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Feasibility Study on Resonance Enhanced Drilling Technology

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Abstract

With the increasing of well depth, the hardness of rock increases which will lead to rock is difficult to be broken. Therefore, Resonance Enhanced Drilling as one of new efficient drilling technologies is presented to improve the efficiency of drilling. The paper is focused on the feasibility study on Resonance Enhanced Drilling, showing the results of the numerical analysis and presenting the implementation methods of the technology. Two kinds of numerical simulations are performed, including modal analysis and harmony analysis of rock and indenter. Also, the excitation frequency is optimized under the actual operation conditions to analyze whether Resonance Enhanced Drilling can be achieved.

Our investigations confirm that both rock and drill bit can be resonant, and there are different resonant frequencies and vibration modes in different orders which are only related to their inherent characteristics. In addition, when the rock drilled is resonant and easily broken, the drill bit will not be destroyed. As a result, the Resonance Enhanced Drilling can be achieved and the optimization of excitation frequency is the resonant frequency of rock drilled.

We suggest that although there are some methods and apparatus have been proposed to achieve resonance drilling technology, more researches are still needed to be conducted to further understand the rock breaking mechanism and promote the realization of the Resonance Enhanced Drilling.

Key words: Resonance enhanced drilling; Modal analysis; Harmony analysis; Resonant frequency; Implementation methods

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INTRODUCTION

With the increasing of well depth, the hardness of rock increases which will lead to rock is difficult to be broken. However, the current drilling technology, which is utilizing impact energy only to drill, cannot meet the demand of efficient drilling[1-2]. As a result, many new drilling techniques have been proposed, for example, Resonance Enhanced Drilling, Laser Jet Drilling, Particle Impacting Drilling and Ultrasonic Drilling, to improve the efficiency of drilling.

In the high frequency harmonic impact drilling, if the excitation frequency is the same as the natural frequency of rock, rock will be resonant, which is called Resonance Enhanced Drilling (RED). The main idea of this technology is that the bit, while rotating, applies a dynamic impacting force with an adjustable high frequency to the rock so as to create resonance conditions for the rock drilled. At this time, the vibration displacement of rock is the largest and the rock becomes easier to be broken.

Although Resonance Enhanced Drilling is still in the laboratory research stage, lots of researchers have made efforts in investigating it[3-6]. Researchers of

Aberdeen University conducted a lot of experiment on Resonance Enhanced Drilling and showed that the penetration rate is 10 times as high as that by traditional drilling methods. Wiercigroch, et al.[7] proposed and investigated a new method of vibrational energy transfer from high-frequency low-amplitude to low-frequency high-amplitude mechanical vibrations, for the purpose of percussive drilling. Then after a few years, a new model[8] of the progression phase of a drifting oscillator is proposed in 2012. This is to account more accurately for the penetration of an impactor through elastoplastic solids under a combination of a static and a harmonic excitation. Followed with this research, Pavlovskaia et al.[9-10] undertook the modeling of the vibro-impact drilling system and presented the results of the numerical analysis and comparison between two selected models which was a newly developed model of an existing experimental rig and a simplified low dimensional model respectively. Also, a series of patents[11-13]. On resonance enhanced rotary drilling has been applied in recent years to ensure the feasibility of the technology further.

As reported in literature[14-15], Resonance Hammer Drilling is investigated to drill hard rock by PUC-Rio University and CSIRO Petroleum. In the meanwhile, Resonant Impact Device is also designed for rotary drilling with a roller-cone bit. In addition, the effect of crack propagation on rock breaking in RED is discussed by Yang Wei of China University of Mining and Technology[16].

At present, Northeast Petroleum University is also working on harmonic vibration impacting drilling technology. Rock breaking mechanisms of the technology were studied both theoretically and experimentally. Basing on the principle of least action, the micro vibration equation of rock was proposed for analyzing the influence of impact frequency of drill tools, natural frequency of rock and other factors on rock breaking effect[17]. Then, the modeling[18] of vibration response of rock by harmonic impact was introduced and the results of numerical analysis and indoor experiments were presented. In addition, Li et al.[19] have applied for patents on Resonance Enhanced Drilling to make rock resonance possibly.

This paper aims to find out whether Resonance Enhanced Drilling technology can be implemented. Since the rock drilled can be made to resonate is the most basic prerequisite, modal analysis of rock is conducted to determine the resonant frequency of the rock. Also, the drill bit shouldn't be resonate when the rock is resonate, therefore modal analysis of indenter is done, too. In order to optimize the excitation frequency, harmony analysis is induced to confirm resonant frequencies of rock and indenter under the actual operation conditions. Finally, implementation methods of Resonance Enhanced Drilling technology are proposed.

1. MODAL ANALYSIS

Rock resonance is the prerequisite for Resonance Enhanced Drilling. In order to investigate whether the rock and drill bit can be resonant and what their resonant frequency are, simulations are conducted using modal analysis module of ANSYS to calculate the resonant frequency of them.

1.1 Modal Analysis of Rock

In the simulation, the element type is selected as Solid65. The rock is simulated as a cube with a size of 300mm×300mm×300mm. Three types of rock are chosen in the simulation, namely sandstone, limestone and granite. The basic physical parameters of rocks are presented in Table 1 and the mesh sample for rock is shown in Figure 1.

Table 1
Basic Physical Parameters of Rocks

Lithology	Elastic Modulus E/ Pa	Poisson Ratio μ	Density ρ/ (Kg·/m^{-3})
Sandstone	4×10^{10}	0.34	2560
Limestone	3.7×10^{10}	0.31	2660
Granite	2.6×10^{10}	0.26	2790

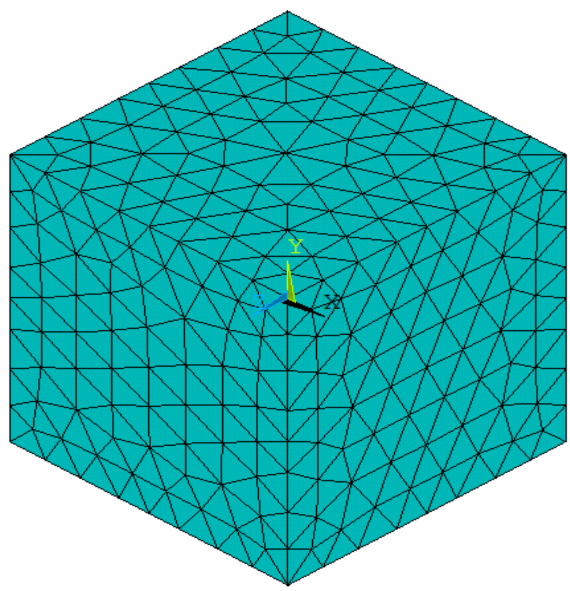

Figure 1
The Mesh Sample for Rock

After solving the model, the resonant frequencies of rock can be obtained, as shown in Figure 2.

The resonant frequency curves of rocks presented in Figure 2 demonstrate that rock can be resonant. It should be noted that since the rock model is with multiple degrees of freedom, there are different resonant frequencies and vibration modes in different orders for a rock. It also can be seen from Figure 2 that different rocks have different

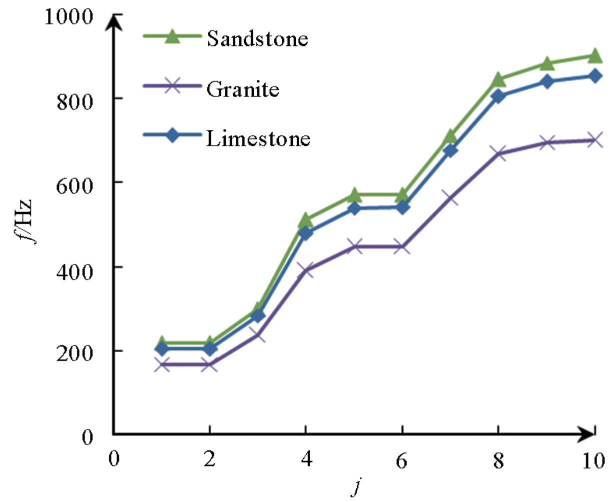

Figure 2
The Resonant Frequencies of Rocks in Different Orders

resonant frequencies, this is mainly depends on the elastic modulus of the rock. Due to the resonant frequency of system is only related to its inherent characteristics, the resonant frequency of rock is related to its physical properties.

1.2 Modal Analysis of Inderter

In order to simplify the computation, drill bit can be regarded as spherical indenter since the resonant frequency has nothing to do with the structure of it. The same method is used to investigate the resonant frequency of indenter. The basic physical parameters of indenter are presented in Table 2 and the mesh sample for indenter is shown in Figure 3.

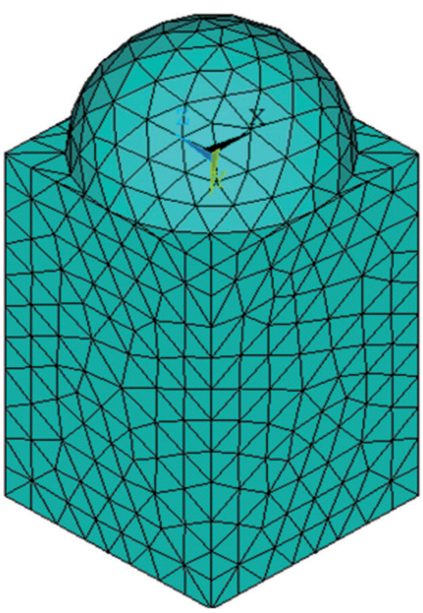

Figure 3
The Mesh Sample for Indenter

Table 2
Basic Physical Parameters of Indenter

Lithology	Elastic modulus *E*/ Pa	Poisson ratio	Density ρ/ (Kg·/m^{-3})
Cemented carbide	2.06×10^{11}	0.3	7850
Diamond	8.59×10^{11}	0.077	3515

The resonant frequency curves of indenter are shown in Figure 4.

As can be seen from Figure 4, the indenter with different materials also has different resonant frequencies. It implies that the indenter can be made resonance, too. Comparing Figure 4 and Figure 2, it can be concluded that the resonant frequency of indenter with cemented carbide is very close to that of rock, however, the resonant frequency of indenter with diamond is significantly higher than that of rock. Thus, it is better to select the diamond drill bit so that the rock drilled can be resonant under the harmonic vibration excitation while the drill bit would not be destroyed.

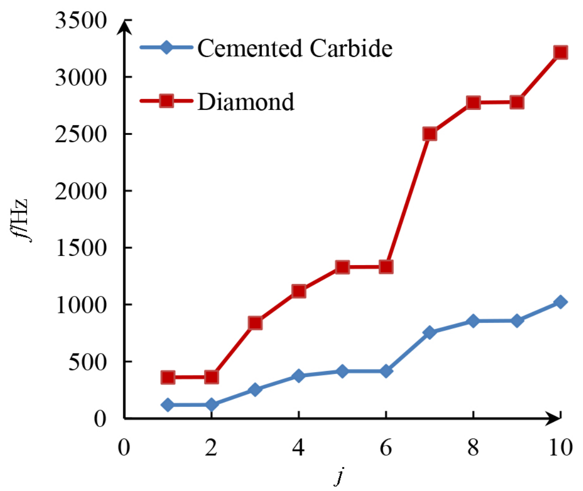

Figure 4
The Resonant Frequencies of Indenter in Different Orders

2. OPTIMIZATION OF EXCITATION FREQUENCY

Based on the comparison between Figure 2 and Figure 4, it should be noted that there is still a possibility that the resonant frequency of rock equals to that of indenter when they are at different stages of vibration mode, respectively. In the actual drilling operation, whether this kind of situation would happen? For clarifying this issue, simulations are conducted according to the following way.

Harmony analysis module of ANSYS is used to estimate the resonant frequencies of rock and indenter under harmonic vibration excitation. The excitation frequency is of 0-1000Hz and 0-2000Hz, respectively. Besides, there are only one degree of freedom in Y direction for rock and only one rotational degree of freedom for indenter.

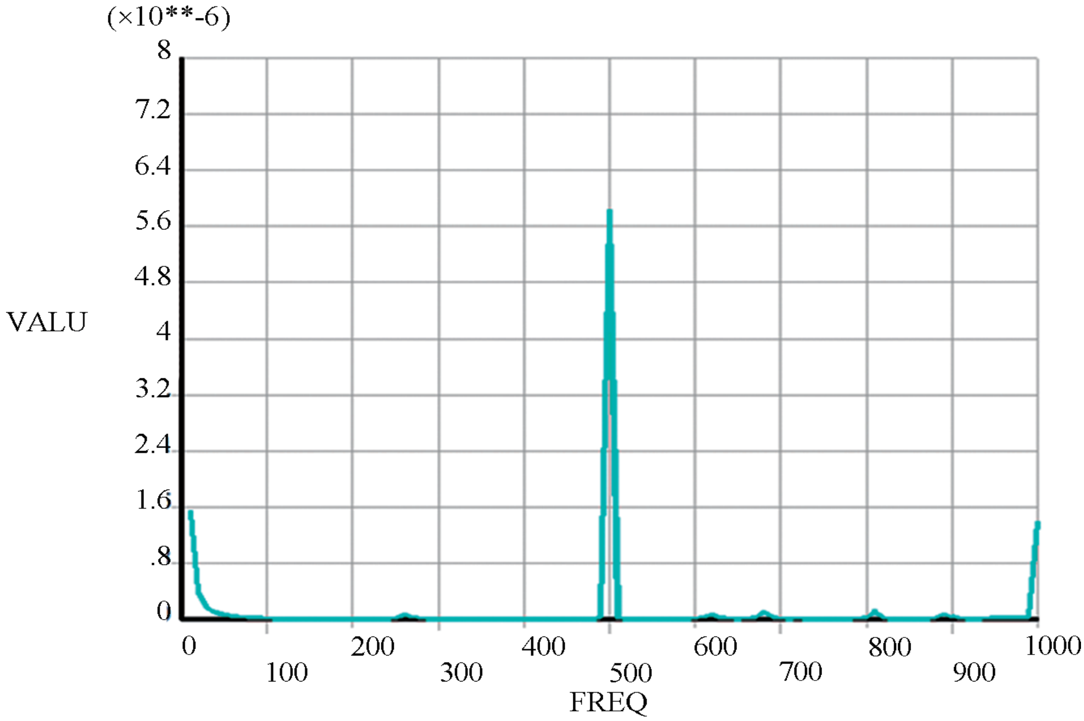

Figure 5
The Resonant Frequency of Sandstone Under the Excitation Frequency of 0-1000Hz

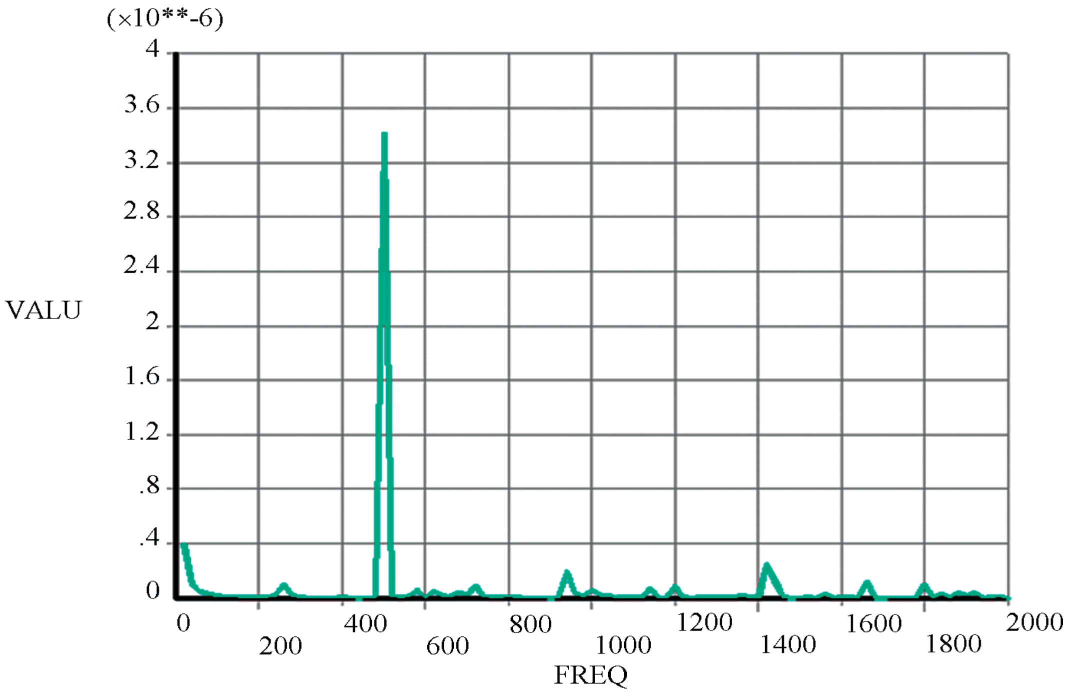

Figure 6
The Resonant Frequency of Sandstone Under the Excitation Frequency of 0-2000Hz

Figure 5 and Figure 6 display the harmonic response curves of sandstone under the excitation frequency of 0-1000Hz and 0-2000Hz, respectively. It is intuitive that the resonant frequency of sandstone is the same in both cases. Here, the sandstone is with only one degree of freedom which is consistent with the actual situation. Based on the theory of vibration, there is only one resonant frequency corresponding to the system

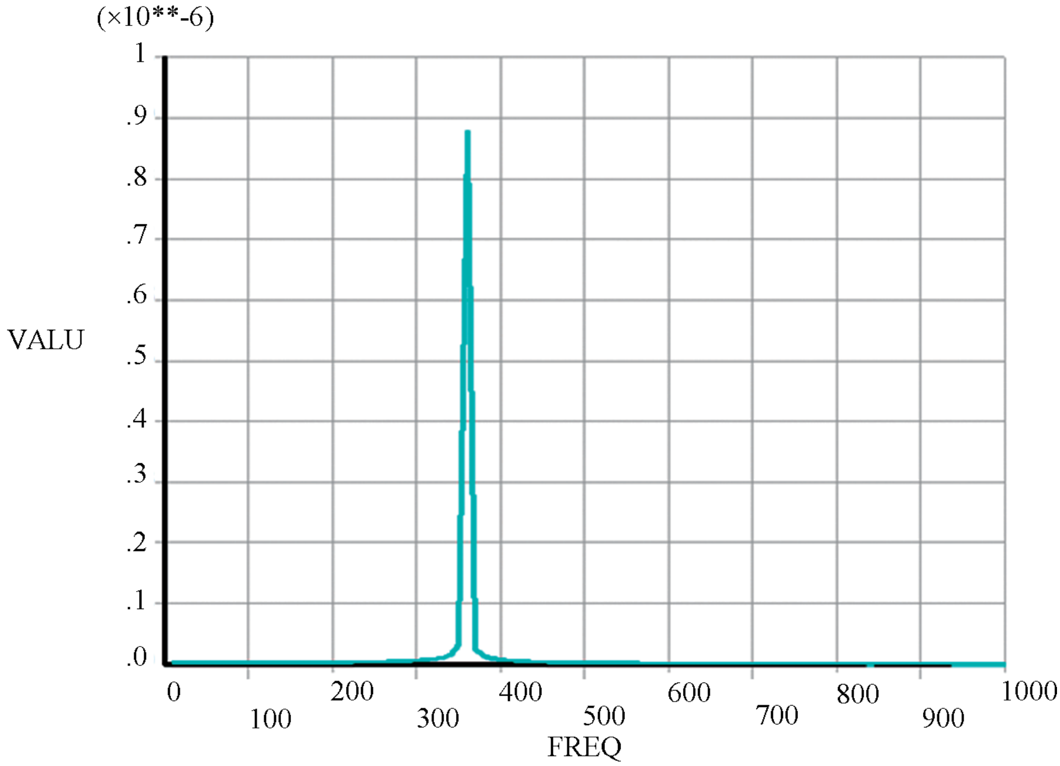

Figure 7
The Resonant Frequency of Diamond Indenter Under the Excitation Frequency of 0-1000Hz

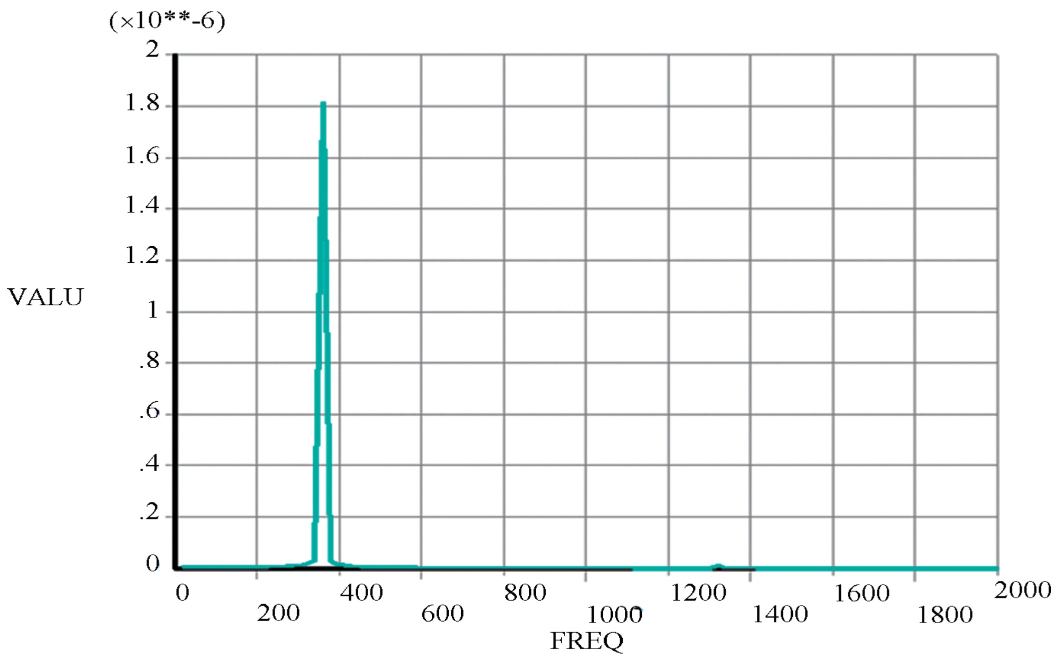

Figure 8
The Resonant Frequency of Diamond Indenter Under the Excitation Frequency of 0-2000Hz

withonly one degree of freedom. Thus, the sandstone will be resonant under any excitation frequency. So does the diamond indenter.

It also can be obtained that the resonant frequency of sandstone is of 500Hz and that of the diamond indenter is of 370Hz under the same excitation frequency, which means that when the rock drilled is resonant and easily broken, the drill bit is stable and secure. As a result, the optimization of excitation frequency is the resonant frequency of rock drilled.

3. IMPLEMENTATION OF RESONANCE ENHANCED DRILLING

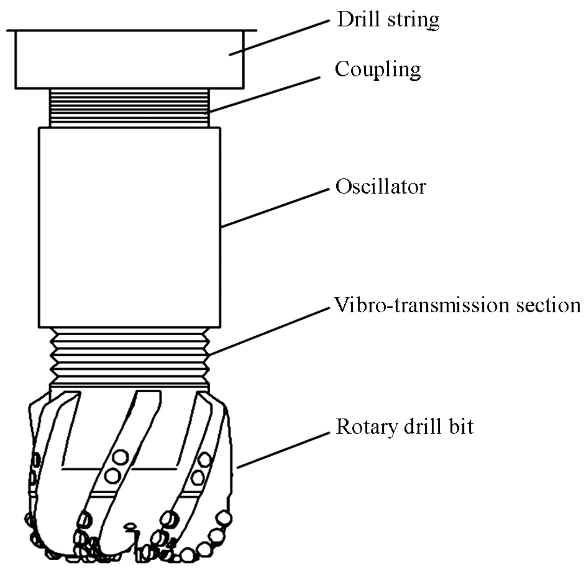

Figure 9
An Illustrative Example of a Resonance Enhanced Rotary Drilling Module

In order to further promote the application of Resonance Enhanced Drilling technology, several methods have been put forward since the drilling technology is proposed. Wiercigroch[11-12] disclosed a method for controlling a resonance enhanced rotary drill comprising a rotary drill bit and an oscillator for applying axial oscillatory loading to the rotary drill bit, as shown in Figure 9. Two main control parameters are considered, including the controlling frequency and the dynamic force of the oscillator which are controlled by monitoring signals representing the compressive strength of the material being drilled. Here, a closed loop real-time feedback mechanism is used to adjust the controlling frequency and the dynamic force according to changes in the compressive strength. It comprises a power source, a controller, an oscillator, sensors and a processor, and the schematic diagram is presented in Figure 10.

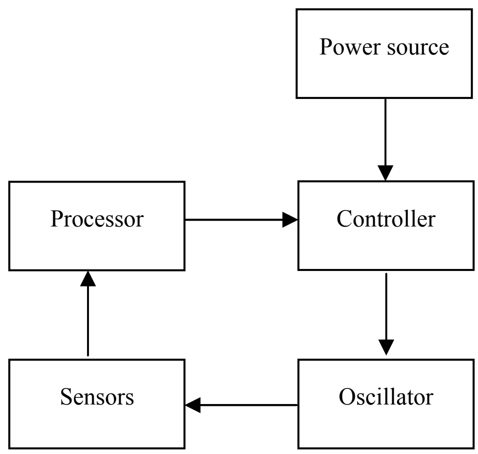

Figure 10
The Schematic Diagram Illustrating a Downhole Closed Loop Real-Time Feedback Mechanism

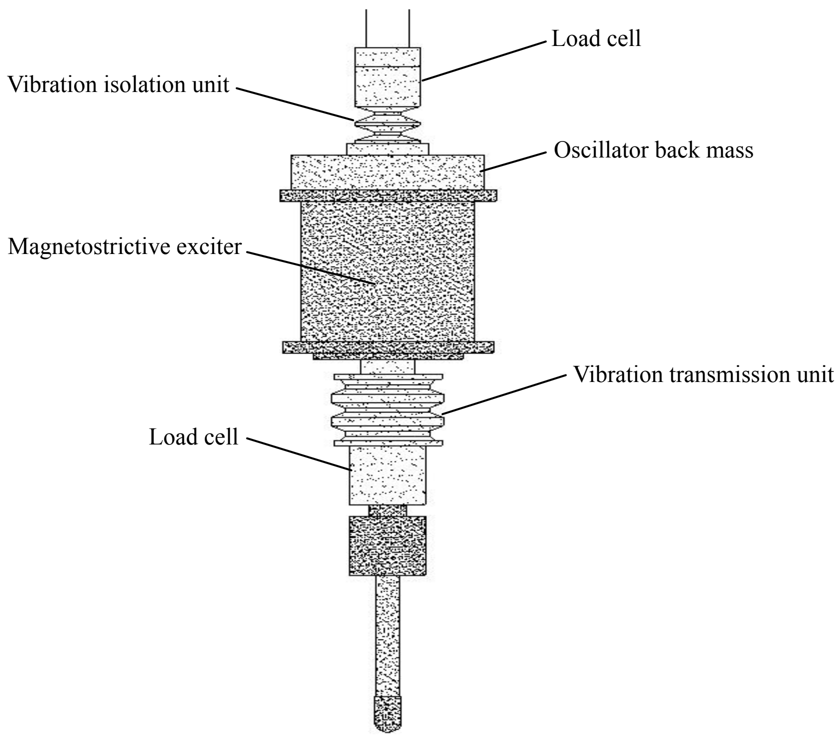

Figure 11
A Schematic of the Resonance Enhanced Drilling Module

In addition, an apparatus[13] is also designed for use in resonance enhanced rotary drilling. Its main components are as follows, an upper load-cell for measuring static and dynamic axial loading, a vibration isolation unit, optionally an oscillator back mass, an oscillator for applying axial oscillatory loading to the rotary drill bit, a vibration transmission unit, a lower load-cell for measuring static and dynamic axial loading, a drill bit connector and a drill bit, having reference to Figure 11. Similarly, it is controlled by the downhole closed loop real-time feedback mechanism.

U.S. Patent 11/693338 proposed a method and a series of apparatus for drilling at a resonant frequency[20]. Figure 12 shows an embodiment of apparatus. The method for drilling a bore hole includes the steps of deploying a drill bit attached to a drill string in a well bore, the drill bit having an axial jack element with a distal end protruding beyond a working face of the drill bit, engaging the distal end of the jack element against the formation such that the formation applies a reaction force on the jack element while the drill string rotates and applying a force on the jack element that opposes the reaction force such that the jack element vibrates and causes the formation to vibrate at its resonant frequency which causes the formation to degrade.

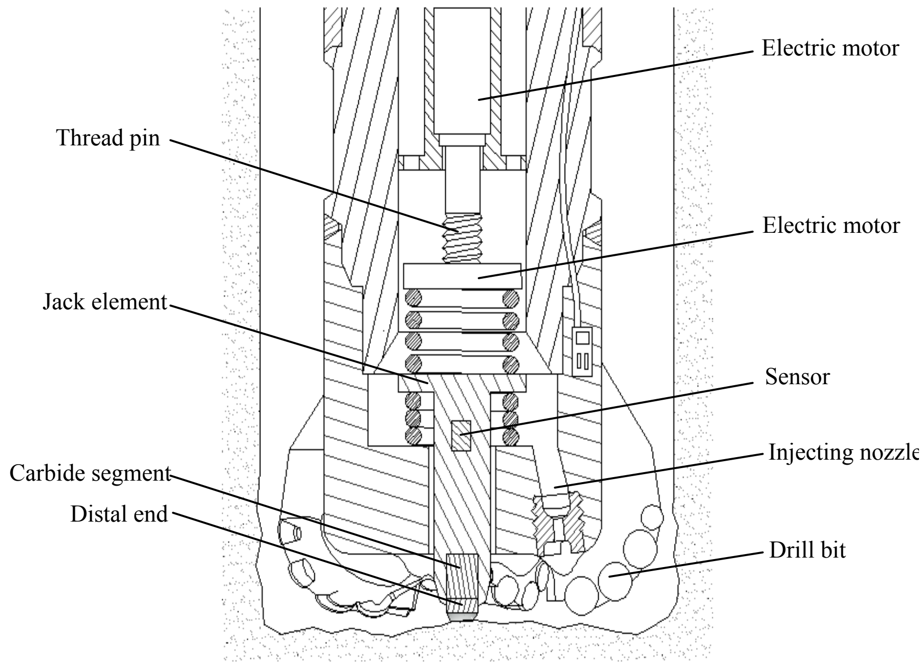

Figure 12
The Cross-Sectional Diagram of an Embodiment of a Drill Bit for Resonance Enhanced Drilling

In 2011, Northeast Petroleum University developed a high frequency pulse jet unit for resonance drilling[19] comprising small hydro-generator, density logger, sonic logging tool, controller and ultrasonic transducer. The structure diagram of the high frequency pulse jet unit is shown in Figure 13. The principle of the unit is that small

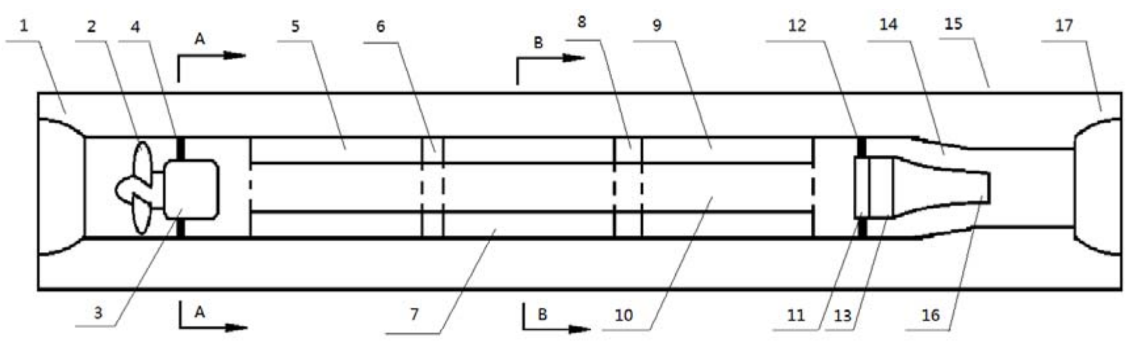

Figure 13
The Structure Diagram of the High Frequency Pulse Jet Unit
1. upper transition joint; 2. leaf blade; 3. electric generator; 4. fixed column; 5. density logger; 6. upper cushion block; 7. sonic logging tool; 8. lower cushion block; 9. controller; 10. drilling fluid channel; 11. fixed end of transducer; 12. fixed column of transducer; 13. ultrasonic transducer; 14. contraction channel of drilling fluid; 15. variable amplitude rod; 16. outer steel sleeve; 17. lower transition joint

hydro-generator produces electricity to density logger and sonic logging tool, and controller analyzes the data from density logger and sonic logging tool to determine the resonant frequency of the rock drilled. Then, the high frequency excitation signal which is assigned to the ultrasonic transducer from the controller is converted into an ultrasonic signal for applying to drilling fluid. After drilling fluid passing through the drill bit, high frequency pulse jet is formed to impact the rock drilled, which makes the rock resonant.

CONCLUSION

The paper is focused on the feasibility study on Resonance Enhanced Drilling, showing the results of the numerical analysis and presenting the implementation methods of the technology. Two kinds of numerical simulations are performed, including modal analysis and harmony analysis of rock and indenter. Also, the excitation frequency is optimized under the actual operation conditions to analyze whether Resonance Drilling Technology can be achieved.

According to the modal analysis, it can be concluded that both rock and drill bit can be resonant, and there are different resonant frequencies and vibration modes in different orders which are only related to their inherent characteristics. Based on the harmony analysis, it is intuitive that when the rock drilled is resonant and easily broken, the drill bit is stable and secure. As a result, the optimization of excitation frequency is the resonant frequency of rock drilled.

In order to implement the Resonance Enhanced Drilling, some methods and apparatus are proposed. The resonance excitation can be applied to the rock through the mechanical vibration and hydraulic shock, and can be controlled by the downhole closed loop real-time feedback mechanism.

However, due to the complexity of Resonance Enhanced Drilling, although some achievements have been obtained in the past several years and it can be realized in theory, there are still difficult challenges for applying the technology to field operation. For example, many other factors, like pressure and temperature of formation, should be included, the changes of rock which makes it difficult to determine the resonant frequency to drill and the security of the application of the technology are also needed to be considered. As a result, more researches will be conducted to further understand the rock breaking mechanism and promote the realization of the Resonance Enhanced Drilling.

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