Numerical investigation on signal transmission characteristic of electromagnetic measurement-while-drilling in underground coal mine

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Abstract. Signal transmission characteristic research of electromagnetic measurement-while-drilling is the theory basis for its application in underground coal mine drilling. However, the existing numerical models of signal transmission are conducted on oil and gas drilling. In this study, based on the equivalent transmission line theory, a numerical model considering the nearly horizontal signal channel for signal transmission in underground coal mine was proposed. Then, factors affecting the received signal strength, including hole depth, coal seam resistivity, excitation voltage and received distance were investigated. Results indicate that received signal strength decreases with the increase of hole depth and decrease of coal seam resistivity, and increasing excitation voltage and orifice received distance reasonably is an effective method to enhance received signal strength.

1. Introduction
The directional drilling technology with measurement-while-drilling (MWD) shows the advantages of borehole trajectory real-time control, deep hole drilling ability, and high drilling efficiency, which is widely used in underground coal mine for gas extraction, water disaster prevention and control, and factor exploration of hidden disaster-causing[1-2]. At present, the cable MWD, using center cable pipes to transmit signal, is widely applied in underground coal mine directional drilling. However, the signal of cable MWD is significantly affected by pipe joints, and its reliability is low in deep hole drilling.

The electromagnetic measurement-while-drilling (EM-MWD) transmits signal with extremely-low frequency electromagnetic through drill pipes and formations. Compared with cable MWD, the signal transmission of EM-MWD is more reliable and adaptive[3-4]. Nevertheless, its measuring depth is limited due to the attenuation of signal transmission. To enhance the measuring depth of EM-MWD, modeling and characteristics analysis for signal transmission have been explored. Trofimenkoff et al. analyzed potential and current distribution on drilling string with image method[5]. Hu et al. established a lossy medium model based on maxwell equation, and studied the influence of formation conductivity, magnetic permeability, and signal emission frequency on received signal strength[6]. Fan et al. established segment-based model based on equivalent transmission line theory, and indicated that formation resistivity, drill string resistivity and excitation frequency were the main factors affecting signal transmission[7].

However, the above researches are conducted on oil and gas drilling. For underground coal mine drilling, the signal channel is nearly horizontal and signal is always in coal measures strata. Due to these two factors, the signal transmission in underground coal mine has not been clarified in the previous
studies in detail. Thus, modeling and characteristics analysis for signal transmission in underground coal mine are very desirable.

In this study, we have developed a numerical model and analyzed the signal transmission in underground coal mine. First, the working principle of EM-MWD in underground coal mine is introduced. Then, based on the equivalent transmission line theory, a novel model for analyzing the signal transmission is proposed. Finally, by simulating the developed model, the signal transmission characteristics including the effect of hole depth, coal seam resistivity, excitation voltage and received distance on received signal strength are analyzed in detail.

2. Working principle of EM-MWD in underground coal mine

The working principle of EM-MWD in underground coal mine is shown in Fig 1. The EM-MWD is composed of hole instruments and orifice instruments. The hole instruments act as transmitter, the drill pipe is divided into two asymmetrical parts (i.e., upper and lower drill string) by a insulation nipple, and a AC source is added on the two end faces of the insulation nipple to produce signal. Then, the signal is transmitted to orifice through drilling and coal measures strata. The orifice instruments act as receiver, the potential difference between the drill pipe and the received electrode is detected as the received signal. Through filtering and decoding, the information measured in hole can be obtained[8-10].

3. Numerical model development

To develop a numerical model for simulating signal transmission, some reasonable assumptions are made as follows: 1) the coal seam is uniform in resistivity; 2) the effect of flushing fluid in the hole is not considered; 3) the coal seam roof and floor are not considered. The physical model of signal transmission is shown in Fig 2.
3.1. Model distribution parameters
The distribution parameters include drill string resistivity and coal seam resistivity, the calculation process is described as below.

3.1.1. Drill string resistivity
The resistivity of the drill string per unit length is[11-13]:

\[
R_0 = \frac{\rho_0}{\pi (r_1^2 - r_0^2)}
\]

(1)

where \(\rho_0\) is the resistivity of the drill string, \(r_1\) is the outer diameter of drill string, and \(r_0\) is the bore diameter of the drill string.

3.1.2. Coal seam resistivity
In this model, the streamline form of the signal in coal seam is rectangular. The rectangular streamline length corresponding to the unit length of the drill string is \(x, x+nL_3/L_1\) and \(x\), respectively, as shown in figure 2. The resistivity of coal seam corresponding to the rectangular streamline is \(R_1, R_2\) and \(R_3\), respectively.

The current flow line in \(R_1\) is cylindrical, and the radial overcurrent area is \(2\pi r_0\). Therefore, \(R_1\) can be obtained by radial integration:

\[
R_1 = \int_0^L \rho \frac{dx_0}{2\pi r_0} = \frac{\rho}{2\pi} \left( \ln x - \ln r_1 \right)
\]

(2)

The current streamline in \(R_2\) is cylindrical, whose radius is \(x\), thickness is \(1\) m, and height is \(x+nL_3/L_1\). Therefore, \(R_2\) can be obtained by radial integration:

\[
R_2 = \frac{\rho \left( x + \frac{L_3}{L_1} \right)}{\pi \left( x+1 \right)^2 - x^2}
\]

(3)

The streamline of \(R_3\) is similar to \(R_1\), except that the streamline height of \(R_3\) is \(L_3/L_1\), and \(R_3\) can be obtained as follow:

\[
R_3 = \frac{\rho L_3}{2\pi L_3} \left( \ln x - \ln r_1 \right)
\]

(4)

From the above, the coal seam resistivity \(R_m\) of the flow line loop per unit length is:

\[
R_m = R_1 + R_2 + R_3
\]

(5)

3.2. Model signal distribution characteristics

3.2.1. Potential distribution on drill string
According to the equivalent transmission line theory, the current and voltage on the drill string satisfy the differential relation of first-order variable coefficient, and the calculation formula of the voltage distribution on the drill string is:

\[
V(x) = \frac{V_c + L_c I_c e^{-\alpha x}}{2} + \frac{V_c - L_c I_c e^{\alpha x}}{2}
\]

(6)

where \(V_c\) is the excitation voltage, \(I_c\) is the excitation current, \(Z_c\) is the circuit impedance constant, \(r\) is the proportionality coefficient.

Compared with \(R_m\), \(R_0\) is very small and can be ignored. Therefore, the total resistivity \(R\) of the streamline circuit can be obtained as follow:

\[
\frac{1}{R} = \frac{1}{(R_1 + R_2 + R_3)_1} + \frac{1}{(R_1 + R_2 + R_3)_2} + \ldots + \frac{1}{(R_1 + R_2 + R_3)_t}
\]

(7)

After obtaining the total resistivity \(R\) of the streamline circuit, the \(I_s\) in Equation (6) can be obtained.
with ohm’s law. Then the potential distribution on the drill string is:

$$V(x) = \frac{V_s + \frac{V_s}{R}Z_s}{2} e^{-\alpha x} + \frac{V_s - \frac{V_s}{R}Z_s}{2} e^{\alpha x}$$  \hspace{1cm} (8)$$

3.2.2. Orifice received voltage

The signal is received by detecting the potential difference between the orifice drill pipe and the received electrode. The potential on the orifice drill pipe can be obtained by equation (8)\textsuperscript{[14,15]}. The loop where the orifice received distance $d$ located is the outermost rectangular loop in the coal seam, and $V_r$ can be obtained by calculating the component voltage of the resistivity $R_d$ between the orifice drill pipe and the received distance $d$ in the outermost rectangular loop:

$$V_r = V_d \frac{R_d}{(R_1 + R_2 + R_3)_{L_1}}$$ \hspace{1cm} (9)$$

$$V_d = \frac{V_s + \frac{V_s}{R}Z_s}{2} e^{-\alpha L_1} + \frac{V_s - \frac{V_s}{R}Z_s}{2} e^{\alpha L_1}$$ \hspace{1cm} (10)$$

where $V_d$ is the potential on orifice drill pipe, $(R_1+R_2+R_3)_{L_1}$ is the resistivity of the outermost rectangular loop.

According the above analysis, the numerical model establishes the relationship between the received signal strength and the model parameters. By simulating the developed model, signal transmission characteristics can be obtained.

4. EM-MWD signal transmission characteristics

To further analyze the signal transmission characteristic considering the effects of various engineering factors, several cases are studied using the developed numerical model. In these cases, the model parameters are set as follows. The outer diameter $r_1$, the inner diameter $r_0$ and the resistivity $\rho_0$ of the upper drill string is 0.0365 m, 0.0295 m and $1 \times 10^{-7}$ Ω·m, respectively. The length of the insulation nipple $L_2$ and lower drill string $L_3$ is 1 m and 6 m, respectively. The resistivity of the lower drill string is $\rho_0$.

4.1. Effect of hole depth on received signal strength

In this case, the excitation voltage $V_s$ is 12 V, and the coal seam resistivity $\rho$ is 40 Ω·m. On the basis of setting the serial values of hole depth $h$ ($L_1+L_2+L_3$), the change rule of the received signal strength is obtained, as shown in figure 3. From Figure 3, it can be found that the received signal strength decreases rapidly with the increase of the hole depth, its attenuation rate is high within 200 m of the hole depth, and decreases after the hole depth exceeds 200 m. In addition, the received signal strength increases with the increase of the orifice received distance, when the hole depth remains unchanged.

![Figure 3. The relationship between received signal strength and hole depth](image-url)
4.2. Effect of coal seam resistivity on received signal strength
In this case, the excitation voltage $V_s$ is 12 V, and the hole depth $h$ is 300 m. On the basis of setting the serial values of the coal seam resistivity $\rho$, the change rule of the received signal strength is obtained, as shown in figure 4. From Figure 4, it can be found that the received signal strength increases slowly with the increase of the coal seam resistivity, and changes approximately linear. In addition, the received signal strength increases with the increase of the orifice received distance, when coal seam resistivity remains unchanged.

4.3. Effect of excitation voltage on received signal strength
In this case, the hole depth is 300 m, and the coal seam resistivity $\rho$ is 40 $\Omega \cdot m$. On the basis of setting the serial value of the excitation voltage $V_s$, the change rule of the received signal strength is obtained, as shown in figure 5. From Figure 5, it can be found that the received signal strength increases rapidly with the increase of the excitation voltage, and is linear relationship. In addition, the received signal strength increases with the increase of the orifice received distance, when the excitation voltage $V_s$ remains unchanged.

5. Conclusions
In this study, a numerical model for simulating signal transmission of EM-MWD in underground coal mine has been proposed. Using the developed model, the received signal strength can be predicted before drilling. By analyzing the signal transmission characteristic, some meaningful conclusions are obtained as follows: 1) the increase of hole depth and decrease of coal seam resistivity will result in the decrease of the received signal strength; 2) increasing the excitation voltage and orifice received distance
can improve the received signal strength.

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Nomenclature

- $L_1$: length of upper drill string, m
- $L_2$: length of insulation nipple, m
- $L_3$: length of lower drill string, m
- $\rho_0$: resistivity of the drill string, $\Omega \cdot m$
- $\rho$: resistivity of coal seam, $\Omega \cdot m$
- $r_1$: outer diameter of drill string, m
- $r_0$: bore diameter of drill string, m
- $x, x + nL_3/L_1, x$: rectangular streamline length, m
- $R_0$: resistivity of drill string per unit length, $\Omega$
- $R_1, R_2, R_3$: resistivity of coal seam corresponding to the rectangular streamline, $\Omega$
- $V_e$: excitation voltage, V
- $I_e$: excitation current, A
- $Z_c$: circuit impedance constant, dimensionless
- $r$: proportionality coefficient, dimensionless
- $V_r$: orifice received voltage, V
- $V_d$: potential on orifice drill pipe, V

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