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Vibration Characteristics of Rock Under Harmonic Impact

JI Guodong[a]; WANG Haige[a]; HU Zhijian[a]; LI Siqi[b],*; YAN Tie[b]; LI Bing[b]

[a]CNPC Engineering and Technology Research Institute, Beijing, China.
[b]Petroleum Engineering College, Northeast Petroleum University, Daqing, China.
*Corresponding author.

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Abstract

Modal analysis of rock is done in this study, and the results of numerical analysis are presented. Meanwhile, the amplitude-frequency characteristic curve of rock in steady state response is investigated based on the principle of vibration. In addition, indoor experiments are carried out to further analyze the vibration characteristics of rock under harmonic impact. Three main control parameters are considered, including drilling way, excitation frequency and impacting amplitude.

Our investigations confirm that the rock has different resonant frequencies and vibration modes in different orders for free vibration system, and there is only one resonant frequency for a rock with one degree of freedom. Based on theoretical analysis and indoor experiments, it can be concluded that the vibration amplitude under resonant frequency of rock is significantly higher than that under non-resonant frequency and in conventional drilling. Also, the vibration response of rock is in the harmonic form by the harmonic impact, and increases with the increase of the impacting amplitude.

The vibration characteristics of rock by harmonic impact are validated by numerical analysis and experimental results. Harmonic vibration impact drilling can greatly enhance the vibration amplitude of rock, and further improve the rate of penetration.

Key words: Harmonic impact; Modal analysis; Amplitude-frequency characteristic; Resonant frequency; Indoor experiment

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INTRODUCTION

Since the idea of utilizing impact energy to drill was put forward, it has been tried in practice for a long time.[1-2] However, the current technologies of impact energy drilling still cannot meet the demand for drilling at ever-increasing well depth.[3-4] As a result, many new drilling techniques have been proposed and harmonic vibration impact drilling is one of them. So far, this technology is still at the laboratory stage which has great potential to improve the rock breaking efficiency.

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.

At present, some researchers have made efforts in investigating harmonic vibration impact drilling technology.[5-7] Researchers of Aberdeen University conducted a lot of experiments on Resonance Enhanced Drilling and showed that the penetration rate is 10 times as high as that of traditional drilling methods. Wiercigroch et al.[8] 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[9] of the progression phase of a drifting oscillator was proposed in 2012. Pavlovskaia et al.[10-11] 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. 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.[12] Then, the modeling[15] 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.[13] have applied for patents on Resonance Enhanced Drilling to make rock resonance possibly.

In fact, realization of the technology is closely related to the dynamic characteristics of rock structure, such as natural frequency, resonant frequency and vibration response. Therefore, this paper is focused on the vibration characteristics of rock under harmonic impact. The rest of the paper is organized as follows. In Section 1, theoretical analysis and numerical simulations are conducted to estimate the resonant frequency of rock. The next section describes the steady-state response of rock under harmonic impact based on the theory of vibration. In addition, indoor experiments are carried out to further analyze the vibration characteristics of rock, and the influence of the parameters on the vibration response are discussed in Section 3.

1. MODAL ANALYSIS OF ROCK

1.1 Theoretical Analysis

Modal analysis is a process which the vibration response of structure is described by its dynamics properties, such as frequency, damping and mode of vibration.[14]

The basic equation of undamped modal analysis of the rock structure is a classical solution of eigenvalue. The differential equation of vibration is given as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F(t)}\,. \tag{1}$$

Where, **M** is mass matrix of rock, kg; **K** is stiffness matrix of rock, N/m; **x** is displacement array of rock, m; is acceleration array of rock, m/s^2, and **F(t)** is excitation force array on the rock, *N*.

Equation (1) is a vector equation. For the free vibration system, **F(t)=0**, it can be rewritten as,

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{K}\mathbf{x} = 0\,. \tag{2}$$

Then, the particular solution is obtained,

$$\mathbf{x} = \mathbf{\Phi} e^{i\omega t}. \tag{3}$$

Where, $\mathbf{\Phi}$ is free response amplitude array of rock, m.

$$(\mathbf{K} - \omega^2\mathbf{M})\mathbf{\Phi} = 0. \tag{4}$$

The necessary and sufficient condition of the equation with non-zero solution is that its coefficient matrix determinant is equal to zero.

$$|\mathbf{K} - \omega^2\mathbf{M}| = 0. \tag{5}$$

Equation (5) is the characteristic equation, and it is *n* times algebraic equation of. There are different positive roots of the equation, and make them in an ascending sort order as follows:

$$0 < \omega_1 < \omega_2 < \cdots < \omega_n\,. \tag{6}$$

Take into Equation (4), the corresponding natural mode of rock vibration will be got,

$$\mathbf{\Phi}_i = [\phi_{1i}, \phi_{2i}, \cdots, \phi_{ni}]^T. \tag{7}$$

Each modal of rock in different orders under excitation frequency can be obtained through the modal analysis and the actual vibration response can be determined considering the effect of external or internal vibration sources.

1.2 Numerical Simulations

Modal analysis of ANSYS is used to estimate the resonant frequencies of rock. In this study, simulations are conducted for three different rocks, namely sandstone, limestone and granite. The basic physical parameters of rocks are presented in Table 1. For all of cases, the rock is simulated as a cube with the size of 300mm×300mm×300mm and its element type is selected as Solid65. Figure 1 shows the mesh sample for rock.

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	2,560
Limestone	3.7×10^{10}	0.31	2,660
Granite	2.6×10^{10}	0.26	2,790

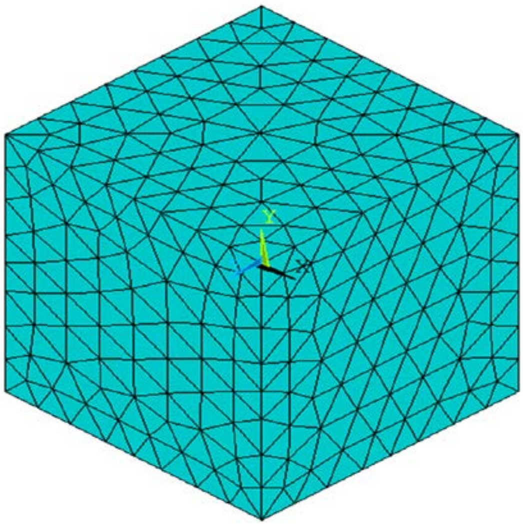

Figure 1
The Mesh Sample for Rock

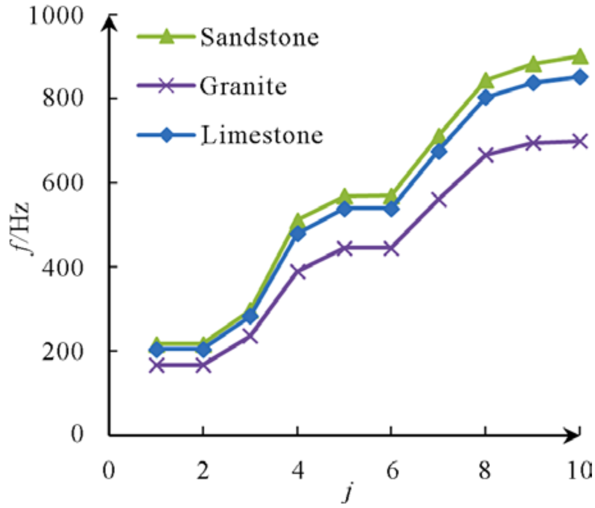

Figure 2
The Resonant Frequencies of Rocks in Different Orders

After solving the model, the resonant frequencies of rock can be obtained. 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, and 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 resonant frequencies. 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.

Besides, Harmony analysis of ANSYS is performed to determine the resonant frequencies of rock under harmonic vibration excitation. The excitation frequency is of 0~1,000Hz and 0~2,000Hz, respectively. Moreover, there is only one degree of freedom in *Y* direction for rock.

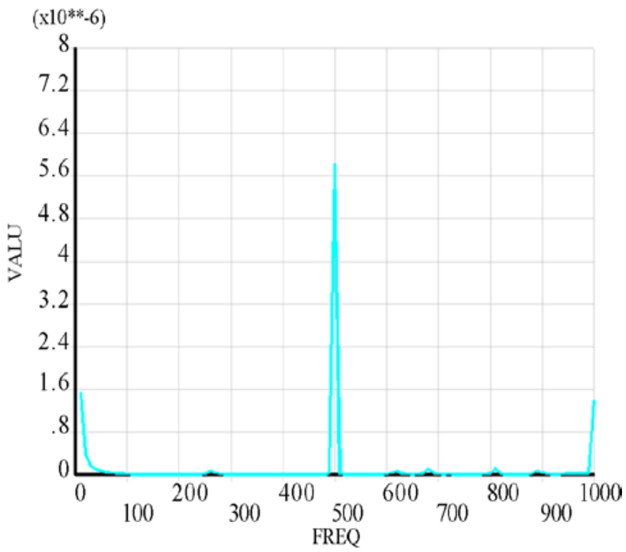

Figure 3
The Resonant Frequency of Sandstone Under the Excitation Frequency of 0~1,000Hz

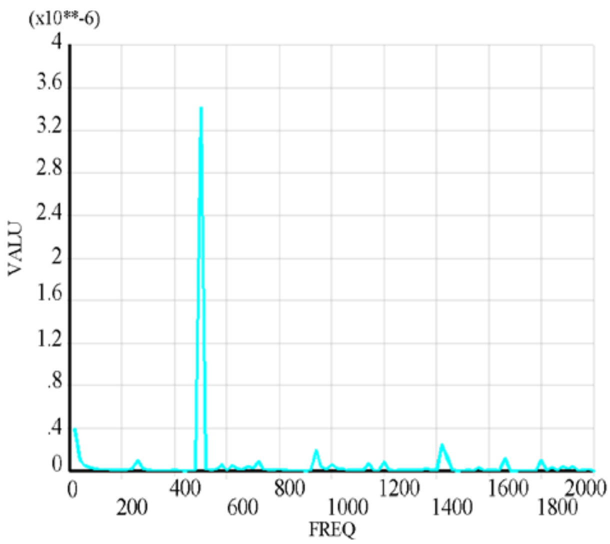

Figure 4
The Resonant Frequency of Sandstone Under the Excitation Frequency of 0~2,000Hz

Figure 3 and Figure 4 display the harmonic response curves of sandstone under the excitation frequency of 0~1,000Hz and 0~2,000Hz, respectively. It is intuitive that the resonant frequencies of sandstone are the same in both cases. Here, the sandstone is with only one degree of freedom which is consistent with the actual operation condition. Based on the theory of vibration, there is only one resonant frequency corresponding to the system with only one degree of freedom. Thus, the sandstone will be resonant under any excitation frequency above.

2. THE VIBRATION RESPONSE OF ROCK UNDER HARMONIC IMPACT

Assume that the rock of bottom hole is a linear system with a single degree of freedom, its equation of motion for forced vibration under harmonic vibration impact is given as

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F\cos\omega t = kA\cos\omega t\ . \quad (8)$$

Where, m is mass of rock, kg; k is stiffness, N/m; x is vibration displacement, m; is vibration velocity, m/s; is vibration acceleration, m/s^2; ω is excitation frequency, rad/s; A is static displacement, m.

In this case, the response of rock is also harmonic vibration, and its displacement amplitude can be obtained,

$$X = \frac{A}{\sqrt{[1-(\omega/\omega_n)^2]^2 + (2\xi\omega/\omega_n)^2}}\ . \quad (9)$$

Where, ω_n is natural frequency of rock, rad/s.

Equation (9) can be rewritten as,

$$X = |H(\omega)|A. \quad (10)$$

Where, $|H(\omega)|$ is defined as the amplitude-frequency characteristic which is the amplification factor of displacement amplitude of rock response, and is given by

$$|H(\omega)| = \frac{1}{\sqrt{[1-(\omega/\omega_n)^2]^2 + (2\xi\omega/\omega_n)^2}}\ . \quad (11)$$

Here, the amplitude-frequency characteristic curve of rock is presented based on Equation (11), as shown in Figure 5

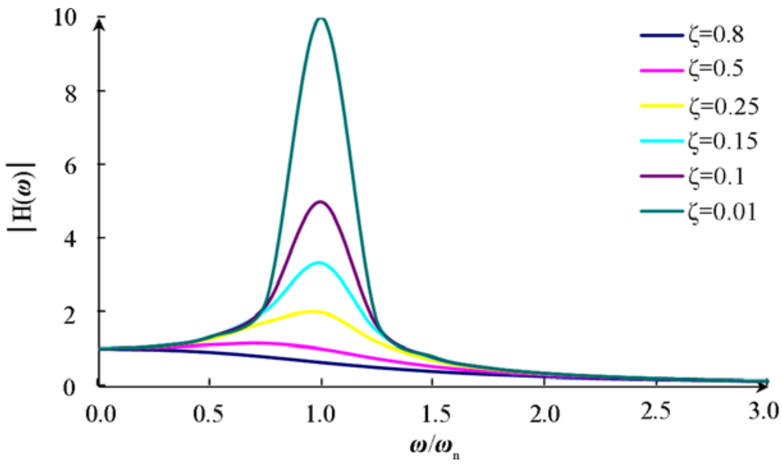

Figure 5
The Amplitude-Frequency Characteristic Curve of Rock by Harmonic Vibration Impact: ω/ω_n Is the Ratio of Excitation Frequency and Natural Frequency and ξ Is the Damping Coefficient of Rock

The amplitude-frequency characteristic curve shows the following three points of view:

(a) If $\omega \to 0, |H(\omega)| = 1$

When the excitation frequency is very low, namely $\omega \ll \omega_n$, β is close to 1. It implies that the vibration amplitude is close to the static displacement when the rock is impacted by a low frequency. In this case, the forced vibration process of bottom hole rock can be approximately described as static deformation process. Therefore, the frequency range $\omega/\omega_n \ll 1$ is also called "quasi- static region".

(b) If $\omega \to \infty, |H(\omega)| \to 0$

When the excitation frequency is very high, namely $\omega/\omega_n \gg 1$, β is less than 1. It means that when the rock is impacted by a high frequency, the bottom hole rock is too late to respond due to its inertia. As a result, the amplitude of rock is very small, and this range is called "inertial region".

(c) If $\omega \approx \omega_n$, $|H(\omega)|$ has a peak value

If the excitation frequency is close to the natural frequency, namely $\omega/\omega_n \approx 1$, β has a peak value. It indicates that the dynamic effect is great at this time and the vibration amplitude is many times as high as the static displacement.

3. INDOOR EXPERIMENT

As it has been shown in numerical simulations from Section 2.2, the resonant frequency of sandstone is 500Hz. Therefore Sandstone is drilled in the ways of conventional drilling and harmonic impact with 500Hz respectively, and the results are shown in Figure 6.

As can be seen in Figure 6, the maximum vibration displacement of sandstone by conventional drilling is 0.13 mm, in comparison to 1.84 mm by the impact of harmonic vibration. It is obvious that the harmonic impact drilling has greatly enhanced the vibration amplitude of rock compared to the conventional drilling. Due to the enhanced vibration intensity of rock, the rate of penetration is improved.

To study the effect of excitation frequency on vibration displacement, sandstone is drilled in the condition of the harmonic vibration with different excitation frequencies.

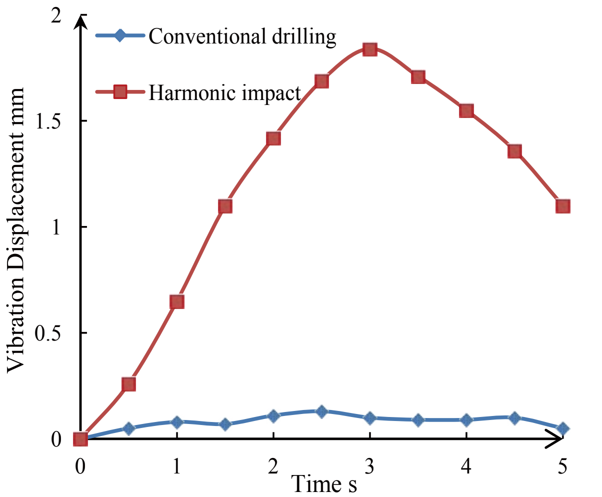

Figure 6
Drilling Curves of Sandstone With Or Without Harmonic Impact

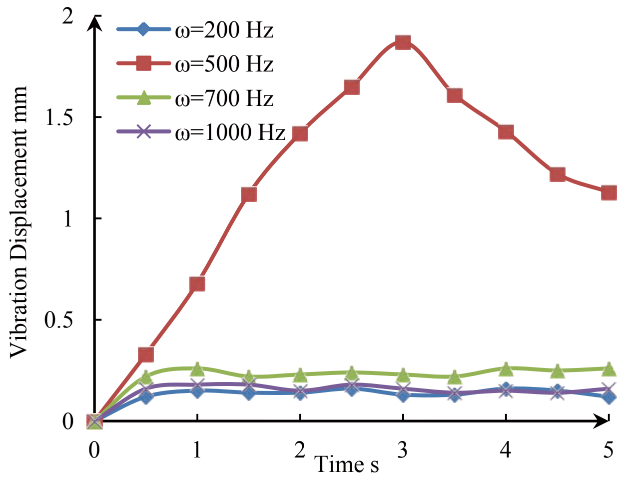

Figure 7
Drilling Curves of Sandstone at Different Excitation Frequencies

As shown in Figure 7, when the excitation frequencies are 200Hz, 700Hz and 1,000Hz, the vibration displacement of sandstone is about 0.12-0.26mm. When the excitation frequency is 500 Hz, the vibration displacement can reach 1.87 mm. This indicates that resonance will occur at the resonance frequency of rock, and the vibration displacement will increase significantly. Moreover, the vibration displacement of rock under the non-resonant frequency is also obviously higher than that of conventional drilling.

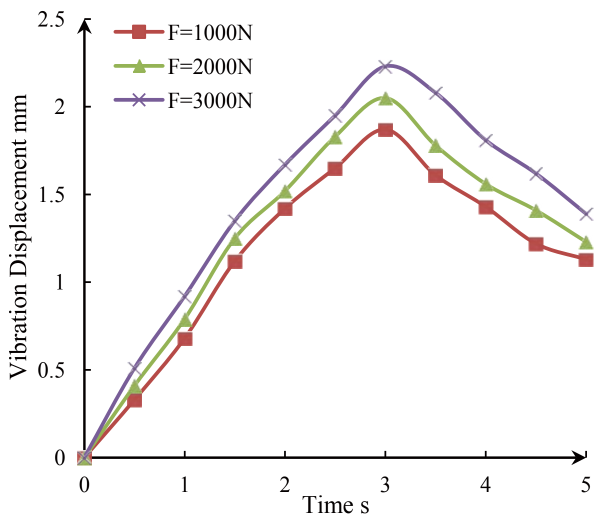

Figure 8
Drilling Curves of Sandstone in Different Impacting Amplitudes

Impacting amplitude is another major parameter that affects the progression. Sandstone is drilled at an excitation frequency of 500Hz and the results are shown in Figure 8. It can be seen that the vibration response of sandstone is in the harmonic form by the harmonic impact. Besides, the vibration response increases with the increase of the impacting amplitude.

CONCLUSION

This paper presents the modal analysis theory of rock showing the results of the numerical analysis. Two types of simulations are involved in this work, namely modal analysis and harmonic response analysis. The aim of the study is to determine whether the rock can be resonant and what the resonant frequency is. The results obtained show that the rock has different resonant frequencies and vibration modes in different orders for free vibration system. However, there is only one resonant frequency for a rock with one degree of freedom.

Vibration response of rock under harmonic impact is performed and it is found that vibration amplitude of rock is very small when the excitation frequency is too low or too high. If the excitation frequency is close to the natural frequency, however, vibration amplitude will have a peak value.

Indoor experiments are conducted considering drilling way, excitation frequency and impacting amplitude. Our investigations confirm that the vibration response of rock is in the harmonic form by the harmonic impact, and increases with the increase of the impacting amplitude. In addition, the vibration amplitude under resonant frequency of rock is significantly higher than that under non-resonant frequency and in conventional drilling.

Based on the analysis undertaken, it can be concluded that the vibration characteristics of rock under the harmonic impact are verified by the numerical analysis and the experimental results. The harmonic vibration impact drilling improves the vibration amplitude of rock greatly, and further improves the rate of penetration compared with the conventional drilling.

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