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Characteristics of Axial Percussive Force of Two-cutter PDC Bit on Carbonate Rock#

Xinkang Fu[1], Zhongwei Huang [1*], Luhai Wang[1], Huaizhong Shi[1], Guodong Ji[2]

1 National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum-Beijing, Beijing 102249, China

2 CNPC Engineering Technology R&D Company Limited, Beijing 102206, China
(Corresponding Author: huangzw@cup.edu.cn)

ABSTRACT

The carbonate reservoir is rich in oil and gas resources and has great exploration potential. The deep carbonate rock has poor drill-ability. Percussive drilling technology has been verified to notably enhance the rock-breaking efficiency in deep and ultra-deep formations. However, the law of rock breaking under different parameters of axial percussion is not clear. A set of experimental equipment for percussive drilling was established. A series of axial percussive drilling tests under different percussive parameters with a double-cutter PDC bit were carried out on carbonate rock. The study analyzed the relationship between axial force and percussive frequency, as well as the relationship between axial force and percussive amplitude. The results indicate that the average value and fluctuation amplitude of the axial force are minimized at the frequency of 16 Hz. When the amplitude of axial percussion reaches 0.8 mm, the average axial force is at its lowest point. The optimum axial percussive amplitude is 0.8 mm. Excessive percussive amplitude is detrimental to rock breaking. The findings will be helpful in determining the optimal parameters for axial percussive drilling.

Keywords: percussive drilling, PDC cutter, percussive frequency, carbonate rock, percussive amplitude

NONMENCLATURE

Abbreviations	
PDC	Polycrystalline Diamond Compact
DTH	Down-the-Hole
UCS	Uniaxial Compressive Strength
RPM	Revolutions Per Minute

1. INTRODUCTION

Carbonate rock is an important oil and gas reservoir rock [1]. Half of the world's oil and gas resources are stored in carbonate formations [2]. The deep and ultra-deep dolomite, as the major carbonatite oil and gas reservoir in western China, has a large potential for exploration and development [3]. Deep rocks have high compressive strength and poor drill-ability. PDC bits often suffer from chipping and severe wear [4]. These problems significantly hinder the efficient development of carbonate oil and gas resources. In order to improve the efficiency of breaking hard rock, percussive drilling technology is widely used in the drilling field [5] [6]. Percussive drilling is a method of breaking rock by applying periodic alternating loads from a special tool to the rock [7]. Fig. 1 shows the graphical illustration of the axial percussive drilling process.

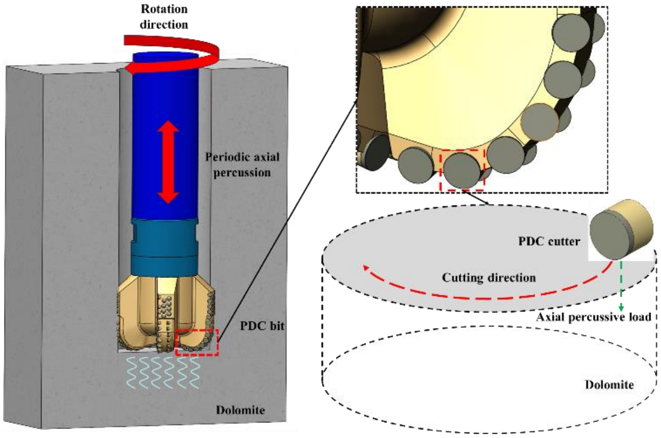

Fig. 1 Engineering model of axial percussive drilling

Due to the high cost of genuine PDC bits used in oil field construction sites, many scholars design simplified drilling bits for laboratory testing. Saksala et al. [8] carried out tests of dynamic indentation into granite using a homemade three-cutter drilling bit. Based on the test results, they utilized the damage-viscoplasticity model to develop a percussive rock-breaking model for simulating rock fracture. Hashiba et al. [9] carried out 48 percussive tests using a 76 mm diameter multi-cutter drilling bit. They concluded that the force-displacement curves were

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downwardly convex during both the loading and unloading stages. Aldannawy et al. [10] carried out dynamic penetration tests using a single conical cutter. It was found that the increase in weight of bit favors the eating of rock by the cutter, but does not affect the cutting process. The increase in percussive energy could lead to deeper drilling pits.

The optimization of percussive parameters is the focus of researchers in related fields. Pavlovskaia et al. [11] considered three parameters in their percussive drilling tests: weight of the bit, percussive frequency, and percussive amplitude. The optimum load parameters were determined. Depouhon et al. [12] analyzed the effects of the weight of the bit, percussive parameters, and the interaction between the drilling bit and rock on the efficiency of percussive drilling through modeling. They concluded that increasing the frequency of percussion could significantly improve the efficiency of rock breaking. Ryu et al. [13] utilized DTH hammers to conduct linear percussive tests under different experimental conditions. Their study analyzed the influence of rotary speed and percussive speed.

Previous researchers have conducted numerous studies on the direction of percussive rock breaking. Most of their experiments were carried out using DTH or SHPB with simple single or multi-cutter drilling bits. This type of experiment can only study the damage caused to rocks by a single percussion. In addition, most of the previous percussive rock-breaking tests were conducted on granite. Carbonate rocks are important reservoir rocks. No thorough research has been carried out on percussion-broken carbonate rocks by previous researchers.

In this paper, a series of axial percussive tests were carried out on carbonate rocks using a self-developed high-frequency percussive rock-breaking experimental device. The axial percussive carbonate rock experiments were conducted under various axial percussive frequencies and amplitudes. The relationship between axial force and axial percussive frequency and amplitude was analyzed. According to the analysis of the axial force data, the optimal axial frequency and amplitude range suitable for percussion breaking carbonate rock were determined. The findings of this study will provide guidance for optimizing parameters for axial percussive drilling in carbonate rocks.

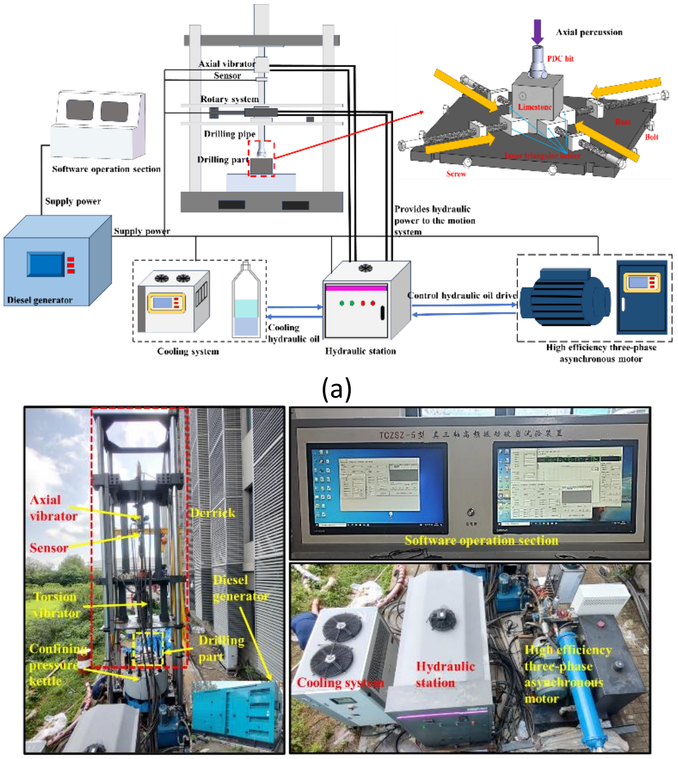
2. EXPERIMENTAL ANALYSIS OF AXIAL PERCUSSION CARBONATE ROCK

2.1 Experimental setup

The axial percussive tests were carried out based on the self-developed high-frequency percussive rock-breaking experimental device. The device is mainly composed of four parts. The components include a hydraulic control and cooling system, drilling section, power system, and software operation console. The hydraulic control and cooling system are used to control the movement of the drilling pipe hydraulically and to cool the anti-wear hydraulic oil. It mainly includes a high-efficiency three-phase asynchronous motor, a cooling system, and a hydraulic oil circulation system. The drilling section is the primary component for conducting the drilling test. It mainly includes a derrick, axial vibrator, drilling pipe, drilling bit, rock sample holder, and sensor. This is the core component of the entire experimental apparatus. The power system provides electricity to operate all the experimental equipment. In fact, the main component of the power system is a diesel generator. The software control console is primarily utilized to configure the parameters of drilling pipe movement, manage the initiation and cessation of the test, and to display and store real-time data on axial force and axial displacement.

Specifically, the functions and parameters of this equipment are described below. The drilling pipe can perform upward, downward, and rotary motions. The upward and downward speeds can reach 50 mm/s. The rotational speed can reach 80 RPM. In addition, a sinusoidal vibration wave can be established to induce periodic oscillation of the drilling pipe, moving it up and down. The frequency can be set up to 50 Hz. During the axial percussive test, a sensor positioned at the top of the drilling pipe measures the downward displacement of the drilling pipe and the axial force generated by its interaction with the rock. The acquisition frequency could be set up to 80 Hz.

Figure 2 (a) shows the schematic diagram of the high-frequency vibration rock-breaking experimental device. Figure 2 (b) shows the real-world diagram of the high-frequency vibration rock-breaking experimental device. In the drilling section, our focus is on the stability of the clamping device for rock samples (as shown in Fig. 2 (a)). The clamping device for rock samples consists of a square base, four inner triangular holders, and four screws. We can adjust the distance between the two inner triangle grippers by tightening the bolts on both sides. This allows us to securely clamp rock samples of different sizes. The maximum sample size that can be clamped by this rock sample clamping device is 250 × 250 × 250 mm. Figure 2 (a) shows the rock sample clamping device.



(a)

(b)

Fig. 2 High-frequency percussive rock-breaking experimental device ((a) Schematic diagram of experimental equipment, (b) Physical drawing of the experimental equipment)

2.2 Experimental Materials

In this paper, the study focuses on carbonate rocks. According to previous literature research, dolomite is identified as a type of carbonate rock with more abundant hydrocarbon reserves. Studying PDC drilling bit percussion in dolomite is very meaningful. Therefore, dolomite was selected as the experimental rock sample. The carbonate rock samples were collected from Baoding City, Hebei Province. The samples were uniformly cut into squares measuring 140 × 140 × 140 mm (as shown in Fig. 3). We performed a series of mechanical properties tests on the collected samples. As shown in Table 1, the basic properties of carbonate rock samples, including density, grindability, UCS, drill-ability level value, Young's modulus, hardness, and Poisson's ratio, were determined.

Table 1 The properties of carbonate rock sample

Property	Value
Density (g/cm^3)	2.41
Young's Modulus (GPa)	9.29
Poisson's ratio	0.33
UCS (MPa)	55
Drillability level value	4.7
Grindability	3.2
Hardness (MPa)	1171.9

According to the previous related study, Meng designed a small double-cutter PDC bit to carry out drilling tests. This also confirmed the feasibility of using the double-cutter bit for drilling tests [14]. The oil and gas drilling market is currently experiencing a significant increase in the global demand for special-shaped cutters [15]. However, planar cutters are still the most-commonly used cutters on PDC drilling bits. They are also the most heavily used cutters. Consequently, the planar cutters are employed for experiments. As shown in Fig. 3, two planar cutters are symmetrically welded onto the PDC drilling bit. The maximum diameter of the PDC bit is 35 mm, and the diameter of the planar cutter is 13 mm. The PDC cutter with a rake angle of 20 degrees have the highest penetrating efficiency [16]. Therefore, the PDC cutters are installed at a rake angle of 20 degrees.

2.3 Experimental procedure

The design and composition of the device are considerably complicated. Therefore, it is necessary to follow the prescribed steps to operate this equipment. The experimental procedure is as follows: (1) The PDC drilling bit needs to be installed on the drilling pipe. (2) The rock sample should be fixed in the rock sample clamping device. (3) Start the diesel generator to provide power. (4) Activate three-phase asynchronous motors and hydraulic stations. (5) Start the cooling system to cool the anti-wear hydraulic oil in the oil tank. (6) Adjust the movement parameters of the drilling pipe, including the distance and speed of upward and downward movement, the frequency and amplitude of axial percussion, and the rotary speed by the controlling software. (7) Start and stop the test by the controlling software. One important point to note is that the drilling bit requires constant watering to keep it cool during the test. Table 2 shows the specific experimental program.

Fig. 3 Double-cutter PDC drilling bit and rock sample

Table 2 Experimental scheme

Rotational speed (RPM)	Downward speed (mm/s)	Frequency (Hz)	Amplitude (mm)
40	0.2	15	0.2/0.4/0.6/0.8/1.0/1.2
40	0.2	4/8/12/16/20/24	0.5

3. ANALYSIS OF EXPERIMENTAL RESULTS

3.1 The relationship between axial force and percussive frequency

There is a contact force between the PDC bit and the rock due to the squeezing and shearing between the bit and the rock, and this contact force is the axial force. Axial force data can reflect the process of rock loading and failure [17]. The variation in axial force was analyzed to understand the rock-breaking process. The process of rock breaking can be determined by analyzing changes in axial forces. It is important to select the stable cutting process for analyzing the axial force data.

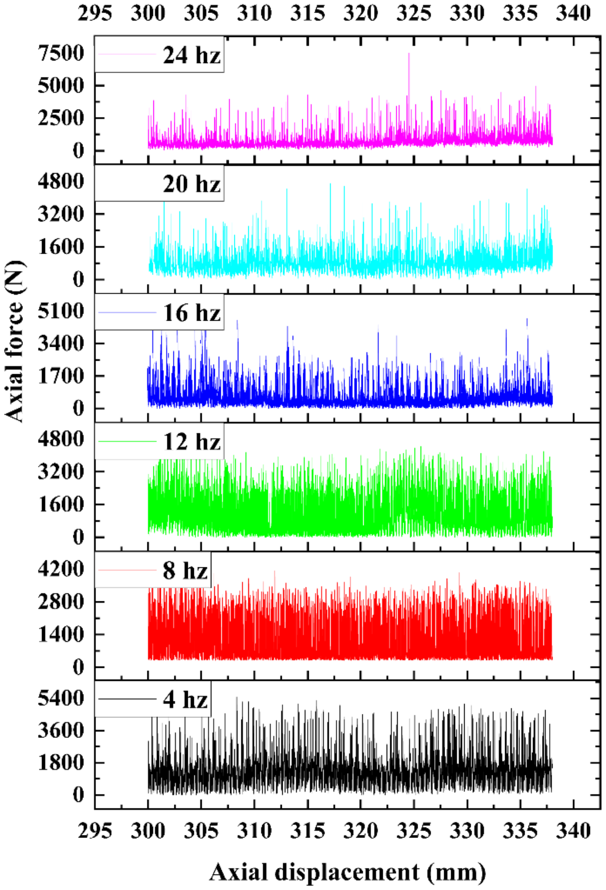


Fig. 4 Variation of axial force with axial displacement at different frequencies

As shown in Fig. 4, axial force curves under different frequencies are observed for the continuous wave state. However, there are obvious differences in the fluctuation characteristics of axial force curves at different frequencies. It is obvious that the waveform of axial force between 4 and 12 Hz is more concentrated. In contrast, the wave curves of axial forces at other frequencies appear sparse. In fact, the frequency of collecting axial force data at different frequencies is consistent. However, the axial force fluctuation changes more frequently with the increase of axial frequency. This results in the visual error of a high frequency of axial force data acquisition at high axial percussive frequencies [18].

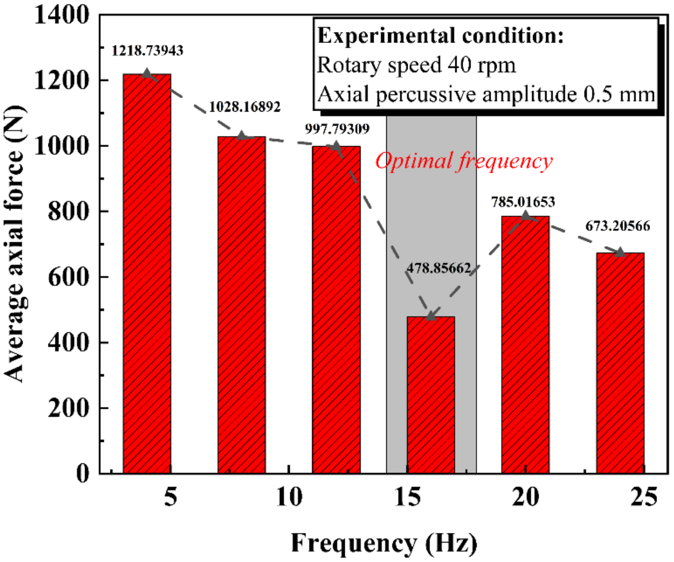


Fig. 5 Average values of axial force at different frequencies

As shown in Fig. 5, as the axial percussive frequency increases, the average axial force demonstrates an overall decreasing trend. The experimental equipment is designed to facilitate drilling by establishing a specific downward speed for the drilling bit. The pressure of the drilling bit is measured using a pressure sensor. This refers to the pressure created by the interaction between the drilling bit and the rock. At the same downward speed, the smaller the interaction force between the drilling bit and the rock, the lower the energy consumption required to break the rock. This indicates that breaking the rock becomes easier. When the frequency is 15 Hz, the average axial force on the drilling bit is the smallest, and we believe that it is easier to break the rock at this frequency.

3.2 The relationship between axial force and percussive amplitude

Figure 6 shows the variation of axial force with axial displacement of the drilling bit at different percussive amplitudes. The curves of axial force versus displacement at different percussive amplitudes show significant differences. When the axial percussive amplitude is between 0.2 mm and 0.4 mm, the axial force curve resembles a comb. The axial force frequently changes rapidly between high and low values. However, as the percussive amplitude increases, the axial force does not fluctuate as frequently between high and low values. It usually exhibits continuous low-value changes with intermittent brief high values. Another interesting phenomenon is that the larger the percussive amplitude, the greater the range of variation in axial force.

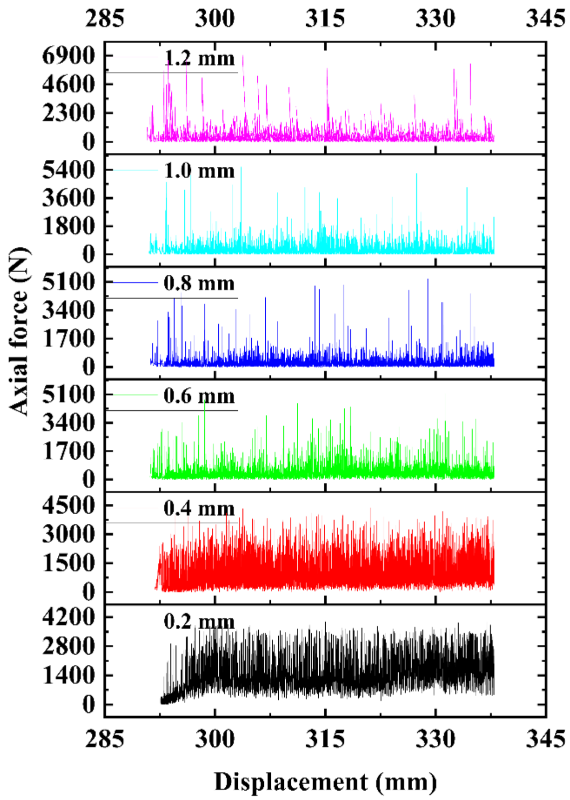


Fig. 6 Variation of axial force with axial displacement at different percussive amplitudes

During the interaction between the PDC bit and the rock, the force between the PDC bit and the rock increases as the interaction between the drilling bit and the rock improves. When the interaction force reaches the peak strength of the rock, the rock breaks and fails rapidly. During the axial percussion process, when the axial percussive amplitude reaches its peak value, the interaction between the drilling bit and the rock is the strongest. Therefore, under the condition of large percussive amplitude, when the percussive amplitude reaches its peak value, the damage caused by the drilling bit to the rock becomes stronger, leading to instant rock failure. The interaction between the drilling bit and the rock is weakened. Therefore, the interaction between the drilling bit and the rock changes from a strong interaction to a weak interaction. This explains the continuous low values of the axial force interspersed with intermittent brief high values under conditions of high percussive amplitude.

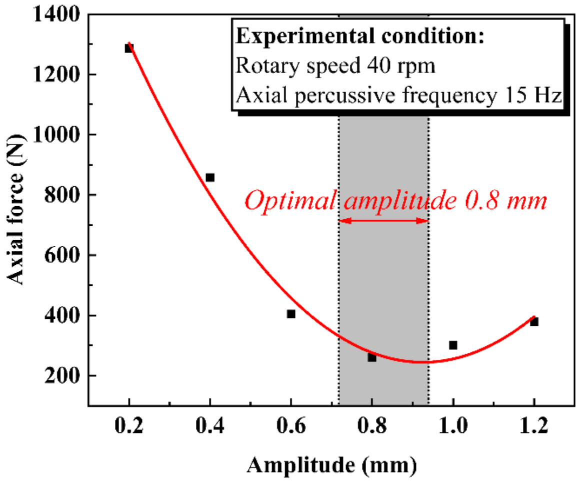


Fig. 7 Variation of average axial force with percussive amplitude

The average value of the axial force for different percussive amplitudes respectively. As shown in Fig. 7, the average value of the axial force shows a tendency of decreasing and then increasing with the increase in percussive amplitude. At the percussive amplitude of 0.8 mm, the average value of axial force is at its lowest point. At different percussive amplitudes, the PDC drilling bit drills to the same depth at a consistent speed. The smaller the axial force, the easier it is to break the rock. Therefore, the amplitude of 0.8 mm is the optimal choice for axial percussive breaking of dolomite. When the maximum value of the amplitude is reached, the axial force also peaks, causing the PDC drilling bit to inflict the most severe damage on the rock. With the failure of the rock under the PDC bit, the interaction between the PDC bit and the rock is disrupted. Until the interaction is re-established, the PDC bit is breaking up the rock that has already failed. Therefore, the axial force is at a low value. With the increase in percussive amplitude, the PDC bit causes rock failure under the PDC bit to a greater extent. Accordingly, the disrupted interaction takes longer to re-establish. Therefore, the period when the axial force is at a low value is correspondingly longer. However, excessive amplitudes are detrimental to rock breaking. At high amplitude, the PDC bit causes multiple strong actions on the rock. The rock under the PDC bit is not thoroughly broken, which can easily lead to repetitive breaking.

4. CONCLUSIONS

In this paper, a series of tests on PDC bit cutting carbonate rock under axial percussion were carried out. The study analyzed the relationship between axial force and percussive frequency, as well as the relationship between axial force and percussive amplitude. The conclusions are as follows:

(1) According to the experimental results of different axial percussive frequencies, when the frequency of axial percussion reaches 16 Hz, the average axial force decreases significantly, and the efficiency of axial percussion rock breaking improves. The optimal axial percussive frequency is 16 Hz.

(2) According to the experimental results of different axial percussive amplitudes, the average axial force initially decreases and then increases with the increase in axial percussive amplitude. When the amplitude of axial percussion reaches 0.8 mm, the average axial force is at its lowest point. The optimum axial percussive amplitude is 0.8 mm. Excessive percussive amplitude is detrimental to rock breaking.

Although the relationship between axial force and percussive frequency, and the relationship between axial force and percussive amplitude have been analyzed. An appropriate range of axial percussive frequencies and amplitudes is recommended for breaking carbonate rock with a PDC bit. The fracturing characteristics of the drilling hole and the distribution characteristics of cuttings should be analyzed in the next step of the study.

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