Study of Signal Processing Algorithm in the Receiving End of Through-the-Earth Communications of Elastic Wave

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Abstract – In the research of elastic wave signal detection algorithm, a method based on adaptive wavelet analysis and segmentation threshold processing of the channel noise removal methods is suggested to overcome the effect of noise, which is produced by absorption loss, scattering loss, reflection loss and multi-path effect during the elastic wave in the transmission underground. The method helps to realize extraction and recovery of weak signal of elastic wave from the multi-path channel, and simulation study is carried out about wavelet de-noising effects of the elastic wave and obtained satisfactory results.

Key words – ***through-the-earth communications of elastic wave*; *weak signal detection*; *adaptive wavelet analysis***

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1 Introduction

Scientific and technical workers, both at home and abroad are always interested in the research of exploring and developing the application of wireless communication system suited to mine. For half a century, the elastic wave receivers in earth exploration also stayed in constant development and perfection, with the rapid development of electronic technology, computer technology, communication technology and the elastic wave earth exploration technology. All sorts of effects to elastic wave propagating in strata are referred to as "strata effect"[1-2]. "Strata effect" which mainly includes wave-front diffusion, absorption effect, reflection and projection, influences the amplitude and frequency characteristics of the elastic wave arriving at the surface of the earth and produces serious interference to it. In order to achieve a high precision of elastic wave reception, necessary measures should be taken to restrain these interferences.

After the sending end of the through-the-earth communications of elastic wave sends elastic wave signal, the first arrived wave is the direct wave which spread directly from wave source to detector. Due to the shortest propagation distance and strongest energy of direct wave, it can make a sudden increase of the geophone output voltage. After the direct wave, the voltage drops sharply. Geophone output voltage will have a jump in the background of decline, whenever an interface reflection wave arrives at the detection point in the continuingly declining process of detector voltage. It can be said that the general trend of overall signal attenuation is caused by the wave-front diffusion and absorption effect. But the ups and downs superimposed in the whole attenuation curve are aroused by arrival of all reflected waves from different surfaces. Using wavelet filter to process these random noises is a kind of effective method to improve the accuracy of elastic wave on receiving.

2 Fundamental of Wavelet Transform (WT)

Wavelet analysis is an analytical method to signal in time scales (time-frequency)[3-5]. If the signal which stays for analysis is an energy-limited one-dimensional function, its continuous wavelet transform is defined as

$$W_{ab}(a,b)=\langle f(x),\psi_{ab}(x)\rangle = \frac{1}{\sqrt{a}}\int_R f(x)\,\overline{\psi(\frac{x-b}{a})}\mathrm{d}x. \qquad (1)$$

In the formula, a is the scale factor, b is the translation factor, $\frac{1}{\sqrt{a}}$ is the normalized factor, the family of functions of wavelet $\psi_{ab}(x)=\frac{1}{\sqrt{a}}\psi(\frac{x-b}{a})$ is obtained by translation and expansion of the mother wavelet $\psi(x)$.

Continuous wavelet transform expressed by the formula (1) is often used in theoretical analysis. $a=2^m$ is called the scale parameter, witch indicates the frequency width of the basic function of wavelet, and decides the frequency information after signal conversion. $b=n2^m$ is called location parameter, which indicates the location of

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the basic function of wavelet, and decides the temporal information after signal conversion.

The family of functions of the discrete wavelet usually used in practical application as follows can be obtained by discretizing the family of functions of the continuous wavelet $\psi_{ab}(x)$ by $a = 2^m$ and $b = n2^m$.

$$\psi_{m,n}(m,n) = 2^{-m/2}\psi(2^{-m}t - n). \tag{2}$$

So the discrete orthogonal wavelet transform is

$$\begin{aligned} W_{m,n}(m,n) &= \langle f(t), \psi_{m,n}\rangle = \\ &\int_{-\infty}^{\infty} f(t)\,\overline{\psi_{m,n}(m,n)}\mathrm{d}t = \\ &2^{-m/2}\int_{-\infty}^{\infty} f(t)\,\overline{\psi(2^{-m}t - n)}\mathrm{d}t. \end{aligned} \tag{3}$$

Using discrete orthogonal wavelet, then the signal can be expressed approximately with arbitrary precision as

$$f(t) = \sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty}\langle f(t), \psi_{m,n}(m,n)\rangle \psi_{m,n}(m,n). \tag{4}$$

In order to reflect the characteristics of signals, it requires both the outline characteristics and the detailed features of signals. In various scales, the wavelet transform is like a band-pass filter. By changing the scale factor m_0, we can make the various scales above m_0 corresponding to low-pass filter group with different bandwidth to extract basic characteristics. And we can make the various scales below m_0 corresponding to band-pass filter group with different center frequency to approximate the thinning characteristics and add details.

Measure signal S with length of 2^n can be decomposed in n layers by discrete wavelet transform to realize an analysis with multi-resolution:

Assume

$$\begin{aligned} C_{m,n} &= W_{m,n}(m,n) = \\ &\langle f(t), \psi_{m,n}(m,n)\rangle = \\ &\int_{-\infty}^{\infty} f(t)\,\overline{\psi_{m,n}(m,n)}\mathrm{d}t, \end{aligned} \tag{5}$$

and

$$C_{m,n} = \sum_l C_{m-l,l}h(l-2k), \tag{6}$$

$$D_{m,n} = \sum_l D_{m-l,l}g(l-2k). \tag{7}$$

In this formula, $h(l)$ and $g(l)$ are wavelet filter banks. $h(l)$ is a low-pass filter, while $g(l)$ is a high-pass filter.

Formula for wavelet coefficients reconstructing

$$C_{m-1,l} = \sum_l C_{m,l}\bar{h}(l-2k) + \sum_l D_{m,l}\bar{g}(l-2k). \tag{8}$$

The process of wavelet decomposition and reconstruction with signal S can be shown as Fig. 1.

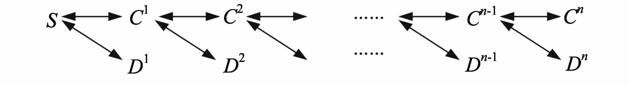

Fig. 1 Wavelet decomposition and reconstruction process

In Fig. 1, → represents the wavelet decomposition, ← represents signal reconstruction, C_j is the part with frequency no more than 2^{-j}, D_j is the part with frequency from 2^{-j} to 2^{-j+1}.

3 The realization of wavelet de-noising in through-the-earth system with elastic wave

Nonlinear filtering can be realized with wavelet transform according to the different characteristics of signal and noise. This method can improve SNR of the system, and it has high time (position) resolution and not sensitive to the form of signal. Therefore wavelet transform is particularly suitable for the weak signal detection in through-the-earth system with elastic wave[6-7], and traditional filtering methods are incomparable with it. The process of threshold de-noising algorithm for the received waveform of through-the-earth system with elastic wave is shown as follows.

1) Take samples of the received signal $f(t)$ with noise to get $f(k)$.

2) Chose a suitable wavelet function to do wavelet decomposition of N layers with the signal, and get wavelet coefficient w_i in each scale.

3) Extract low-frequency wavelet coefficients and high-frequency wavelet coefficients of each layer.

4) Select wavelet coefficients with soft threshold.

5) Do threshold processing with high-frequency wavelet coefficient of each scale, and get estimated value of wavelet coefficient $\hat{w}_i$.

6) Make wavelet reconstruction using estimated value of wavelet coefficient to get the de-noising signal $\hat{f}(k)$ which is the estimated value of $f(t)$.

7) Does SNR meet the requirement? Yes, go to 2), while No, going to the End.

3.1 The wavelet decomposition of elastic wave in receiving end

Due to the in-homogeneity of the earth medium and the particularity of the elastic wave propagation, elastic wave will be decayed by many factors, such as wave-front diffusion, dielectric absorption and transmission loss. That makes the received elastic wave signals contain both steady signals and noises, also contain non-stationary signals and noises changing along with time. Therefore, we adopt adaptive wavelet algorithm to do wavelet decomposition, according to partial characteristics of the signal and adaptively selecting wavelet analysis function. Choose a wavelet and confirm N as layers of wavelet decomposition, then we do N layers wavelet decomposition with the signal.

The specific realizing process is: Setting the initial conditions for data $\beta_{J+1,k} = y(t_k)/\sqrt{n}$, and then making filtering processing with orthogonal mirror filter, getting wavelet coefficients with noise $j = j_0, j_1, \cdots, J$; $k = 0, 1, \cdots, 2^j - 1$.

3.2 The threshold processing with high frequency coefficients of elastic wave wavelet decomposition

Choose a threshold for each layer to make threshold processing with the coefficients from the first layer to the N layer. There are two kinds of processing methods: Set W for the wavelet coefficients, W_λ is wavelet coefficient after imposing the threshold, and λ is the threshold.

1) Soft threshold. When the absolute value of wavelet coefficients is less than the given threshold, make it to 0, and while it is more than the threshold, make it to subtract the threshold, that is

$$W_\lambda = \begin{cases} [\mathrm{sign}(W)](|W| - \lambda), & |W| \geqslant \lambda; \\ 0, & |W| < \lambda. \end{cases} \tag{9}$$

2) Hard threshold: when the absolute value of wavelet coefficients is less than the given threshold, make it to 0, and when it is more than the threshold, keep its constant, that is

$$W_\lambda = \begin{cases} W, & |W| \geqslant \lambda; \\ 0, & |W| < \lambda. \end{cases} \tag{10}$$

From the perspective of minimum norm errors, hard threshold processing method is better than the soft threshold. But the estimating signals obtained form hard threshold processing will usually have many oscillations out of expectation, and they do not have the same smoothness with the original signal. Considering that the estimated signal $\hat{x}$ obtained by adopting soft threshold processing methods is equally smooth with the original signal x , and compared with the original signal x,$\hat{x}$ does not generate additional oscillation. Adopt the soft threshold processing method with optimal estimation under the reduced condition to estimate the signals in elastic wave de-noising and extraction of through the earth communication in a permitted error range.

In the choice of de-noising threshold, we choose different thresholds for different wavelet functions. And the thresholds adopted are related to the scales of different layers. The specific realizing process is:

1) Calculate the initial threshold respectively in every signal section

$$t_0(i) = \sigma\sqrt{2\ln N}. \tag{11}$$

2) Among them, σ is the strength of noise, N is decomposing layers.

3) The threshold of level j, $t_j(i) = a^{j-1}t_0(i)$, when $a = 0.5$ and it has a good performance. And j is the stage number of wavelet decomposition.

Use the soft threshold processing function sign $(W)(|W| - t_j(i))_+$ to do data processing. And calculateas $\alpha_{j,k}$ the estimate of wavelet coefficient $\omega_{j,k}$, according to the floating threshold $t_j(i)$.

3.3 One-dimensional wavelet reconstruction with elastic wave

Do wavelet reconstruction with one-dimension elastic wave signals according to low-frequency coefficient of the N layer of elastic wave wavelet decomposition and the high frequency coefficients from the first layer to the N layer after threshold processing. The specific realizing process is making all the wavelet coefficients $\alpha_{j,k} = 0$, when $j > J$. Then do inverse wavelet transformation and reconfiguration to recover the sub-carrier signal $f(t)$.

4 Simulation analysis

This paper adopts Blocks, one of the MATLAB 6.5 simulation signals superimposed with Gaussian white noise, to simulate elastic wave transmitting through the earth channel. The total leogth of data is 2 100, and the signal being to processing is shown in Fig.2. The Gaussian white noise used to simulate the additive noise in earth channel is evenly distributed in the range of $[-1,1]$. And use Db1 wavelet function to process. The largest scale of wavelet transform is $N=3$. Make adaptive wavelet analysis and threshold processing with the received elastic wave signal shown in Fig.2. And the recovered elastic wave signal is shown in Fig.3.

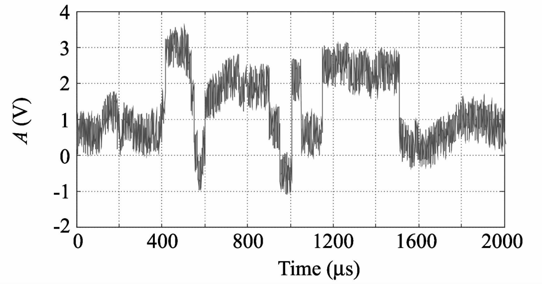

Fig.2 Irregular square-wave signal with white noise

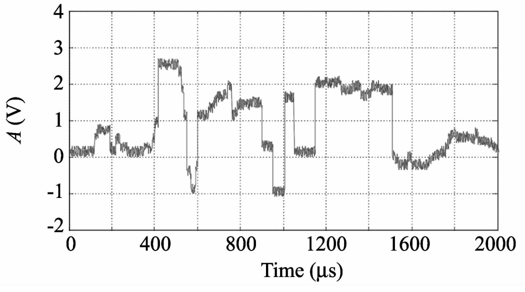

Fig.3 De-noising results using sub-adaptive wavelet and sub-threshold

The analysis of wavelet de-noising simulation results about the received waveform in through-the-earth system with elastic wave. From Fig.3, we can conclude that using variable threshold de-noising and adjusting the threshold according to the noise variance in each layer of wavelet decomposition, the additive noises of earth channel are almost completely eliminated. The waveform of elastic wave after reconstruction retains a curve profile with sharp steep change as original signal. These two characteristics overcome the shortcoming of de-noising processing simply with fixed thresholds. And it achieved the effect of squelch processing about received waveform of through-the-earth system with elastic wave.

5 Conclusion

In through-the-earth communication system with elastic wave, the "strata effect" of earth channel produces serious interference to the transmission of elastic wave. In order to receive the elastic wave with high-precision, we did wavelet filtering processing with these noises. In order to improve the SNR and receiving sensitivity, we adopted wavelet analysis method which has a better performance and is particularly suitable for weak signal detection to extract the signals transmitted through the earth, on the basis of the introduction of the basic principle of wavelet transform. This paper mainly used an earth channel de-noising method based on adaptive segmented wavelet analysis and segmented threshold processing including wavelet decomposition of elastic wave, threshold processing with high frequency coefficients of elastic wavelet decomposition and one-dimensional wavelet reconstruction for elastic wave, etc. as the procedure. Finally, we did simulation with wavelet de-noising effects of the elastic wave and obtained satisfactory results.

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