A New De-Noising Method for Ground Penetrating Radar Signal

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Abstract. The de-noising of data has become the key problem of ground penetrating radar (GPR) research. In this paper, the de-noising method based on combination of complete ensemble empirical mode decomposition (CEEMD) and wavelet decomposition is proposed. By combining CEEMD and wavelet decomposition, the effective signal information can be extracted from the removed intrinsic mode function (IMF) components in de-noising based on CEEMD. Numerical simulation results show that the quality of the GPR signal can be obviously improved by using the combination method.

Keywords: GPR, CEEMD, wavelet, de-noising.

1. Introduction

GPR method is one of the geophysical prospecting methods, so as to understand the distribution of the electromagnetic characteristics of the medium or extract a certain object embedded. It is widely used in civil engineering because of its several advantages such as high precision, non-destructive characteristics, the portability of the equipment, relative low cost of the survey and so on. However, there are still many problems to be solved for the successful introduction of GPR technology. Especially, the de-noising of GPR data is one of the core tasks. In de-noising of data, it is important to decompose signal according to frequency and statistic characteristics of the noise and the effective signal. To achieve this target, it is used the composition methods like Fourier transform, Karhunen-Loève (KL) transform, empirical mode decomposition (EMD), wavelet decomposition and so on. So, let's take a look at the EMD and wavelet decomposition.

EMD that was proposed by Huang et al. is an adaptive signal analysis method suitable for processing nonlinear and non-stationary signals. EMD are widely used in processing various signals. Yu et al. applied EMD and local mean decomposition (LMD) method to de-noising of the earthquake signal, and experimental results showed that LMD and EMD have a good performance of de-noising signal simultaneously [1]. R.Ostoori et al. introduced a GPR random noise reduction method using BPD in combination with EMD methods [2]. Compared with the traditional Fourier transform,
wavelet transform and S transform, EMD does not need to set the basis function before decomposition. However, EMD also has some disadvantage such as the mode mixing. In order to resolve the problem of mode mixing in EMD, ensemble empirical mode decomposition (EEMD) based on original signal plus Gaussian white noise is proposed, this method can effectively overcome the mode mixing phenomenon of EMD, but there are still some problems such as percentage of adding white noise and residual noise of reconstructed signal. To resolve these problems, CEEMD is proposed and successfully applied to process of signal. CEEMD is applied to the fault diagnosis of rolling bearing [3], GPR signal de-noising [4], nuclear magnetic resonance signal noise reduction [5], etc.

Then, the wavelet de-noising method is widely applied to the de-noising of various signals, because of its advantage like simple algorithm and superb effect. Recently, scholars are investigating in two aspects, the improving of threshold function and the combining of wavelet method and other method. It is well known the hard, soft, semi threshold and nonnegative garrote threshold function as conventional function. Zhang et al. proposed the method added a new parameter to threshold function to resolve the disadvantages of hard and soft threshold method and Lin et al. calculated optimal value of the parameter by using midpoint method [6, 7]. To increase the flexibility and capability of nonnegative garrote method, Nasri et al. added three shape tuning factors to the threshold function [8]. Liu et al. proposed a new wavelet threshold function based on noise variance estimation and then proved that it can effectively eliminate the interference of transient signals [9]. Zhang et al. improved the quality of magnetic resonance image by proposing a new threshold function in a wavelet de-noising method [10]. In the wavelet de-noising method, proper selection of the threshold value is also very important. Various threshold selection methods are introduced in [11-13], and Zhou et al. proposed a new choice algorithm [14].

Recently, scholars have applied modern signal processing methods to GPR data, and achieved many results. However, there are not so many researches on combined utilization of various data processing methods in processing of GPR data. This paper aims to evaluate the validation of de-noising method based on combining of CEEMD and wavelet decomposition. Experiment results show that the combination approach has better signal-to-noise ratio (SNR) and root mean squared error (RMSE) than the individual method based on CEEMD or wavelet composition.

2. CEEMD

CEEMD is a new proposed signal decomposition method to overcome the shortcomings of EMD and EEMD. This method can not only effectively overcome the mode mixing phenomenon in the EMD but also reduce residual white noise and resolve the complicated processing problems in EEMD. In CEEMD algorithm, Gaussian white noise with plus and minus signs is respectively added to raw signal, this make effectively reduced the final white noise residue. The procedure of CEEMD algorithm is as following:

Step1: Two signals are generated according to Eq.1.

\[ x_1^i(t) = x(t) + n^i(t) \]
\[ x_2^i(t) = x(t) + n^i(t) \]  

Where \( x(t) \) is the original signal, \( n^i(t) \) is the added white noise and \( i = 1 \sim m \) is iteration times.

Step2: \( x_1^i(t) \) and \( x_2^i(t) \) are decomposed by using EMD method and intrinsic mode function \((\text{imf}_{1,j}^i, \text{imf}_{2,j}^i)\) components and a residual \((R_1^i, R_2^i)\) are obtained.
Where $n$ is the number of IMF components in each decomposition.

Step3: The above steps are repeated several times ($m$) and two sets of ensemble IMFs are obtained. The final IMF is the sum average of both the IMFs.

\[
{x_1^i(t) = \sum_{j=1}^{n} imf_{1,j}^i + R_{1}^i}
\]

\[
{x_2^i(t) = \sum_{j=1}^{n} imf_{2,j}^i + R_{2}^i}
\]

3. Wavelet de-noising method
The wavelet de-noising method is based on the difference of statistic characteristic between effective signal and noise in raw signal. The energy of noise is approximately concentrated on the small wavelet coefficient and the energy of effective signal is mostly concentrated on the large wavelet coefficient. Therefore, if a certain threshold value is set, larger decomposition coefficients than the threshold are remained and smaller one be 0, then the noise can be effectively eliminated. This is just the principle of hard thresholding. In addition, there are soft thresholding, semi-thresholding, nonnegative garrote thresholding and various advanced thresholding rules.

The wavelet de-noising procedure is as following:

Step1: The basis wavelet and decomposition layer are selected reasonably, and then the detail and approximation coefficients are obtained by decomposing signal.

Step2: The thresholding method is applied to the detail coefficients and the new detail coefficients are obtained.

Step3: The signal is reconstructed with the new detail coefficients.

4. GPR data de-noising based on combination of CEEMD and wavelet decomposition
GPR technology uses electromagnetic wave signal with a wide frequency band so as to keep as much effective information as possible. Therefore, in addition to the effective information, a large number of noises will be also recorded at the same time in GPR data.

\[
{r(t) = s(t) + n(t)}
\]

Where $r(t)$ is the received wave in GPR, $s(t)$ is the effective wave and $n(t)$ is the noise.

Now there are many methods in de-noising of the GPR data. The method based on wavelet decomposition and CEEMD is widely used in processing GPR data.

The de-noising method based on CEEMD also achieves the purpose of de-noising by removing one or more IMF components corresponding to noise after decomposition. Choice of removed one or more IMF components are carried out by autocorrelation analysis. However, at this time, because the removed mode components still include some effective information of signal, the de-noising result make be rough, even can lead to signal distortion.

So, we combined CEEMD with wavelet de-noising method and applied to the de-noising of GPR signal. Firstly, the raw signal is decomposed by CEEMD. At this time, the obtained IMF components
can be divided into high-frequency components and low-frequency components according to their autocorrelation characteristics. Then, the high-frequency IMF components are processed by wavelet threshold method, and the low-frequency IMF components remain unchanged. Finally, the de-noised signal can be obtained by reconstructing the modified IMF component.

5. Numerical experiment and result analysis
To compare combination de-noising method with CEEMD and wavelet method, we carried out the de-noising process for GPR signal. We add a Gaussian white noise being SNR=5dB to a synthetic GPR data and the results are shown in Fig. 1 (a). Then, the three methods (CEEMD, wavelet and combination method) are used to de-noise this noisy GPR data.

![Fig. 1 The noisy GPR data (a) and de-noised GPR data: (b) CEEMD, (c) wavelet, (d) combination method](image)

Fig. 2 (a) is the result of 4-level wavelet decomposition of the noisy data (Fig.1 (a). The approximation coefficient reflects the effective signal information and other detail coefficients reflect the noise. We carried out the process of soft threshold for detail coefficient, reconstruct the signal (Fig.1(c)), and improved SNR from 5 to 16.05 (Table 1).

Fig. 2 (b) is the CEEMD decomposition result of the noisy data (Fig. 1(a)). CEEMD decomposition result showed that Imf1-Imf3 components are corresponding to noise, and the other components are corresponding to the effective signal. This can be clearly known through its autocorrelation analysis.
We improved SNR from 5 to 14.98 (Table 1) by removing the Imf1-Imf3 components and reconstructing the signal (Fig. 1(b)).

Different from the CEEMD method, the wavelet threshold processing is carried out on the components that are directly removed, and the signal is reconstructed (Fig. 2(d)). As seen the results of de-noising (Fig. 1 (b-d) and Table 1), the combination method has a significant advantage over CEEMD and wavelet one.

**Table. 1 Result of GPR data de-noising by CEEMD, wavelet and combination method**

| Data type              | SNR (dB) | RMSE  |
|------------------------|----------|-------|
| Noisy data             | 5        | 109.91|
| CEEMD de-noising       | 14.98    | 67.68 |
| Wavelet de-noising     | 16.05    | 37.21 |
| Combination de-noising | 17.16    | 30.63 |

6. Conclusions

In this paper, combination de-noising method of CEEMD and wavelet soft thresholding applied to processing of GPR signal. The numerical experiment results show that the combination method proposed in this paper can improve the SNR of raw signal and reduce RSME than individual applying method. Recently, in many papers, a variety of advanced wavelet thresholding rule and threshold calculation methods are proposed to improve the effect of de-noising. In the empirical mode decomposition method, a lot of investigations have been carried out so as to simplify the algorithm and improve the accuracy and efficiency of calculation. In addition, in de-noising method based on empirical mode decomposition, the investigation into introducing the threshold method is carried out. However, as an individual use method, it can only improve the signal quality to a certain extent. In order to further improve the quality of signal, it is necessary to combine various de-noising methods. If we combine the advanced individual de-noising methods properly, the signal quality will be further improved.

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