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The ROP mechanism study in hard formation drilling using local impact method

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Abstract. The low rate of penetration and short lifetime of drilling bit served as the most common problems encountered in hard formation drilling, thus leading to severe restriction of drilling efficiency in oil and gas reservoir. This study developed a new local impact drilling method to enhance hard formation drilling efficiency. The limitation length formulas of radial/lateral cracks under static indentation and dynamic impact are derived based on the experimental research of Marshall D.B considering the mud column pressure and confining pressure. The local impact rock breaking simulation model is conducted to investigate its ROP raising effect. The results demonstrate that the length of radial/lateral cracks will increase as the decrease of mud pressure and confining pressure, and the local impact can result in a damage zone round the impact crater which helps the rock cutting, thus leading to the ROP increase. The numerical results also demonstrate the advantages of local impact method for raising ROP and the vibration reduction of bit in hard formation drilling. This study has shown that the local impact method can help raising the ROP and vibration reduction of bit, and it may be applied in drilling engineering.

Keywords: local impact; acceleration mechanism; rock-breaking mechanism; hard formation

1. Introduction

The onshore oil and gas exploration has extended to the deep and ultra-deep formations in recent years in China. The 4500 meters deep well in eastern region and 6000 meters deep well in western region of China have achieved essential breakthroughs in exploration. The depth of wells in Tarim oilfield has been exceeded 6000 meters in the past four years, and broke the 8000 meters deep pass (8023 meters in Keshen-7 well), the exploration wells in eastern basin also broke the 6000 meters deep pass (6027 meters Niudong-1 well) (Sun *et al.* 2013, Liu *et al.* 2018). The deep formation has the characteristics of high strength, high abrasive resistance, high plasticity etc., those hard formation drilling comes to be inevitable in oil and gas exploitation, and how to improve the rate of penetration (ROP), i.e. making the bit drill through the hard formation fast, serves as the main technical problem encountered in the drilling industry. The new rock breaking method that can improve the ROP is urgently desired in the hard formation drilling.

Taking Xujiahe in west Sichuan and Songnan area for instance, the poor drill capacity phenomenon, low drilling ROP and low lifetime of bit appeared in Xujiahe because of the compact, high quartz and abrasive of the rock. The drilling footage of single bit is only 99.83 meters, the average ROP is 1.07 meter/h; the average ROP in section four less than 1 meter/h and the average drilling footage in section two is only 45.36 meters, leading to frequent tripping and low efficiency of pure drilling (Zhu *et al.* 2010, Xiao *et al.* 2012). Quantou group, Denglouku group and Yingcheng group in Songnan area also met poor drill ability, low drilling ROP, short drilling footage of single bit. The drilling circle is even 183 days for a 4500-meter deep well, while the average ROP in Quantou group is 1.07 meter/h and the average drilling footage in Yingcheng group is only 47.35 meters (Li *et al.* 2008, Mu *et al.* 2010). What is more, there also exist many complex problems such as drilling fluid leakage and serious bit bouncing. There are many formations similar to Xujiahe in west Sichuan and Songnan area in drilling engineering, their common characteristics are rock hardness, strong abrasive and poor drill ability, resulting in low drilling ROP, and low lifetime of bit in those formations. In order to enhance the hard formation drilling efficiency, various new acceleration drilling technologies have been developed by researchers, such as percussive drilling (Su *et al.* 2017, Lundberg and Huo 2017, Zhu *et al.* 2017), mud underbalance drilling (Mayans *et al.* 2016, Akhshik and Rajabi 2018) and air drilling (Li *et al.* 2014, Tian *et al.* 2015) etc. Besides, the corresponding drilling tools (hydraulic hammer, air hammer and PDC) have also been designed; however, those drilling tools have not been widely applied (except for PDC bit) in drilling engineering because of its complex construction,

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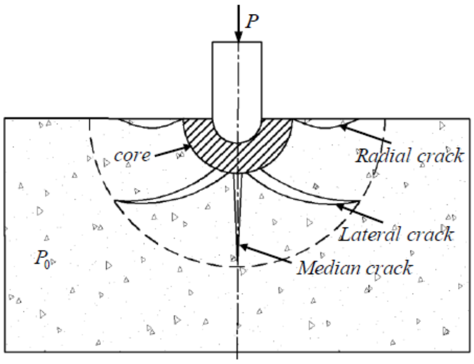


Fig. 1 Static fracture morphology

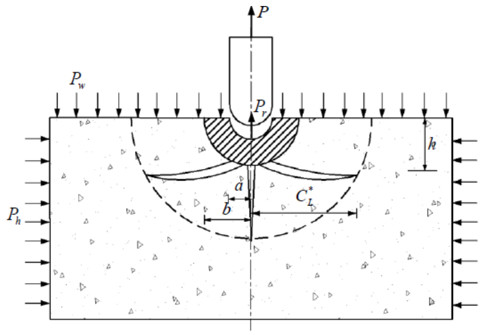


Fig. 2 Lateral cracks system

relative low lifetime and high cost in use.

In view of the above problems, this study proposed a new local impact drilling method. The limitation length formulas of radial/lateral cracks under static indentation and dynamic impact are derived based on the experimental research of Marshall D.B. Furthermore, the rock breaking simulation model of local impact are utilized to investigate its ROP raising effect.

2. Rock breaking mechanism of local impact method

2.1 The rock fracture analysis under static indentations

2.1.1 Static fracture morphology

The main discrepancies between elasticity indentation and elastic-brittle indentation are the indenter shape and the properties of indented material. The rock indentation can be considered as elastic-brittle indentation type. Radial crack, median crack and lateral crack will be generated during the indentation; besides, a core beneath the indenter will also be generated, shown in Fig. 1.

2.1.2 Static fracture morphology analysis

It is of high essence to establish the relationship between penetration load and fracture length for investigating the fracture propagation, strength reduction, damage degree of rock material, as well as its breaking mechanism. In line with Swain M.V.'s invasion theory (Xu and Yu, 1984, Yu *et al*. 2015), the relationship between penetration load and fracture length can be expressed as $P \propto C^{3/2}$. Marshall (1982, 1983) proposed the analytical methods for many indenters based on two common experimental observations: first, the final form of crack in elastic-brittle invasion is fully developed until the indenter leaves the material surface, in another word, the residual field plays a significant role in the crack form evolution. Second, the shape of irreversible deformation region under indentation is approximately hemispherical. The stress intensity factor (SIF) closely related to the radial crack evolution can be expressed as

$$K_r = \beta (EH)^{1/2} (\delta V)^{2/3} / C^{3/2} \tag{8}$$

where β means dimensionless coefficient, E depicts elastic modulus of rock, H indicates material hardness, δV means the volume of the indentation.

The plane strain fracture toughness K_c was measured through experiment, if $K_r \geq K_c$, the radial cracks will develop.

$$P / C^{3/2} = K_c / x_b \tag{9}$$

where $x_b = \beta (E/H)^{1/2} (a \cot \psi)^{2/3} / a_0$, ψ represents the characteristic angle of the indenter, a indicates a characteristic dimension of indentation, a_0 means geometrical constant of the indenter.

Lateral crack is the most essential crack during rock breaking process. It has been proved that the lateral crack is developed during unloading process of indenter. A simplified analytical model of lateral cracks is established assuming the lateral cracks to be parallel to free face and ignoring the effect of multi-layer cracking as illustrated in Fig. 2.

$$P_r / P_{ro} = 1 - u_r / u_{ro} \tag{10}$$

where P_{ro} means the maximum residual stress, u_{ro} depicts the initial displacement when $P_r = 0$, u_r indicates the displacement resulted from residual stress P_r.

The plane strain SIF and residual stress are calculated as

$$K_c = \left[A / 2\pi (1 - \nu^2) \right]^{1/2} P_r / h^{3/2} \tag{11}$$

$$P_r = P_{r0} / (1 + A P_{r0} c^2 / E u_{r0} h^3) \tag{12}$$

where ν represents Poisson's ratio, A depicts a dimensionless, geometrical constant. P_{ro} can be determined from the elastic/plastic mismatch stress, integrating over the zone cross sectional area without crack; whereas u_{ro} can be obtained in terms of the radial displacement of the zone boundary from the fully compressed to the fully relaxed state; the thickness of the material above the crack plane can be identified with the depth of the plastic zone.

$$\left. \begin{array}{lll} P_{ro} & \propto & (E/H)^{1/2} (\cot \psi)^{2/3} P \\ u_{ro} & \propto & \left[(H/E)/H^{1/2} \right] (\cot \psi)^{1/3} P^{1/2} \\ h & \propto & \left[(H/E)^{1/2} / H^{1/2} \right] (\cot \psi)^{1/3} P^{1/2} \end{array} \right\} \tag{13}$$

The maximum length of lateral crack can be illustrated as

$$C_L^* = \left\{(\xi_L / A^{1/2})(\cot\psi)^{5/6}\left[(E/H)^{3/4}/K_c H^{1/4}\right]^{1/2}\right\} P^{5/8} \quad (14)$$

where ξ_L is dimensionless constant, independent of the material/indenter system.

2.2 The rock fracture analysis under dynamic indentations

The rock fracture under dynamic indentations is similar to that under static (Zhang and Kou, 1990), because both will cause Hertz, median, radial and lateral cracks; the Hertz, median and radial cracks are generated during loading process and developed after unloading, however, the lateral cracks are totally generated and developed during unloading process. There exists a critical indentation load for the crack formation under static indentations; in contrast, a critical impact energy $\pi rE/C_p$ (Li and Gu 1994) also exists under dynamic indentations. The strength of rock will decline because of the Hertz, median, radial and lateral cracks resulted from impact load, so the drilling will become easier, the ROP will thus be improved and the vibration will be lessened.

2.2.1 Dynamic fracture morphology analysis

The length of radial cracks

According to the mechanical analyses of dynamic and static, the maximum impact force F_{m0} during pure dynamic impact is calculated as

$$F_{m0} = 2mV_1\gamma^{\gamma/1-\gamma} \quad (15)$$

where V_1 represents the last impact velocity, *m* indicates the average wave resistance of impact bar, $\gamma = m^2/MK$, K depicts invasion coefficient, *M* represents the weight of impact bar.

The hardness and modulus of rock will alter as the loading speed changes under the impact load (Marshall *et al.* 1982). Therefore, the length of radial cracks should be taken into consideration of the change of hardness and modulus.

Replacing *H, E* and *P* with H_d, E_d and $2mV_1\gamma^{\gamma/1-\gamma}$ respectively, following equation can be obtained.

$$C = \left[\xi^{2/3}((E_d/H_d)^{1/3})/K_c^{\,2/3}\right]\left[mV_1\gamma^{\gamma/1-\gamma}\right]^{2/3} \quad (16)$$

where $\xi = \beta a_1^{\,2/3}(2\cot\psi)^{2/3}$, $a_0 = 2$, $a_1 = 2/3$, $\gamma = m^2/MK$.

The radial crack length under the mud column pressure and confining pressure

The bottom hole rock suffers compressive load or tensile load (P_L) under the combined action of the mud pressure and overburden pressure, shown in Fig. 3. The bottom hole rock will break easily when it is suffering tensile load, and the ROP will thus be improved. In accordance to the investigation of Marshall (1984), following formulas can be obtained.

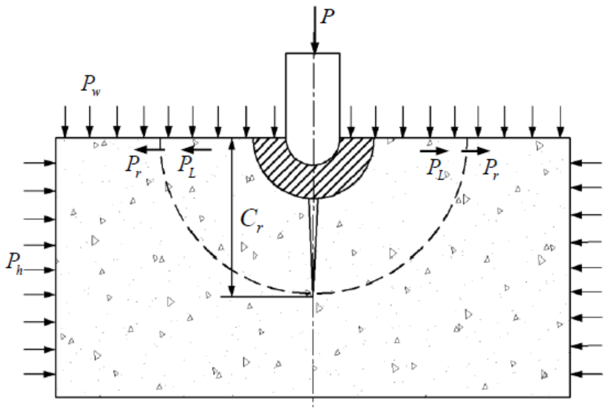


Fig. 3 Median/radial crack

$$\left.\begin{aligned} &P_r \propto pV^{2/3} \\ &p \propto E\delta V/V \\ &K_{r0} \propto (P_r - P_L)/c^{3/2} \\ &\delta V/V \propto (H/E)^{3/2} \\ &\delta V = a_1 a^3 \cot\psi \\ &H = P/a_0 a^2 \end{aligned}\right\} \quad (17)$$

The SIF of rock under compressive load and tensile load is derived using the above formulas.

$$K_{r0} = \left[\beta(EH)^{1/2}(\delta V)^{2/3} - P_L\right]/C^{3/2} \quad (18)$$

If $K_r \geq K_c$, the radial cracks will initiate. The SIF of rock considering the influence of mud column pressure and confining pressure can be calculated with following equation

$$K_{c0} = \left[\beta(EH)^{1/2}(\delta V)^{2/3} - P_L\right]/C^{3/2} \quad (19)$$

So, the length of radial cracks can be written as

$$C_r = \left[\xi^{2/3}((E_d/H_d)^{1/3})/K_{c0}^{\,2/3}\right]\left[mV_1\gamma^{\gamma/1-\gamma}\right]^{2/3} \quad (20)$$

The tensile load P_L will increase if mud pressure P_w decreases. With the equations (19) and (20), the length of radial crack will increase while the SIF K_{c0} decreases.

The length of lateral cracks

According to the experiment of static/dynamic indentations, the ratio of depth to width of deformation region is approximately 0.5 in static indentations and it is hemispherical, however, the ratio is approximately 0.8 in dynamic indentations (Marshall, 1984). When the contact radius a is the same, the deformation region in dynamic indentations is smaller than in static indentations, but the length of lateral cracks is bigger.

Replacing *H, E* and *P* in Equation (14) with H_d, E_d and $2mV_1\gamma^{\gamma/1-\gamma}$ respectively. The length of lateral cracks can be assessed with

$$C_L^* = \left\{ (\xi_L / A^{1/2})(\cot\psi)^{5/6} \left[(E_d / H_d)^{3/4} / K_c H_d^{1/4} \right]^{1/2} \right\} (2mV_1 \gamma^{\gamma/1-\gamma})^{5/8} \quad (21)$$

The length of lateral crack under the mud column pressure and confining pressure

The residual stress P_r and mud pressure P_w will induce the lateral cracks generated during the unloading process. The lateral cracks will cause the rock breaking, as shown in Fig. 2. The SIF of rock can be written as

$$K_{c1} = \left[A / 2\pi(1-\nu^2) \right]^{1/2} (P_r - P_w) / h^{3/2} \quad (22)$$

The length of lateral cracks can be expressed as

$$C_L^* = \left\{ (\xi_L / A^{1/2})(\cot\psi)^{5/6} \left[(E_d / H_d)^{3/4} / K_{c1} H_d^{1/4} \right]^{1/2} \right\} (2mV_1 \gamma^{\gamma/1-\gamma})^{5/8} \quad (23)$$

According to the Eqs. (22) and (23), the SIF K_{c1} will decrease when the mud pressure P_w decreases, so the length of lateral crack will increase.

In conclusion, the length of cracks induced by dynamic indentations is larger than static and the damaged zone is also larger, so the rock under dynamic indentation becomes easier to be broken. By utilizing the local impact method in drilling engineering, the drilling efficiency can be improved.

3. Numerical analysis of local impact method

3.1 The working mechanism of local impact method

The structural scheme of PDC bit with impact bar is illustrated in Fig. 4. This new tool consists mainly of turbine drive, rotary distributing valve, impact device, cap, impact bar, outer cylinder, inner casing, seal ring, guide plate, shell and PDC bit etc. The working mechanism can be simply summarized as that the flow potential energy of drilling mud can be transmitted into the kinetic energy of impact bar through the turbine drive and rotary distributing valve, leading to the impact bar impact the bottom hole rock with a certain frequency. As shown in Fig. 4, the initial position of impact bar (13) is decided by the two springs (7 and 10); number 15 is the impact load; the other numbers represent the other parts of bit, respectively.

3.2 Numerical model establishment

Basic hypothesis are as follows

a) The wear and passivation of bit are ignored during drilling;

b) The rock is isotropic material without considering the formation dip;

c) Ignoring the effects of bottom hole flow field in the rock breaking.

The numerical model of the new PDC with impact bar and traditional PDC are shown in Figs. 5 and 6, respectively. The hexahedral eight nodes reduced integral unit (C3D8R) is applied for the rock model. Manual grids just refine the area of rock where it shall contact with the bit, and the other meshes try to simplify. As a result, the rock is divided into 164,280 units. The rock is considered as an elastic plastic body and Drucker-prager failure criterion is utilized, and the physical parameters of rock are shown in Table 1.

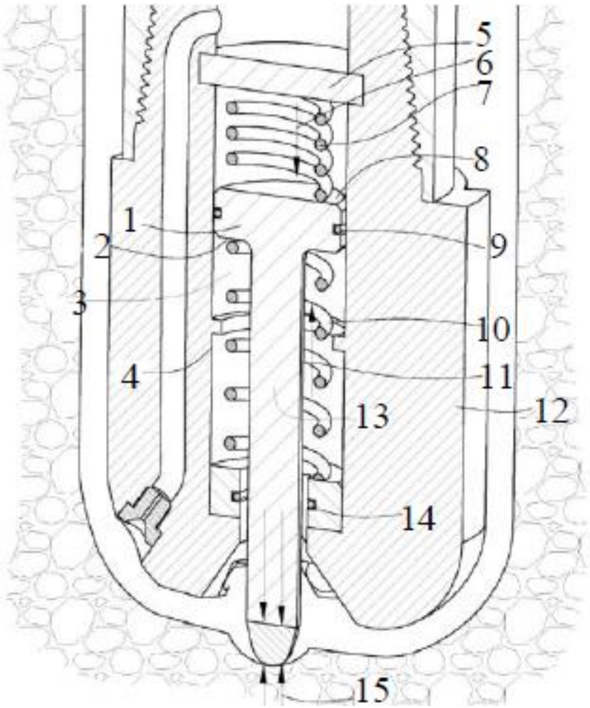


Fig. 4 Structure scheme of PDC with local impact method (Keskiniva *et al*. 2011)

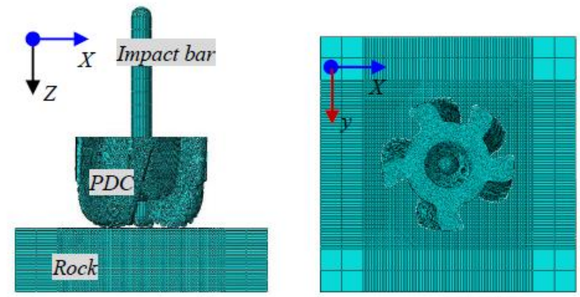


Fig. 5 The rock breaking simulation model of bit with impact bar

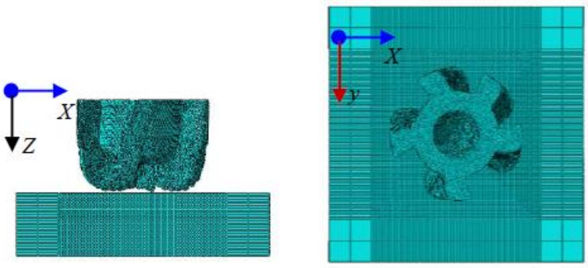


Fig. 6 The rock breaking simulation model of traditional bit

The PDC bit and impact bar are defined as a discrete rigid body and tied in the corresponding reference point. General contact is adopted in the numerical model. The degree of freedom in *z* direction of rock is restrained and horizontal stress and nonreflecting boundary condition are

Table1 Triaxial compression test parameters of rocks

Sample	Confining pressure (MPa)	Number	Elastic modulus(MPa)	Poisson's ratio	Compressive strength (MPa)	Angle of dilation(°)	Shear strength	
							Cohesion (MPa)	Friction angle(°)
Ya'an granite	5	1-1	24680.6	0.355	141.7	41.3	37.86	30.16
	10	1-2	25871.1	0.404	151.8			
	30	1-3	19622	0.412	193.5			
	60	1-4	45561.1	0.394	233.3			

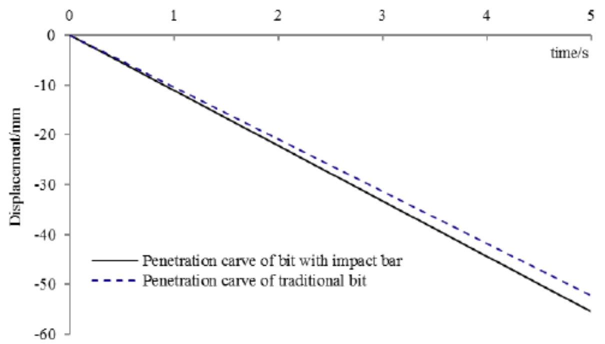


Fig. 7 The displacement carve of two bits

applied in x direction and y direction. The bit size is 216 mm, the rotational speed of PDC is 9.42 rad/s, the weight on bit is 5 Tone, and the impact frequency of the bar is 33 Hz.

3.3 ROP raising effect of local impact method

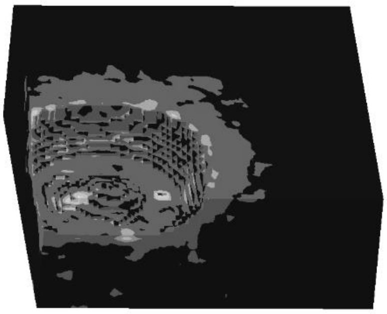
The ROP raising effect of local impact method is investigated utilizing the aforementioned above numerical model. The results demonstrate that the ROP of PDC bit with local impact bar is faster than the traditional PDC bit with 9.8%. The main reason is that the strength of bottom rock will decrease due to the Hertz, median, radial and lateral cracks resulted from impact load, so the drilling will be easier, the ROP will be strengthened and the vibration will be reduced. The PDC bit with local impact bar is better for hard formation drilling, and it helps improving the drilling efficiency, reducing the drilling cycles and saving the drilling cost.

The drilled bottom-hole rock obtained in experiments and numerical analysis are shown in Fig. 8. Fig. 8(a) illustrates the result of drilled bottom-hole rock in experiment; Fig. 8(b) illustrates the simulation result of traditional PDC bit and Fig. 8(c) shows the result of PDC bit with local impact bar. The numerical results are similar to the experimental results, and it indicates that the numerical simulation model in this study is credible to some extent. Comparing with the stress cloud of Figs. 8(b) and 8(c), the rock damage area is larger while using PDC bit with impact bar. This is why the local impact method has ROP raising effect.

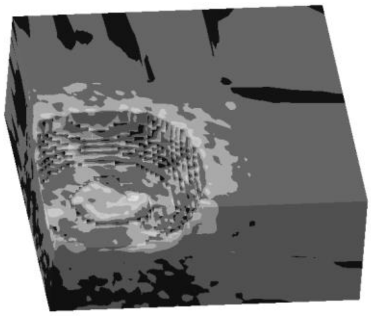
3.4 Vibration reduction effect of local impact method

The vibration intensity of bit largely influences the bit life, the larger the vibration is, the lower the bit life will be. The vibration intensities of traditional bit and bit with

(a)



(b)



(c)

Fig. 8 The bottom-hole rock obtained from experiment and simulation

Table 2 The mean square roots of vibration intensity

	Traditional bit/g	Bit with impact bar/g
X	29.09	19.03
Y	32.54	19.50
Z	13.52	14.37

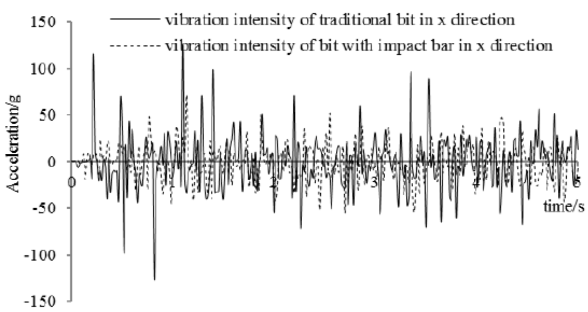


Fig. 9 The vibration intensity of bit in x direction

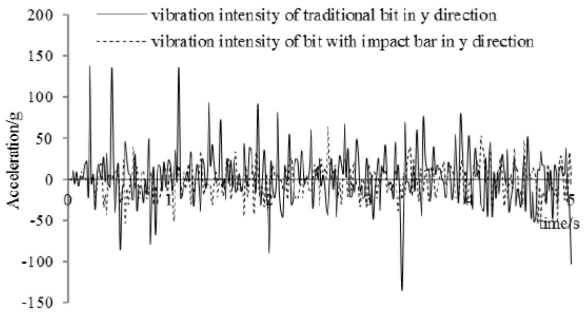


Fig. 10 The vibration intensity of bit in y direction

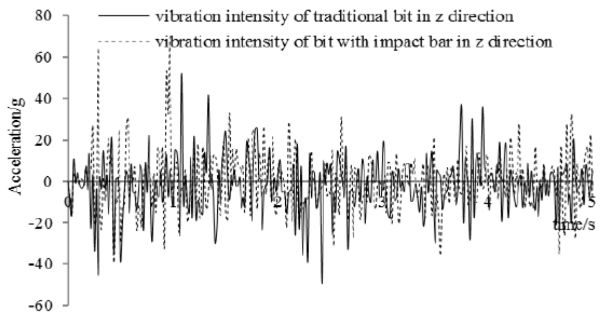


Fig. 11 The vibration intensity of bit in z direction

impact bar are shown in Figs. 9 to 11, and the roots mean square of vibration intensity are list in Table 2. From Table 2, the vibration intensities of the bit with impact bar in *x* and *y* direction are much smaller than those for the traditional bit, the vibration intensities in *z* direction are basically the same.

3.5 Other advantages of local impact method

The local impact method utilized for the bit does not make the structure so complex and it will not increase the size. Besides, the design and manufacturing process of the bit are also relatively simple. The drilling cost is herein cut down, and the ROP and service life are ensured comparing with hydraulic hammer, air hammer and traditional PDC bit. Moreover, the lateral vibration of the bit is decreased and the problems of drilling tool fatigue failure and wellbore instability caused by drill bit vibration are alleviated using local impact method; this new bit can be utilized in extensive formations, it can apply in distinct formations either in mud drilling and underbalanced drilling through adjusting the impact energy of impact bar. The above advantages of local impact method overcome the shortcomings of other existing bits, and it makes the new bit more suitable for the increasingly serious and complex drilling conditions.

4. Conclusions

This study aims to propose a new bit and a local impact method for improving the short lifetime and ROP of drilling bit in hard formation drilling. With the discussion above, the following conclusions can be summarized:

The length of radial/lateral cracks will increase as the decrease of mud pressure and confining pressure, and the local impact can cause a damage zone round the impact crater that helps the rock cutting; the simulation results demonstrate that the local impact method can improve the ROP and reduce the vibration of bit in hard formation drilling.

This new bit with local impact method can apply in extensive formations, and it can also apply in distinct formations either in mud drilling and underbalanced drilling through adjusting the impact energy of impact bar. The advantages of local impact method can overcome the shortcomings of existing bits, and it makes the new bit more suitable for the increasingly serious and complex drilling conditions.

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