Investigation on Characteristics of Longitudinal Acoustic Wave Propagation in Coal Mine Drill Rods

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Abstract. In order to investigate the feasibility of drill rods used for wireless data transmission in coal mine, the properties of longitudinal acoustic wave propagation in drill string are studied. The results show that: the spectral properties of drill string for coal mine show like a comb filter with wide passbands; when single drill rod become longer, numbers of passbands become more, the width of total passband become narrower; bigger diameter of drill rod makes the width of total passband narrower and amplitudes lower; for integral type and joint-connection type drill rod with same diameter and length, they have little difference in total passband width; the drill strings with different total length have almost same spectral characteristics. In the drill strings investigated, the drill strings composed by drill rods with 42mm diameter and 1m length has the widest passband which occupy 70% of the whole frequency scope. All results indicate that drill rods can be used as channel in data transmission in coal mine gallery.

1. Introduction

It is often required gas drainage, water exploration and other drilling operations in coal mines. In order to ensure the accurate extension of drilling hole in the target layer, accurate control of the drilling trajectory is required. The precise measurement of the drilling trajectory has become the basis and the key to directional drilling.

In the measurement of drilling trajectory, measurement while drilling (MWD) is the most ideal way. It can get the trajectory immediately without stop drilling. MWD can be divided into: Wired and wireless. Wired MWD has made considerable development and application. However, the wired mode brings some problems, such as the complex structure of the drill pipe, the strict processing technology and the high cost (Shi Zhijun, 2016).

Wireless measurement is an effective and alternative way. There is ideal channel downhole that can be used for signal transmission: the drill string, which is mostly made in metal (steel). Metal is a good waveguide for acoustic or elastic wave. So the drill string can be used as the channel of acoustic signal transmission. The technology has been applied in oil drilling and production (Thinh Vo, 2017; ZHENG Lichen, 2017).

This paper investigates the propagation characteristics of longitudinal acoustic wave in the drill pipe, and lays the foundation for the sound-based wireless MWD measurement.
2. Model

Two types of drill pipe: the integral and the joint-connection are studied in this paper, which are ruled in the People's Republic of China coal industry standards and common used in coal mines (National Development and Reform Commission, 2006). The structures are showed in Figure 1.

In order to obtain the basic rules of the acoustic characteristics of the drill string and to facilitate the analysis and calculation, according to the structural characteristics of the drill pipe and its connection mode and characteristics in use, the drill string are simplified without affecting the validity of the results.

![Figure 1. Structure of drill rod](image)

A model is set as shown in Figure 2. The drill string consists of pipes and joints. Pipes have the smaller cross-sectional area and longer length. Joints have the larger cross-sectional area and shorter length.

![Figure 2. Model of the drill string](image)

According to the basic wave equation, there is:

\[
\frac{\partial^2 u}{\partial t^2} = \frac{1}{\rho_c a^2} \left( \frac{\partial}{\partial z} \left( \frac{\partial u}{\partial z} \right) \right)
\]

\[
\frac{\partial^2 F}{\partial t^2} = \frac{1}{c_p h^2} \frac{\partial F}{\partial z^2}
\]

\[
m = \int_0^z \rho(\zeta) a(\zeta) d\zeta
\]

Where \(u(x,t)\) is the Displacement at any point; \(F\) is the axial force at this point; \(z=\rho a c\) is the wave impedance; \(\rho\) is the density of pipe and joint; \(a\) is the cross-sectional area; \(c=\sqrt{E/\rho}\) is the sound speed; \(E\) is the elastic Modulus.

Using simple-centered finite differences, the displacement \(u(x,t)\) can be approximated by a discrete set of \(u_n\) values where \(j\) and \(n\) denote the value at time and position. The finite-differences algorithm is obtained:

\[
u_{n+1}^j = \frac{2\Delta r_{n+1/2}}{\Delta r_{n+1/2} + \Delta r_{n-1/2}} u_n^j + \frac{2\Delta r_{n-1/2}}{\Delta r_{n+1/2} + \Delta r_{n-1/2}} u_{n-1}^j - u_n^j
\]

And \(\Delta r_{n+1/2} = \rho_{n+1/2} a_{n+1/2} \Delta x_{n+1/2}; \Delta x_{n+1/2} = x_{n+1} - x_n; x_n\) is the mesh points position.

When determining the time step and the number of grids, the following relations should be satisfied, \(L_p = c_p n_p \Delta t\) and \(L_j = c_j n_j \Delta t\). The \(\Delta t\) is the time step, \(L_p\) is the length of pipe, \(L_j\) is the length of joint, \(c_p\) is the sound speed in pipes, \(c_j\) is the sound speed in joints, \(n_p\) is the mesh number of a pipe, \(n_j\) is the mesh number of a joint. In general, the pipe is the same as the material of the joint, so \(c_p = c_j\), can be unified as \(c\).
3. Calculation and analysis of results

The propagation characteristics of drill string consisting of equal length drill pipe and joint are calculated and analyzed. It means that all pipes are in the same length and all joints are also in the same length. In this condition, the integral type and joint connection type drill strings are analyzed respectively, and the two are compared. The parameters are shown in Table 1 and Table 2.

### Table 1. Sizes and parameters of integral type rods

| Diameter/mm | Overall length/mm | Pipe length/mm | Joint length/mm |
|-------------|-------------------|----------------|-----------------|
| 42          | 1000              | 935            | 65              |
| 42          | 1500              | 1435           | 65              |
| 42          | 3000              | 2935           | 65              |
| 50          | 1000              | 935            | 65              |
| 50          | 1500              | 1435           | 65              |
| 50          | 3000              | 2935           | 65              |
| 89          | 1000              | 895            | 105             |
| 89          | 1500              | 1395           | 105             |
| 89          | 3000              | 2895           | 105             |

### Table 2. Sizes and parameters of joint-connection type rods

| Diameter/mm | Overall Length/mm | Pipe length/mm | Joint length/mm |
|-------------|-------------------|----------------|-----------------|
| 42          | 1000              | 900            | 140             |
| 42          | 1500              | 1400           | 140             |
| 42          | 3000              | 2900           | 140             |
| 50          | 1000              | 900            | 140             |
| 50          | 1500              | 1400           | 140             |
| 50          | 3000              | 2900           | 140             |

In calculation, the material density is $7870\text{kg/m}^3$, and the sound speed is $5050\text{m/s}$. The left and right boundaries are treated as infinite boundary, that is, $u_n^j = u_{n+1}^j$ at the left boundary and $u_n^j = u_{n-1}^j$ at the right boundary. A unit impulse excitation is applied near the left boundary to analyze the change of the displacement of the node at the right boundary with time. The transient response of the drill string to the unit excitation pulse can be obtained, and the spectral characteristics can be obtained by Fourier Transform.

3.1 Characteristics of drill strings in different single rod length

The frequency spectrum curves of the drill string composed of length 1m and 1.5m drill rods with the same diameter (40mm) are showed in Figure 3.

It can be seen that, with the drill rods are lengthened, the band pass number is more, and the total passband width is narrowed due to the existence of stop bands. The 3 passbands of the 1.5m drill rod cut the width of the two passbands of the 1m drill rod. That is to say, the number of passbands is proportional to the multiples of the length of a single drill rod. Due to the segmentation of the stop band, the overall passband width decreases proportionally.

3.2 Characteristics of drill strings in different outer diameters.

The spectrum curves of three kinds of drill rods with length of 1m and different diameters are shown in Figure 4.

It can be seen that the difference between spectral curves of 42mm and 50mm rods is very small cause of their small difference in diameters. The passbands and stopbands of the two are approximate. However, the width and amplitude of the 50mm drill rods are slightly smaller than the 42mm. The spectrum of 89mm drill rods is very different from that of the former; the overall passband width and amplitude are smaller. Thus, with the increase of the diameter, the passband width becomes narrower.
Through the above analysis, it can be seen that, the drill string composed of the diameter 42mm and the length 1m has the widest passband. The total available bandwidth is about 28.1KHz, over 70% of the whole frequency range.

3.3 Difference between the integral and the joint-connection rods

Figure 5 is the spectrum curves of two types of drill string with the same diameter (42mm) and the same length (1m). It can be seen that the spectrum curve of the integral shifts to the right as a whole, compared with the joint-connection, which shifts to the high frequency section. There is a little difference between the width and amplitude of passbands. The overall width of the passbands are almost the same.

3.4 characteristics of drill strings in different total length

The spectral characteristics of three lengths of drill string are calculated. Figure 6 shows the frequency spectrum of the drill string with the total length of 150m, 300m and 610m respectively, which have the same diameter (50mm) and the same length (1.5m). It can be seen that the spectrum curves of the three are almost the same. Therefore, the total length of the drill rod has little influence on its frequency characteristics when the parameters of a single drill rod remain unchanged.

4. Conclusions

Conclusions can be drawn from the above study.

1) The coal mine drill string has the characteristics of comb filter on the whole. In all the drill rods studied, the drill string with diameter 42mm and length 1m has the widest passband width, which can reach more than 70% of the whole frequency range.

2) The length and diameter of the drill rods will affect the frequency spectrum characteristics. The increase of the length will lead to the increase of the number of passbands and the decrease of the overall passband width. With the increase of the diameter, the bandwidth becomes narrower and the amplitude becomes smaller.
(3) The spectrums of the integral and the joint-connection are similar in the overall pass band width when rods are in the same diameter and length.

(4) The difference of the overall length of drill string has little influence on its frequency spectrum characteristics.

In conclusion, coal mine drill string can be used as acoustic transmission channel for downhole data transmission.

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