flat bottom with one tooth on which the axial force Pi acts from the bottom (Fig.4) [21]. For simplicity and clarity, we will consider a two-cone bit.

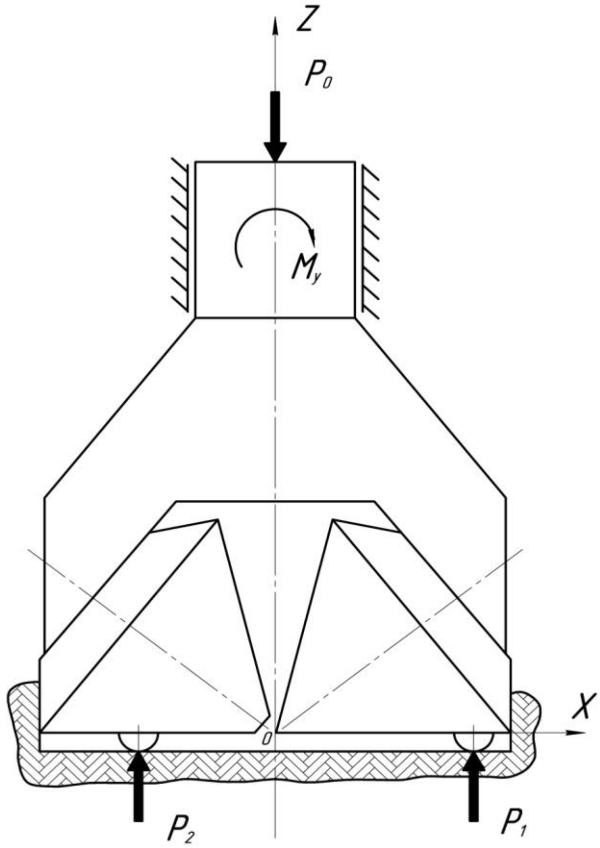

Fig.4: A diagram of forces acting on the bit

The resulting system of forces is statically indefinable since to determine the unknown values P_1 and P_2 we can use only one static equation:

$$\sum Z_i = 0; \; P_1 + P_2 = 0 \quad (1)$$

To compose an additional equation of deformation, we introduce some assumptions. The bottom will be considered undeformable. Deformations of the bit body are also not taken into account, and, moreover, we assume that the bits can only move parallel to the Z-axis without distortions when the load is applied. Under these assumptions, we can further simplify the scheme by replacing the cones with springs. Then, when the load P_0 is applied to the bit, the deformation of both springs will be the same:

$$\Delta_1 = \Delta_2 \qquad (2)$$

For a tricone bit, the sequence of reasoning remains the same and the task of determining the reactions of interaction between the cone teeth and the bottom with the assumptions made is reduced to determining the vertical stiffness of the roller-cone assembly of each cone. Such dependencies were obtained analytically [21] and experimentally [22] for the Sh215.9K-PV bit. To calculate the forces acting on the teeth of bit cones with different variants of interaction between the cutting structure and the bottom, it is necessary to have analytical expressions relating the vertical displacements of the point of the cone in which the load Δ is applied, the value of the current load P and the radius of the load R (Fig.5).

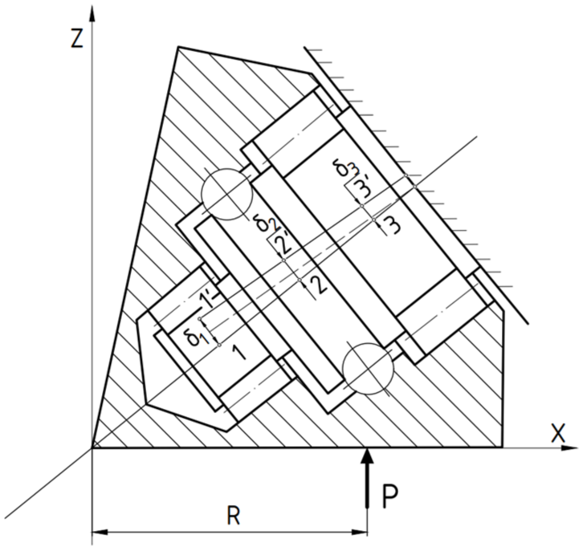

Fig.5: A design scheme of the roller-cone assembly

III. RESULTS

For this purpose, the dependencies obtained analytically and as a result of the experiment are approximated by segments of the following polynomials:

$$\Delta_C = C_{1P} \cdot P_I + C_{2P} + R_I + C_{3P} \cdot R_I^2 + C_{4P} \cdot P_I \cdot R_I + C_{5P} \cdot P_I R_I^2 \qquad (3)$$

$$\Delta_E = C_{1E} \cdot P_I + C_{2E} + R_I + C_{3E} \cdot R_I^2 + C_{4E} \cdot P_I \cdot R_I + C_{5E} \cdot P_I R_I^2 \qquad (4)$$

The resulting expressions well describe the original dependencies Δ_{calc} and Δ_{exp} on P_i and R_i. Deviation does not exceed 5%. To calculate the force acting on each bit cone in contact with the bottom with only one tooth, we need to solve a system of three equations:

$$P_1 + P_2 + P_3 = P_0 \qquad (5)$$

$$\Delta_1 = \Delta_3$$

$$\Delta_1 = \Delta_2$$

Since the dependencies Δ on P_i and R_i are calculated and experimentally described by a function of the same type, we solve system (5) in a general form. As a result of substituting into the system (5) the values of Δ_I with their expressions through Pi and Ri and the solutions of this system, expressions for determining the forces and P_1 , P_2 and P_3, acting on each cone, were obtained:

$$P_3 = P_0 \cdot в_4 + a_4$$
$$P_2 = (P_3 \cdot в_3 + a_3 - a_2)/в_2 \qquad (6)$$
$$P_1 = (P_2 \cdot в_2 + a_2 - a_1)/в_1$$

here P_0 is the axial load on the bit $в_1 - в_4$ and $a_1 - a_4$ are coefficients depending on R_i and on the values of the coefficients of polynomials (3) and (4) $C_1 \div C_5$.

Using expressions (6), it is possible to calculate the force acting on each bit cone in any variant of the interaction of the bit with the bottom. The calculation of the loads acting on the tooth rows of the cones was carried out in relation to the layout of the cutting structure for the cones of the Sh215,9K-PV bit. Assuming that all the cones rotate with the same frequency, and choosing any arbitrary mutual position of the cones as the original, we determine for each point of time the radius of the position of one tooth on each cone that is in contact with the bottom and whose axis is in a vertical plane in a given time. The teeth, which at a given time are also in contact with the bottom, but which axes are not in a vertical plane, are not taken into account in the calculation. Thus, during the time each roller cone makes a full turn (i.e., all the teeth interact with the bottom), we will get a number of combinations of the radii of the teeth on the first - R_1, the second - R_2 and the third - R_3 cones. For the Sh215,9K-Sh bit, there were 37 such combinations. The load perceived by different teeth of the same tooth row of the roller cone will be different, since its magnitude depends on which rows of the other cones are currently in contact with the bottom, therefore the force acting on the individual tooth rows of the cones was determined as the average for one revolution of the cone. According to expressions (6), the values of the forces acting on the tooth rows of all the cones of the Sh215,9K-PV bit were calculated. The calculation was carried out in two versions. In the first case, dependency (3) obtained as a result of theoretical analysis of the deformability of the bit parts is taken as the dependency of the vertical stiffness of the roller cone on the magnitude and radius of force application, and the experimental values of deformations determined by expression (4) are taken as the calculated ones.

IV. DISCUSSION

The results of the calculations of the forces acting on the cone teeth P_i depending on the radius R_i with the axial load on the bit P_0 = 80 kN are shown in Fig.6. Here, for comparison, the dependency of the axial load distribution along the tooth rows of the Sh215,9K-PV and Sh215,9TKZ-TsV bits obtained experimentally [23] is presented.

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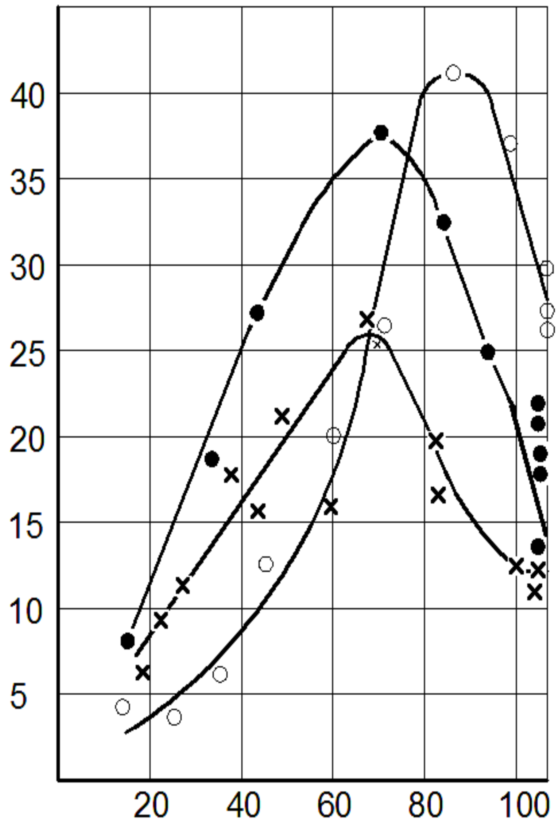

Fig.6: Calculated and experimental dependencies of forces P_i (kN), acting on the cone tooth rows, R_i (mm) with the axial load on the bit
P_0 = 80 kN
o - theoretical, ● - experimental - theoretical, x – experimental

All three curves have approximately the same nature: the maximum load acts on the tooth rows located in the middle part of the bit radius. However, if the position of the maxima of the experimental and experimental-theoretical dependencies coincide and fall on the middle tooth row of the cone I located on the radius R = 71mm, then the position of the maximum of the theoretical dependency is shifted closer to the periphery and falls on the middle tooth row of the cone II located on the radius R = 84mm. In addition, the experimental-theoretical values of the forces on all the tooth rows and the theoretical values of the forces on the tooth rows located on the radius R> 65 mm exceed the actual values of the forces. This is probably due to the fact that in the calculations it was assumed that each roller cone is in contact with the bottom with only one tooth in an upright position. In fact, at each moment of time, along with the tooth in question, one or even several teeth interact with the bottom, perceiving a part of the load acting on the considered roller cone. The values of the forces acting on the various tooth rows of the roller cones, determined by the experimental-theoretical method, differ from the actual values of the forces determined experimentally by no more than 30–35%. Therefore, in our opinion, the use of the experimental-theoretical method proposed here for estimating the magnitudes of the forces acting on the tooth rows of the bit cutters is quite acceptable for checking the optimality of the layout of the cutting structure of the bit cones at the design stage.

V. CONCLUSIONS

The obtained results allow us to conclude that the uneven loading of individual tooth rows of cones, located on different radii of the bit, when drilling hard rocks, for which the penetration of the bit into the rock during one act of interaction with the bottom is insignificant, is caused mainly by different vertical stiffness of the system "roller cone-bottom hole", changing when the position of the point of contact of the cone with the bottom along the bit radius changes. The change in the vertical stiffness is due to the change in the nature of the stress state and, consequently, the change in the stiffness of the support assembly of the roller cone when the external load point is moved along the generatrix of the roller cone. The roller cone will have the greatest vertical rigidity if the line of action of external force passes through the center of the lower, most loaded ball. In this case, the load is distributed between all three bearings of the support, which significantly increases the contact stiffness of the support assembly. When the position of the point of application of the load is changed, the load is redistributed between the bearings. In this case, the load will be perceived only by two bearings - ball and large roller, or ball and small roller bearings. Thus, when rolling the roller cone, the teeth located on different radii of the bit alternately enter into contact with the bottom, and the roller cone constantly reciprocates around the lower ball of the retaining bearing.

The proposed method of analytical evaluation of the value of the forces acting on the teeth of the bit cones can be used to optimize the design of the cutting structure and supports of the roller bit.

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