Vibration Failure and Anti-Vibration Analysis of an Annular-Grooved PDC Bit

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Highlights:

1. The cause of the vibration failure of the bit and transverse bit motion are analyzed;
2. Designs and manufactures annular-grooved experimental bit with variable parameters;
3. The developed annular-grooved PDC bit can reduce bit vibration and improve bit's drilling stability.

Abstract: To extend the service life of drill bits through reducing various drilling vibrations, this paper presents a fundamental analysis of the root cause of failure for polycrystalline diamond compact (PDC) bits during the drill-based process of vortex generation. In this work we develop a new type of PDC drill bit, namely the annular-grooved PDC bit, which can form one or more annular convex rock ridges at the bottom of the hole, having a raised ring that can limit transverse vibration. Our experimental results confirm that the accelerations of the annular-grooved PDC bit in axial, tangential, and radial directions are smaller than that of a conventional PDC bit. More specifically, acceleration declines by 33.5%, 21.6%, and 25.9% in tangential, axial, and radial direction, respectively. Our experimental investigation also shows that, as the weight on bit and the rotation speed increase, bit vibration intensifies, and the impact load on bit increases which can worsen bit stability. However, as the height and the width of the rock ridge increase, the drilling vibrations in three directions can decline. Therefore, the developed annular-grooved PDC bit can reduce bit vibration and improve bit's drilling stability.

Keywords: Annular-grooved; PDC bit; Vibration; Rock ridge; Downhole drilling

1. Introduction

Polycrystalline diamond compact (PDC) bits break rock via shearing and offer many advantages for drilling, such as high efficiency in rock breaking, enhanced safety (e.g., no moving cutting elements), and long cutting life thanks to PDC teeth wear. Given these benefits, PDC bits are widely used in oil and gas well drilling[1-3], and researchers have conducted extensive work on the improvement of drilling speed focusing on two main aspects: (1) how to improve bit's performance to feed into the formation, e.g., the development of a new cutting-teeth structure or combinations of various rock-breaking methods; and (2) the matched use of drilling tools, drill bits, and downhole tools, e.g., screw drill, turbodrill, axial impactor, peripheral impactor, or hydraulic oscillator. To deliver efficient drilling, drill bits require aggression and a long service life. In particular, bit service life is closely related to bit's drilling stability[4].

PDC bit stability refers to (a) the stability of transverse movement of the bit and (b) the azimuth stability of the bit during guided drilling[5]. Transverse vibration (i.e., whirling) of the bit is a main culprit of cutting-teeth breakage. Therefore, the stability of transverse movement of the bit has a significant impact on bit's working life and rock-breaking efficiency. Bit's azimuth stability directly affects hole trajectory control during guided drilling. A bit with poor azimuth stability will lead to trajectory drift referring to a deviation from its predetermined trajectory during guided drilling. Such stability is thus essential to consider in bit design. Existing methods to improve PDC bit stability include the following: (1) adjusting PDC teeth parameters to ensure that the unbalanced bit force is less than 5% of the weight on bit (WOB); (2) optimizing the shape of the drill bit's crown contour and increasing the angle of the inner cone to help to prevent transverse vibration to some extent; (3) setting the PDC teeth to form grooves at the bottom of the hole, which can suppress bit vibration; (4) using a spiral blade, dispersing the cutting force directed at the shaft wall, and reducing contact stress between the bit-retaining part and the shaft wall; and (5) improving the impact resistance of PDC teeth by improving their processing technology[6-10].

Current anti-vibration measures can reduce early drill bit failure to some extent, albeit with suboptimal effectiveness. In this paper, we propose an annular-grooved PDC bit that relies on an annular rock ridge raised at the bottom of the well to suppress bit vibration. The design and manufacturing of an experimental annular-grooved PDC bit with adjustable parameters was completed to perform an indoor vibration test. The vibration performance of a conventional PDC bit and the annular-grooved PDC bit was then compared and analyzed. Finally, a new bit structure was presented to reduce bit vibration and increase bit life.

2. Vibration failure of PDC bit

Bit vibration generally includes axial, transverse, and tangential vibrations. Axial vibration occurs when the vibration direction of the drill bit is parallel to the axial direction of the bit. Transverse vibration (i.e., radial vibration) occurs when the vibration direction of the drill bit is perpendicular to the axial direction of the bit. Frequent contact between the drill bit and the shaft wall can occur easily due to small clearance between the bit and the wall. Such a collision is serious, manifesting as bit whirling. Tangential vibration occurs when the drill tool does not rotate at a constant speed, resulting in fluctuation around the axial direction of the bit. When the rock cutting torque and the torque provided by the drill bit do not match, the bit presents a stick-slip phenomenon. In this case, slippage during high-speed movement of the drill bit causes violent vibration upon impact.

The drilling process of PDC bit at the bottom of a well is always associated with an unstable cutting process, particularly when drilling in layers with an uneven texture or a gravel-bearing formation. Also, bit's cutting teeth can fail easily when the teeth produce high-frequency vibration due to a constant impact load. Impact failure of the PDC bit generally manifests as diamond-layer fracturing, spalling, or fatigue as well as tooth loss or tooth fracture as shown Fig. 1.

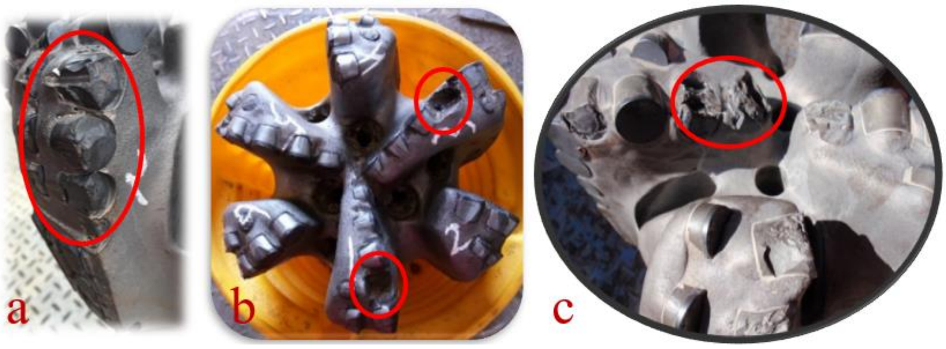


Fig. 1 Failure modes of PDC teeth: (a) spalling of diamond layer; (b) tooth loss; (c) tooth fracture

In the process of directional drilling, especially during compound drilling, bit cutting conditions are complex. PDC teeth can easily bear the reverse load and impact load under these conditions, and rapid teeth failure may occur. When a tooth fails in the absence of corresponding remedial measures, the working load of adjacent teeth in the bottom of the hole ring increases, and the adjacent teeth exhibits linkage failure. These consequences lead to severe PDC teeth failure in bit region. Such a failure can present in several forms as presented in Fig. 2. When the failure area is at bit core, the core of the bit fails (Fig. 2a). When the failure area is at the top of bit crown, the ring groove of the bit fails (Fig. 2b). When the failure area is at bit sizing section, the bit exhibits reduced-diameter failure (Fig. 2c).

Fig. 2 Severe bit failure modes: (a) core failure; (b) ring-groove failure; (c) reduced-diameter failure

Tangential bit vibration is caused by a rock's soft and hard staggered surface. This uneven surface can increase the collision frequency between the cutting gear and the rock leading to vibration. This vibration is determined by the rock-breaking mode of the PDC bit, which is unavoidable and can only be reduced to a certain extent. Axial bit vibration is mainly caused by fluctuation of the load between the drill string and the drill assembly. While transverse force is the main factor behind transverse bit vibration, the force received by the PDC bit during drilling is the resultant force at each cutting gear, which can be decomposed into axial force along the axial direction of the bit and transverse force along the radial direction of the bit. The transverse force of the bit should therefore be reduced in bit design.

As displayed in Fig. 3a, the internal structure design and external factors (e.g., rock properties, WOB, and torque) of a bit during rotational drilling have significant influence on the bit in terms of the transverse force F along the radial direction. Under the action of force F, the bit will deviate from its lateral movement trajectory and drill into the borehole wall, resulting in lateral vibration of the bit and a larger hole diameter. In general, the greater the lateral force is, the greater the effect is, and the larger the clearance between the bit and the wall will be. A large clearance between the drill bit and the shaft wall could lead to bit whirling. As shown in Fig. 3b, bit whirling refers to the phenomenon wherein the bit rotates and the rotary center on the working surface of the bit constantly changes. In this case, the instantaneous rotary center deviates from the geometric center of the bit and moves to the bit crown or to the diameter-retaining location, resulting in periodic transverse bit vibration, namely bit cyclotron.

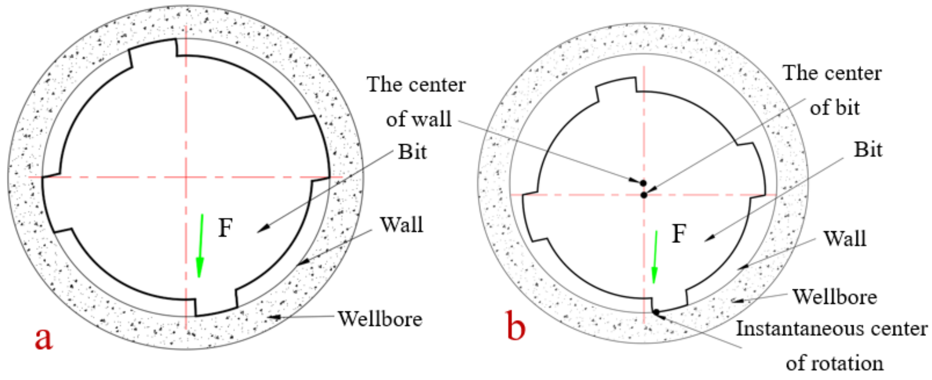


Fig. 3 Transverse bit motion: (a) transverse vibration of bit; (b) whirling motion of bit

3. Structural characteristics and anti-vibration mechanism of the annular-grooved PDC bit

3.1 Structural characteristics

Because drill bits are prone to ring-groove failure, an annular groove around the center of the bit is preset on the bit body based on reverse thinking in this work. So an annular-grooved type diamond bit is proposed. This bit is suitable for PDC bits and diamond-impregnated bits as presented in Fig. 4[11].

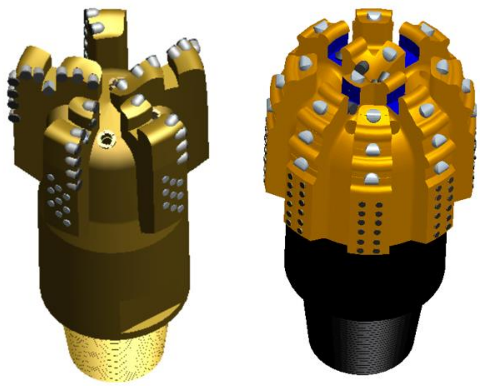


Fig. 4 Annular-grooved diamond bits

The structural features of the annular-groove PDC bit are as follows: In the annular-groove PDC bit, there is at least one empty annulus around the center of the drill bit at the bit body , and the blade is inwardly concave at the position of the annulus , forming a circumferential continuous annular groove, of which a secondary cutting element is set at the bottom or side. The cutting element arranged on the blade is called the main or primary cutting element . The empty annulus on the annular-groove drill bit produces a corresponding raised annular ridge (hereinafter referred to as the ridge) at the bottom of the hole. The empty annulus on the drill bit and the ridge raised at the bottom of the hole are matched to each other, The bit on the ring band and the bottom raised-ring blank rock ridge match as shown in Fig. 5. As the stress around the rock ridge is released, when the cutter breaks the rock ridge (as shown in Fig. 5), it is easier to form the bulk fracture of the rock and improve the rock-breaking efficiency of the bit. Grooves on the cutting wing of the drill body can suppress transverse bit movement, thus reducing transverse bit vibration and improving bit stability. The proposed drill-bit structure can also limit energy consumption and enhance rock-breaking efficiency while improving bit stability and extending bit service life.

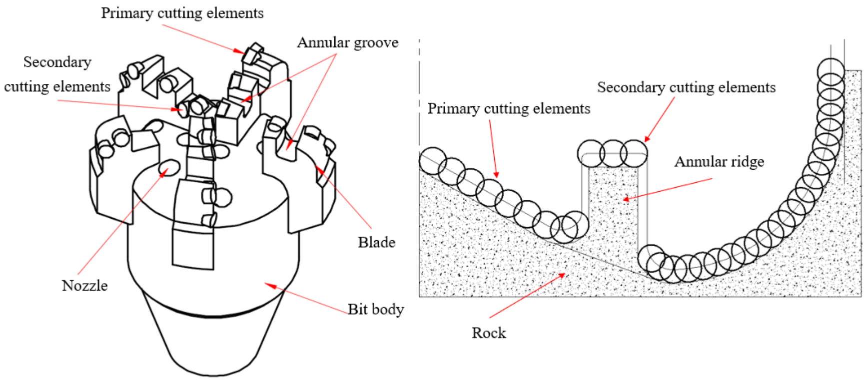
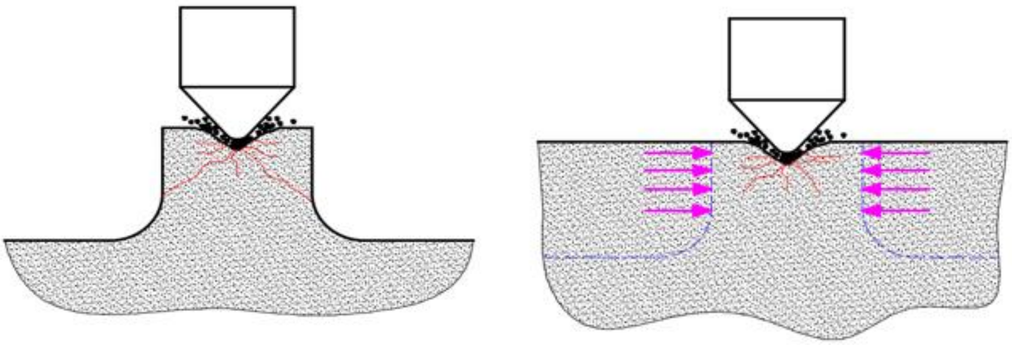


Fig. 5 Schematic diagram of structural characteristics of the annular-grooved PDC bit



(a) A ridge **(b) A flat rock**

Fig. 6 The way a cutter breaks a ridge

3.2 Anti-vibration mechanism

Research has shown that annular-grooved PDC bits can improve the rate of penetration. When at least one annular groove exists in the radial cover diagram of the drill bit, a raised-ring rock ridge corresponds to the annular groove. The wider the rock ridge is, the more efficient the drilling is. This arrangement allows for a larger lateral contact surface between the drill bit and the bottom of the hole, thereby increasing the anti-drift control parameters of the bit. In Fig. 7, F_1, F_2, F_3, F_4, and F_5 represent the drift forces generated by drilling, where all the left drift forces are combined into F_{fg1}, all the right drift forces are combined into F_{fg2}, and F_n denotes for the guiding force. As shown in Fig.7, the lateral net force of outer cone cutter of the drill is opposite to that of the inner cone cutter, and the lateral force of the outer cone exceeds the one for the inner cone. The difference between these two forces produces the bit drift force causing drilling trajectory deviation. To reduce this deviation, it is necessary to reduce the drift force, i.e., to reduce the difference between the two opposing lateral forces. As the number of the annular grooves increases, bit's anti-drift capability increases along with its gradually enhanced stability.

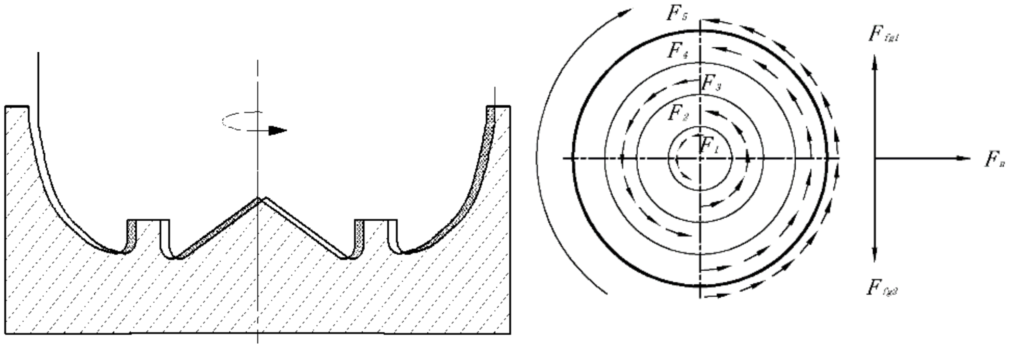


Fig. 7 Anti-drift diagram of the annular-grooved PDC bit

4. Experimental vibration test of the annular-grooved PDC bit

4.1 Design and manufacturing of the experimental drill bit

An experimental bit, i.e., an annular-grooved PDC bit, with a diameter of 9.5 inches (241.3 mm) was designed with four straight blades. The structural parameters of the bit can be adjusted by adopting modules with different sizes. Fig.8 presents a schematic diagram of the test bit, which can be used to simultaneously perform indoor experiments with an annular bit and a conventional full-cover bit. The bit body contains a module-mounting groove, and the full bit-teeth coverage can be achieved by changing the module.

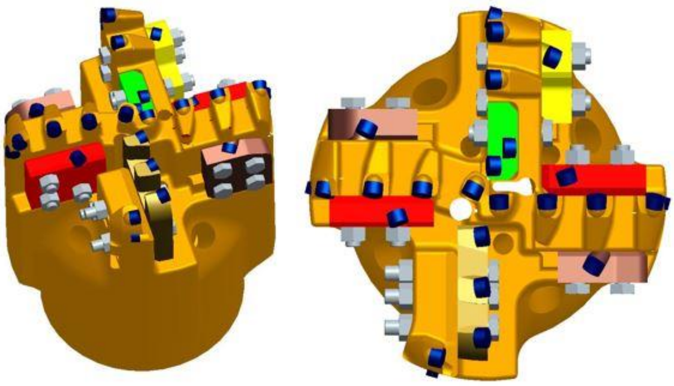


Fig. 8 Annular-grooved experimental bit

In the design of the test bit, bit's crown contour includes a shallow inner cone in a single circular arc shape. The crown contour of the test bit is shown in Fig. 8, where the inner cone angle is 85° . The annular-grooved test bit includes three annular grooves at the base of the crown profile curve, and three annular grooves with a width of 15 mm and a height of 22.5 mm are set at a radius of 30.16 mm, 60.325 mm, and 90.5 mm from the bit, respectively. The blank bands were marked as annular grooves I, II, and III from the center of the bit, respectively, and the cutting element (see dotted-line area in Fig. 9) was set in the annular-groove area as a fully covered PDC test bit. The heights of the blank bands are 0 mm, 7.5 mm, 15 mm, and 22.5 mm, which can be adjusted by replacing the cutting-tooth module. A moving blade was set on the bit, and the blank-band width was adjusted from 5 mm to 15 mm by moving the blade. For our purpose, the cutting teeth were designed to a diameter of 13.44 mm and a height of 8 mm according to the principle of equal cutting.

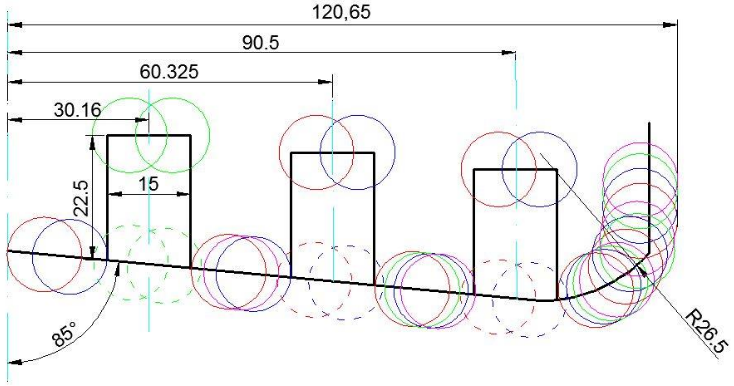


Fig. 9 Radial overlay tooth layout of the test bit

After finalizing the design, the body of the test bit was processed and manufactured in the five-axis CNC machining center, after which the PDC tooth was welded to the bit body via brazing. The adjustment module for bit structural parameter was firstly processed by wire cutting, and the PDC tooth groove was then processed in the CNC machining center, and finally the PDC tooth was brazed on the module. We used the adjustment module of the test-bit structural parameter (see Fig.10) to fix the well-processed adjustment module to the test-bit body by using bolts (Fig. 11).

Fig. 10 Structural parameter adjustment module **Fig. 11 Test bit**

4.2 Vibration test experiment of the annular-grooved PDC bit

4.2.1 Experimental preparation

For the annular-grooved PDC bit bench test, we used a bit experiment bench independently developed by the bit laboratory at Southwest Petroleum University (Fig. 12). On this bench, the upper turntable of the bit test stand allows for clockwise rotation of the bit around its own axis; the lower turntable allows for counterclockwise rotation of the rock; and the loading and lifting of bit pressure are realized by a hydraulic system. According to different experimental needs, either rock rotation or bit rotation can be adopted. Additional auxiliary equipment used for testing included a line bridge box, strain gauge, acquisition system, and accelerometer. The rock samples were limestone (400×400×400 mm^3).

Fig. 12 Bit experiment lab

4.2.2 Experimental design

In this experiment, the structural parameters of three annular grooves were considered to perform a rock-breaking experiment of the designed annular-grooved PDC bit. A rock-breaking comparison experiment was performed under the same conditions using a conventional PDC bit. These experiments enabled a comparison and analysis of the advantages and disadvantages of drilling as well as the size of annular grooves on bit stability. Specific experimental parameters are listed in Table 1.

Table 1 Experimental parameters

Experiment No.	Experimental Content	WOB (KN)	Rotation Speed (r/min)	Experimental Runs
#1	Three annular grooves of varying widths (5 mm, 10 mm, 15 mm)	10–30	10–50	3
#2	Conventional PDC bit drilling	20	30	3
#3	Three annular grooves of varying heights (7.5 mm, 15 mm, 22.5 mm)	20	30	3

4.2.3 Experimental process

In the experiment, different-sized modules were replaced to adjust the annular-groove parameters to complete a rock-breaking comparison. The rock-breaking law of the proposed annular-grooved PDC was assessed by comparing and analyzing the bottom of the hole model, bit pressure fluctuation, torque, and mechanical drilling speed during drilling. The bit slowly drilled down and completed the bottoming work of the rock samples. We initiated the lower turntable and applied bit pressure to force the bit drill to operate normally (Fig. 13). We then launched the dynamic test analysis system, performed channel balance and zeroing, and gathered experimental data. After reaching the predetermined drilling depth, drilling stopped and cutting was completed. Each set of experiments was repeated at least 3 times.

Fig. 13 Drilling process of experimental bit

4.3 Experimental results

The experimental bit consists of 4 blades with a cutting dimension of Φ16mm × 13mm.Drilling site test data indicated that when the test position was near the drill bit, the bit exhibited larger vibration amplitude. The centralizer effect of the bit was better when the centralizer location was near the bit. When a ring-groove PDC bit in the bottom ring rock ridge (equal to one) was installed on the top of the drill bit centralizer, bit stability was enhanced more clearly. Fig. 14 presents a comparison of the acceleration amplitude for the annular-grooved PDC bit and the conventional PDC bit with a WOB of 30 KN and rotation speed of 30 RPM. The annular-groove PDC bit exhibited lower acceleration amplitude in the axial, tangential, and radial directions irrespective of PDC bit coverage; specifically, the acceleration amplitude declined by 33.5% in the tangential direction, 21.6% in the axial direction, and 25.9% in the radial direction compared to the conventional bit. As such, the proposed annular-grooved PDC bit was found to reduce drill-bit acceleration. The drilling impact in the drilling process was thus reduced, leading to improved service life for the bit's cutting teeth. Additionally, harmful vibration of the drill bit from the broken convex rock ridge was reduced and resulted in a greater energy utilization rate of the bit.

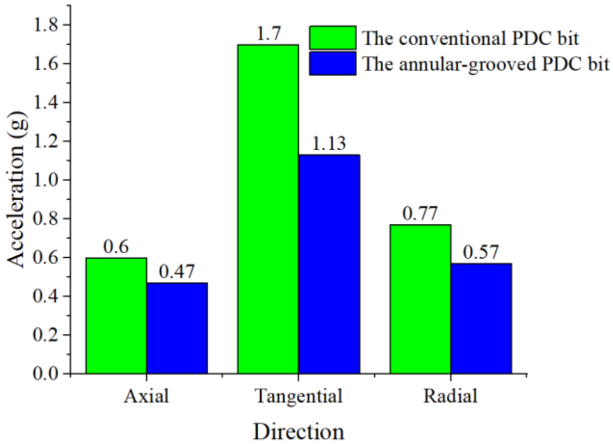


Fig. 14 Comparison of acceleration of annular-grooved PDC bit and conventional PDC bit

(1) WOB

Fig. 15 displays variations in the annular-grooved PDC bit's acceleration amplitude at different bit weights and a rotation speed of 30 RPM, annular-groove height of 15 mm, and annular-groove width of 10 mm. As the WOB increased, the amplitude of the vibration acceleration of the ring-groove PDC bit increased gradually, as did the acceleration amplitude in the axial, tangential, and radial directions. Because the rock-breaking mechanism of the PDC bit requires the bit to engage in axial drilling before drilling into the formation, bit pressure should not be reduced to lessen bit vibration. Bit stability should be improved in other aspects instead.

(2) Rotation speeds

Fig. 16 depicts variations in the annular-grooved PDC bit's acceleration amplitude at different rotation speeds and a WOB of 10 KN, annular-groove height of 15 mm, and annular-groove width of 10 mm. As the rotation speed increased, so did the bit's acceleration amplitude. The acceleration amplitude in the tangential direction increased notably. Once the drill speed increased, a strong bit–rock collision occurred, the impact speed was faster, and vibration was readily apparent. The bit vibration in the three directions influenced each other and exhibited mutual coupling: an increase in vibration in one direction drove vibration in the other two directions. Therefore, to better control bit vibration, it is only necessary to control one vibration direction to limit drill-bit vibration.

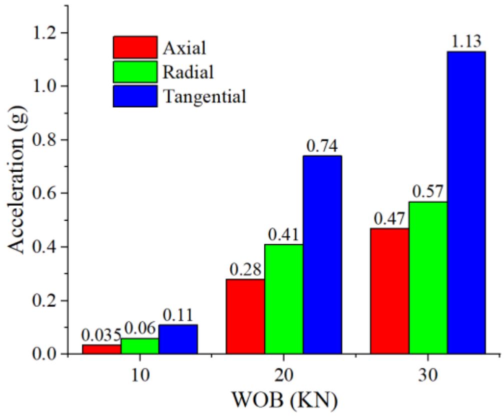


Fig. 15 Variation in acceleration amplitude of annular-grooved PDC bit under different WOB

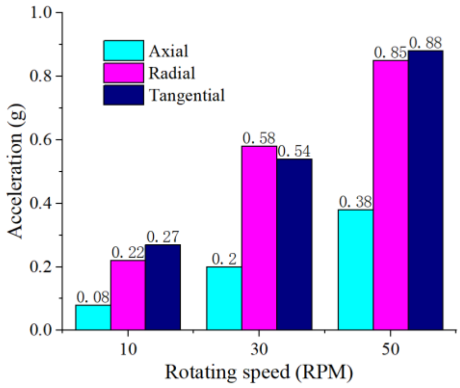


Fig. 16 Variation in acceleration amplitude of bit at different rotation speeds

(3) The width of ridge

Fig. 17 illustrates variations in bit acceleration at different rock-ridge widths and a WOB of 10 KN, rotation speed of 30 RPM, and rock-ridge height of 15 mm. As the rock-ridge width increased, the acceleration amplitude of the bit gradually declined in the tangential, axial, and radial directions. Following downhole annular rock-ridge formation, a wider rock ridge was more beneficial in reducing drill vibration in the three directions. Drill vibration in the radial direction became more obvious when the rock-ridge width increased from 5 mm to 15 mm; at this point, the bit acceleration amplitude declined by 57% in the radial direction, 50% in the tangential direction, and 46% in the axial direction.

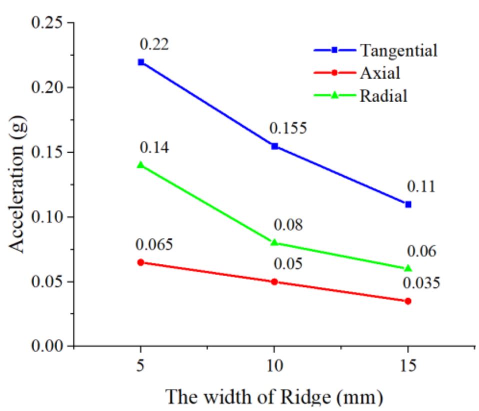


Fig. 17 Variation in bit acceleration with ridge width

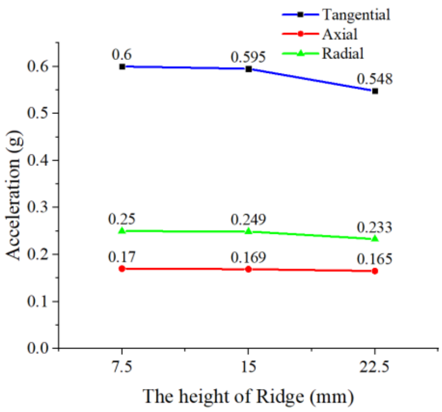


Fig. 18 Variation in bit acceleration with ridge height

(4) The height of ridge

Fig. 18 shows variations in bit acceleration at different rock-ridge heights and a WOB of 20 KN, rotation speed of 30 RPM, and rock-ridge width of 10 mm. As the rock-ridge height increased, the drill's acceleration amplitude gradually declined in the three directions. The taller the rock ridge, the better the formation of the ring rock ridge and the lower the drill-bit vibration. A comparison of Figs. 17 and 18 reveals that the rock-ridge width influenced bit acceleration more strongly than rock-ridge height.

5. Conclusions

Vibrations in the axial, tangential, and radial directions of the PDC bit is coupled with each other. As long as the vibration in one direction increases, the vibrations in the other two directions will be influenced accordingly. Therefore, when controlling bit vibrations, the vibration in only one direction can limit the vibrations of the entire bit. This paper carried out a fundamental analysis of the root cause of failure for PDC bits during the drill-based process of vortex generation in order to extend the service life of drill bits through reducing various drilling vibrations. We developed a new type of PDC drill bit, namely the annular-grooved PDC bit, which can form one or more annular convex rock ridges at the bottom of the hole, having a raised ring that can limit transverse vibration. Our experimental results indicated that the accelerations of the annular-grooved PDC bit in axial, tangential, and radial directions were smaller than that of a conventional PDC bit. In detail, acceleration was declined by 33.5%, 21.6%, and 25.9% in tangential, axial, and radial direction, respectively. Our experimental investigation showed that, as the WOB and the rotation speed increased, bit vibration intensified, and the impact load on bit was also increased which could degrade bit stability. However, as the height and the width of the rock ridge increased, the drilling vibrations in three directions were reduced. Therefore, the developed annular-grooved PDC bit can reduce bit vibration and improve bit's drilling stability.

Acknowledgements

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