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Modeling of vibration response of rock by harmonic impact

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ABSTRACT

Modeling of vibration response of rock by harmonic impact is done in this study, and the results of numerical analysis and indoor experiments are presented. Also, the amplitude-frequency characteristic curve of rock in steady state response is investigated based on the principle of vibration. Three main control parameters are considered, including the density of rock, the excitation frequency and the impacting amplitude of the indenter.

It is confirmed that when the excitation frequency is the same as the natural frequency of rock, the maximum vibration displacement of rock can be obtained. The vibration response of rock increases with the increase of excitation frequency and impacting amplitude, and decreases with the increase of the density of rock.

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

1. Introduction

Since the idea of utilizing impact energy to drill was put forward, it has been tried in practice for a long time (Wang et al., 2005; Jiang et al., 2006). However, the current technologies of impact energy drilling still cannot meet the demand of drilling at ever-increasing well depth. It is necessary to develop a more efficient technology for rock breaking to enhance penetration rate (Chang et al., 2011; Zeng and Liu, 2005; Wang et al., 2006). Therefore, the high frequency harmonic impact drilling technology is proposed.

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.

A series of studies on drilling mechanism, rock breaking effect and frequency characteristics of high frequency harmonic impact drilling technology have been done by a number of researchers (Liu et al., 2013; Zou et al., 2012; Li et al., 2013). 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. Yang et al. (2007) investigated the effect of crack propagation on rock breaking in RED. Batako et al. (2004) analyzed the penetration of a drilling tool into a hard medium under periodic impact action and presented a simulation model. It was further development of previously investigated model of a self-excited percussive-rotary drilling system. Ekaterina et al. (2013) 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. Marian et al. (2008) 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. Romulo et al. (2007) proposed the design and development of the first prototype that would operate in resonance, and would be capable of generating considerable dynamic forces. Based on the excitation of a particular higher vibration mode of a turning tool, Ostasevicius et al. (2010) proposed an approach for surface quality improvement by taking into account that quality of

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machined surface is related to the intensity of tool–tip vibrations.

This paper is focused on the modeling of vibration response of rock by the harmonic impact, presents the results of the numerical analysis and the indoor experiments. The aim is to investigate the influence of the parameters, such as the density of rock, the excitation frequency and the impacting amplitude of the indenter, on the vibration response. The micro vibration model of rock by the harmonic impact is introduced in Section 2 and the corresponding steady-state response of rock is presented in Section 3. In addition, the influence of the parameters on the vibration response is discussed in Section 4 and Section 5.

2. The micro vibration model by harmonic impact

2.1. Physical model

Assume that rock is isotropic and homogeneous, the influence of pressure and temperature on the rock is neglected, and the bit is simplified as a flat indenter. A micro vibration model of rock is proposed, where the flat indenter is simulated as a series of springs, as shown in Fig. 1.

Divide the area under the indenter infinitely and select one of the infinitesimal elements to analyze, as shown in Fig. 2. The interaction between the spring and the rock element is simulated as follows: the rock element has a mass of m and a natural frequency of ω, and the spring applies an excitation force F with an excitation frequency ω_1 on the rock element. Assume that the stress under the flat indenter is evenly distributed, and there is no coupling effect among the springs. Therefore, the interaction between the flat indenter and the rock can be simulated by the interaction between a spring and an infinitesimal element of rock. Equation (6) shows the motion equation of the infinitesimal element of rock in the condition of the harmonic vibration.

2.2. Mathematical model

The applied energy from external force field can be regarded as a potential energy $U'(x, t)$. Make it be expressed by power series expansion at $x = 0$ and omit the infinitesimals of 2 orders. The resulting equation is given as

$$U'(x,t) = U'(o,t) + x\frac{\partial U}{\partial x}\bigg|_{x=0} \tag{1}$$

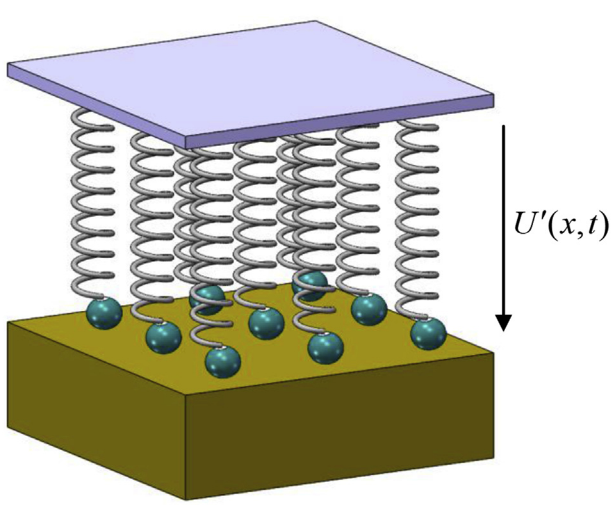

Fig. 1. The model of rock vibration.

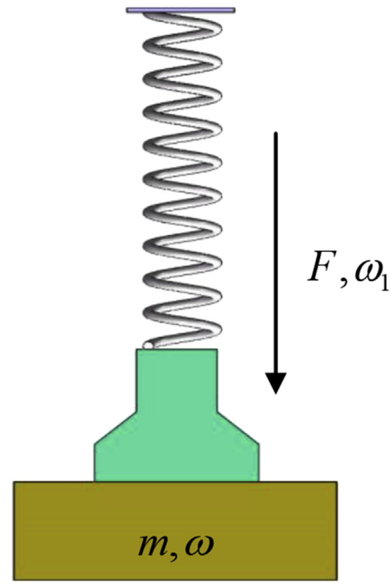

Fig. 2. The interaction between a spring and an infinitesimal element of rock.

The first item is the total derivative of time, and it will disappear at the variation of time. Lagrange's equation can be obtained, based on the definition of potential energy.

$$L = \frac{m\dot{x}^2}{2} - \frac{kx^2}{2} + xF(t) \tag{2}$$

The corresponding differential equation after variation is given as follows,

$$m\ddot{x} + kx = F(t) \tag{3}$$

The force applied by the spring is harmonic, and it can be defined as follows:

$$F = b\cos(\omega_1 t + \beta) \tag{4}$$

Substitute equation (4) into equation (3), and its general solution is obtained,

$$x = a\cos(\omega t + \alpha) + \frac{b}{m(\omega^2 - \omega_1^2)}\cos(\omega_1 t + \beta) \tag{5}$$

Equation (5) is the micro vibration equation of rock by harmonic impact. Because the vibration state of the whole rock is the same under the flat indenter, the whole region can be described as the vibration state of infinitesimal.

When the excitation frequency ω_1 of the spring is equal to the natural frequency ω of the rock element, the system is in the state of resonance. In this case, the vibration is enhanced and is no longer weak. Thus, equation (5) is no longer applicable for solving the vibration displacement of the rock. In the resonant state, equation (5) will be evolved into,

$$x = a\cos(\omega t + \alpha) + \frac{b}{m(\omega^2 - \omega_1^2)}[\cos(\omega_1 t + \beta) - \cos(\omega t + \beta)] \tag{6}$$

When $\omega_1 \to \omega$, based on L′ Hospital rule, equation (6) can be rewritten as,

$$x = a\cos(\omega t + \alpha) + \frac{b}{2m\omega}t\sin(\omega t + \beta) \tag{7}$$