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The transient impact of the resonant flexible drill string of a sonic drill on rock

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ABSTRACT

Sonic drilling is a fast and efficient method for the undisturbed sampling of soft soils and is widely used in overburden layer drilling such as in soft soil and gravel. This technique can also be used to quickly drill through bedrock using vibration shock technology with rotary drilling, a process that differs from the general vibratory immersed-pipe/pile method. To date, little has been published at home or abroad regarding how to determine the impact of sonic drill bits on rock to rationally design button bits for highly efficient rock penetration. This paper establishes a mathematical model of a sonic drill with a flexible drill string on rock, succeeds in determining a transient solution for flexible drill string vibrations under complex boundary conditions, and systematically studies the influential impulse factors of the sonic resonant flexible drill string on rock by a button bit. As the bedrock stiffness and order of the resonance increase, the magnitude of the impact peak increases, and the impact duration becomes shorter. As the drilling hole is extended, the drill string becomes longer, and the largest impulse obviously decreases. In addition, the damping increase is approximately proportional to the attenuation inhibition effect on the impact force. Through systematic research on the modeling and determination of the impact of the sonic drilling process, the design theory of sonic drilling can continue to be improved.

1. Introduction

The essence of sonic drilling is high-frequency vibration drilling, which can be performed using an efficient percussive-rotary pressure drilling method by combining the impact of a sonic resonant drill string with low-speed rotation and static pressure. In addition to environmental drilling, this technique currently has a wide range of applications in geo-construction drilling, geothermal drilling, mineral exploration, sand and gravel exploration, and water well drilling [1]. Sonic drilling is defined as when the vibration frequency of the sonic vibrator is between 50 and 200 Hz, which is the typical range of human hearing. When the frequency driven by a vibrator is the same as the natural modal frequencies of the drill string, drill string resonance occurs and can transfer a tremendous amount of energy to the drill bit to achieve high-speed drilling. Sonic drilling has become an indispensable means of environmental drilling because of its high drilling speed, high-fidelity sampling, lower environmental pollution, good construction security, and ability to adapt to a wide range of formations [2–4].

Sonic drilling can not only sample at high speeds with good quality in soft formations but also even penetrate hard rock directly when equipped with an appropriate bit [1,3,5]. Additionally, the vibration frequency of the conventional vibratory immersed-pipe/pile is low (less than 50 Hz) and cannot achieve the natural frequencies of a fixed-length pipe/pile [6]. As such, it is difficult to penetrate hard soil layers with conventional vibratory techniques, not to mention rock.

Ultrasonic percussive drilling rock with diamond-coated tools has been studied under laboratory conditions to investigate the applicability of this technique to down-hole drilling. A research project conducted at the University of Aberdeen in the last few years aims to develop Resonance Enhanced Drilling (RED), the actuator in which consists of a piezo-electric ultrasonic transducer or a magneto-strictive device and rotating on two ball bearings mounted at ultrasonic displacement node points. The technique can determine appropriate loading parameters for the drill bit to achieve and maintain resonance between the drill bit and the drilled material in contact therewith. The studies on ultrasonic percussive drilling demonstrated that the introduction of high-frequency axial vibration significantly enhances drilling rates compared to the traditional rotary type method. The RED drill string is modeled as a three-mass system, where a frictional slider is included to account for the rock dynamics. This simplified nonlinear model provides insight

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into the overall dynamics of the RED drill string during the drilling process on the surface of the earth [7–9]. Sonic drilling by a sonic top-drive vibrator, the frequency of which is significantly lower than ultrasonic frequency, is different from ultrasonic down-hole percussive drilling.

A sonic drilling rock process differs from the percussive drilling method used for conventional broken rock. The conventional impact of broken rock generally consists of two steps: the piston strikes the drill bit, and the drill bit strikes the rock (such as in a DTH hammer). The impact bit can move freely in a certain range relative to the drill string [10,11]. The sonic drill bit always links together with the drill string, both of which vibrate according to the elastic vibration of the drill string itself to generate the impact force on the rock.

Studies of drill string dynamics are mostly focused on the self-excited vibration of deep well drilling in the literature. The behavior of stick-slip vibration in drill strings has been investigated, which can be attributed to the friction effects at the bit. These motions are called self-excited vibrations [12,13]. Kyllingstad and Halsey [14] studied drill string dynamics caused by stick-slip motion, using a mathematical stick-slip model which takes friction effect into consideration. In their study, the drill string is assumed to be a simple torsional pendulum, and the bottom hole assembly is treated as a rigid flywheel. In this way, the drill string can be regarded as a simple torsional pendulum with one degree of freedom. In addition, viscous friction is neglected for mathematical convenience. Yigit and Christoforou [15–17] modeled the drill string based on the assumed mode method. Their algorithm takes into consideration the coupling between axial and transverse vibrations and that between torsional and transverse vibrations, as well as the coupling between axial, transverse and torsional vibrations. Batako et al. [18,19] studied the problem of nonlinear self-excited vibration induced by stick-slip friction of a drill string and conducted experiments on self-excited impact vibration. Many researches on the effect of stick-slip vibration between bit and rock on self-excited vibration of the drill string have been made. It is of great significance to suppress deep well drill string vibration to improve drilling performance.

The impact force of the bit on the rock is an important parameter in the design of the button bit. Therefore, an important scientific proposition for drilling engineering is concerned with how to determine the impact of sonic drilling bits at different depths in rock to design a reasonable drill bit to penetrate rock strata effectively.

Because the drilling process when using a sonic drill is complex at the bottom of a hole, particularly in deep holes, it is difficult to obtain accurate measurements during sonic resonant drilling. Currently, few studies on how to measure or calculate the impact force of a sonic drill bit on rock have been published [2,5]. The greatest impact between the drill bit and rock is an important reference in the drill bit design. To voluminously break the rock, it is necessary to design the shape of the drill bit and guarantee a reasonable contact area between the rock and the button of the drill bit according to the impulse. This paper mainly studies the maximum possible impact force and its influencing factors between the sonic drill bit and rock.

2. Modeling and solving the sonic drill impacting rock

The high-frequency vibration of the sonic vibrator periodically induces drill string resonance and transmits stress waves to the sonic drill bit through the drill string to the bottom of the hole, where it then exerts an impulse on the rock by the bit that is not simply equal to the vibrator exciting force exerted directly on the rock. The response of the resonant drill string with the sonic vibrator when it suddenly encounters rock can be divided into two parts: 1) the sonic vibrator continuously conveys vibration energy to the flexible drill string to maintain steady vibration itself, and 2) the resonant drill string impacts transiently on the rock at the bottom of the hole, whose response in the elastic range can theoretically be calculated using linear superposition. Based on the calculation and analysis, it was found that when the drill string gets resonant with the sonic vibrator's frequency from 50 Hz to 200 Hz and impacts on a rock, the duration of the impact is shorter than the time it takes for the energy produced by sonic vibrator to be transmitted from the top of the drill string to the bit. That is, the energy input from the sonic vibrator has no effect on the first impact between the drill bit and rock during the transient impact. Therefore, the first impact between the drill bit and the rock is mainly caused by the steady elastic vibration of the drill string.

Step 1 Stable solution before the impact of drill string and rock.

Jeffrey notes that the sonic drill string fluidizes the soil and creates a thixotropic transformation of clayey soils, which is very thin, and the data Jeffrey used indicated that the influence zone of fluidization around the drill rod and core was no more than a few millimeters across, typically in the range of 0.8–2.0 mm [2]. When sonic drill is working in saturated stratum or with little circulating fluid, vibration deformation liquefies the soil rapidly near the drill string, and the soil shear strength and stiffness drop almost to zero. Therefore, only the damping effect of viscous liquid on the vibration of drill string is considered, and the effects of gravity and lateral deformation are ignored, too. In this way, the mathematical model of steady forced vibration of the drill string induced by sonic vibrator can be established, as shown in Fig. 1, and both ends of the drill string are movable hinges when spring k was not considered.

The nomenclature used in this paper is shown in Table 1.

Before the impacting, the longitudinal vibration differential equation of the uniform section sonic drill string under the longitudinally distributed load $f(x, t)$ is:

$$\rho S\frac{\partial^2 u}{\partial t^2} + c\frac{\partial u}{\partial t} - ES\frac{\partial^2 u}{\partial x^2} = f(x, t) \tag{1}$$

For the sonic drill system $f(x, t) = m_e\omega^2 \sin\omega t\delta(x) = \begin{cases} m_e\omega^2 \sin\omega t & x = 0 \\ 0 & x \neq 0 \end{cases}$, and the boundary conditions can be defined by Eq. (2).

$$\frac{\partial u(0, t)}{\partial x} = \frac{\partial u(l, t)}{\partial x} = 0 \tag{2}$$

Applying the separation of variables method (the detailed solving process can be seen in Ref. [20]), the solution of the Eqs. (1) and (2) can be obtained as:

$$u(x, t) = \frac{2m_e\omega^2}{\rho Sl}\sum_{i=0}^{\infty}\frac{\sin(\omega t - \varphi_i)}{\sqrt{(\omega_i^2 - \omega^2)^2 + (2\xi_i\omega_i\omega)^2}}\cos\frac{i\pi x}{l} \tag{3}$$

in which $\omega_i = \frac{i\pi}{l}\sqrt{\frac{E}{\rho}}$, i=0, 1, 2 ….

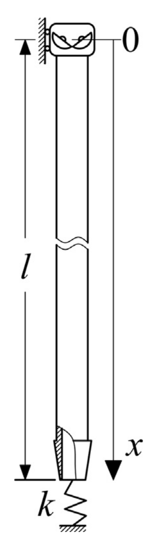

Fig. 1. Modeling of the steady resonant drill string duration of the bit impacting rock.