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Hybrid Noise Reduction for Wind Turbine Blade Fault Diagnosis

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Abstract:

Accurate diagnosis of wind turbine blade faults relies heavily on the analysis of fan audio signals, which are often contaminated by noise. Effective noise reduction is essential to extract useful diagnostic information and ensure reliable analysis. Traditional spectral analysis techniques, such as Fourier transform-based filtering, face limitations in handling complex and non-smooth signals. Wavelet transform methods provide multi-resolution analysis but lack adaptive decomposition capabilities. Empirical Mode Decomposition (EMD) offers a promising solution by adaptively decomposing signals into intrinsic mode functions (IMFs) based on their inherent characteristics. This paper presents an improved noise reduction method that combines EMD thresholding with Savitzky-Golay filtering. High-frequency IMFs are processed using thresholding to preserve critical signal details, while low-frequency IMFs undergo Savitzky-Golay filtering to ensure smoothness. Experimental results on wind turbine blade audio signals demonstrate that the proposed hybrid approach achieves superior noise reduction performance compared to standalone EMD thresholding or filtering techniques, enhancing the reliability of fault diagnosis.

Keywords:

EMD; SG Filters; Noise Reduction Algorithm.

1. Introduction

The analysis of the fan audio signal is the key step of the fan blade fault diagnosis, however, the fan audio signal contains a large number of noise components in addition to the information useful for fault analysis. Only by effectively filtering out the noise can we obtain useful information and thus obtain a reliable analysis conclusion.

In traditional signal processing methods, noise reduction is achieved by spectral analysis techniques, i.e., the signal is mapped in the frequency domain for analysis using the Fourier transform. When the noise and the signal are separable in the frequency domain, a suitable filter can be designed to filter out the frequency band corresponding to the noise [1]. However, most of the signals have significant non-smoothness and their spectral components are very complex, so that the traditional filtering and noise reduction methods cannot meet the requirements.

Wavelet transform with "mathematical microscope" and multi-resolution properties is an important signal noise reduction method. Typical methods include threshold noise reduction based on the orthogonal wavelet transform [2]. However, the wavelet decomposition result obtained after the selected decomposition scale is a time-domain waveform of a fixed frequency band, and the included frequencies are only related to the analysis frequency of the signal, but not to the signal itself, from this point of view, the wavelet transform does not have the adaptive signal decomposition characteristics.

Empirical mode decomposition (EMD) is a new method for nonlinear and nonsmooth time series analysis proposed by E Norden, Huang et al [3] in 1998. The difference with the traditional signal analysis method is that it does not need to choose the basis functions in advance, but generates suitable intrinsic mode functions IMFs adaptively according to the characteristics of the signal itself, and these intrinsic mode functions can well reflect the local frequency characteristics of the signal at any time. A number of noise reduction methods based on empirical mode decomposition have been proposed, and these methods can be broadly classified into two categories. EMD noise reduction methods based on threshold processing [4]; EMD noise reduction methods based on filtering [5]. In this paper, we propose an improved EMD noise reduction method based on the combination of two types of methods, and the experiments show that the improved method exhibits good noise reduction performance and can be applied to the wind turbine blade sweeping audio signal noise reduction problem.

2. Organization of the TextWind Turbine Blade Sweeping Wind Sound Signal Characteristics

Wind turbines are usually established in high mountains, seaside and other places rich in wind resources, these places are usually harsher environments, and when collecting audio signals, some background noise from nature is bound to be collected. For example, wind whistling, rain and thunder, biological calls, some artificially caused by the sound and so on. These sound signals and blade sweeping wind sound mixed together, will cause greater trouble to our anomaly recognition work, but it is unavoidable. In this paper, the wind turbine blade sweeping wind sound collected in the field contains three types of environmental disturbance signals: biology specific call, wind sound, rain sound. After analysis, this paper classifies the three types of noise according to certain characteristics, as shown in Table 1.

Table 1. Fan blade sweeping wind audio noise composition

Interference noise	Noise Type	Noise duration/(s)	Noise frequency range/(Hz)
Creature calls	High frequency noise	1.5~5	5000~8000
The Sound of the Wind	Low frequency noise	Over 50	50~2000
Sound of Rain	Low frequency noise	Over 50	20~2500

As can be seen from the table, the noise data in the fan blade sweeping wind audio can be divided into two categories, one of which is distributed in the frequency range of 5000 Hz ~ 8000 Hz, which belongs to high frequency noise, and the other is in the frequency range of 20 Hz ~ 2000 Hz, which belongs to low frequency noise.

3. EMD Noise Reduction Method

The EMD method decomposes the signal into a finite number of implicit modal functions IME, each IME being a single component of the signal [6]. This method does not require prior selection of basis functions, but adaptively generates suitable representation functions according to the characteristics of the signal itself, and these representation functions can well reflect the local frequency characteristics of the signal at any time.

The EMD method has strong adaptive features in signal processing: (1) automatic generation of basis functions, the EMD method is direct and adaptive in the whole "sieving" process, unlike wavelet decomposition, which requires pre-selection of basis functions. (2) Adaptive filtering characteristics: EMD method decomposes the signal to obtain a series of IMF components containing different frequency components from high to low, unequal bandwidth, these frequency components and bandwidth are changing with the change of the signal. (3) Adaptive multi-resolution. Each IMF component contains different characteristic time scales, so that the signal characteristics can be displayed at different resolutions, so the EMD method can achieve multi-resolution analysis. These adaptive features make it show good performance in signal noise reduction processing.

3.1 Noise Reduction Method based on EMD Threshold Processing

The EMD Min-based noise reduction method can be described as follows: first decompose the noise-containing signal into a series of IME components, then determine a threshold value for each IMF component, use the threshold value to noise reduce each IMF component, and use the noise reduced individual IME components to reconstruct the signal to obtain the noise reduced signal.

The literature [4] utilizes a soft thresholding approach for signal noise reduction. The definition of the soft thresholding function used in the paper [8] is:

$$IM_j(t) = \begin{cases} IMF_j(t) - \tau_j & if \quad IMF_j(t) \quad \geq \quad \tau_j \\ 0 & if \quad |IMF_j(t)| \quad < \quad \tau_j \\ IMF_j(t) + \tau_j & if \quad IMF_j(t) \quad \leq \quad -\tau_j \end{cases}$$

r_jThe values were taken using the method in the literature [9].

$$\tau_j = \sigma_j \sqrt{2\log(N)}$$

$$\sigma_j = \frac{MAD_J}{0.6745}$$

where σ_j is the noise level of the jth IMF component and N is the signal length. MAD_J is determined by equation (1).

$$MAD_J = Median\{|\ IMF_j(t) - Median[IMF_j(t')]\ |\}$$

3.2 Savitzky-Golay Filter-based EMD Noise Reduction Method

Wenwen Zhao [5] obtained the modal decomposition of the noise-containing signal IMF . This filter is a convolutional sliding window weighted averaging algorithm, which can ensure that the shape and width of the signal remain unchanged when filtering the noise, and the obtained data waveform is as metadata waveform as possible, which is widely used for data smoothing and noise reduction. Let a data waveform with x(i).A window centered on 2M+1 data points, construct a p polynomial of order q(n) to fit this array, as in equation (2):

$$q(n) = \sum_{m=0}^{p} a_m n^m, -M \leq n \leq M, p \leq 2M+1$$

In the test, the $a_0, a_1, \dots, a_l$ is the fitting coefficient. After least squares method to obtain the residuals C:

$$C = \sum_{n=-M}^{M}(q(n) - x(n))^2 = \sum_{n=-M}^{M}(\sum_{m=0}^{p} a_m n^m - x(n))^2$$

When C minimum, the filtering effect is optimal. First find the C polynomial coefficients at the minimum to get the fitted curve; then take the fitted value at the data center point as the filtered value; and finally get the fitted point of the original data by moving the window.

Wenwen Zhao first decomposes the signal into a finite number of IMF components using EMD and then filters the first few IMFs with Savitzky-Golay filter, and finally reconstructs the signal using the first few IMF components after filtering and the unprocessed IMF components, i.e., the filtered signal is obtained, which is referred to as the EMD-SG method later in this paper.

3.3 Improved EMD Noise Reduction Method

Through experiments on some signals containing noise, the authors found that the EMD-SG-based method is better for noise reduction of low-frequency IMF components, the reason being that the Savitzky-Golay filter actually fits the low-frequency components of the signal and smooths out the high-frequency components. If the noise is located in the high frequency band, then the result of filtering just removes the noise and can be used to eliminate the low frequency wind noise in the wind turbine blade sweeping audio; while the EMD threshold-based method has a better noise reduction effect on the high frequency IMF components and can keep the high frequency characteristics of the signal better, so the high frequency biological calls in the wind turbine blade sweeping audio can be

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removed by this method. Therefore,the combination of EMD threshold noise reduction method and Savitzky-Golay filtering method is considered. The first few IMF components (higher frequency) of the wind turbine blade sweeping audio after EMD decomposition are applied to the EMD Min noise reduction method, and the later IMF components (lower frequency) are applied to the Savitzky-Golay filtering noise reduction method. In this way, the noise in the high and low frequency bands of the wind turbine blade sweeping sound can be effectively removed, and the signal of the defective blade is effectively retained.

4. Experiment and Analysis

It can be seen from Figure 1 that there is a large difference between the front and rear analog signals before and after noise reduction, and the signal after noise reduction is much clearer on the waveform graph.

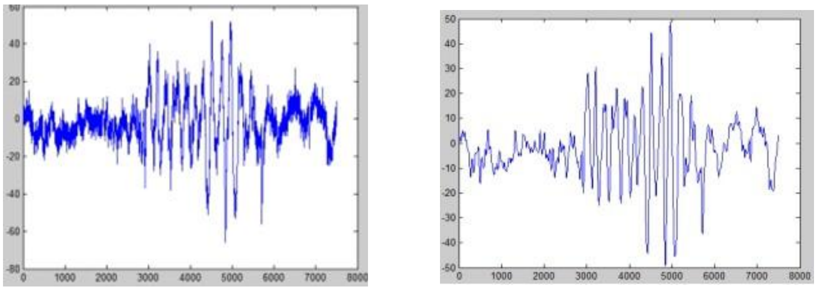

Fig 1. Before and after noise reduction

It can be observed from Fig. 2 that the audio signal with noise reduction by EMD-SG method has a better cleaning effect at low frequencies, and it can be seen from Fig. 3 that the audio signal with noise reduction by EMD threshold method has a better effect at high frequencies, while it can be seen from Fig. 3 that the fan blade sweeping audio signal after noise reduction by improved EMD method has a better effect at both low and high frequency bands The comparison shows that the improved EMD method is better than the EMD threshold method and the EMD-SG method.

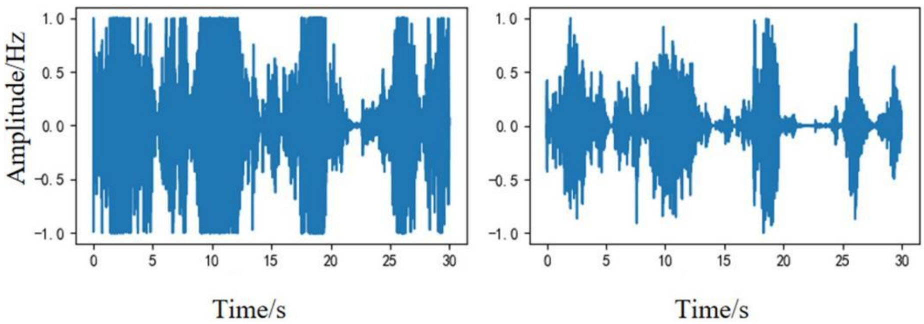

Fig 2. Effect of EMD-SG noise reduction method

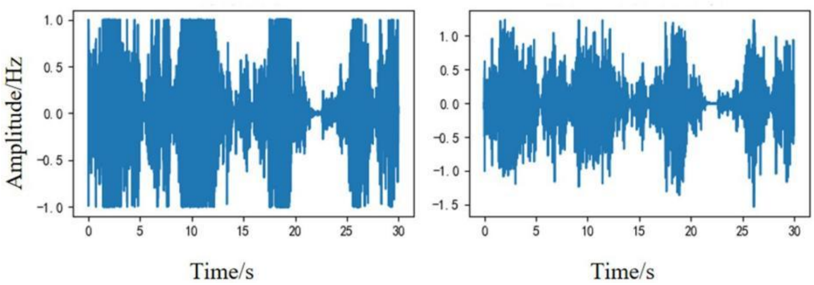

Fig 3. Effect of EMD-SG noise reduction method

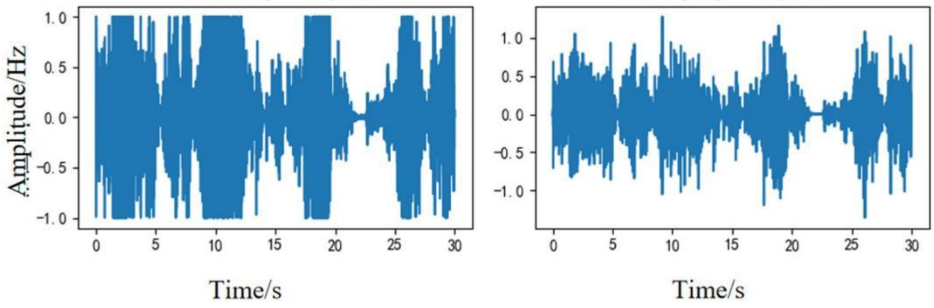

Fig 4. Effect of improved EMD noise reduction method

The noise reduction experiments were conducted on the analog signal containing noise using EMD threshold method, EMD-SG method, and improved EMD method, respectively, and the noise reduction examples of the analog signal after noise reduction by the three methods are shown in Table 2.

Table 2. Noise reduction effect of three methods on data signal

Signal-to-noise ratio before noise reduction	EMD Threshold	EMD-SG	Improved EMD method
12.01	16.92	16.40	17.09

5. Conclusion

This paper designs an improved EMD noise reduction method based on the combination of EMD thresholding method and Savitzky-Golay filtering method, which adopts the threshold noise reduction method for the higher frequency embedded mode functions and the Savitzky-Golay filtering noise reduction method for the lower frequency embedded mode functions, so that the high frequency part of the signal can be better maintained while the low frequency part of the signal can be kept smooth. This can maintain the smooth characteristics of the low-frequency part of the signal while maintaining the high-frequency part of the signal. Experiments on the wind turbine blade sweep audio show that the improved EMD noise reduction method outperforms the EMD thresholding method or Savitzky-Golay filtering method alone in terms of signal-to-noise ratio.

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