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Ground Penetrating Radar Signal Processing Algorithm in Advance Detection of Coal Seam

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Abstract: According to the electromagnetic propagation characteristics of Ground Penetrating Radar (GPR) in the medium, how to identify the target in coal seam using the relative permittivity of the dielectric object is studied, the identification algorithm of dielectric object based on electromagnetic echo field intensity with propagation loss and reflection loss are analyzed. The simulation results show that coal seam attenuation coefficient has extremely weak influence for echo field strength, when the relative permittivity of the dielectric object is less than 3, the phase of incident wave is the same as it in echo, when the relative permittivity of the dielectric object is more than 3, the situation is just opposite. Therefore, according to the echo field strength can probe gas and water contained in coal previously and efficiently and provide pre-judgment basis for the safety of coal mine.

Key words: GPR, coal seam, wave propagation, advanced detection, MUSIC

INTRODUCTION

For different coal seam geological conditions, there may be gas and water in the coal seam. When digging the coal there may be a disaster which will threaten the security of staff and the equipment. So using the advanced detection technology to judge whether there is potential risk in the coal is very significant to for the efficient production of coal mine.

In the process of coal mining advanced prediction is widely used. GPR is an efficient detecting method (Feng, 2012; Zeng *et al*., 2010). According to signal form, GPR is divided into three categories, which is FMCW GPR, pulse mode GPR and stepped frequency GPR. The FMCW GPR is the GPR of the frequency domain, whose receiver range is larger and has higher power. And it can get higher resolution ratio than

GPR in time domain and more suitable to work in large loss situation: In the coal research of Ground penetrating radar technology, the coal production characteristics is carried out the development work for coal mine explosion proof mine geological radar (Song, 2002). For the detection of coal spontaneous combustion zone, it used of the coal conductivity higher, spontaneous combustion zones overlying by baking coal spontaneous combustion, the small water content, low conductivity characteristics (Song *et al*., 1999). The finite difference time domain (FDTD) method is used to establish a model of mine geological radar (He and Wei, 2000). It carried out a new coal mine explosion Ground penetrating radar equipment and underground probe method (Song *et al*., 2007; Liang, 2011).

However, due to the different with the working condition of the coal mine, tunnel ground and the electromagnetic wave propagation in the medium seam characteristics difficult theoretical research, the paper seam radar signal processing and target body media recognition has been studied.

TRANSMISSION CHARACTERS OF ELECTRIC MAGNETIC WAVE IN COAL SEAM

Because of the very complicated underground medium, the echo signal of GPR is mixed-signal which generated by multiple scattering Center. Measuring changes in the size of echo signal amplitude varies as the target media. When using GPR to do the advanced detection of coal seam media, the electromagnetic

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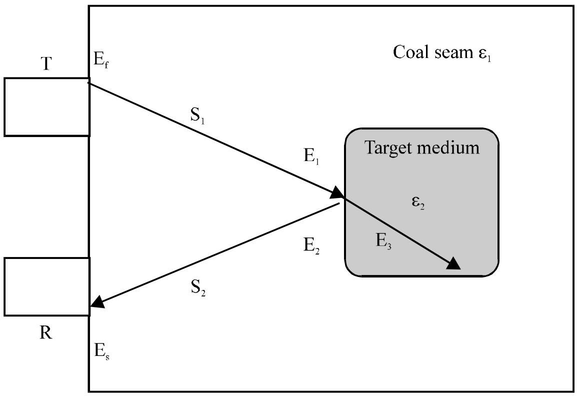

Fig. 1: Detecting model of GPR in coal seam

waves with different propagation path loss, if the target was not coal. The electromagnetic waves which emitted by GPR antenna has two main types of losses in the transmission path: Attenuation loss and reflection loss (Xu, 2007).

Electromagnetic waves emitted by ground penetrating radar for advanced detection in coal, its simplified model show in Fig. 1.

Seam medium is imperfect dielectric, therefore, assuming that the electromagnetic wave spread along the L direction, then the expression of electric field and magnetic field (Yin, 2009) is:

$$\begin{cases} E_L = E_0 e^{-\alpha l} e^{-j\beta l} \\ H_L = H_0 e^{-\alpha l} e^{-j\beta l} \end{cases} \tag{1}$$

E_0 and H_0 represents the amplitude of electric field strength and magnetic field strength, α represents attenuation constant, β represents phase constant, the computational formula of α and β expressed as follows:

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\delta}{\omega\varepsilon}\right)^2}-1\right)} \tag{2a}$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\delta}{\omega\varepsilon}\right)^2}-1\right)} \tag{2b}$$

ω is the angular frequency of the electromagnetic wave, ε is the dielectric constant, μ is magnetic permeability medium, δ represents the electrical conductivity.

Because the GPR is according to the reflection of different dielectric surface reflected wave frequency, amplitude and phase information for advanced detection, the research of reflection wave for GPR is very important. It will use the vertical incident as an example to discuss the electromagnetic wave reflection coefficient. When a sinusoidal plane wave normally incident on the interface of two media, the angle of incidence, refraction, reflection angle are zero, E_{i0} incident and reflected and refracted waves E_{t0} and E_{r0} relationship:

$$\begin{cases} E_{r0} = \dfrac{\eta_2 - \eta_1}{\eta_2 + \eta_1} E_{i0} \\ E_{t0} = \dfrac{2\eta_2}{\eta_2 + \eta_1} E_{i0} \end{cases} \tag{3}$$

η_1 and η_2 represent respectively medium wave impedance of 1 and 2. when GPR advanced detection used in coal seams, most of the coal and rock are non-conductive, non-magnetic media, so the phase velocity of the electromagnetic wave expression is:

$$V_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\varepsilon_r}} \tag{4}$$

in where $\varepsilon = \varepsilon_r \varepsilon_0$

Electromagnetic field of transmitter and receiver was E_f and Es, E_1 and E_2 respectively incident and reflected on the surface of the target media electric field intensity, E_3 is the electric field intensity into the target medium, according to the time difference t between transmitting antenna and the receiving antenna calculate the propagation distance in the figure S_1 and S_2:

$$S_1 = S_2 = \frac{1}{2} t_{vcoal} \tag{5}$$

For:

$$E_1 = E_f e^{-S_1 \alpha_{coal}} \tag{6}$$

E_2 and E_3 can be work out:

$$\begin{cases} E_2 = \dfrac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} E_1 \\ E_3 = \dfrac{2\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} E_1 \end{cases} \tag{7}$$

ε_1 andε_2 denote the permittivity of coal seam and the target respectively. The relationship between Es, which is the electric field intensity of receiving electromagnetic and E_2 is similar to Eq. 6, so the relative dielectric constant of target media can be deduced as Eq. 7, in where, ε_{rcoal} and $\varepsilon_{rmedium}$ is the relative permittivity of coal and the target media, The electromagnetic wave attenuation coefficient in the coal seam α_{coal} can be calculated by Eq. 2. The $\varepsilon_{rmedium}$ can be identify the target object:

$$\varepsilon_{r\,medium} = \left(\frac{\frac{E_s}{E_f}\exp\left(t\alpha coal \frac{c}{\sqrt{\varepsilon_{rcoal}}}\right) - 1}{\frac{E_s}{E_f}\exp\left(t\alpha coal \frac{c}{\sqrt{\varepsilon_{rcoal}}}\right) + 1} \right)^2 \varepsilon_{rcoal} \quad (8)$$

MUSIC ALGORITHMS IN GPR SINGLE PROCESSING

When the FMCW GPR is used in advance detection of Coal Seam, the frequency accuracy of the measurement is directly related to the accuracy of the positioning of objects. But also in the processing, to simultaneously define a plurality of signal frequency. MUSIC algorithm due to its ultra-high frequency resolution capabilities and can realize multi-target detection capability, makes a deal with the MUSIC algorithm FMCW

GPR signal main algorithm: MUSIC algorithm is a typical spatial spectrum estimation algorithm, which is the array received data characteristic decomposition, to strike its eigenvalues and corresponding eigenvectors, resulting in two subspaces signal subspace and noise subspace, the signal subspace and the received signal and the noise have a relationship and the noise subspace is only related on the noise. MUSIC algorithm is the use of noise and signal subspace orthogonal to each component of the signal characteristics to the wave direction or frequency estimation MUSIC algorithm processing steps:

Step 1: According to the received echo signal to estimate the autocorrelation matrix. First, assume that the received signal x (n) is a combination of k sinusoidal signals and white noise, the signal vector can be expressed as:

$$x(n) = Gs(n) + B(n) \quad (9)$$

In where, G is a matrix which formed by the signal frequency vector g (ω), s (n) is used to express the single's amplitude vector, B (n) is used to express the white noise single that the mean value is zero and the variance is δ^2. Assume R express the autocorrelation matrix of x (n), then R could be written as:

$$\begin{aligned} R &= E\{x(n)x^H(n)\} \\ &= E\{[GS(n)+B(n)][S^H(n)G^H+B^H(n)]\} \\ &= GPG^H + E\{B(n)B^H(n)\} \end{aligned} \quad (10)$$

Because we have assumed B (n) is used to express the white noise single that the mean value is zero and the variance is δ^2, Eq. 10continue to simplify as:

$$\begin{aligned} R &= GPG^H + E\{B(n)B^H(n)\} \\ &= GPG^H + \delta^2 I \end{aligned} \quad (11)$$

I represents MHM identity matrix

Step 2: By the analyses of the estimated autocorrelation matrix, we can gain a noise subspace from the autocorrelation matrix

Step 3: Using the derived spectral function p (ω) to calculate:

$$P(\omega) = \frac{1}{\sum_{i=K+1}^{M} \left| g^H(\omega)V_i \right|^2}, \ \omega \in [-\pi, \pi] \quad (12)$$

p (ω) is the derived spectral function which is used to do the frequency estimation. V_i is the orthogonal normalized feature vectors which correspond to M eigenvalues of matrix GPG^H. The spectrum peak position of the P (ω) is the estimated angular frequency of the signal.

Step 4: According to the orthogonality of the signal subspace and the noise subspace to identify the spectrum peak position of p (ω), then calculates the signal frequency.

PERFORMANCE SIMULATIONS:

The dielectric property of common medium in coal seam is shows as Table 1. It conduct simulation on the relationship about the electric field intensity and the depth of the coal seam, the electric field intensity and the relative dielectric constant of the target media, the electric field intensity and the attenuation quotient of the coal seam.

Assumed the target media are gas, rocks and water and their relative dielectric constant are set to

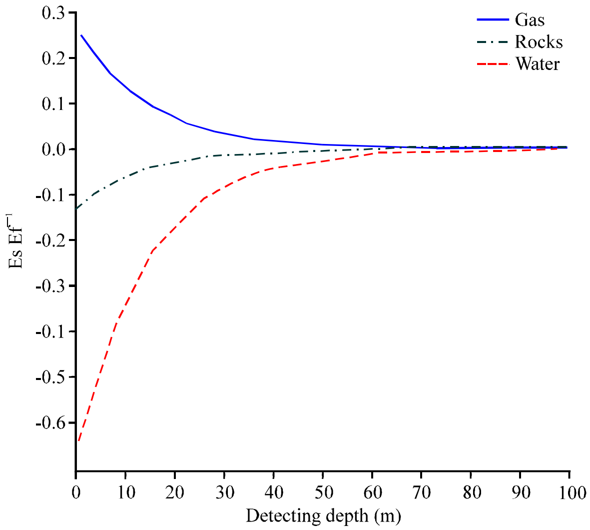

Fig. 2: Relationship of Es/Ef and detectable range

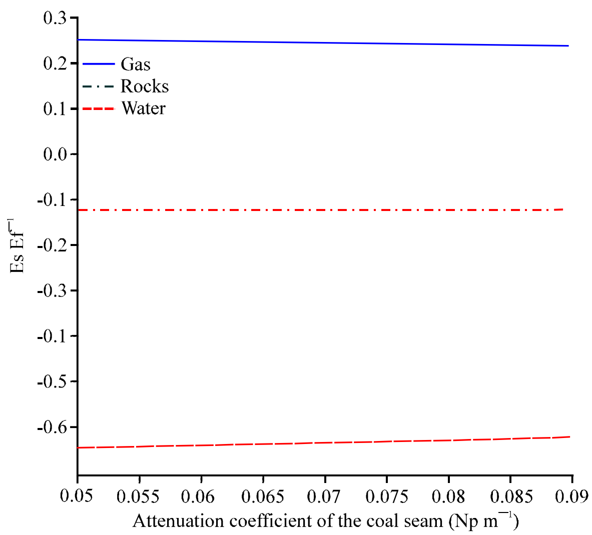

Fig. 3: Effect of attenuation coefficient

Table 1: Dielectric properties of medium in coal measure strata

Medium in coal seam	Relative dielectric constant	Conductivity (ms m^{-1})	Electromagnetic wave velocity (m ns^{-1}).
Gas	1	0	0.3
Water	81	0.5	0.033
Coal	2.3~3.6	0.001~0.01	0.158~0.19
Limestone	4~8	0.5~2	0.1~0.15
Shale	5~15	1~100	0.09
Siltstone	5~30	1~100	0.07
Clay	5~40	2~1000	0.06
Granite	4~6	0.01~1	0.13

1, 5 and 81, the attenuation coefficient of coal seam is set to 0.06 Np m^{-1}, the relative dielectric constant of coal seam is set to 3, the relationship between electromagnetic field strength and probing depth of coal seam is shown in

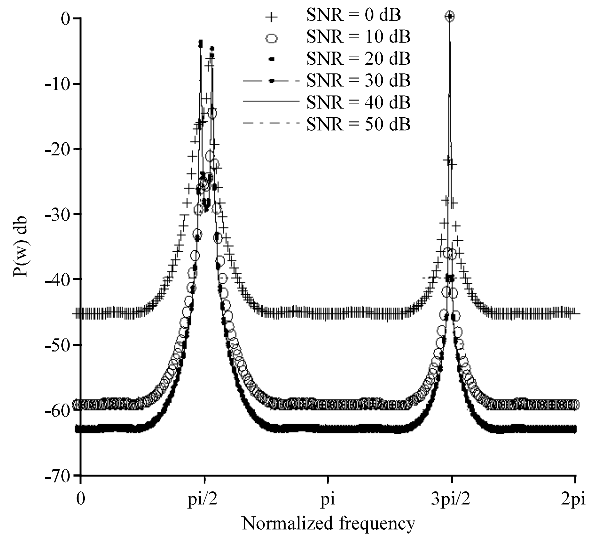

Fig. 4: Performance in different SNR

Fig. 2, when gas is the target media, the incident wave and the echo wave have the same phase, when the target medium is the rock and water, case is just the opposite; Fig. 2 provided the basis for determination of penetrating depth. If we given the parameters of GPR antenna, it can get the maximum depth of penetrating. Assuming the detection depth to 10 m, the range of the attenuation coefficient of coal seam is 0.05~0.09 Np m^{-1}, the influence of the attenuation coefficient of coal seam to the echo field strength is shown in Fig. 3, if the probing depth and dielectric constant of coal seam are known, the effect of attenuation coefficient of coal seam to the field strength of the echo is extremely weak.

For the MUSIC algorithm, assume the length of the receiving signal is 1000, the receiving antenna of the GPR is uniform linear array and the number of the array is 10.And assume there are three receiving signal, the normalized frequency are, respectively $\pi/2$, $35*\pi/64$, $3*\pi/2$. Assume the SNR are, respectively 0, 10, 20. 30, 40 and 50 dB, we do a simulation about the influence of the receiving signal SNR to the resolution of the algorithm as shown in Fig. 4. Obviously, the higher the SNR, the higher the resolution of the algorithm. Assume the SNR is 50dB, the receiving antenna of the GPR is uniform linear array and the number of the array is 10.And assume there are two receiving signal, the normalized frequency interval are respectively $\pi/100$, $\pi/50$, $3*\pi/100$, $\pi/25$.The influence of the different normalized frequency interval to the resolution of the algorithm as shown in Fig. 5. The results show that the algorithm apply to multi signal recognition when the normalized frequency interval is bigger than $3*\pi/100$.

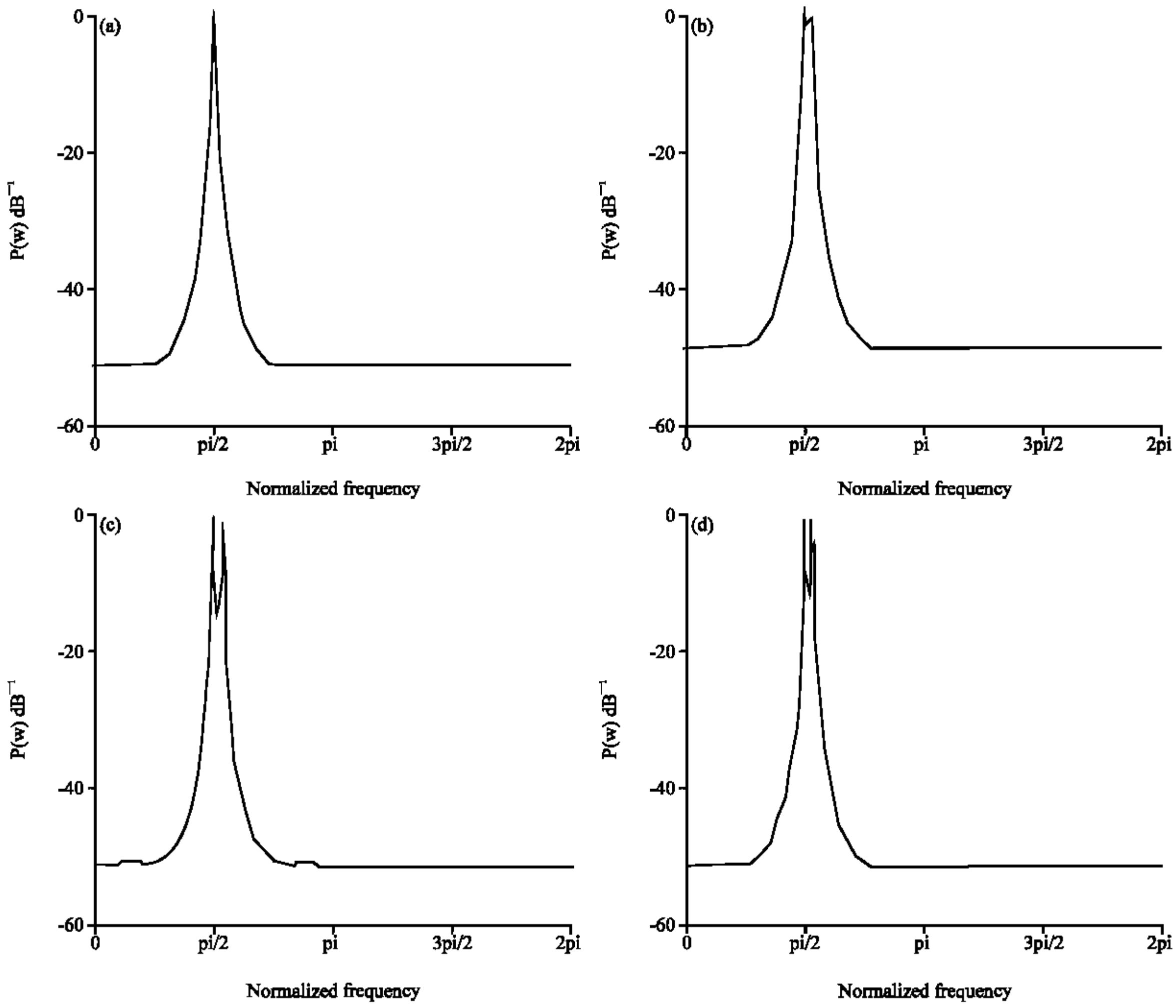

Fig. 5(a-d): Performance in different frequency interval, (a) Normalized frequency interval is pi/100, (b) Normalized frequency interval is 2*pi/100, (c) Normalized frequency interval is 3*pi/100 and (d) Normalized frequency interval is 4*pi/100

CONCLUSION

According to the features of coal medium, then analysis of the propagation loss and the reflecting loss of the electromagnetic wave in mixed medium of the coal seam. Because of the reflection loss is closely related to relative permittivity of the target medium, it can use the strength of the received electromagnetic waves and the emitted electromagnetic waves and to combine the propagation distance that electromagnetic waves in coal seam and the reflecting loss of the electromagnetic waves in the surface of the target medium to get the relative dielectric constant of the target medium and last, we can achieve the purpose of target recognition. The simulation shows the feature recognition of target media based on the Echo's electric field strength can effectively identify the target medium in the coal seam, thus judge the disaster which caused by gas and water in advance.

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