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An experimental study of the vibration of a drill rod during roof bolt installation

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1. Introduction

Statistics show that the total length of roadways excavated annually by state-owned coal mines in China has reached 1200 km, more than 80% of which are in coal or coal-rock seams.[1] The safety of mine workers, and efficient and profitable production are all significantly influenced by the integrity of these roadways.[2] Roof-related accidents, such as roof collapse, are the most frequent type of mining disasters in Chinese coal mines. Evidently, roof support is a key factor in safe production[3] and many studies have shown that roof structural deterioration is the main cause of roof collapse in bolt-supported roadways.[4–6] Roof deterioration generally results from weak interbeds or cracked layers of soft rock. The weak interbeds consist of thin belts or slices of rock between rock layers and these have low integrity, poor cementation and are susceptible to deformation and fracture development. Such deterioration occurs most easily in soft rock layers, cracked rock layers and muddy rock layers.[7,8]

When most anchorage points are installed in deteriorated strata, or only a few in stable strata, it becomes difficult to detect the position of weakened areas, resulting in increased risk of roof collapse. Therefore, it is important to develop a method for estimating the position and characteristics of weak interbeds by detecting the intensity and thickness of roof strata to accurately select bolt support parameters.

Many studies have been made on rock quality recognition. Teal[9] proposed a concept of specific energy(the energy required to excavate unit volume of rock), which can be the index of the mechanical efficiency in a rock drilling process. Soma[10] used the SWD (seismic-while-drilling technique) to identify the subsurface structure. Zhang et al.[11] provided a method based on stacked sparse autoencoders to identify the rock-coal interface in top coal caving, given that differences in size and hardness between coal and rock may generate different tail beam vibrations. Gu[12] found that effective installation of rock bolts is highly dependent on correct identification of the geological conditions such as discontinuities and differences in ground conditions, even over short distances. Itakura[13,14] demonstrated the potential for improved roof drilling and bolting analysis by estimating rock UCS and identification of discontinuities. Peng et al.[15] showed that the responses of drilling equipment can be used to estimate down-hole geological conditions. Li[16] presented the concept of MWD(Measurement-while-drilling) system for roof logging to evaluate roof structures. Other researchers in China have used simulations and field tests to show that the reaction torque applied to the drill bit by the rock, as well as drilling rate and rotation rate, vary with rock properties.[17–18]

When drilling roof bolt holes, the drill rod is subjected to vibrations caused by interaction between the roof rock and the bit. There have been very few studies on the relationship between drill rod vibrations and rock properties, but intensive studies have been conducted on bit working conditions and boundary identification in terms of drill rod vibration characteristics.[19–21] There are obvious differences in terms of structure, size, working mode and stress state between drill rod and drill string. Therefore, it is useful to establish mechanical models of drill rod vibration in coal mines and analyze the relationship between drill rod vibration and roof rocks to detect weak interbeds, optimize parameters of bolt support and prevent roof collapse.

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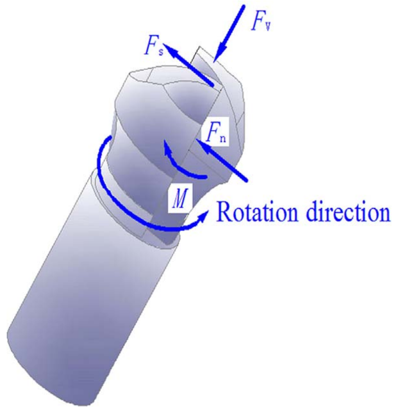

Fig. 1. Illustration of the four main forces involved in roof bolt drilling: response force (*Fv*), reaction torque (*M*), cutting resistance (*Fn*) and frictional force (*Fs*).

2. Relationship between drill rod vibration and mechanical parameters of roof rock

2.1. Mechanical analysis of the drill bit

Owing to the strong axial force and driving torque of the roof bolter, the roof rock will generate two modes of failure when cracked: compression failure and shear failure. Three forces will be applied on the bit:[22,23] (1) the force applied to the two drill bit prongs by the roof rocks (response force) and (2) the resultant frictional force and pressure on the side surfaces of the two prongs that causes axial torque (reaction torque). These forces are illustrated in Fig. 1.

To clarify the relationship between F_v, M and the rocks being cut, mechanical analysis was carried out on the drill bit prong and cutting body, as shown in Fig. 2. According to the principle of action and reaction, F_v denotes the pressure applied on the rock by the prong (the resultant force of normal stress). The rocks are in a state of limited equilibrium before being broken and the resultant force is zero in all directions. Based on these parameters it is possible to obtain the values of F_v and M, as follows:[24,25]

$$F_v = 2F_v{}' = 2\sigma_b S' \tag{1}$$

$$M = \frac{2C\cdot B\cdot H\cdot R}{\sin\alpha(\cos\alpha - \sin\alpha\tan\phi)} + 2\mu\sigma_b S'R \tag{2}$$

where C and Φ denote cohesion strength and internal friction angle, respectively. The area of the shear plane (S) can be determined as follows:

$$S = \frac{BH}{\sin\alpha} \tag{3}$$

The factors B and H denote the cutting width and depth, respectively, both of which are related to the shape of the drill bit and driving conditions of the roof bolter. The factors τ and σ_n denote shear stress and normal stress on the shear plane, respectively. The distance between the equivalent concentrated force on the bit and drill rod axes is denoted as R.

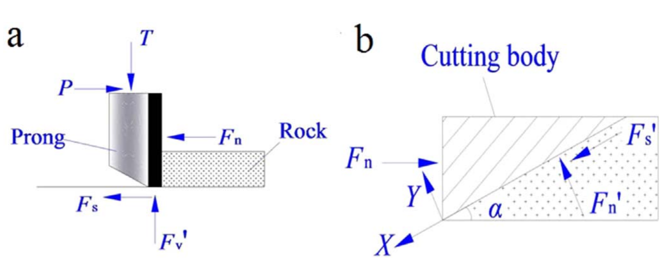

Fig. 2. Mechanical analysis of the drill bit. (a) the prong. (b) the cutting body. The angle between the shear plane and cutting direction (α) is related to the internal friction angle. The various forces shown are denoted as cutting force (P), propulsive force (T), cutting resistance (Fn), frictional force of one prong (Fs), response force of one prong (Fv'), reactive shear force (Fs') and reactive force applied to the cutting body (Fn').

The process of rock cutting by the prong can be regarded as occurring under conditions of uniaxial compression in an equilibrium state. As such, α can be determined as follows:

$$\alpha = 45^\circ + \frac{\phi}{2},\ \sigma_b = 2C\tan\left(45^\circ + \frac{\phi}{2}\right) = 10f, \tag{4}$$

where f denotes the Protodyakonov coefficient of the rock. When roof bolter parameters and driving conditions are constant, the response force and reaction torque can be determined as follows:

$$F_v = F_v(f) \tag{5}$$

$$M = F_m(C, \phi, \mu) \tag{6}$$

2.2. Mechanical analysis of drill rod vibration

2.2.1. Drill rod transverse vibration

The response force causes transverse elastic deformation in the drill rod that initiates transverse vibration, as shown in Fig. 3(a). The transverse vibration equations can be written as:[23,26,27]

$$\frac{\partial^4 Y}{\partial x^4} + \frac{F_v \sin\omega(t)}{EI}\frac{\partial^2 Y}{\partial x^2} - k^4 Y = 0 \tag{7}$$

and

$$k^4 = p^2\frac{\rho A}{EI},\ \omega(t) \tag{8}$$

where k^4 is the rate of change with time of the response force and p is the natural frequency of the drill rod. The factors EI, ρ and A denote bending rigidity, density and cross-sectional area, respectively. The transverse vibration amplitude of the micro-unit dx at position x is denoted as $Y(x,t)$, which can be determined by combining Eqs. (5) and (7):

$$Y(x,t) = Ae^{\lambda_1 x} + Be^{-\lambda_1 x} + C\cos\lambda_2 x + D\sin\lambda_2 x \tag{9}$$

The value of λ_1 is determined as follows:

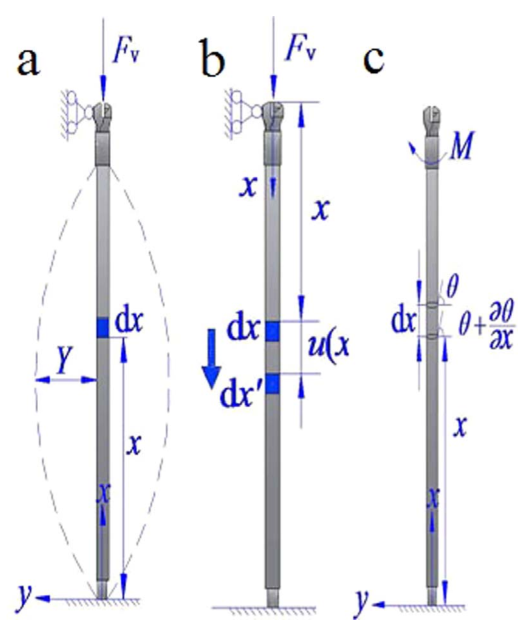

Fig. 3. Mechanical parameters of drill rod vibration. (a) transverse vibration. (b) longitudinal vibration. (c) torsional vibration.