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Noise Reduction Model of Blasting Seismic Wave Signal

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Abstract. The existence of noise will make the results of time-frequency analysis of blasting seismic wave lack of authenticity. In order to obtain the real blasting vibration characteristics, a method based on the complementary ensemble empirical mode decomposition with adaptive noise and establishing objective function is proposed. The process of noise reduction is divided into three steps. Firstly, the noise signal is decomposed by the complete ensemble empirical mode decomposition with adaptive noise, and the noise reduction algorithm is established based on the intrinsic mode function obtained from the decomposition; secondly, the objective function considering the smoothness of the noise reduction algorithm and its correlation with the measured signal is established; finally, the algorithm corresponding to the optimal solution of the objective function is found, which is the noise reduction model of blasting seismic wave signal. The model is analyzed by the noise reduction error ratio. The analysis results show that the model can reduce the noise of the seismic monitoring signal with noise on the premise of fully preserving the real components of the blasting seismic signal.

1. Introduction

The blasting seismic wave signal has strong background noise and non-stationary characteristics ^[1], which results in the lack of authenticity of the time-frequency analysis result of the blasting seismic wave signal. It is difficult for time-frequency analysis method to extract reliable characteristic parameters from blasting seismic signals to reflect the attenuation law of blasting vibration ^[2]. In order to obtain accurate blasting vibration characteristics, noise reduction must be performed on the blasting seismic wave signal ^[3-4].

At present, Empirical mode decomposition (EMD)^[5] and its improved algorithm^[6] have been widely used in noise reduction. The decomposition results of EMD under noise interference will cause modal confusion^[7], and the impact of its improved algorithm on the completeness of the original signal cannot be completely removed^[8].

In summary, this paper proposed a noise reduction model based on the complementary ensemble empirical mode decomposition with adaptive noise (CEEMDAN) and establishing objective function. CEEMDAN plays the role of noise reduction in the first stage; controlling the smoothness coefficient in the objective function can perform noise reduction in the second stage; controlling the correlation coefficient in the objective function can avoid excessive noise reduction. The obtained noise reduction model is used in the actual seismic wave signal noise reduction processing, and the noise reduction effect of the model is analyzed by the noise reduction error ratio ^[9].

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2. Complete Ensemble Empirical Mode Decomposition with Adaptive Noise

Complementary ensemble empirical mode decomposition with adaptive noise (CEEMDAN)^[10] is to add a limited number of adaptive white noises at each stage of the EMD, which can achieve a reconstruction error of almost zero with fewer average times. See reference [10] for the detailed decomposition process.

According to reference [10], it can be seen that after the original signal S(t) is decomposed by the CEEMDAN algorithm, *k* intrinsic mode functions(IMFs) and the remainder(R)^[11] can be obtained. See equation (1) for specific expression.

$$S(t) = \sum_{i=1}^{k} IMF_i + R \tag{1}$$

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A noise reduction algorithm (NR) is constructed based on the IMF obtained in equation (1). For the specific expression, see equation (2). R is ignored here.

$$NR = S(t) - \sum_{i=1}^{k} IMF_i$$
⁽²⁾

3. Establishing objective function

3.1. Correlation coefficient between NR and original signal

The method for calculating the correlation coefficient between NR and the original signal S(t) is shown in equation (3), where N is the number of sampling points, and x and y correspond to the S(t) and NR.

$$r_{xy} = \frac{\sum_{i=1}^{N} \left(x_i - \bar{x} \right) \left(y_i - \bar{y} \right)}{\sqrt{\sum_{i=1}^{N} \left(x_i - \bar{x} \right)^2 \left(y_i - \bar{y} \right)^2}}$$
(3)

According to equation (3), it can be known that the larger r_{xy} is, the higher the degree of similarity between NR and S(t) is, otherwise it is the opposite. The goal in this paper is to make r_{xy} as large as possible to preserve the authenticity of S(t).

3.2. Smoothness coefficient between NR and original signal

The smoothness coefficient between NR and S(t) is solved as follows. It is known that any smooth curve f(x) has a first-order continuous derivative in its domain, then the derivative at any point x_0 in its domain satisfies equation (4), Where *h* is the increment of *x*.

$$f_{-}'(x_{0}) = \lim_{h \to 0^{-}} \frac{f(x_{0} + h) - f(x_{0})}{h} = f_{+}'(x_{0}) = \lim_{h \to 0^{+}} \frac{f(x_{0} + h) - f(x_{0})}{h}$$
(4)

If f(x) is a smooth curve composed of u(x) and v(x), then the connection point w_0 (within the domain) of the curve also satisfies equation (5).

$$u'_{-}(w_{0}) = \lim_{h \to 0^{-}} \frac{u(w_{0} + h) - u(w_{0})}{h} = v'_{+}(w_{0}) = \lim_{h \to 0^{+}} \frac{v(w_{0} + h) - v(w_{0})}{h}$$
(5)

According to the definition of curvature, satisfying $K_{u|_{w=w0}}=K_{v|_{w=w0}}$ at w_0 , and then combining equation (5), equation (6) can be obtained, where $u''(w_0)$ and $v''(w_0)$ are the second derivative at w_0 . Expanding $u''(w_0)$ and $v''(w_0)$ in equation (6), we get equation (7) and equation (8) respectively.

$$u''(w_0) = v''(w_0) \tag{6}$$

$$v''(w_0) = \left[\frac{v(w_0 + h) - v(w_0)}{h}\right] = \lim_{h \to 0} \frac{v(w_0 + 2h) - 2v(w_0 + h) + v(w_0)}{h^2}$$
(7)

$$u''(w_0) = \left[\frac{u(w_0 + h) - u(w_0)}{h}\right]' = \lim_{h \to 0} \frac{u(w_0 - 2h) - 2u(w_0 - h) + u(w_0)}{h^2}$$
(8)

It is known that the derivable function must be continuous, and equation (6) to equation (8) can be sorted out to obtain equation (9). Equation (9) studies the smoothness of the combined curve. Then for any smooth curve y=f(x), the smoothness coefficient (r_{sc}) is shown in equation (10), where h is the sampling interval.

$$v(w_0 + 2h) - u(w_0 - 2h) - 2\left[v(w_0 + h) - u(w_0 - h)\right] = 0$$
(9)

$$r_{SC}\Big|_{x=x_0} = f(x_0 + 2h) - f(x_0 - 2h) - 2\Big[f(x_0 + h) - f(x_0 - h)\Big]$$
(10)

From equation (10), it can be found that the smaller r_{sc} is, the smoother the curve is around x_0 , and the higher the noise reduction degree is. By controlling r_{sc} , the degree of noise reduction can be controlled. Too high noise reduction will lead to the loss of the real components of S(t), so the control of r_{sc} is very important.

3.3. Establishing objective function considering correlation coefficient and smoothness coefficient

By setting the weight coefficient ξ , the objective function(F_{obj}), can consider both the smoothness of NR itself and the correlation between NR and S(t). The expression is shown in equation (11), and the relevant parameters are defined as before. Through the analysis of Sections 2.1 and 2.2, it can be seen that the NR at which F_{obj} obtains the minimum value is the noise reduction model of the blasting seismic wave.

$$F_{obj} = \xi \cdot \frac{1}{r_{xv}} + (1 - \xi) \cdot r_{SC}$$

$$\tag{11}$$

4. Application research on the noise reduction model of the measured blasting seismic wave signal

4.1. Project overview

Loushan Tunnel is located at the intersection of Luzetai First-class Highway and Dashi Line, and is the main traffic route. In order to meet the transportation needs, the original two-way four-lane tunnel was expanded in situ into a two-way eight-lane tunnel. During the closed construction period of the right tunnel, the left tunnel needs to be kept open to traffic.

According to the design of the construction organization, it is known that the distance between the right tunnel and the left tunnel during blasting is about 27 to 33m. The blast vibration monitoring adopts TC-4850 blast vibration meter, and the arrangement of measuring points is shown in Figure 1. It is necessary to consider the impact of blasting operation in the right tunnel on the left tunnel of maintaining traffic operation, and the noise reduction of blasting seismic wave signal is the first step of blasting hazard control.



Figure 1. Layout of measuring points

4.2. Processing of the measured signal by the noise reduction mode

According to the on-site blasting vibration monitoring plan, a typical blasting seismic wave monitoring signal is selected as the noise reduction processing object, as shown in Figure 2. Using CEEMDAN to decompose the signal in Figure 2, the decomposition results are shown in Figure 3.



Figure 2.Blasting seismic wave monitoring signal



Figure 3. Decomposition results of CEEMDAN

According to the analysis in Section 1, and based on the IMF obtained by CEEMDAN, the NR for the measured blasting seismic wave signal S(t) is established, as shown in equation (12).

$$\begin{cases}
NR_{1} = S(t) - IMF_{1} \\
... \\
NR_{6} = S(t) - \sum_{i=1}^{6} IMF_{i}
\end{cases}$$
(12)

The r_{sc} of NR₁-NR₆ and the reciprocal of correlation coefficient between NR and S(t) are calculated, and the results are shown in Table 1. In order to facilitate comparative analysis, the $1/r_{xy}$ and r_{sc} obtained in this paper are the result of linear standardization.

Table 1 Relevant parameters of noise reduction algorithm				
noise reduction	$1/r_{\rm xy}$	$r_{\rm sc}$	$F_{ m obj}$	
NR ₁	0.0237	1.0000	0.2189	
NR_2	0.0398	0.0948	0.0508	
NR ₃	0.2026	0.0076	0.1636	
NR4	0.3749	0.0006	0.3000	
NR5	0.4785	5.7581×10 ⁻⁵	0.3828	
NR_6	1.0000	7.8761×10 ⁻⁸	0.8000	

According to table 1, NR_1 is optimal when only correlation coefficient is considered. NR_6 is optimal when only the smoothness coefficient is considered. When the correlation coefficient and smoothness coefficient are considered comprehensively, NR_2 is optimal. Therefore, when the smoothness coefficient of NR and its correlation coefficient with the S(t) are considered comprehensively, the optimal noise reduction model of blasting seismic wave signal is NR_2 .

By further analysis, a comparison chart between the S(t) and NR₁-NR₆ is drawn. As shown in Figure 4, it can be found that NR₂ can retain the true information of the original signal and perform noise reduction. NR₅ and NR₆ excessively consider the smoothness of the algorithm, resulting in distortion of the noise reduction algorithm. In particular, NR₆ has deviated from the S(t). This result

reflects from the side that any noise reduction model cannot only consider a single noise reduction factor, but also should control the degree of noise reduction.



Figure 4. Comparison between noise reduction algorithm and S(t)

4.3. Analysis of Noise Reduction Effect of Measured Signal

Cite the noise reduction error ratio (*dnSNR*) formula in reference [9] to evaluate the noise reduction effect of the measured signal. See equation (13), where P_s is the noise-containing signal power and P_n is the noise reduction error power, and the *dnSNR* of NR₁-NR₆ is calculated by MATLAB.

$$dnSNR = 10\log_{10}\frac{P_s}{P_n}$$
(13)

Algorithm model	Ps	Pn	dnSNR
NR ₁	1.0903×10 ⁻⁶	5.1689×10 ⁻⁷	3.2413
NR ₂		9.6321×10 ⁻⁷	0.5381
NR ₃		9.2147×10 ⁻⁷	0.7298
NR ₄		9.2021×10 ⁻⁷	0.7372
NR ₅		9.1897×10 ⁻⁷	0.7408
NR ₆		9.0074×10 ⁻⁷	0.8278

Table 2 Noise reduction error ratio relative parameters

According to equation (13), it is known that the larger the dnSNR, the less obvious the noise reduction is. From Table 2, it can be seen that the noise reduction algorithm NR₂ has the best noise reduction effect. This result is consistent with the result of the optimal solution of the objective function, which reflects the rationality of the proposed model for blasting seismic wave noise reduction based on complementary ensemble empirical mode decomposition with adaptive noise and establishing objective function. Therefore, the noise reduction model of seismic wave signal proposed in this paper can be used in the noise reduction processing of seismic wave monitoring signal with noise. This model can reduce the noise of the original signal on the premise of retaining the real components of the original signal.

5. Conclusion

(1) Based on the IMF obtained by CEEMDAN, a noise reduction algorithm is established to realize the first stage of noise reduction. Considering the smoothness coefficient of the noise reduction algorithm to achieve the second stage of noise reduction, the correlation coefficient between the noise reduction algorithm and the original signal is controlled to avoid excessive noise reduction and retain the real components of the original signal.

(2) The comparison between the S(t) and NR shows that the noise reduction model cannot only consider a single noise reduction parameter. Pursuing noise reduction blindly will cause the true details of the original signal to be filtered by the noise reduction model.

(3) The noise reduction model of blasting seismic signal is evaluated by noise reduction error ratio. The results show that the noise reduction error ratio is consistent with the optimal solution of the objective function. It is scientific and reasonable to reflect the establishment of noise reduction model from the side.

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