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Application and Optimization of Continuous Wavelet Transform in Weak Impulse Signal Processing

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Abstract

This paper investigates the application and optimization method of continuous wavelet transform (CWT) in weak impulse signal processing. Weak impulse signals widely exist in many fields, but the low signal strength and susceptibility to noise interference make signal detection and feature extraction challenging. The continuous wavelet transform shows superior signal processing potential by virtue of its multi-scale analysis capability and sensitivity to non-stationary signals. This paper firstly introduces the basic principle of wavelet transform, and analyzes the application of CWT in signal feature extraction, denoising and pulse detection; subsequently, for the high computational complexity and parameter selection problems of CWT in practical applications, optimization strategies such as wavelet basis and scale parameters are proposed, and the effectiveness of the optimization method is verified through experiments. It is shown that the optimized CWT method significantly improves the detection accuracy and processing efficiency of weak signals, and provides a reliable solution for accurately extracting and identifying weak pulse signals.

Keywords

Continuous Wavelet Transform (CWT); Weak Signal Processing; Impulsive Signals; Feature Extraction; Denoising; Signal Enhancement; Parameter Optimization; Wavelet Basis Selection; Signal-To-Noise Ratio (SNR); Unsteady Signals.

1. Introduction

With the wide application of various types of precision testing equipment, the processing of weak pulse signals has become particularly important in many fields, such as the detection of ECG signals in medical signal processing, the capture of seismic signals in geophysical exploration, and the detection of small faults in engineering monitoring[1]. However, due to the low amplitude of the weak pulse signals, which are often accompanied by complex background noise, their detection and analysis become much more difficult[2]. Traditional signal processing methods, such as the Fourier transform and the short-time Fourier transform, can handle frequency domain information, but they are often incompetent in the face of non-smooth signals, and it is difficult to effectively extract transient signal features[3].

In recent years, Continuous Wavelet Transform (CWT), as a powerful non-stationary signal processing tool, has gradually attracted the attention of researchers[4]. It has the ability of multi-scale analysis, and can perform joint time-frequency analysis of signals, showing unique advantages in weak signal feature extraction, denoising, and impulse signal localization.CWT can analyze the detailed and global features of signals in different scales by using translation and scaling operations, which is especially suitable for the capture and enhancement of weak impulse signals[5].

The research objective of this paper is to improve the detection accuracy and noise immunity of weak impulse signals using continuous wavelet transform, and to optimize the wavelet transform for the

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bottlenecks in parameter selection and computational efficiency[6]. This paper will introduce the theoretical foundation of wavelet transform in detail and discuss the application of CWT in feature extraction, denoising and detection of weak signals; a series of optimization strategies will be proposed in this paper, including wavelet basis selection, scale parameter adjustment and computational complexity optimization, in order to enhance the effectiveness of the application and processing efficiency of CWT. Through experimental verification, this paper expects to provide an efficient and reliable solution for the accurate extraction and analysis of weak pulse signals, and further promote the expansion of the application of CWT in the field of signal processing.

2. Basic Theory of Continuous Wavelet Transform

Continuous wavelet transform is a tool for decomposing signals through multi-scale analysis, and unlike the Fourier transform, it is able to unfold simultaneously in both the time and frequency domains, which is particularly suitable for analyzing non-smooth signals[7]. In signal processing, wavelet transform can be divided into two categories: continuous wavelet transform and discrete wavelet transform[8]. In contrast, continuous wavelet transform has higher resolution and is especially suitable for accurately capturing the instantaneous characteristics of signals. The wavelet transform convolves the signal with wavelet basis functions of different scales to achieve a comprehensive analysis of the signal details and the overall trend. Continuous Wavelet Transform Definition:

$$W(a,b) = \int_{\{-\infty\}}^{\{\infty\}x(t),} \psi^*(frac\{t - b\}\{a\}), dt \tag{1}$$

The basic principle of the continuous wavelet transform is to decompose a signal by scaling and translating the wavelet basis functions[9]. The scaling parameter determines the width of the wavelet, which in turn affects the frequency resolution and translation position of the transform[10]. By continuously adjusting the scaling and position, the signal can be projected into a time-frequency space to achieve a fine analysis of the signal at different frequency components, which is particularly suitable for feature extraction of signals containing non-smooth or mutated components.

When applying continuous wavelet transform for signal processing, the selection of wavelet bases directly affects the accuracy and efficiency of the analysis results. Different wavelet bases have their own time-frequency characteristics, and commonly used wavelet bases include Morlet wavelet, Mexican Hat wavelet and Meyer wavelet. Usually, for signals with obvious impulse characteristics, it is more suitable to choose wavelet bases with good frequency domain characteristics; while for signals with sharp transient characteristics, wavelet bases with strong resolving ability in time domain can be chosen. Reasonable selection of wavelet bases can be better adapted to the characteristics of the target signal, thus improving the accuracy of signal analysis.

The multi-scale analysis characteristics of continuous wavelet transform make it show significant advantages in non-smooth signal processing. Compared with the traditional Fourier transform, continuous wavelet transform can analyze the local characteristics of the signal at different scales and effectively separate the weak pulse components in the signal. In addition, continuous wavelet transform has strong anti-interference ability under complex background noise and can maintain high signal detection accuracy. Despite its high computational complexity, the continuous wavelet transform has become an ideal choice for weak pulse signal processing due to its outstanding performance in time-frequency resolution,showed in Figure 1:

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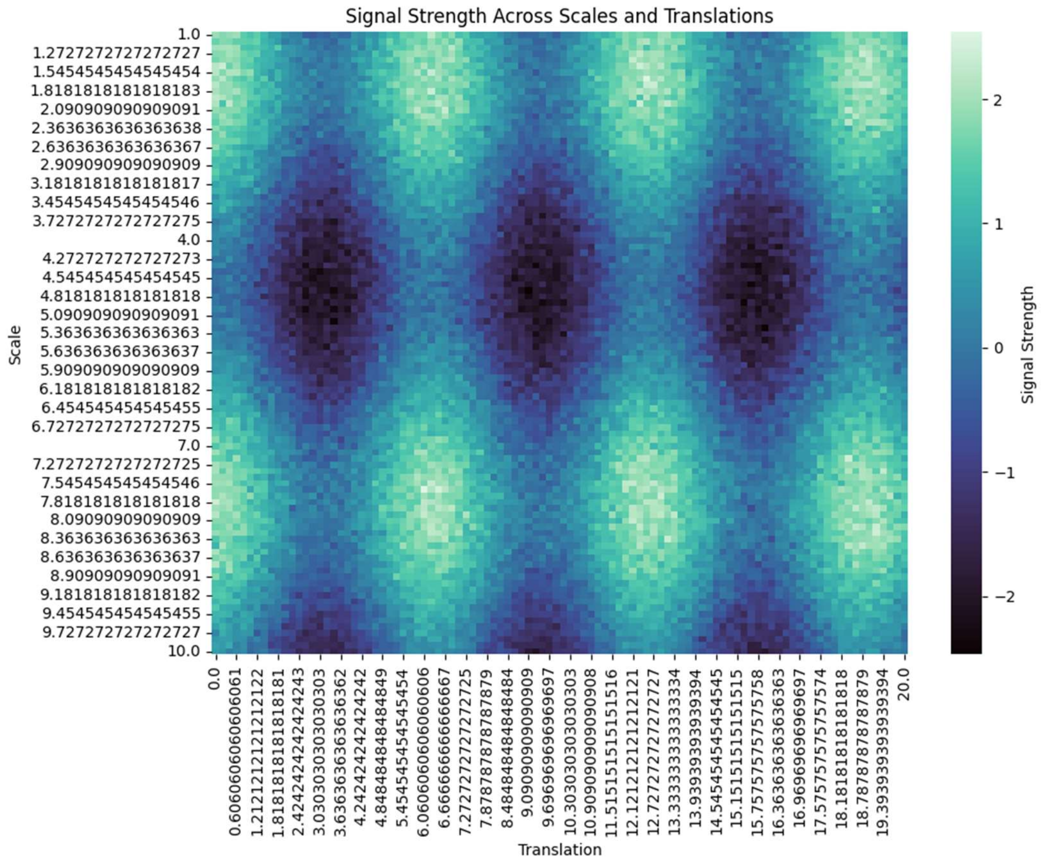

Figure 1. Signal Strength Across Scales and Translations

3. Application of Continuous Wavelet Transform in Weak Pulse Signal Processing

In weak pulse signal processing, continuous wavelet transform has become an important analysis method by virtue of its excellent time-frequency resolution and noise resistance. Specifically, the application of continuous wavelet transform mainly focuses on three aspects: feature extraction, denoising and pulse signal detection: the wavelet transform can accurately capture the characteristics of weak signals and improve the reliability of signal processing; with the help of wavelet denoising technology, the noise interference can be effectively filtered out, and the clarity of the target signal can be strengthened; in the detection of impulse signals, the detection of weak impulses can be significantly improved by using multi-scale analysis. In pulse signal detection, the use of multi-scale analysis can significantly improve the detection accuracy and sensitivity of weak pulses. These applications fully demonstrate the advantages and potentials of continuous wavelet transform in weak signal processing.

3.1 Signal Feature Extraction

In weak pulse signal processing, feature extraction is a key step to ensure effective signal identification and processing. The continuous wavelet transform has superior time-frequency resolution and is capable of comprehensively analyzing the subtle features of signals at multiple scales, which provides an effective means for accurately extracting weak signal features. By adjusting the scale and position of the wavelet, the local features of different frequency components can be captured in both the time and frequency domains, which helps to distinguish the signal from the noise and maximize the retention of the signal detail information in the feature extraction process.

The selection of wavelet bases has a direct impact on the effect of feature extraction, and different wavelet bases have their own advantages in time-frequency characteristics. In the feature extraction of impulse signals, wavelet bases suitable for impulse detection are usually selected, such as Morlet

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wavelet or Mexican Hat wavelet, which shows good resolution in the frequency domain and is suitable for periodic and sinusoidal-like signals, while Mexican Hat wavelet has high resolution in the time domain and is suitable for impulse signals with more obvious transient characteristics. By choosing appropriate wavelet bases, the accuracy of feature extraction can be improved and the separability of weak impulse signals from background noise can be enhanced,showed in Figure 2:

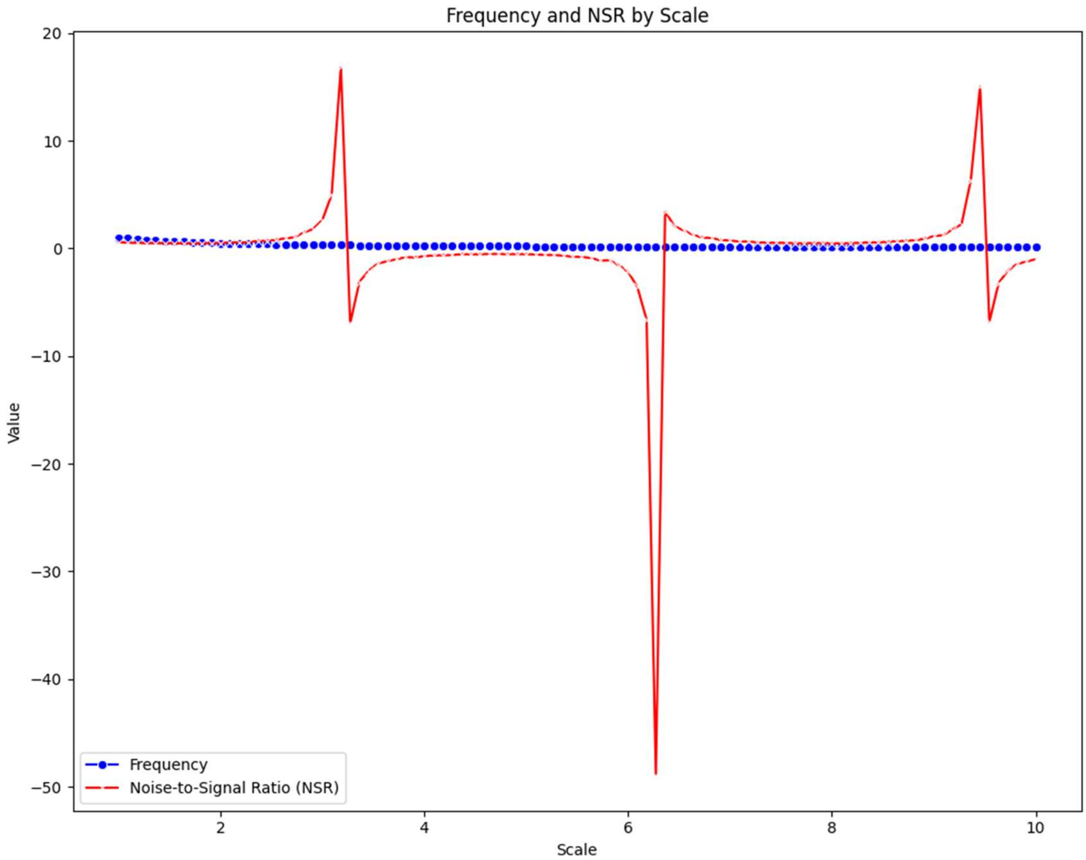

Figure 2. Frequency and NSR by Scale

The adjustment of scale parameters is also an important part of signal feature extraction, and different scales correspond to different frequency components of the signal. In weak pulse signal processing, the large-scale wavelet can capture the low-frequency components of the signal, which helps to obtain the overall trend of the signal; while the small-scale wavelet is suitable for capturing the high-frequency details, which is more suitable for extracting the subtle features in the pulse signal. Therefore, through multi-scale analysis, the details and overall features of the signal can be observed at different resolutions, providing comprehensive information for subsequent signal processing and identification. The time-frequency distribution characteristics of the wavelet transform give it an advantage in the feature extraction of real-time dynamic signals. For non-smooth and weak pulse signals, wavelet transform can provide accurate frequency information at different time points to realize dynamic analysis of signals. This feature is especially important in the variable and easily disturbed practical application scenarios, which can effectively enhance the feature extraction effect of weak pulse signals, and ultimately improve the overall accuracy and stability of signal processing.

3.2 Denoising and Signal Enhancement

In weak pulse signal processing, noise interference is a major factor affecting signal quality. Since the amplitude of weak signals is usually low and easily overwhelmed by background noise, denoising and signal enhancement become important steps to improve the signal-to-noise ratio. By virtue of its multi-scale characteristics, the continuous wavelet transform is able to differentiate between signal

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and noise in different frequency bands, thus removing unnecessary noise while retaining the effective signal and significantly improving the observability of weak signals.

Wavelet threshold denoising is a classical method in continuous wavelet transform to remove noise by setting appropriate thresholds on wavelet coefficients after wavelet decomposition. Typically, the wavelet transform decomposes the signal into coefficients of different scales, where the high frequency coefficients tend to contain more noise components. By applying thresholding to these high-frequency coefficients, the effective signal information in the low-frequency part is retained, thus realizing denoising. This method can be flexibly adjusted at different scales and is applicable to a variety of noise environments, providing an effective means of noise reduction for weak impulse signals. Scale and Frequency Relationship:

$$f = frac\{f_c\}\{a\} \tag{2}$$

Multi-scale analysis can also realize local enhancement of signals, i.e., to highlight the significance of weak signals by amplifying the detailed features of signals on some specific scales. Unlike conventional filtering methods, the wavelet transform can selectively enhance specific frequency bands at different scales, thereby effectively amplifying the characteristic details of weak impulse signals. This method is particularly suitable for signals containing transient impulses, making them more clearly distinguishable in a noisy background and enhancing the recognition and analysis of the signals.

Continuous wavelet transform also performs well in denoising and enhancement of real-time dynamic signals. As it can process time and frequency information simultaneously, it has obvious advantages in processing non-stationary signals. In practical applications, continuous wavelet transform can effectively remove the time-varying noise components and enhance the signal details at critical moments, providing strong support for real-time monitoring and dynamic analysis. This flexible denoising and enhancement not only improves the quality of weak signals, but also provides a more reliable basis for subsequent analysis and processing.

3.3 Pulse Signal Detection and Localization

In weak impulse signal processing, the detection and localization of impulse signals are the key links to ensure the effective identification and response of signals. Since the amplitude of weak pulse signals is usually lower than the background noise, the use of continuous wavelet transform for pulse signal detection can give full play to its advantage of multi-scale analysis. By decomposing the signal into different scales, the continuous wavelet transform can effectively capture the instantaneous characteristics of the pulse signal and realize precise localization in the time-frequency domain, thus improving the detection accuracy of the weak signal.

Using the time-frequency properties of the wavelet transform, the detection algorithm can set a suitable threshold to identify and localize the impulse components in the signal. Usually, the high-frequency components are closely related to the noise, while the low-frequency components contain the effective information of the impulse signal. Therefore, after wavelet decomposition, the coefficients of different frequency bands can be analyzed, and the high-frequency noise below a certain level can be filtered out by setting the threshold value, while the significant impulse signals are retained. This method not only enhances the recognizability of the signal, but also realizes the accurate positioning of the starting position of the signal, which provides an important basis for the subsequent analysis.

In the real-time detection of pulse signals, continuous wavelet transform can dynamically monitor the changes in the signal. In practical application scenarios, the signal may be subject to various interferences, leading to changes in the pulse characteristics. By analyzing the changes in the wavelet coefficients in real time, the appearance of the pulse signal can be quickly identified and localized in the time-frequency domain. This dynamic monitoring capability allows the continuous wavelet

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transform to excel in rapidly changing signal environments, capturing weak pulse signals in a timely manner and ensuring efficient and accurate detection.

The continuous wavelet transform also shows its strong application potential in the detection and localization of multi-source impulse signals. In practice, signals may come from multiple sources, and the pulse characteristics of these signals may overlap with each other. Through the multi-scale analysis of wavelet transform, the signals from different sources can be separated and identified, so as to realize the effective detection and localization of weak impulse signals in the complex signal environment. This capability makes continuous wavelet transform an important signal processing tool in many fields, such as medical monitoring, sonar detection and communication systems.

4. Parameter Optimization and Performance Enhancement of Continuous Wavelet Transform

In weak pulse signal processing, parameter optimization and performance enhancement of continuous wavelet transform are the key factors to achieve efficient signal analysis. The parameter settings directly affect the decomposition effect of the wavelet transform, especially when dealing with weak signals, the selection of appropriate scales and wavelet bases can significantly improve the detection and analysis of signals. By optimizing the parameters of the wavelet transform, the noise interference can be minimized on the basis of ensuring the integrity of the signal features, and more accurate signal recognition can be achieved.

The choice of scale parameters is crucial to the effectiveness of the wavelet transform. Different scales correspond to different frequency components, and when dealing with weak impulse signals, it is usually necessary to find the best balance between wide and narrow scales. Wide-scale wavelets can capture the low-frequency components of the signal and help identify the overall characteristics of the signal, while narrow-scale wavelets are suitable for capturing the high-frequency details, which can effectively highlight the transient characteristics of the pulse signal. Therefore, in practical applications, the optimal scale range can be found through multiple trials and parameter adjustments to improve the accuracy and reliability of signal processing. The selection of wavelet bases also has a significant impact on the performance of signal processing. Different wavelet bases have their own unique time-frequency characteristics and have different processing effects on weak signals. In the optimization process, the selection of a suitable wavelet basis according to the characteristics of the target signal can be considered. For example, Morlet wavelet is excellent in frequency resolution and suitable for analyzing periodic signals, while Mexican Hat wavelet is stronger in time resolution and suitable for processing transient signals. Therefore, comprehensively considering the characteristics of the target signal and the properties of the background noise can help to improve the overall performance of the wavelet transform.

Optimization of algorithms is also an important part of improving the performance of wavelet transform. By introducing improved wavelet threshold denoising algorithms, enhancement learning and other intelligent algorithms, weak pulse signals can be processed more accurately. The application of modern machine learning technology makes the signal analysis not only limited to the traditional threshold setting, but also can be dynamically adjusted according to the actual data, so as to achieve better denoising effect and signal enhancement. In addition, the parallel computing capability of the optimization algorithm can also significantly improve the processing speed and provide support for real-time signal monitoring. The process of parameter optimization and performance enhancement should be combined with practical application scenarios. Through the in-depth understanding of the characteristics of weak pulse signals in specific fields, the wavelet transform parameters can be adjusted and optimized in a targeted manner. This process requires not only a solid understanding of signal processing theory, but also a clear understanding of the practical application background. Through continuous optimization and experimentation, the reliability and effectiveness of the continuous wavelet transform in various complex signal environments can be ensured, thus providing strong support for weak pulse signal processing.

5. Conclusion

In weak pulse signal processing, continuous wavelet transform shows its unique advantages and becomes an important tool for effectively extracting signal features, denoising, and realizing signal detection and localization. Through the optimization of wavelet transform parameters, especially in the scale selection and the precise setting of wavelet bases, the accuracy and reliability of signal processing can be significantly improved. In addition, the optimization of algorithms and the introduction of advanced techniques, such as machine learning and improved wavelet thresholding denoising strategies, provide stronger support and flexibility for the processing of weak signals.

The application of continuous wavelet transform in feature extraction, denoising and detection of weak impulse signals is obvious, especially in the face of complex signal environments, its multi-scale analysis capability makes the extraction and localization of weak signals become more efficient and accurate. In the future, with the continuous development of signal processing technology, the application scope of continuous wavelet transform will be further expanded, especially in the fields of medical monitoring, sonar detection, communication systems, etc., will still play an important role. In order to better cope with the increasingly complex signal processing needs, researchers should continue to explore the optimization methods and application strategies of the wavelet transform to achieve more efficient weak signal processing and analysis.

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