Research on the method of dynamic PDC cutters distribution

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Abstract. PDC bit design, especially the design of the crown and cutters of PDC bit, is a relatively complex analysis process, which involves many factors such as the back-dip angle, cutting depth, cutting force, cutting power and other factors of PDC cutters. At present, the traditional design methods of PDC cutters distribution are mostly based on analysis of rock breaking efficiency of single cutter, which can only reflect the working state of the single cutter under the set parameters, and cannot fully reflect the differences of different positional cutters during the cutting process. In order to solve this problem, this article proposes a dynamic method through target formation lithology characteristics. The working parameters of all the PDC cutters are analyzed in detail basing on equal wear theory and bottom hole covering theory. The working parameters include static parameters (cutting position, back dip angle, cutting depth, effective cutting area.) and dynamic parameters (cutting force, cutting power, cutting torque and cutting energy etc.). The energy required by all the PDC cutters to break rock of per volume during drilling process is taken as the target constraint condition for iterative analysis. This design method can intuitively and effectively analyse the working parameters of cutters which located bit core, nose, shoulder and gauge area, and it provides a good reference for dynamic balance design of PDC bit.

1. Introduction

In recent years, more and more attention is paid to the issues of improving the efficiency of PDC bits. Opportunities have emerged to create artificial super hard materials, which has led to the creation of modern bits. They are more versatile and have high reliability and durability. With the advancement of diamond material and bit design theory, PDC bit have gradually become the main role of rock-breaking tools in petroleum exploration industrial by their advantages: fast drilling speed, long working time and long footage. With the development of PDC bit technology, the bit design theory has been managed in three stages: conceptual design (1970s) [1-2], empirical design (1980s) [3-4], and scientific design (1990s) [5-8]. Conceptual design stage: simply use PDC composite sheet are used to replace natural diamond as the cutting edge, but PDC bit balling seriously, and cutters falling off and breaking frequently. Empirical design stage: according to the experience of laboratory and field test, design method has improved but PDC bits performance unstable and the design cycle is long. Scientific design stage: based on the research of the rock breaking mechanism and wear law of PDC bits, the crown section design method, PDC cutters distribution are respectively proposed. This paper proposes a PDC bit cutters layout method based on dynamic analysis. The experience of scientific studies devoted to the regularities of the work of bits has shown that, along with the properties of rocks, design features have a significant impact on its efficiency. Proceeding from this, the problem of
improving the design of PDC bits, calculations and selection of the mutual orientation of cutters, to which the presented manuscript is devoted, is urgent. A brief history of the development and improvement of these types of bits is given, as a result, an analysis of the cutters distribution in dynamics is proposed.

2. Profile curve model of PDC bit crown

Whatever super hard materials are used to make PDC cutters, the layout design of bit cutters still follows the three most basic design principles: equal cutting, equal wear and equal power. In the previous literature, the general crown curve equation according to equal cutting, equal wear and equal power theory [9]:

$$h = \int \frac{(R/R_0)^2}{n} \, dR + C \quad (R \geq R_0)$$

(1)

In formula (1), $h$ is the height of the crown, $R$ is the nominal radius of the drill bit, $R_0$ is the crown radius, and the value of $n$ is determined by design principles. In equal cutting theory, $n=1$. In equal wear theory, $n$ takes the experimental index $n_r$ of the relationship between pressure and cutting depth. In equal power theory, $n$ takes the experimental index $n_c$ of the relationship between circumferential cutting force and cutting depth.

The common "straight line + arc + straight line" of the crown curve from inside to outside is the core, nose, shoulder and gauge. The core cutters are linearly distributed along the inner cone, the nose and shoulder cutters are distributed along the elliptical arc curve, and the gauge cutters are linearly distributed almost perpendicular to the radius. If the centre of the drill bit is taken as the coordinate origin, the radial direction of the drill bit is the abscissa, and the direction of the centre axis of the drill bit away from the bit is the ordinate, the "straight-arc-straight" crown contour equation can be expressed as [10]:

$$y = kx + b$$

$$((x-r_0)^2 + (y-R)^2 = R^2$$

$$y = k_1(x-r) + b_1$$

(2)

Among them, $R$ is the radius of the crown arc, $k$ is the slope of the inner cone straight line, and $k_1$ is the slope of the outer cone straight line.

Bottom hole covering theory: any two adjacent cutters satisfy the following relationship [11]:

$$\sqrt{r_n^2 - \frac{(r_{n+1}-r_n)^2+(H_{n+1}-H_n)^2}{4}} = \varepsilon (r_n - \delta)$$

(3)

$r_n$ is the radius of the nth cutter, and $R_n$, $H_n$, $R_{n+1}$, $H_{n+1}$ are the coordinates of the $n$ and $n+1$ cutter, respectively. $\delta$ is the thickness of the area covered by adjacent cutters. Only when $\varepsilon$ is equal to or greater than 1, adjacent cutters can meet the coverage design requirements. When the size of the cutters and the cutting depth of the cutters are constant, the smaller the cutters spacing, the greater the minimum bottom hole coverage coefficient. The higher the cutters density, the greater torque required and more energy to maintain rate of penetration (ROP). Therefore, in order to get the high ROP, the value of the minimum bottom hole coverage coefficient should be small, and it is recommended to take $\delta=1.1~1.2$. Moreover, the above situation is the case without considering the influence of the cutters back-dip angle.

3. Basic principles of cutters layout

The design of PDC bit cutters arrangement includes radial cutters arrangement and circumferential cutters arrangement. Radial cutters arrangement, also known as bottom hole covering cutters arrangement, is mainly to arrange all the cutters of the drill bit radially along the bottom of the well at a suitable interval to completely cover the hole bottom. Circumferential cutters arrangement is to adjust the position of each cutters on the horizontal plane, so that it is distributed on the appropriate
position on the surface of the crown of the bit. According to the principle of equal volume, equal power and equal wear, the calculation formula of the corresponding cutter distribution is as follows [12]:

\[
\text{Equal volume cutters: } V_r = 2\pi r A_r = C_1\tag{4}
\]
\[
\text{Equal power cutters: } P = 2\pi r N F_d = C_2\tag{5}
\]
\[
\text{Equal wear cutters: } \frac{dV_w}{dr} = C_3\tag{6}
\]

In the above formula, \( V_r \) is the cutting volume of the cutter, \( r \) is the radius, \( A_r \) is the effective cutting area of the cutter, \( P \) is the arbitrary cutter cutting power, \( N \) is the number of revolutions, \( F_d \) is the cutting force, and \( V_w \) is wear volume of the cutter. Due to the advantages and disadvantages of the bit designed by each cutting method, and each bit manufacturer keeps the design ideas and methods secret, there is no unified radial cutters arrangement method.

4. Circumferential distribution and optimization of cutters

1. Set parameters such as stratum drill ability extreme value, depth of cut each turn, cutters diameter, back dip angle, etc.;
2. According to the bottom hole full coverage theory, set the cutters spacing \( r_s \) and the radial coordinates of the cutters at the center of the bit;
3. Choose a certain cutters (1~4) in the core of the cutters as the reference cutters, combine the crown contour equation of the bit and the adjacent cutters coverage theory to calculate the radial coordinate and height coordinate of the fifth cutter, and calculate the cutting area, cutting arc length, and iteratively calculate the coordinates of \( i \) cutter, \( i = 5, 6, \ldots n \);
4. According to the calculation of all cutters coordinates and geometric dimensions, draw the bottom hole cutting coverage map.
5. Circumferential cutters distribution principles are as follows: (1) The number of blades should meet the requirements of cutters layout; (2) The cutters of the same blade should not interfere with each other when installed; (3) The cutters should be evenly distributed on each blade at a certain interval; (4) The blade design and cutters distribution is conducive to improving the stability of PDC bit. (5) The arrangement of cutters and blades is conducive to improving the effect of hydraulic power. The specific calculation formulas are shown in formula (7) ~ formula (10) [13-17].

\[
\Delta l < \sqrt{(R_{n+1} - R_n)^2 + (H_{n+1} - H_c)^2 - 2r}
\]

Minimum distance of inner cone:

\[
\Delta l_1 = \frac{R_{i+1} - R_i}{\sin(\phi/2)} = \frac{2}{\sin(\phi/2)} \sqrt{\frac{r^2 - x^2 \sin^2(\phi/2)}{1 + \cot(\phi/2)^2}} \quad (i = 1, 2, 3 \ldots)
\]

Minimum distance of arc:

\[
\Delta l_2 = \frac{(2r + x)(r - r)}{R - r - \sin \alpha} - 2r
\]

\( \Delta l_2 \) is the cutters spacing, \( r \) is the cutter radius; \( l \) is the cutter length; \( R \) is the crown arc radius; \( \alpha \) is the cutter rake angle (°); \( x \) is the rear distance of the cutters.

Inner core area:

\[
\Delta l_1 < \sqrt{(R_{n+1} - R_n)^2 + (H_{n+1} - H_c)^2 - 2r}
\]

Outer cone area:

\[
\Delta l_2 < \sqrt{(R_{n+1} - R_n)^2 + (H_{n+1} - H_c)^2 - 2r}
\]

6. Constraints for the optimization of the cutters arrangement scheme: as shown in conditions a ~ e, the calculation results in the optimization process cannot meet all the constraints at the same time. Therefore, the design scheme selects the constraint condition e and satisfies other conditions as much as possible. Return to step ①~⑤ iterate, until the following constraints are met as much as possible.

a. Cutting volume conditions:

\[
V_{R_r} = \frac{2\pi r A_r}{R_r}
\]

where \( V_{R_r} \) is the volume of rock cut by the cutter, \( R_r \) is the radial coordinate of the cutter, and \( A_r \) is the effective cutting area of the cutter.

b. Minimum fluctuation of wear ratio:

\[
W(R_l) = \frac{(F_m R_c)_l}{(F_m R_c)_r}
\]
\[ W_{av} = \frac{1}{n-m+1} \sum_{i=m}^{n} V(R_i) \]  
\[ \min \sum_{i=m}^{n} W(R_i) - W_{av} V^2 \]  
(12b)  
(12c)

c. Minimum of cutting force, normal force, axial force:
\[ \min \sum_{i=m}^{n} F_c(R_i) \]  
\[ \min \sum_{i=m}^{n} F_n(R_i) \]  
\[ \min \sum_{i=m}^{n} F_a(R_i) \]  
(13a)  
(13b)  
(13c)

d. Minimum of the total cutting power:
\[ \min \sum_{i=m}^{n} F_c(R_i) v_i \]  
(14)

e. Minimum of total cutting work:
\[ \min \sum_{i=m}^{n} F_c(R_i) 2 \pi R_i \]  
(15)

where, \( W(R_i) \) is the wear ratio of the cutter number \( i \), \( W_{av} \) is the average wear volume of cutter from \( m \) to \( n \), \( V(R_i) \) is the wear volume of cutter number \( i \), \( F_c(R_i) \) is the circumferential cutting force of cutter number \( i \), \( F_n(R_i) \) is the normal cutting force of cutter number \( i \), \( F_a(R_i) \) is the axial cutting force of cutter number \( i \), \( v_i \) is the cutting speed of cutter number \( i \).

5. Design and analysis of cases

Based on kuqa piedmont structure glutenite formation in Tarim oilfield [15], the basic parameters of lithological characteristics are shown in Table 1:

| Lithology  | Modulus of elasticity (MPa) | Poisson’s ratio | Compressive strength (MPa) | Cohesion (MPa) | Internal friction angle (°) |
|------------|-----------------------------|----------------|---------------------------|---------------|--------------------------|
| Glutenite  | 15.3                        | 0.26           | 161.2                     | 34.47         | 52                       |

According to the above-mentioned design method the minimum total cutting power, a single-row cutter PDC bit with 6 blades was designed and optimized, with a total of 42 cutters, including 9 cutters on the 1st blade and 8 cutters on the 2nd blade, 8 cutters on the 3rd blade, 6 cutters on the 4th blade, 6 cutters on the 5th blade, and 5 cutters on the 6th blade. The longitudinal cross-sectional two-dimensional crown curve distribution diagram is shown in Figure 1, and the top view of each cutter is shown in Figure 2, and the cutters gradually become denser from the core to the gauge area.

Figure 1. PDC bit crown cutters envelope curve.

Figure 2. Top view distribution of PDC bit cutters.

Figure 3 is a radial distribution diagram of back-dip angle of each cutter. It can be seen from Figure 3 that the back-dip angle of cutters gradually increases from the inside to the outside. The first cutter which is close to the bit axis has the smallest angle (15°), and the outermost 6 cutters of the gauge have the largest angle (30 °). The back-dip angles of core cutters are distributed from 15° to 20°, and the back-dip angles of the nose and shoulder cutters are distributed from 20° to 28° to ensure the aggressiveness of the cutters. The back-dip angles of gauge cutters are distributed from 28° to 30°. In
terms of the back-dip angle only, the aggressiveness of each cutter along the radial direction increases first and then decreases. It ensures the high aggressiveness of the nose and shoulder cutters and the denser and low aggressiveness of the gauge cutters. It is mainly used to repeatedly grind the borehole wall making the well wall smooth, and reducing the irregularity of wellbore.

**Figure 3.** Back dip angle PDC bit cutters. **Figure 4.** Cutting depth of PDC bit cutters.

The cutting depth, cutting arc length, and effective cutting area of PDC bit cutters are shown in Figure 4, Figure 5, and Figure 6. It can be seen from Figure 4 that the cutting depth of cutters gradually decreases in the radial direction. The cutting depth of the core cutters have the largest value, with an average of 0.59 mm, nose area average is 0.48 mm, shoulder area average is 0.29 mm, gauge area average is 0.09 mm, and the outermost 6 cutters are 0. It can be seen from Figure 5 that the cutting arc length of cutters also gradually decreases from core area to gauge area. The effective cutting area of cutters in core area decreases fastest, and cutting arc length of cutters decreases gradually from the nose. The average cutting arc lengths of the core, shoulders, nose, and gauge area is 8.21 mm, 6.37 mm, 5.16 mm, 0.91 mm, respectively. The cutting arc length of the outermost 6 cutters of gauge area are 0 mm. Figure 6 describes the effective cutting area of cutters. The effective cutting area of cutters gradually decreases from core area to gauge area. The average cutting area of core, shoulders, nose, and gauge area is 5.68 mm$^2$, 3.62 mm$^2$, 1.85 mm$^2$, and 0.09 mm$^2$, respectively. The cutting area of the second cutter in core area decreases faster. The main reason is that its corresponding cutting arc, back dip angle, cutters angle and cutting depth are larger than the first cutter, which is the result of a comprehensive effect.

**Figure 5.** Cutting arc length of PDC bit cutters. **Figure 6.** Effective cutting area of PDC bit cutters.

The bit pressure is set to 10 tons and the rotating speed at 100 rpm to analyse the force and torques of each cutter. The force of each cutter is shown in Figure 7. The normal force $F_n$, the circumferential cutting force $F_c$, and the axial force $F_z$, and resultant force $F$ of each cutter gradually decrease with the
radial direction. Among them, except for the first cutter in the centre, the force of the other 8 cutters is not much different. The core cutters are selected mainly for their impact resistance ability. The cutters of nose/shoulder area close to the centre axis of the bit have a relatively uniform force. The cutters with higher wear resistance ability will be preferred. The shoulder cutters outer row and the gauge section have less force, but the cutters density in this area is higher, so the cutters with better temperature resistance can be selected. Figure 8 shows the rectangular coordinate system established with the centre of the bit as the origin, and the torque distribution in the X-axis, Y-axis and Z-axis directions of each cutter. The positive and negative torques only represent different directions. The cutters in the X-axis, Y-axis and Z-axis in the radial direction all show a trend of first increasing and then decreasing. There is a linear increase from core area to shoulders area, and the increase trend at the shoulders slows down. At the junction of the nose and shoulders area, the torque reaches the maximum, then shoulder area decreases rapidly, and it drops to 0 in a straight line in gauge area.

According to above parameters, the cutting volume of each cutter per minute is shown in Figure 9. It can be seen from Figure 9 that the cutting volume of rock cut by cutters increases first and then decreases along the radial direction. The cutting volume of core cutters increases rapidly, and the cutting volume of nose cutters increases slowly. At the joint of the nose and shoulder area, the single-cutter cutting volume reaches the maximum value (1.75 cm³), and then rapidly decreases, and finally almost straight down to 0 in the gauge area. It can be seen that in the normal rotating cutting process, the cutting volume of the nose and shoulder cutters are the largest, followed by the core area, and the smallest at gauge area. As shown in Figure 6, the effective cutting area of each cutter decreases gradually from core area to gauge area. Since the increase rate of radius is higher than the decrease rate of effective cutting area of each cutter from the core area to the gauge area, it can be seen from equation 11 that the cutting volume of rock increases gradually, but the increasing rate is gradually decreasing. However, the decrease rate of effective cutting area of each cutter is higher than that of radius growth rate from shoulder area to gauge area, so the comprehensive cutting volume of each cutter begins to decrease and finally decreases to 0.

Figure 10 describes the cutting power of each cutter during the drilling process. The cutting power changing trend of each cutter is similar to the trend of cutting volume, which increases first and then decreases. The circumferential cutting power P_c of the same cutter is the largest, followed by the normal cutting power P_n, and the axial cutting power P_z is the smallest. The cutting power from core to nose area increases faster, and the cutting power from nose area to shoulder area increases slowly. It decreases rapidly after reaching the maximum at the junction of nose and shoulders area, and it drops almost linearly to 0 in gauge area.
Figure 9. Cutting volume distribution of PDC bit cutters.

Figure 10. Cutting power distribution of PDC bit cutters.

Figure 11 describes the distribution of the cutting work of each cutter. The changing trend of the cutting work of each cutter is as the same as that of the cutting power. This is because the cutting work of each cutter can be calculated by $W=P\cdot t$. According to the definition of mechanical specific energy: the energy required to break rock of per volume, its mathematical expression is $\text{MSE}=W/V$. If the influence of rock heterogeneity and geological structure difference is not considered, the MSE of each cutter is shown in Figure 12. It can be seen from Figure 12 that the MSE value difference between different cutters is very small, and the overall trend is slowly increasing first and then decreasing. The average value of MES is $10.32\times10^3\text{ J/m}^3$, except for the 3 cutters near the axis and gauge outside cutters, the MSE value of other cutters are no more than 6% deviation from the average value. In this design scheme, the MSE value of each cutter is basically the same and the total MSE is as small as possible, which is beneficial to improve the rock cutting efficiency and ensure the average life of cutters are similar.

6. Conclusions

As the key cutting element of PDC bit, the performance of PDC cutters directly determines the quality of the bit. The layout design of PDC cutters distribution plays a key role in rock breaking efficiency for PDC bit. Based on the equal cutting power, the crown shape curve is established. The dynamic design method of PDC cutters distribution is established based on the principle of adjacent cutters undisturbed with each other. Combined with the properties of rocks, the final layout design model of PDC cutters can be dynamically optimized according to different constraints. A case study shows a concert step-by-step sequence of bit design, especially the calculation and selection of the mutual orientation of cutters. The result of crown cutters envelope curve and top view of PDC cutters distribution shows that the distribution of cutters is not axisymmetric, but to ensures the dynamic balance of radial and axial forces. In addition, the back-dip angle of cutters gradually increases from core to gauge. However, the change rule of cutting depth, cutting arc length, and effective cutting area of cutters is just the opposite in radial direction. The design result can be dynamically adjusted and optimized according to the requirement of cutting fore, torque, cutting volume, cutting power and
MSE of each cutter. The dynamic PDC cutters distribution method is a complex multi-objective calculation and optimization process, and it deserves to be recommended to other PDC bits designers.

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References
[1] DAN S 2015 A Bit of History: Overcoming Early Setbacks, PDC Bits Now Drill 90% 90%—Plus of Worldwide Foot/Decades after Invention of Polycrystalline Diamond Cutters, PDC Bits Edge Out Roller Cones with Advances in Cutters, Stability, Hydraulics Drilling contractor (7/8)
[2] ZHANG Y H, RYAN B, YURI B, et al. 2013 Innovative Rolling PDC Cutter Increase Increases Drilling Efficiency Improving Bit Performance in Challenging Applications IADC/SPE 163536
[3] Liu Xiaofei 2008 Research and Application of PDC bit composite impact rock breaking Mechanism [J] Western Mineral Exploration Engineering 30(09) 46-49+52
[4] Kuang Yuchun, Wang Yuanji, Feng Ming, Han Yiyi 2017 Reverse Design and Optimization of PDC bit tooth distribution parameters [J] Journal of engineering design 24(05) 545-554
[5] YANG Q L 2007 Research on personalized design and application of PDC bit in complex stratum. China University of Petroleum (East China)
[6] Gao Mingyang, ZHANG Kai, Zhou Qin, Zhou Hufeng, Liu Baolin 2015 Research on cutting Gear Wear of PDC bit in drilling in high temperature hard stratum [J] Mineral Exploration Engineering (Rock and Soil Drilling engineering) 45(10) 185-189
[7] Luo H R 2007 Design and application of directional PDC bit. China University of Petroleum
[8] Xie Zong-Liang 2018 Study on rock-breaking Mechanism of ring-groove Diamond Drill [D]. Southwest Petroleum University
[9] Sun Yuanxiu 2016 Study on rock breaking mechanism of conical PDC and development of new drill bit [D] China University of Petroleum (East China)
[10] Gao Haijian 2018 Study on the Mechanism of PDC tooth shear rock breaking based on discrete element Method [D] Northeast Petroleum University
[11] Kuang Yuchun, Zhang Mingming, Feng Ming, Guo can, Zhang Yi 2018 Rock breaking simulation model and full bit experiment of PDC [J] Journal of underground space and engineering 14 (05) 1218-1225
[12] Yang L, Chen K M 2005 Three-dimensional design method of PDC drill bit Mechanical Science and Technology 22(2)35-36
[13] Zhang S H, Xie X H, Fang H J, et al. 2010 The influence of PDC bit exposure and linear velocity on the wear law of composite disc Zhongnan Gongye Daxue Xuebao, Ziran Kexueban (06) 2173-2177
[14] Michael A, Segal W A 2013 Steven Pointing Towards Improved PDC Bit Performance: Innovative Conical Shaped Polycrystalline Diamond Element Achieves Higher ROP and Total Footage[R] SPE 163521
[15] Liu Z P, Zeng H, Zhou X J 2013 Personalized design of PDC bit suitable for specific formations. Tianranqi Gongye 33(3) 59-63
[16] Jin Y N, Chen Z T, You C Y, et al. 2015 New ideas for the design of PDC bit cutter. Exploration Engineering (Rock and Soil Drilling and Tunneling) 05 72-76
[17] David S, Anthony D, Danielle F, et al. 2014 Innovative Non-planar Face PDC Cutters Demonstrate 21% Drilling Efficiency Improvement in Interheded Shales and Sand [R] SPE 168000