The research on denoising of long-offset transient electromagnetic stacked signals based on windowed interpolation and singular spectrum analysis integration.

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SUMMARY

The Long Offset Transient Electromagnetic method is a widely used electromagnetic exploration technique. However, due to external interference, the signals collected by this method often contain a large amount of noise, seriously affecting the credibility of subsequent inversion interpretation. Therefore, this paper proposes a research on denoising of stacked signals based on the combination of windowed interpolation and singular spectrum analysis. Firstly, the superposition method and windowed interpolation method are used to remove most of the random noise and power frequency and its harmonic noise. Then, through singular spectrum analysis, further noise suppression is applied to the signals to obtain higher quality data. Through validation, this method can effectively remove noise interference from underground media, providing important technical support for inversion interpretation.

Keywords: Long offset transient electromagnetic method, signal denoising

INTRODUCTION

The Long Offset Transient Electromagnetic (LOTEM) method is an important geophysical exploration technique. LOTEM data acquisition often includes complex and diverse types of noise interference; therefore, denoising LOTEM signals is a crucial foundational task prior to inversion and interpretation.

In the denoising methods for LOTEM (Long Offset Transient Electromagnetic) signals, the periodic stacking method is widely applied (Macnae J C et al., 1992). This approach first excludes cycles of poor quality from the signal, then employs periodic stacking to denoise the signal, effectively eliminating most random noise interference. Wavelet denoising is another primary method for LOTEM signal denoising. This technique can accurately identify noise signals that differ from the trend of the effective signal. It then stretches, compresses, and shifts the segments of the signal to magnify them before denoising, which shows considerable efficacy in mitigating white noise and telluric noise (Bouchedda et al., 2010; Mao Xinxin et al., 2021). Additionally, several filtering algorithms such as median filtering (Cui Z et al., 2005), adaptive filtering (Zhou Yuxuan, 2018), and digital recursive notch filtering (Zhang Wenwei et al., 2020) have demonstrated certain effectiveness. In this paper, based on the characteristics of LOTEM noise signals, a noise suppression process and method integrating windowed interpolation and singular spectrum analysis is proposed on the foundation of signal stacking.

METHODS

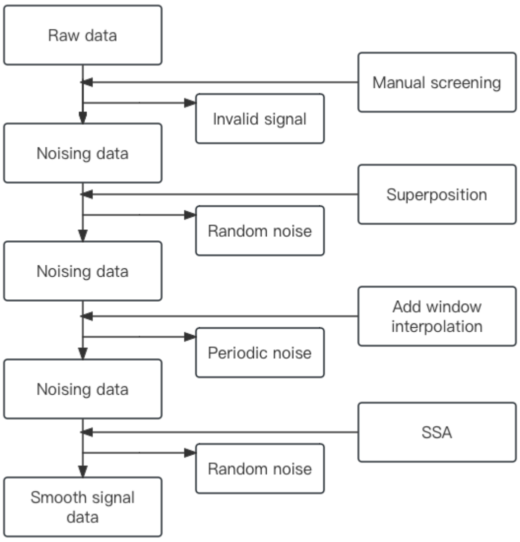

Figure 1. Flowchart of this method of denoising

As illustrated in Figure 1, the LOTEM denoising process initially involves manual screening to eliminate invalid periodic signals. Subsequently, the method of multi-cycle and polarity signal stacking is employed to remove substantial random interference. The signal is then processed using the windowed interpolation method, which accurately calculates the relevant parameters of the fundamental frequency and its harmonics of fixed interference signals, thereby achieving the removal of periodic noise. Finally, singular spectrum analysis is utilized to effectively identify and separate the useful signal from the noise, ultimately obtaining a high-quality LOTEM secondary field decay curve.

Windowed Interpolation Method

The windowed interpolation method is a commonly used technique in power signal analysis for computing the parameters of various harmonics, including amplitude, frequency, and phase.

Without loss of generality, let the m-th harmonic signal be:

$$x_{ma}(t) = A_m \cdot e^{j(2\pi f_m t + \varphi_m)} \tag{1}$$

After windowing and truncation, the signal sequence is:

$$x_m(n) = x_{ma}(nT_s) \cdot w_h(n)m, (n = 0,1, \dots, N-1) \tag{2}$$

In the equation, $x_{ma}(nT_s)$ represents the infinite-length sampled sequence of $x_{ma}(t)$, T_s is the sampling period, $w_h(n)$ denotes the Hanning window, N is the number of sampling points, and f_m is the harmonic frequency.

The frequency spectrum of the infinite-length sampled sequence $x_{ma}(nT_s)$ is:

$$X_{ma}(e^{j\omega}) = 2\pi\delta(\omega - \omega_m)e^{j\varphi_m} \tag{3}$$

In the equation, $\omega_m = 2\pi f_m / f_s$.

Based on the properties of the Fourier transform, the Discrete-Time Fourier Transform (DTFT) of the sampled sequence $x_m(n)$ truncated with a window, is given by:

$$\begin{aligned} X_m(e^{j\omega}) &= \frac{1}{2\pi}\int_{-\pi}^{+\pi} X_{ma}\left(e^{j\theta}\right) w_h\left[e^{j(\omega-\theta)}\right] d\theta \\ &= w_h(\omega - \omega_m) \cdot e^{j\left(\varphi_m - \frac{N-1}{2}\right)\omega} \end{aligned} \tag{4}$$

Furthermore, let the discrete frequency points corresponding to the sampled harmonic signal sequence be:

$$k_m + \delta_m = N \cdot f_m / f_s \tag{5}$$

Where k_m is an integer, $0 \le \varphi_m < 1$.Considering that the number of sampling points N is generally large, and $|\varphi_m| < 1$:

$$\left|X_m(e^{j\omega})\right|_{\omega = k_m \frac{2\pi}{N}} \approx \frac{A_m sin(\pi\delta_m)}{2\delta_m(1-\delta_m)(1-\delta_m)\pi} \tag{6}$$

$$\left|X_m(e^{j\omega})\right|_{\omega = (k_{m+1})\frac{2\pi}{N}} \approx \frac{A_m sin(\pi\delta_m)}{2\delta_m(1-\delta_m)(2-\delta_m)\pi} \tag{7}$$

Let the $\beta_m = \frac{\left|X_m(e^{j\omega})\right|_{\omega = k_{m+1}\frac{2\pi}{N}}}{\left|X_m(e^{j\omega})\right|_{\omega = k_m \frac{2\pi}{N}}}$,then:

$$\delta_m = \frac{2\beta_m - 1}{1 + \beta_m} \tag{8}$$

The estimates of harmonic amplitude, frequency, and phase can be obtained from equations (4) and (8) as follows:

$$A_m = \left|X_m(e^{j\omega})\right|_{\omega = k_m \frac{2\pi}{N}} \cdot \frac{2\pi\delta_m(1-\delta_m)(1-\delta_m)}{sin(\pi\delta_m)} \tag{9}$$

$$f_m = (k_m + \delta_m)/t_p \tag{10}$$

$$\varphi_m = angle\left(\left|X_m(e^{j\omega})\right|_{\omega = k_m \frac{2\pi}{N}}\right) - \pi\delta_m(N-1)/N \tag{11}$$

Singular Spectrum Analysis

The denoising principle of Singular Spectrum Analysis (SSA) lies in the use of Singular Value Decomposition (SVD) to separate the main components of a time series, such as trends and periodicities, from noise. Noise typically manifests as smaller singular values and their corresponding singular vectors. By selecting and retaining the singular values and vectors associated with the main components, and reconstructing the time series accordingly, SSA effectively removes noise while preserving the primary features of the signal. If one-dimensional LOTEM data is represented as y(n)=[y(1),y(2),…,y(N)] the algorithm proceeds through the following stages:

- Embed

  The embedding can be viewed as a delayed mapping process that maps the aforementioned one-dimensional LOTEM data into a trajectory matrix Y of dimension L*K.

$$Y = \begin{bmatrix} y(1) & y(2) & \dots & y(K) \\ y(2) & y(3) & \dots & y(K+1) \\ \vdots & \ddots & \dots & \vdots \\ y(L) & y(L+1) & \dots & y(N) \end{bmatrix} \tag{12}$$

Here, L represents the embedding window length, which is an integer satisfying 1 < L < N; K = N - L + 1.

- Singular Value Decomposition

Performing singular value decomposition (SVD) on the trajectory matrix Y:

$$Y = U\Sigma V^T \tag{13}$$

Where $U \in R^{L\times L}, \Sigma \in R^{L\times K}, V \in R^{K\times K}$. The above expressions can be written in the form of a sum of column vectors multiplied by row vectors:

$$Y = \sum_{i=1}^{r} \sigma_i u_i v_i^T = X_1 + X_2 + \cdots + X_r \tag{14}$$

Here, r denotes the rank of matrix Y, which also represents the number of non-zero singular values.

- Grouping

The purpose of grouping is to decompose the matrix Y into linearly independent submatrices:

$$X = X_1 + X_2 + \cdots + X_m \tag{15}$$

The process of Equation 11 is as follows: first, the singular values are grouped into m sets, denoted as $\{I_1, I_2, \ldots, I_m\}$.

- Diagonal Averaging

For each group $\{I_1, I_2, \ldots, I_m\}$,the matrices undergo diagonal averaging. Each group results in a sequence of length N=L+K-1.Summing these m vectors yields the reconstructed values of the original time series y.

SIMULATION EXPERIMENT

This study utilized the LOTEM forward modeling algorithm to generate theoretical response signals with a sampling rate of 1000 Hz and a period of 1 second. To simulate noisy LOTEM acquisition signals, 50 Hz power line noise and its harmonics, Gaussian white noise with a signal-to-noise ratio of 10 dB, and random impulse noise were added. Figure 2 presents the attenuation curve and the spectrum of the noisy LOTEM signal.

Firstly, the noisy LOTEM signal was subjected to periodic stacking. The attenuation curve and the spectrum of the stacked signal are shown in Figure 2. It is evident that most of the random noise has been effectively removed, leaving only a small amount of random noise and periodic noise at the power line frequency and its harmonics.

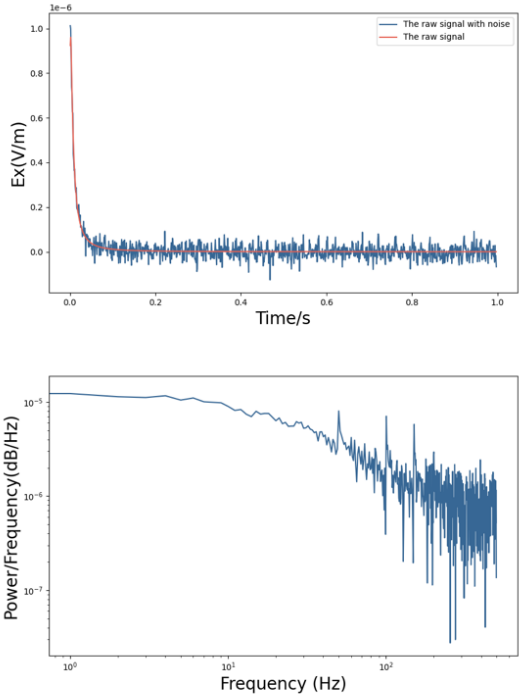

Figure 2. Original signal and after-noising signal attenuation curve and its spectrum

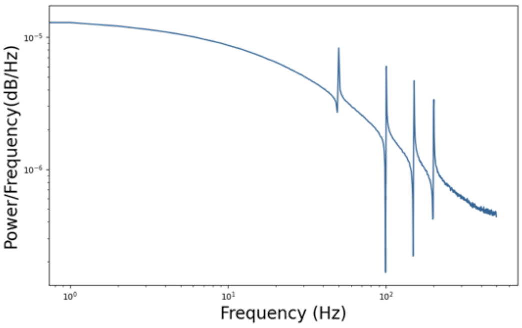

Figure 3. Signal spectrum after denoising by superposition

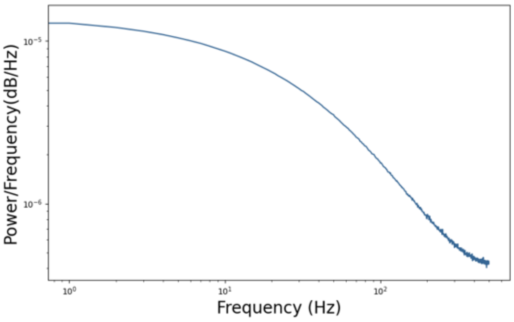

Figure 4. Signal spectrum after denoising by window interpolation

Windowed interpolation was employed to remove the 50 Hz noise and its harmonics. Figure 3 shows the spectrum of the signal after denoising using the windowed interpolation method. Building on the previous two methods, singular spectrum analysis (SSA) was applied for further denoising of the signal. Figure 4 presents the spectrum of the signal after denoising using SSA. It is evident that random interference, the 50 Hz power line frequency, and its harmonics have been largely eliminated.

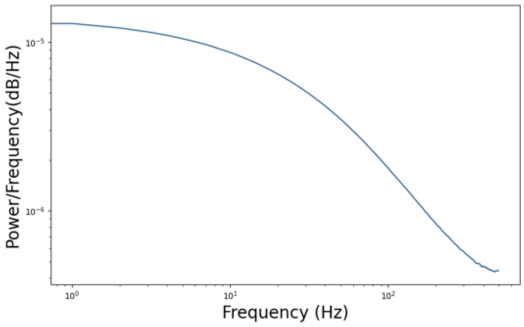

Figure 5. SSA denoising signal spectrum

According to the results shown in Table 1, before denoising, the signal had a root mean square error (RMSE) of 2.9810^-08 and a signal-to-noise ratio (SNR) of 8.29. After applying the denoising algorithm proposed in this study, the RMSE was reduced to 3.5910^-10 and the SNR was significantly increased to 46.66, representing a 5.6-fold improvement in SNR. These results indicate that the proposed algorithm substantially enhances the quality of LOTEM signals.

Table 1. Comparison of RSME and SNR before and after denoising of algorithm in this paper

Signal	RSME	SNR
Analog noise-containing signal	2.98*10-08	8.29
Denoising signal	3.59*10-10	46.66

CONCLUSION

This study builds on the periodic stacking of LOTEM signals by addressing random and characteristic frequency noise using windowed interpolation and singular spectrum analysis (SSA) for denoising. This approach can significantly enhance the signal-to-noise ratio (SNR) of actual LOTEM acquisition signals, providing reliable raw data for subsequent inversion and forward modeling.

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