

Article

Time-Frequency Feature Extraction Method for Weak Acoustic Signals from Drill Pipe of Seafloor Drill

Jingwei Xu ^{1,2}, Buyan Wan ^{1,*}, Weicai Quan ¹, Yi Xi ² and Xianglin Tian ²¹ National-Local Joint Engineering Laboratory of Marine Mineral Resources Exploration Equipment and Safety Technology, Hunan University of Science and Technology, Xiangtan 411201, China; xujwhnust@163.com (J.X.)² School of Mechanical Engineering, Hunan University of Science and Technology, Xiangtan 411201, China

* Correspondence: cimrwby@vip.sina.com

Abstract: The acoustic signals of the drill pipe of a seafloor drill present weak features under noise interference such as marine environmental noise and the mechanical vibration of the seafloor drill. Accurately extracting the features of the weak acoustic signals of a drill pipe under a strong background noise is an effective means of realizing wireless acoustic communication for a seafloor drill. However, the existing short-time Fourier transform and wavelet transform methods have the defects of fixed window length, wavelet basis function, and decomposition layers, which lead to the inability to accurately extract the weak acoustic signal features of a drill pipe. To overcome these challenges, this study investigates the application of S-transform (ST) in the weak acoustic signal feature extraction of a seafloor drill pipe based on its fundamental principles. Firstly, a time-frequency analysis of the drill pipe's acoustic signal using ST is conducted, which yields the distribution of the signal across the time and frequency axes. Secondly, singular value decomposition (SVD) is applied to mitigate the noise within the time-frequency matrix. Finally, the noise-reduced time-frequency matrix is analyzed to extract the subtle features of the acoustic wave present within the signal. In order to more accurately assess the differences between the different time-frequency analysis methods in the extraction of weak acoustic wave signals, short-time Fourier transform, wavelet transform, and ST are used to extract the weak acoustic wave characteristics of the drill pipe, respectively. The results show that the ST-based method can effectively improve the accuracy of weak acoustic wave signal feature extraction and provide strong support for reliable transmission of cone penetration test data from the seafloor drill.



Received: 8 February 2025

Revised: 28 March 2025

Accepted: 4 April 2025

Published: 8 April 2025

Citation: Xu, J.; Wan, B.; Quan, W.; Xi, Y.; Tian, X. Time-Frequency Feature Extraction Method for Weak Acoustic Signals from Drill Pipe of Seafloor Drill. *J. Mar. Sci. Eng.* **2025**, *13*, 740. <https://doi.org/10.3390/jmse13040740>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: drill pipe of seafloor drill; ST; wavelet transform; singular value decomposition; weak acoustic signals

1. Introduction

The ocean contains extremely rich resources, and with the continuing advancement of China's ocean power strategy, the efficient and scientific development of marine resources has become an urgent priority. This is closely tied to the acceleration of deep-sea development and the implementation of the ocean power strategy. Marine geological exploration plays a pivotal role in the realization and utilization of marine resources, and its significance is growing increasingly evident [1]. Whether for the exploitation of marine resources or the construction of marine engineering infrastructure, it is indispensable to test and investigate the seabed soil. Since the seabed soil primarily consists of loose, saturated sediment, conventional drilling core and laboratory tests are prone to disturbing it, making it difficult to accurately reflect the basic physical and mechanical properties of the soil in its undisturbed

state [2]. For this reason, the in situ testing method represented by the cone penetration test (CPT) has gradually entered the field of marine geological exploration. It has been widely recognized by construction units for its high efficiency, accuracy, and cost-effectiveness and has rapidly evolved into one of the core technologies of marine geological exploration [3]. CPT technology is an in situ field testing method primarily performed by placing a probe equipped with multiple sensors at a certain speed. The probe penetrates the seabed soil, and real-time measurements of the physical and mechanical properties of the strata are acquired through the sensors on the probe, providing essential geological data for marine engineering projects [4]. Currently, the subsea CPT systems used in the vast majority of countries are generally categorized into two types: the seabed CPT and the downhole CPT. The CPT probe is the core component in direct contact with the soil, where it obtains soil stress data. The probe converts the data collected by its internal sensors into digital signals, which are transmitted via cable (or wirelessly) to the host computer for display and storage. Among these, data communication is a critical element of the CPT system, primarily involving the transmission of data from the probe to the probe rod's end. Achieving stable and reliable transmission of probe data in the complex and dynamic seabed environment, as well as with specialized operating equipment, is crucial to the success or failure of the entire CPT operation [5]. At present, the communication methods used in the three CPT systems mentioned above primarily rely on cable transmission for data communication. The cables that connect the probes must pass through each section of the probe rods, which significantly complicates the assembly process and increases its length. Additionally, the cables are prone to damage in harsh marine conditions, potentially leading to data loss and equipment damage. Furthermore, the presence of the cables restricts the movement of the probe rods [6].

To address the shortcomings of the current cable transmission method in submarine in situ testing systems, the CPT based on seafloor drilling represents a novel approach. It represents a significant advancement in the current development of the submarine CPT, as shown in Figure 1, representing a significant advancement in subsea static testing. At present, the data measured by the seafloor drilling-based CPT can only be stored in the probe circuit [7]. The CPT data can only be obtained once the CPT operation is completed and the seafloor drill is recovered, which does not meet the demand for real-time transmission of CPT data. Wireless acoustic transmission uses acoustic waves as the carrier and the drill pipe as the channel, enabling real-time transmission of CPT data and offering advantages such as a high transmission rate, broad applicability, a low development cost, and ease of operation. When a seafloor drill is used to conduct wireless acoustic CPT tests, the seafloor geotechnical data collected by the probe are transmitted back to the signal receiver on the seafloor drill in the form of acoustic waves through the drill pipe and finally transmitted to the vessel via the armored umbilical cable. However, the reliable extraction of weak acoustic signals from drill pipes in dynamic seabed environments remains a critical challenge. Due to the special structure of the seafloor drill and the complex and dynamic working conditions of the seabed, the signals generated by various excitation sources tend to interfere with each other, causing the acoustic signals transmitted through the drill pipe to often be drowned out by strong background noise, making them difficult to identify. These signals are often corrupted by mixed noise conditions, including Gaussian ambient noise (e.g., marine currents) and non-stationary interference (e.g., mechanical vibrations from drilling operations). Traditional time-frequency analysis methods struggle to balance adaptive resolution and noise immunity under such conditions, limiting the accuracy of wireless acoustic communication for real-time CPT data transmission, which affects the success or failure of the entire test.

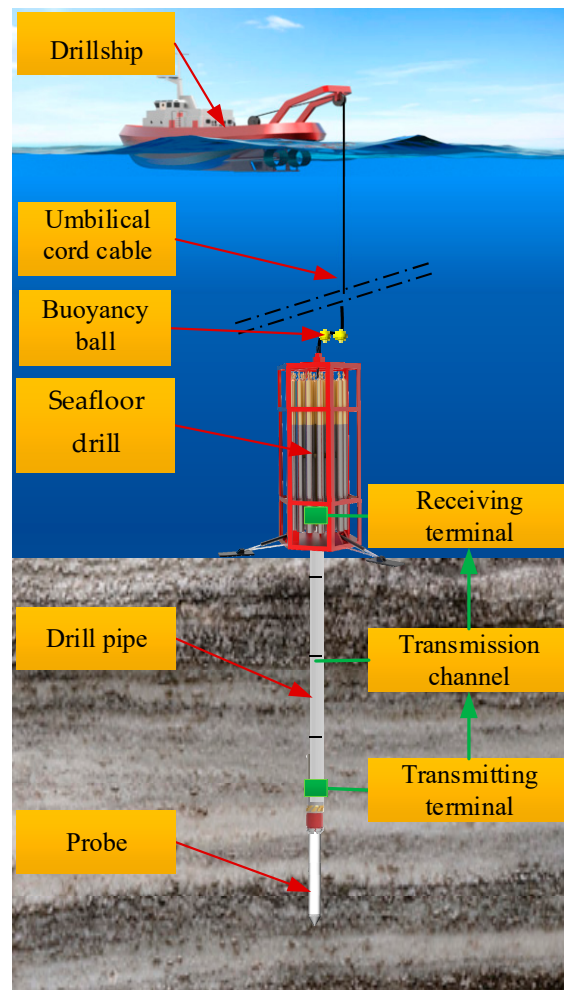


Figure 1. Seafloor drill CPT principle diagram.

In recent years, time-frequency analysis methods such as short-time Fourier transform (STFT) and wavelet transform (WT) have been applied to the extraction of weak acoustic wave feature information from a drill pipe. For example, Qin et al. [8] used the STFT method to analyze the acoustic signals of drill pipes collected during rock drilling and effectively captured the frequency characteristics of the acoustic signals, revealing significant differences in the spectral characteristics of different types of rocks. Li et al. [9] studied the downhole drill pipe and achieved effective extraction of the acoustic feature information from the drill pipe using the STFT method. Kajiwara et al. [10] employed the wavelet transform method for time-frequency analysis of acoustic signals collected during pipeline drilling, effectively identifying characteristic parameters related to pipeline damage. Although STFT and WT have been applied to extract acoustic waveform feature information from drill pipes, the recognition accuracy of these time-frequency analysis methods depends on factors such as window length, wavelet basis function, and the number of wavelet decomposition layers [11].

Among the traditional signal feature extraction methods, the Fourier transform has significant limitations in analyzing non-smooth signals due to the lack of time and frequency localization functions. With the gradual development of time-frequency analysis theories such as STFT and WT, they provide a new approach for the fast and accurate extraction of time-frequency features from non-smooth signals. However, the existing time-frequency analysis methods have certain limitations, such as the fact that the size and shape of

the STFT time window are fixed, independent of frequency, making it impossible to simultaneously obtain accurate moments and frequencies [12].

In addition to traditional STFT and WT methods, some novel time-frequency analysis methods have been applied to acoustic signal feature extraction in recent years. For example, sparse wavelet (SW) can better suppress noise interference by introducing sparse constraints in the time-frequency domain [13]; cyclostationary analysis (CA) analyzes signals using their cyclic properties and is suitable for acoustic signals with periodic characteristics [14]. However, SW requires pre-determination of sparse basis functions, increasing computational complexity; CA mainly targets strictly periodic signals and has poor adaptability to non-stationary signals. In order to overcome the shortcomings of the above methods, Stockwell et al. [15] studied a new time-frequency analysis method (ST). In recent years, the ST method has been successfully applied to extract weak fault feature information in the field of rotating machinery equipment fault diagnosis. For example, Guo et al. [16] proposed a weak fault information extraction method based on the ST for the outer ring of rolling bearings. Liu et al. [17] used the ST method to effectively identify the weak fault characteristic information of cylindrical roller bearings under variable operating conditions. Although the results from the above studies show that the ST method can effectively identify weak fault characteristic information, further research is needed to analyze the weak acoustic wave characteristic information of the drill pipe in the strong background noise of the seafloor drill using the ST method. This is of great significance for realizing the effective extraction of acoustic feature information from the drill pipe under strong background noise.

The aim of this study is to develop a robust time-frequency feature extraction framework for weak acoustic signals in seafloor drill pipes. The complex seabed environment and the structure of seafloor drills lead to strong background noise that interferes with the acoustic signals transmitted through drill pipes. This makes it difficult to accurately extract the features of weak acoustic signals, which affects the wireless acoustic communication and the acquisition of CPT data. The proposed method aims to address the challenges posed by noise interference and the non-stationary characteristics of these signals. The key contributions of this study are as follows:

- (1) A time-frequency feature extraction method based on ST is proposed for weak acoustic signals from a seafloor drill pipe, which overcomes the limitations of STFT's fixed window length and WT's requirement for preset basis functions;
- (2) Singular value decomposition is introduced for noise reduction of the ST time-frequency matrix, effectively improving the extraction accuracy of drill pipe acoustic signal features under strong background noise;
- (3) The effectiveness of the proposed method under actual seafloor drill operating conditions is verified through simulation and experiments, providing a new solution for realizing wireless acoustic transmission technology in drill pipes.

2. Methodology

The seafloor drill of drill pipe acoustic wave time-frequency feature extraction aims to use time-frequency analysis methods to accurately identify the weak acoustic wave features of the drill pipe under strong background noise. Since the drill pipe acoustic wave features are usually closely related to the frequency features of the excitation signal, identifying the frequency features of the excitation signal within the drill pipe acoustic wave signals is crucial for realizing the time-frequency feature extraction of weak acoustic wave signals. In this section, a feature information extraction method for weak acoustic wave signals of a drill pipe based on the combination of ST and SVD is proposed; Figure 2 shows a flowchart of the method. The method first decomposes the drill pipe acoustic wave signal using

ST to obtain the time-frequency matrix; next, the time-frequency matrix is noise-reduced using SVD; and finally, the noise-reduced time-frequency matrix is analyzed to extract the excitation signal's frequency features. This method aims to explore new techniques for the effective extraction of weak acoustic wave features from drill pipes.

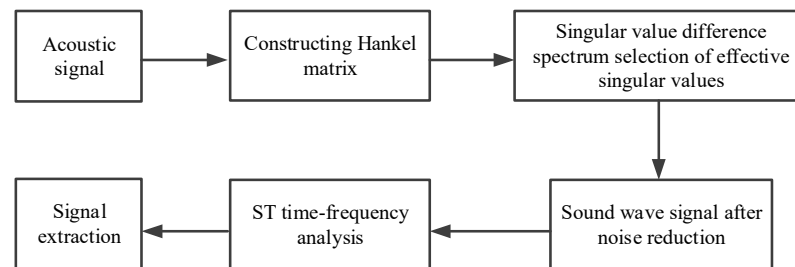


Figure 2. The flowchart of the proposed method.

2.1. Time-Frequency Analysis Methods

Since the time-domain detection and frequency-domain detection of the signal cannot show the time-frequency local characteristics of the signal, this local characteristic can best reflect the most fundamental properties of the non-stationary signal [18]. The time-frequency analysis method is an important means of dealing with non-stationary signals. Time-frequency analysis uses time-frequency joint representation of the signal and analyzes the signal in the time-frequency domain to fully reflect the time-frequency joint characteristics of the observed signal. At the same time, it can grasp the time-domain and frequency-domain information of the signal and can clearly understand the law of signal frequency change with time.

2.1.1. STFT and WT

The drill pipe acoustic signal is a typical non-stationary signal, and its features can be effectively extracted using time-frequency analysis methods. STFT and WT are widely used time-frequency analysis methods in acoustic signal feature extraction [19]. For a given drill pipe acoustic signal $x(t)$, the mathematical expressions of STFT and WT are given by:

$$F(\tau, f) = \int_{-\infty}^{+\infty} x(t)\gamma(t - \tau)e^{-j2\pi ft} dt \quad (1)$$

$$W(a, b) = \int_{-\infty}^{+\infty} x(t)\psi(t - b, a)dt \quad (2)$$

where t is the time; f is the frequency; τ is the position of the window function on the time axis; $\gamma(t - \tau)$ is the window function of STFT; $F(\tau, f)$ is the STFT time-frequency matrix; $\Psi(t - b, a)$ is the window function of the WT method, also known as the wavelet basis function; a and b are the scale and translation parameters, respectively; and $W(a, b)$ is the WT time-frequency matrix.

The schematic diagrams of the STFT and WT methods are shown in Figure 3. The principle of the STFT method is to extract acoustic signal features by applying windows with equal spacing to the signal and then applying fast Fourier transform (FFT) to the signal within each window.

Although STFT can obtain information about the spectral changes of acoustic signals over time, its time-frequency resolution depends on the window width. As shown in Figure 3a, STFT uses a fixed window function, and the shape of the window function remains fixed once chosen. Therefore, when STFT is used for time-frequency analysis of the acoustic signal $x(t)$, it has the disadvantage of single-frequency resolution, which can hinder the identification of weak features in the acoustic signal. The WT method provides a

“time-frequency” window that adapts with frequency. As shown in Figure 3b, the window function in the WT method has two parameters: the scale parameter a and the translation parameter b . The scale parameter a is used to adjust the length of the window, and different window lengths correspond to different frequency resolutions; the translation parameter b is used to adjust the position of the window function. Thus, the WT method overcomes the limitation of the STFT’s single-frequency resolution. However, despite the multi-resolution analysis characteristic of the WT method, the selection of wavelet basis functions in the WT method lacks adaptivity.

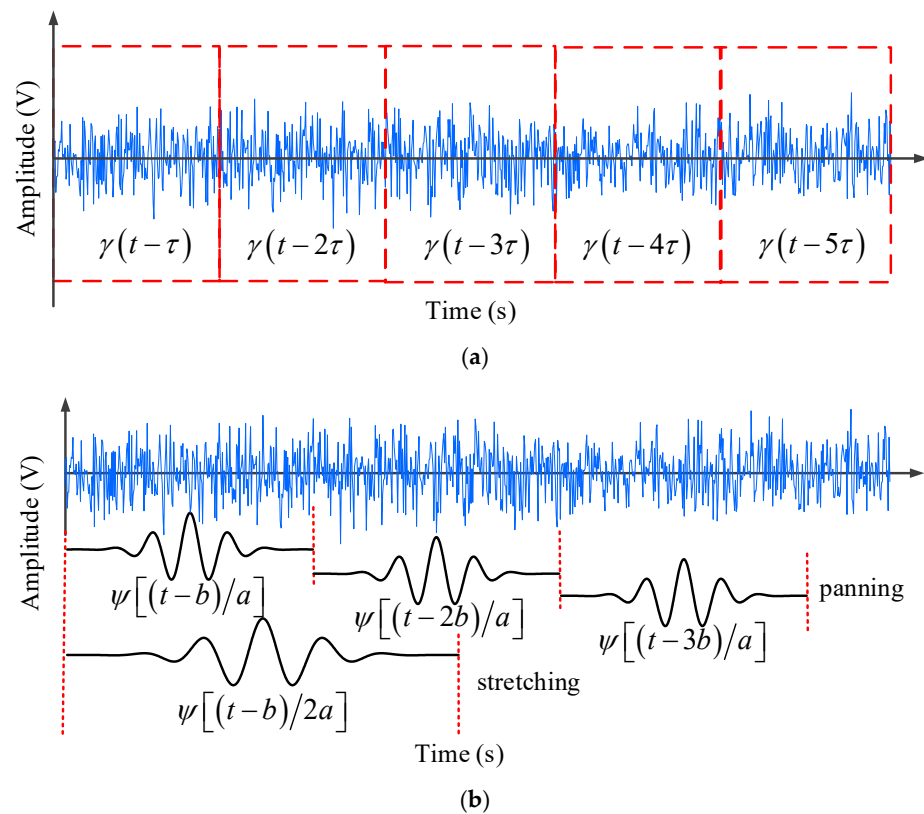


Figure 3. Common time-frequency analysis methods for feature extraction of drill pipe acoustic signals. (a) STFT; (b) WT.

2.1.2. ST

ST is a time-frequency analysis method derived from STFT, and its mathematical expression is given by [15]:

$$S(\tau, f) = \int_{-\infty}^{\infty} x(t)g(t - \tau, f)e^{-i2\pi ft} dt \quad (3)$$

$$g(t - \tau, f) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t-\tau)^2 f^2}{2}} \quad (4)$$

where $S(\tau, f)$ is the ST time-frequency matrix; $g(t - \tau, f)$ is the Gaussian window function; σ is the standard deviation of the Gaussian window function, which determines the window length; and $\sigma = 1/|f|$.

Figure 3 shows the schematic diagram of the ST method. As shown from Figure 3 to Figure 4, the key difference between ST and STFT is that the window length of the Gaussian function changes with frequency, effectively addressing the limitation of STFT, where the fixed window length is incompatible with both temporal and frequency resolution. In

addition, ST overcomes the lack of adaptivity in the selection of wavelet basis functions in the WT method.

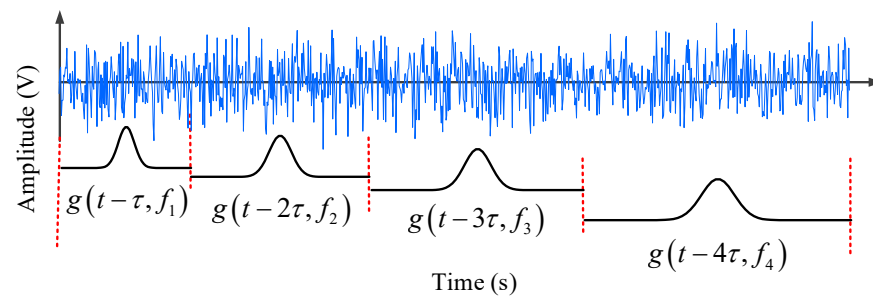


Figure 4. Schematic diagram of the ST method.

2.2. Weak Acoustic Signal Feature Extraction Based on ST

The identification of weak acoustic wave time-frequency features in drill pipe signals focuses on extracting excitation signal frequency features from acoustic signals disturbed by strong background noise. In this section, an ST-based feature extraction method for weak acoustic wave features of drill pipe signals is proposed. This section describes the proposed method for extracting weak acoustic signal features from a drill pipe. The method consists of three main steps:

- (1) Time-frequency analysis of drill pipe acoustic wave signals;
- (2) Noise reduction of drill pipe acoustic wave signals;
- (3) Extraction of weak acoustic wave features from the drill pipe signals.

2.2.1. Time-Frequency Analysis of Drill Pipe Acoustic Signals

To preliminarily verify the effectiveness of the method, a simulated drill pipe acoustic wave simulation signal $x(t)$ is constructed, which mainly consists of two parts: the drill pipe acoustic wave signal $s(t)$ and the noise signal $r(t)$. Specifically, the drill pipe acoustic signal $s(t)$ consists of the fundamental frequency f_0 and its harmonics; the noise signal $r(t)$ is modeled as a Gaussian noise signal with a mean of 0 and a variance of 2. The mathematical expressions of the drill pipe acoustic wave simulation signals are shown in Equations (5) and (6).

$$x(t) = s(t) + r(t) \quad (5)$$

$$s(t) = 5e^{0.1 \times 2\pi \times f_0 \times t} \sin(2\pi f_0 \sqrt{1 - g^2 t}) \quad (6)$$

where f_0 is the fundamental frequency, and $f_0 = 50$ Hz; g is the resistance coefficient, and $g = 0.1$.

The sampling frequency is 20 kHz, and the number of sampling points is 2000. Figure 5 shows the time-domain waveform of the drill pipe acoustic signal before and after noise addition. As shown in Figure 5a, the time interval of the acoustic wave feature is 0.02 s, corresponding to the fundamental frequency of the drill pipe acoustic wave signal. As shown in Figure 5b, the acoustic wave signal feature in the simulated signal, after noise addition, is weak, and the fundamental frequency information can no longer be extracted from the time-domain waveform.

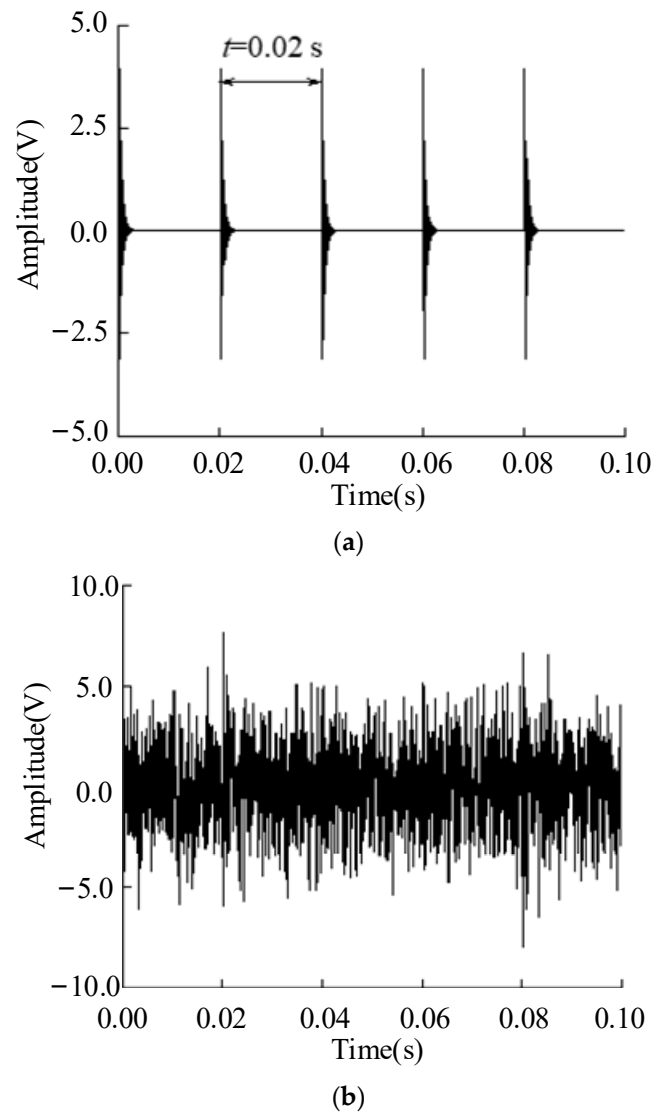


Figure 5. Time-domain waveforms of acoustic signals from drill pipe before and after noise addition. (a) Time-domain waveform before noise addition; (b) time-domain waveform after noise addition.

Time-frequency analysis of the drill pipe acoustic signals, both before and after noise addition, was performed using the STFT, WT, and ST methods. The results are shown in Figures 6 and 7. In the WT method, the wavelet used is the Morlet wavelet with a scale of 64.

From Figure 6a,b, it can be observed that although the acoustic wave feature information in the simulated signal before noise addition can be identified using the STFT and WT methods, in both the STFT and WT methods, the scale distribution band is wider in the time and scale directions, the energy distribution is more dispersed, and the time-frequency resolution is lower. As a result, the energy cannot be well clustered near the characteristic scale of the signal itself. As shown in Figure 6c, the time-frequency analysis of the simulated signal using the ST results in a finer frequency distribution band. The energy distribution of the signal is more concentrated in both time and frequency, resulting in a higher time-frequency resolution, with the energy more closely clustered around the signal's fundamental frequency.

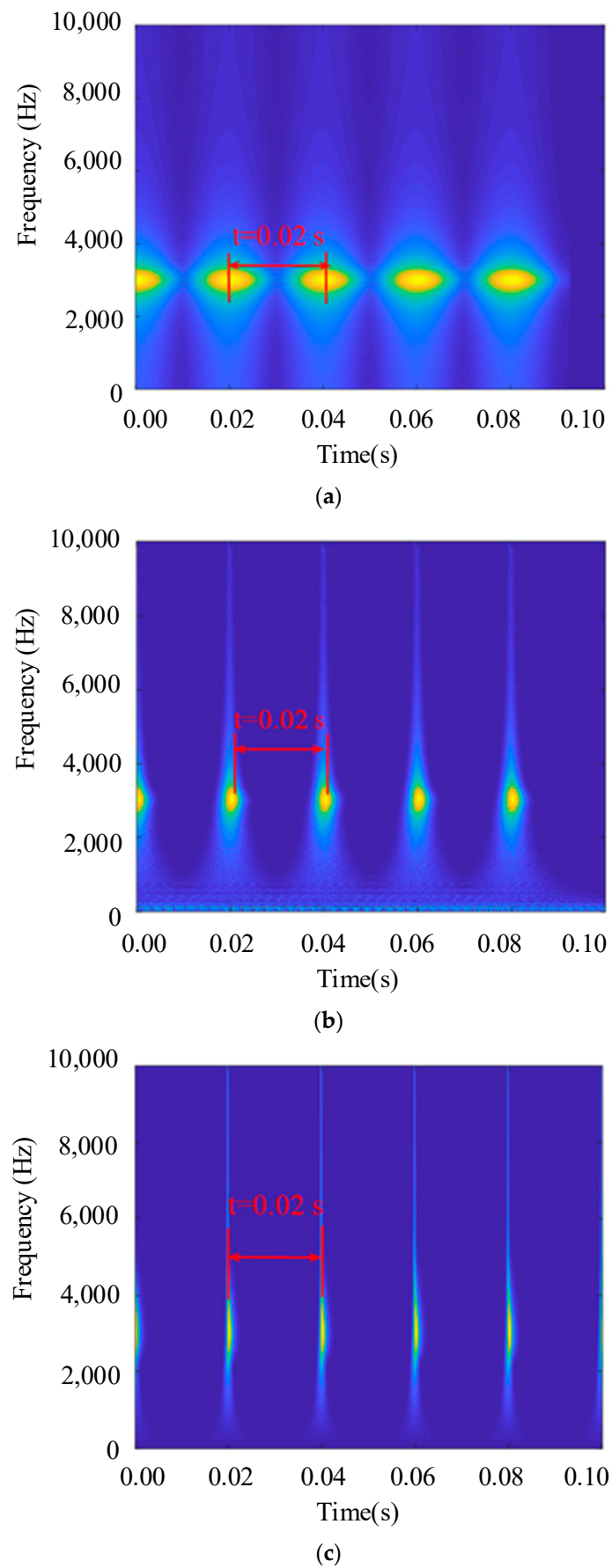


Figure 6. Time-frequency spectrum of the acoustic signal of the drill pipe before noise addition. (a) STFT; (b) WT; (c) ST.

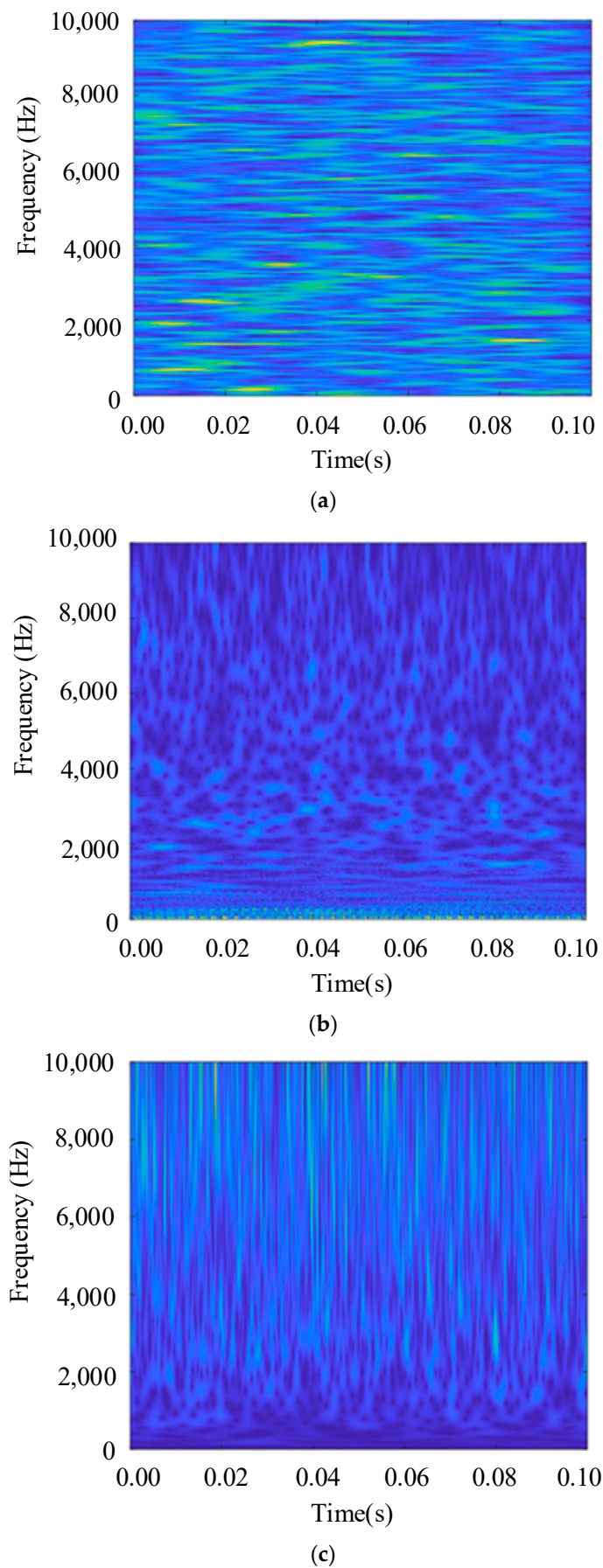


Figure 7. Time-frequency spectrum of the acoustic signal of the drill pipe after noise addition. (a) STFT; (b) WT; (c) ST.

As can be seen from Figure 7, when the acoustic signal is weak and obscured by strong background noise, it is difficult to effectively identify the acoustic signal feature information in the noise-added signal using all three time-frequency analyses: STFT, WT, and ST. Therefore, to effectively extract the characteristic information of the weak acoustic signal from the drill pipe under actual working conditions, it is necessary to apply noise reduction techniques to the drill pipe's acoustic signal.

2.2.2. Acoustic Signal Noise Reduction for Drill Pipe

The SVD noise reduction method is a technique that effectively suppresses random noise in signals and has been widely used in many fields [20]. The basic principle of SVD noise reduction is to exploit the low-rank property of the signal, decomposing the signal matrix into a singular value matrix and a singular vector and removing the noise by truncating the smaller singular values, thus achieving the noise reduction of the signal. Taking the ST as an example, for the drill pipe acoustic signal, the time-frequency decomposition is performed using the S-transform to obtain the time-frequency matrix, as shown in Equation (7).

$$\mathbf{s}_{m \times n} = \begin{bmatrix} \mathbf{S}_1 \\ \mathbf{S}_2 \\ \vdots \\ \mathbf{S}_m \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ s_{m1} & s_{m2} & \cdots & s_{mn} \end{bmatrix} \quad (7)$$

where m is the number of the sampling frequency; n is the total number of sampling time points; the matrix column vector is the sampling time; the matrix row vector is the sampling frequency; and the matrix element s_{lk} ($l = 1, 2, \dots, m; k = 1, 2, \dots, n$) is a complex number, containing the corresponding signal amplitude and phase information at a specific moment and frequency.

According to the definition of SVD [18], an $m \times m$ orthogonal matrix $\mathbf{U}$ and an $n \times n$ orthogonal matrix $\mathbf{V}$ exist such that:

$$\mathbf{S} = \mathbf{U}\mathbf{D}\mathbf{V}^T \quad (8)$$

where $\mathbf{D}$ is an $m \times n$ non-negative diagonal matrix, and the main diagonal of $\mathbf{D}$ is the singular value σ_i ($i = 1, 2, \dots, r$), $r = \min(m, n)$.

According to the theory of singular value decomposition and the Frobenius norm-based matrix approximation theorem, the useful signal is primarily represented by the first r largest singular values, while the noise signal is represented by the smaller singular values. By removing the smaller singular values representing the noise, the noise in the signal is effectively reduced. For a detailed explanation of this process, please refer to [21]. Thus, the signal after noise reduction can be obtained.

The singular values are arranged in decreasing order, i.e., $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_r$. A threshold value is set for the singular value sequence, and singular values below this threshold are set to zero, achieving noise reduction in the ST time-frequency matrix. In this study, we use the singular value difference spectrum method, as proposed in [22], to determine the threshold. Figure 7 illustrates the singular value difference spectrum of the ST time-frequency matrix for the drill pipe acoustic signal. As seen in Figure 8, the ST time-frequency matrix can be denoised by retaining the first 12 singular values. Similarly, the STFT and WT time-frequency matrices can also be denoised using the SVD method.

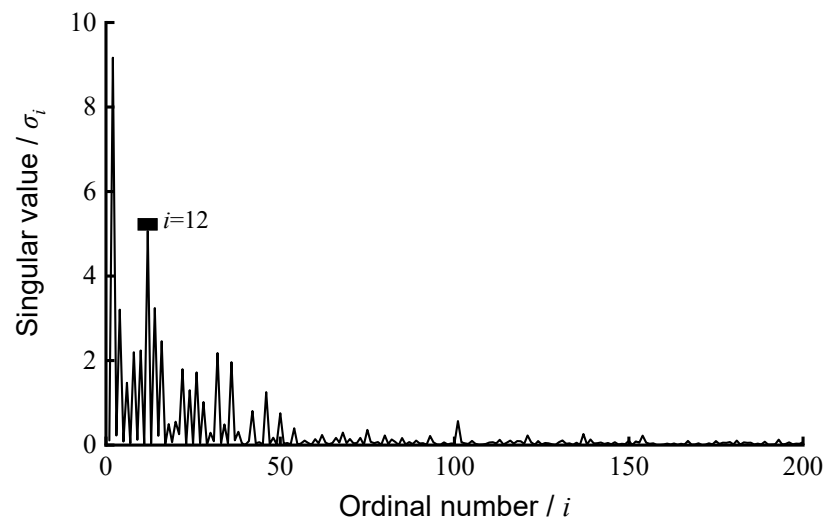


Figure 8. Singular value difference spectrum of the ST time-frequency matrix of drill pipe acoustic signals.

3. Results and Discussion

In this section, we present the results of the proposed time-frequency feature extraction method for weak acoustic signals from drill pipes. The aim is to validate the effectiveness of the ST-based approach in extracting weak acoustic signal features under strong background noise conditions. We compare the proposed method with the conventional STFT and WT methods through both simulation and experimental validation.

3.1. Simulation Verification

To validate the effectiveness of the proposed method, this section applies the S-transform (ST) and singular value decomposition (SVD) framework to simulated weak acoustic signals. The workflow includes three steps: (1) constructing a simulated drill pipe acoustic signal composed of a fundamental frequency (50 Hz) and harmonics, superimposed with Gaussian noise; (2) performing time-frequency analysis using STFT, wavelet transform (WT), and ST methods; and (3) comparing their noise reduction capabilities via SVD. The simulation results demonstrate the superiority of the ST-based method in feature extraction accuracy and noise immunity compared to conventional approaches.

Figure 9 presents the time-frequency spectrograms after noise reduction. As shown in Figure 9a,b, the drill pipe acoustic signal features cannot be effectively identified in the time-frequency spectrograms after noise reduction of the STFT and WT time-frequency matrices using the SVD method. As seen in Figure 9c, the noise in the ST time-frequency matrix is effectively suppressed, allowing the drill pipe acoustic signal features to be clearly identified.

The time-frequency spectrum, after noise reduction using the SVD difference spectrum, is inverted to extract the time-domain acoustic pulse signal characteristics of the simulated signal, as shown in Figure 10. By comparing Figures 3a and 10, it can be seen that while the acoustic pulse signal features extracted by the proposed method may exhibit some distortion, the key frequency and amplitude information of the acoustic pulse signal is extracted effectively.

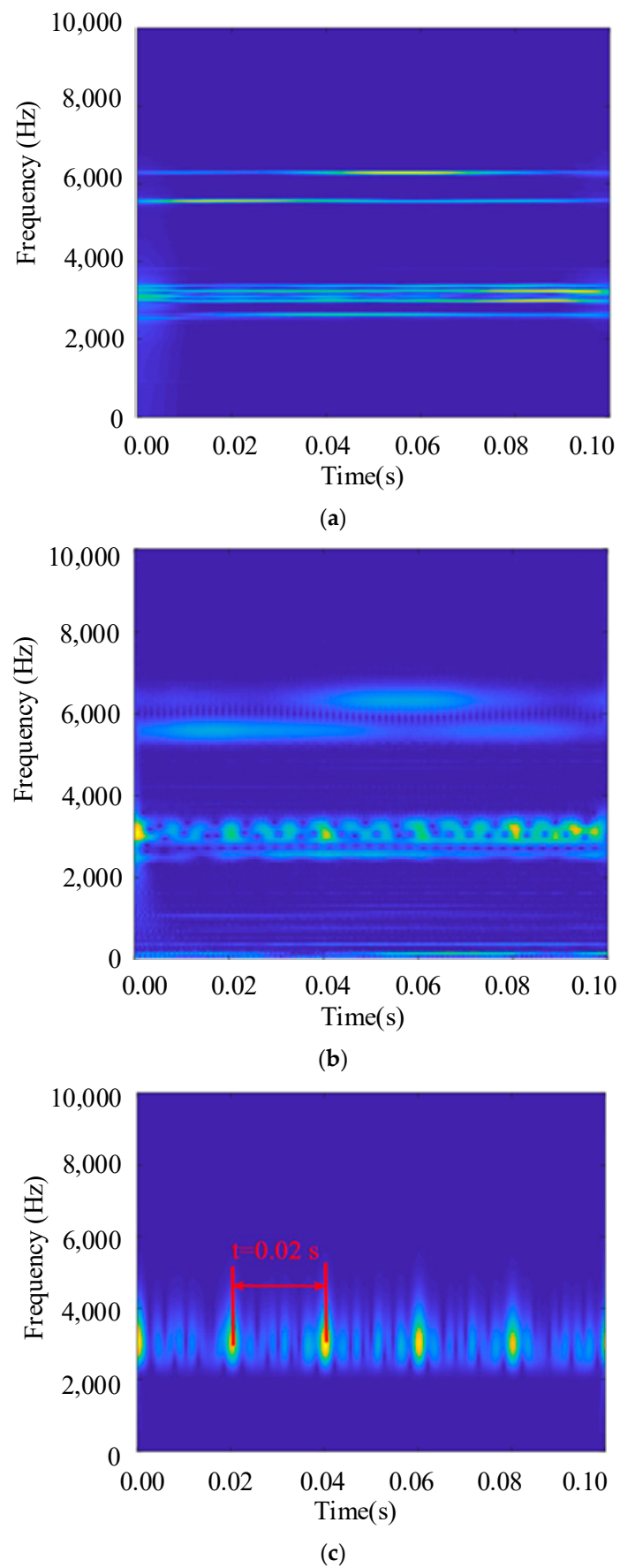


Figure 9. Spectrogram of the time spectrum after noise reduction. (a) STFT; (b) WT; (c) ST.

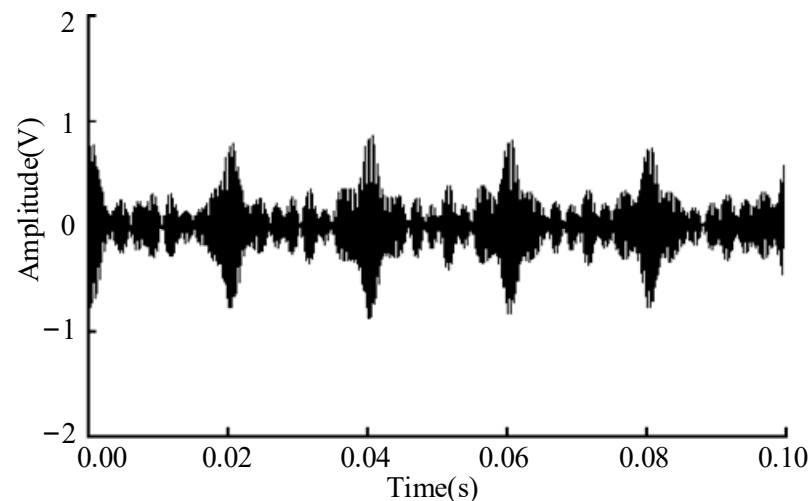


Figure 10. The time-domain acoustic signal feature of simulation signal.

3.2. Experimental Validation of Drill Pipe Acoustic Signals

After verifying the method's effectiveness through simulation, we further validate its performance using actual drill pipe acoustic signals. This section presents the experimental setup, data collection process, and analysis results.

A 1 m drill pipe was selected as the research object, with an outer diameter of 89 mm and an inner diameter of 77.8 mm. The block diagram of the test system is shown in Figure 11. The signal generator Agilent (33521A) produces a square wave signal with a frequency of 50 Hz, an amplitude of 2 V, and a 50% duty cycle. This signal is amplified by a power amplifier to drive the shaker. The shaker, positioned at one end of the drill pipe, converts the electrical signal into mechanical vibration, which excites the drill pipe to produce an acoustic signal. A triaxial acceleration sensor (INV9837B-50) is placed at the opposite end of the drill pipe to measure the acoustic signal generated by the excitation response. The measured signal is then transmitted to a vibration signal analyzer (INV3065N2-8). Finally, the vibration data are collected and analyzed using the vibration analysis software (DASP-V11), with a sampling frequency of 200 Hz and a sampling length of 0.5 s. The installation setup of the instruments and equipment is shown in Figure 12. After collecting the test data using this system, time-frequency analysis was performed on the collected data.

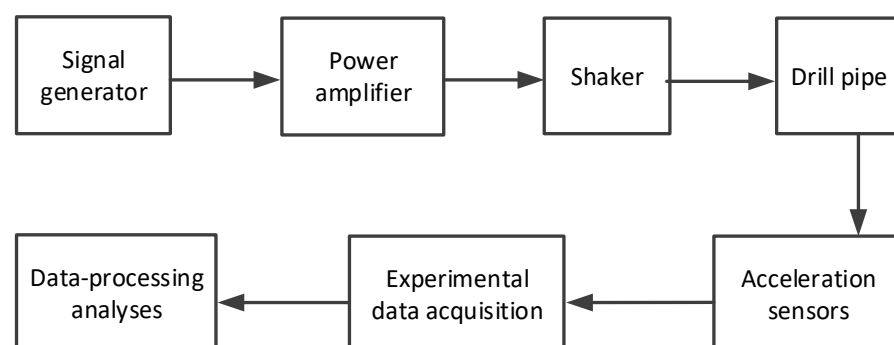


Figure 11. Block diagram of the acoustic transmission test system.

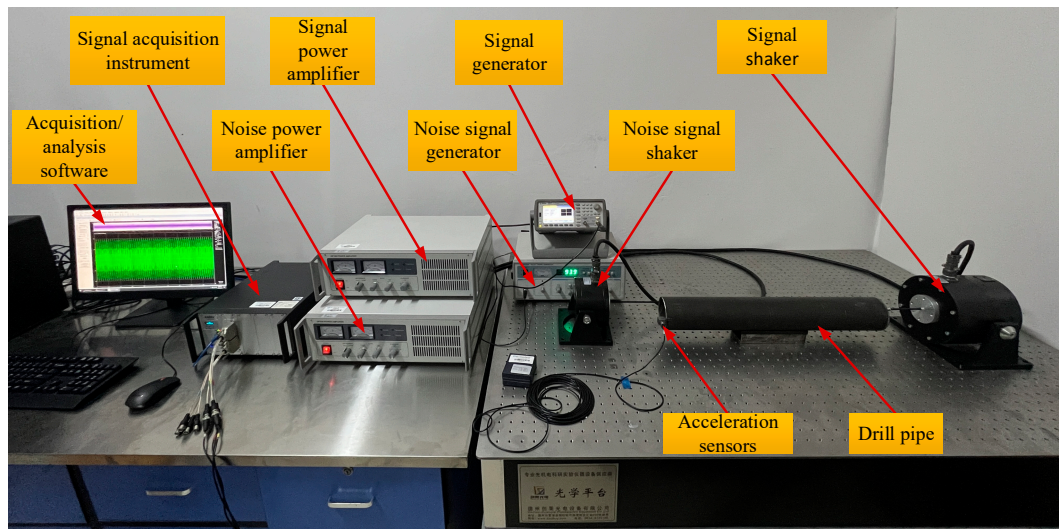


Figure 12. The experimental equipment diagram.

Considering the actual working conditions of the seafloor drill system, the acoustic signal propagating along the drill pipe is often affected by strong background noise. To simulate these real-world conditions during testing, a random vibration signal is introduced at the left end of the drill pipe, coinciding with the background noise. Figure 13 presents the waveforms of the drill pipe's acoustic vibration signal both before and after the addition of noise. As shown in Figure 13b, after the noise is added, the characteristics of the acoustic wave signal propagating along the drill pipe become faint, making it difficult to extract the acoustic signal features from the time-domain waveform.

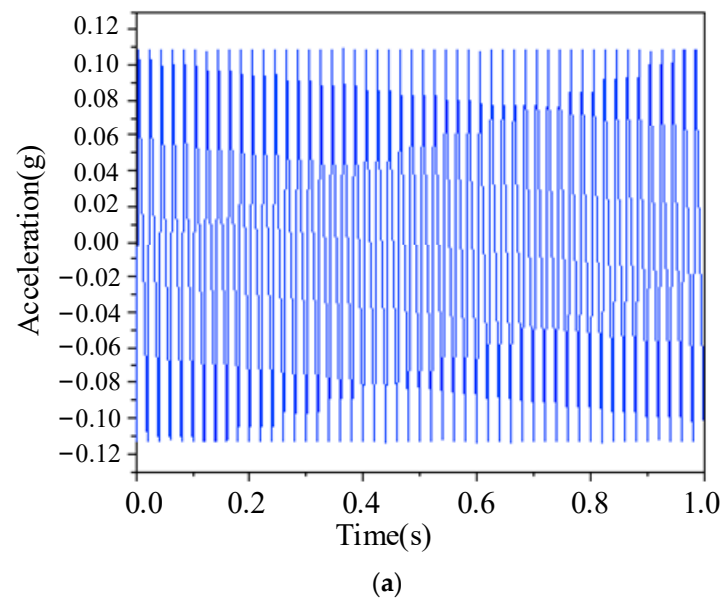


Figure 13. Cont.

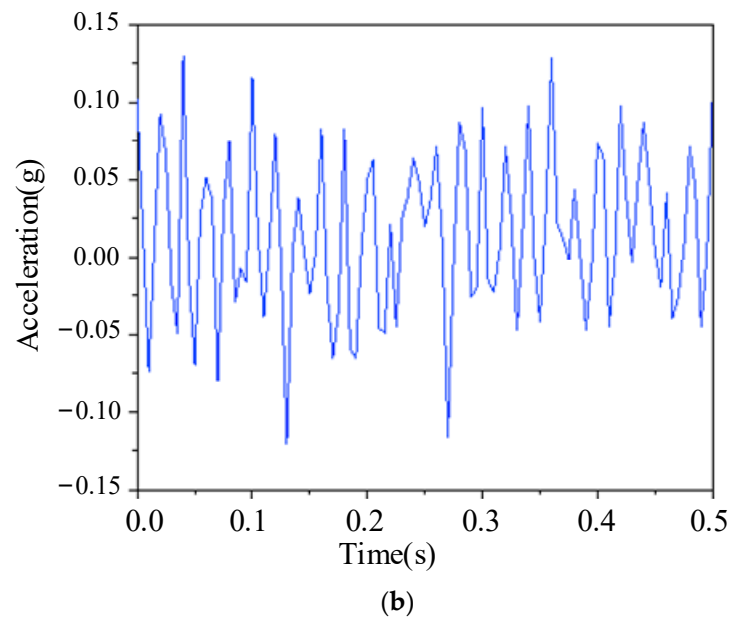


Figure 13. Wave of drill pipe acoustic signals before and after noise addition. (a) Normal drill pipe acoustic signals; (b) noisy drill pipe acoustic signals.

The results of the time-frequency analysis of the drill pipe acoustic signal, both before and after the addition of noise, using the ST method, are shown in Figure 14. As seen in Figure 14a, the ST method effectively identifies the acoustic signal characteristics of the drill pipe in the time-frequency spectrogram before noise is added. However, in Figure 14b, it is evident that under strong background noise, the acoustic signal features of the drill pipe become weak and difficult to discern using the ST method. Therefore, to accurately identify the drill pipe's acoustic signal features in the presence of strong background noise, noise reduction processing is required.

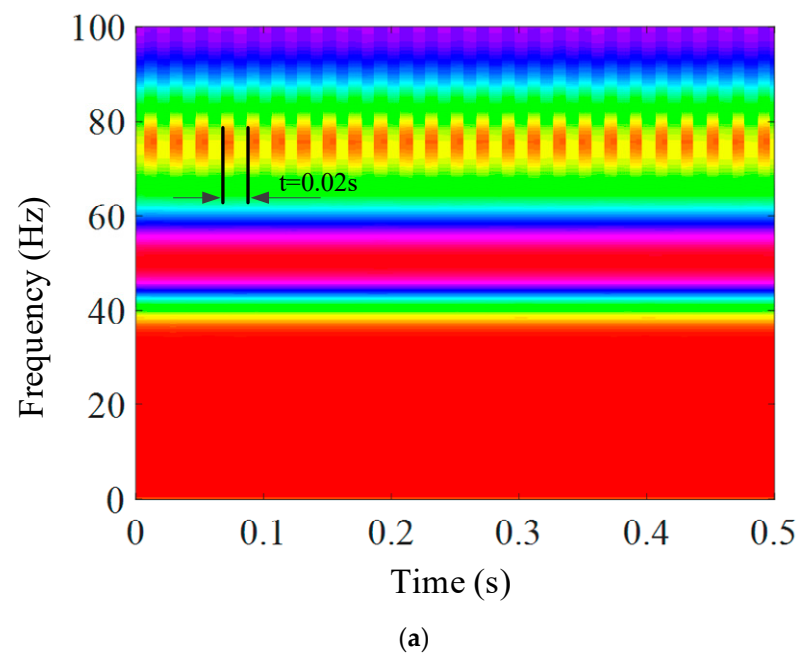


Figure 14. Cont.

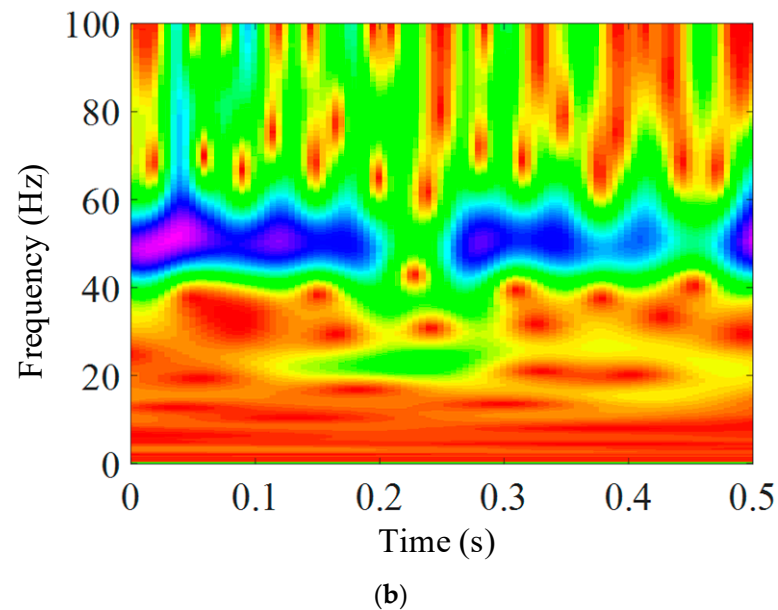


Figure 14. The spectrum of the drill pipe acoustic signals before and after noise addition. (a) Before noise addition; (b) after noise addition.

The ST time-frequency matrix is decomposed using singular value decomposition (SVD), and the effective singular values are selected based on the singular value difference spectrum. Figure 15 illustrates the singular value difference spectrum of the signal. As shown in Figure 15, noise reduction in the ST time-frequency matrix is achieved by retaining the first eight singular values.

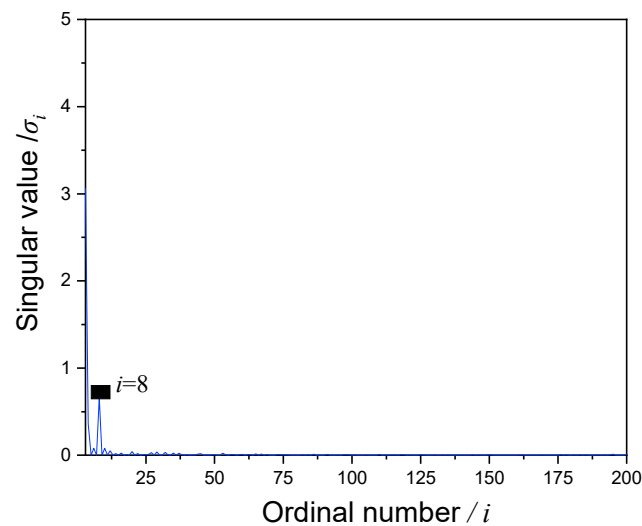


Figure 15. Singular value difference spectrum of drill pipe acoustic signal.

Figure 16 displays the time-frequency spectrum of the drill pipe acoustic wave signal after noise reduction. As shown in Figure 16, the noise in the ST time-frequency matrix is effectively suppressed, allowing clear identification of the drill pipe acoustic wave signal characteristics. Along the time axis, a distinct periodic shock characteristic appears at approximately 80 Hz on the frequency axis, with a period of about 0.0201 s, corresponding to a frequency of 49.75 Hz. This is in close agreement with the acoustic wave excitation frequency of 50 Hz.

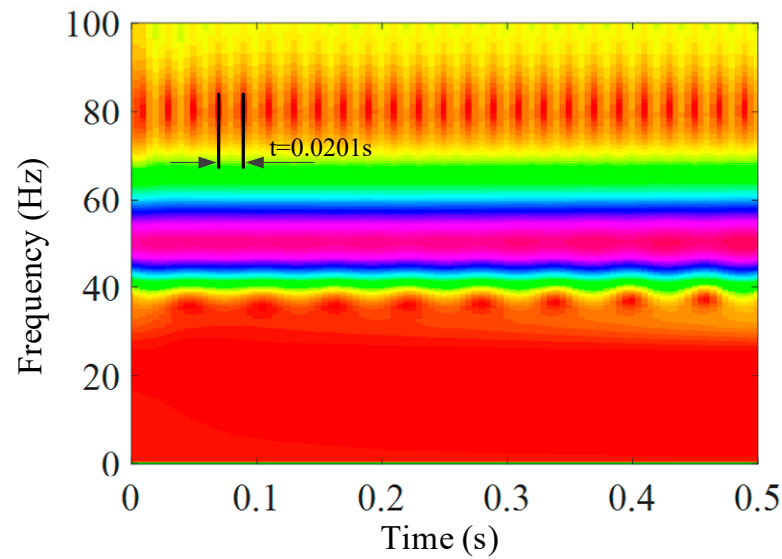


Figure 16. The spectrum of drill pipe acoustic signal by SVD denoising.

The ST's frequency-dependent Gaussian windows enable adaptive resolution: wider windows at low frequencies capture detailed frequency features, while narrower windows at high frequencies improve temporal localization. This adaptability explains its superior performance in extracting weak signals (e.g., 49.75 Hz) compared to fixed-resolution STFT and WT.

The S-inverse transformation of the time-frequency spectrum, following noise reduction through the SVD difference spectrum method, was applied to extract the time-domain features of the drill pipe acoustic signal, as shown in Figure 17.

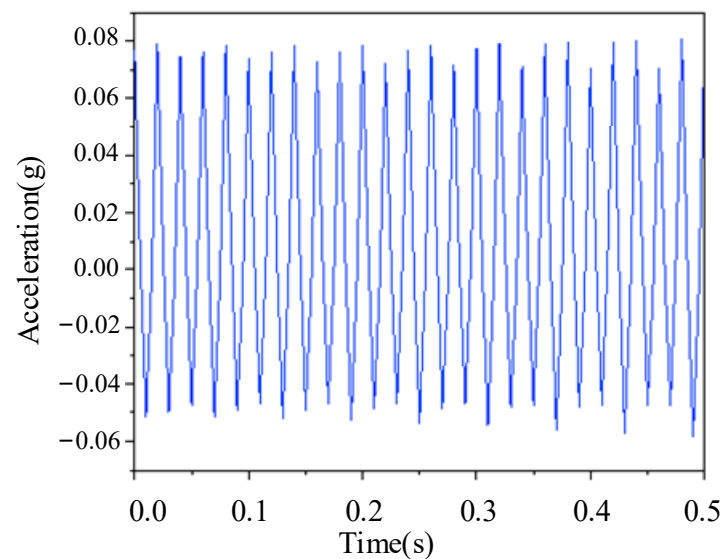


Figure 17. Time-domain signals of drill pipe acoustic signals.

By comparing Figures 13a and 17, it can be observed that while the acoustic signal features of the drill pipe, under strong background noise, exhibit some distortion and a reduction in amplitude, the essential frequency and amplitude information of the acoustic signal is still extracted effectively and comprehensively.

4. Conclusions

This study proposes a time-frequency feature extraction method based on the S-transform (ST) method for weak acoustic signals in seafloor drill pipes, addressing challenges posed by strong background noise. The key contributions and findings are synthesized as follows:

- (1) A time-frequency feature extraction method based on ST is proposed for weak acoustic signals from drill pipes. The method involves (a) performing time-frequency analysis of the drill pipe acoustic signal; (b) applying noise reduction using the SVD difference spectrum; and (c) performing S-inverse transformation on the noise-reduced signal, enabling the effective extraction of weak acoustic signal features from the drill pipe under strong background noise.
- (2) A comparison of three methods—STFT, WT, and ST—is conducted to identify weak signal features. The simulation and experimental results reveal that (a) STFT fails to identify weak acoustic signal features; (b) WT can identify weak signal features but has poorer time-frequency resolution and aggregation compared to ST; (c) ST significantly improves time-frequency resolution and aggregation and effectively identifies weak acoustic signal features under strong background noise.
- (3) The effectiveness of the proposed time-frequency feature extraction method for weak acoustic signals from drill pipes, based on ST, is validated through acoustic transmission tests. The method successfully extracts the most important frequency and amplitude information from the acoustic signals, offering a novel technical approach for feature extraction of weak acoustic signals from a drill pipe.

Despite the promising results, there are several aspects that need to be further investigated and improved in our future research: signal amplitude recovery could be further optimized; the method's performance under varying noise conditions needs further investigation; and computational efficiency could be enhanced for real-time applications.

Author Contributions: Conceptualization, J.X.; methodology, J.X.; software, Y.X.; investigation, X.T.; resources and validation, B.W.; writing—original draft preparation, J.X.; writing—review and editing, W.Q.; visualization, X.T.; supervision, B.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Programme of China (No. 2022YFC2806901), the National Key Research and Development Programme of China (No. 2022YFC2805901), and the China Postdoctoral Science Foundation (No. 2023M731822).

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors thank the anonymous reviewers for constructive comments that helped improve this manuscript.

Conflicts of Interest: The authors declare that none of the authors has any competing interests.

References

1. Liu, D.; Jin, Y.; Wan, B.; Peng, Y.; Huang, X. Review and Development Trends of Deep sea Mineral Resource Core Sampling Technology and Equipment. *China Mech. Eng.* **2014**, *25*, 3255–3265.
2. Zhang, H.; Jia, Y.; Liu, X.; Ji, C. Progress in in-situ measurement of sediment mechanical. *Mar. Geol. Front.* **2019**, *35*, 1–9.
3. Eslami, A.; Heidarie, G.S.; Naghibi, M.H. Developed triangular charts; deltaic CPTu-based soil behavior classification using AUT: CPTu-Geo-Marine Database. *Probabilistic Eng. Mech.* **2023**, *71*, 103380. [[CrossRef](#)]
4. Bombasaro, E.; Kasper, T. Evaluation of spatial soil variability in the Pearl River Estuary using CPTU data. *Soils Found.* **2016**, *56*, 496–505. [[CrossRef](#)]
5. Yu, X.X.; Liu, S.T.; Pei, H.X. Design of cone penetration test Sdata relay transmission by magnetic communication. *Sensors* **2022**, *22*, 4777. [[CrossRef](#)]

6. Li, Y.M.; Shen, Y.H.; Wang, X.Q.; Li, S.; Li, T.; Zhao, Q. Theoretical Studies and Implementation on the Temporary Data Storage Method for Cone Penetration Test. *Sensors* **2021**, *21*, 575. [[CrossRef](#)] [[PubMed](#)]
7. Chen, Q.; Geng, X.; Wan, B.; Jin, Y.; Luo, B.; Shi, Z. Multi-function In-situ Tester Development Based on Seabed Drill Rig. *J. Hunan Univ. Sci. Technol. (Nat. Sci. Ed.)* **2017**, *32*, 10–15.
8. Qin, M.; Wang, K.; Pan, K.; Sun, T.; Liu, Z. Analysis of signal characteristics from rock drilling based on vibration and acoustic sensor approaches. *Appl. Acoust.* **2018**, *140*, 275–282. [[CrossRef](#)]
9. Li, Y.F.; Wang, J.; Shan, Y.G.; Wang, C.; Hu, Y. Measurement and analysis of downhole drill string vibration signal. *Appl. Sci.* **2021**, *11*, 11484. [[CrossRef](#)]
10. Kajiwara, I.; Akita, R.; Hosoya, N. Damage detection in pipes based on acoustic excitations using laser-induced plasma. *Mech. Syst. Signal Process.* **2018**, *111*, 570–579. [[CrossRef](#)]
11. Liu, X.; Yu, C.; Shi, W.; Qian, X. Load spectrum editing method for automotive components based on generalised S-transformation. *J. Vib. Eng.* **2024**, *8*, 1–8.
12. Liu, Y.; Li, K.; Chen, P. Fault Diagnosis for Rolling Bearings Based on Synchrosqueezing Wavelet Transform. *China Mech. Eng.* **2018**, *29*, 585–590.
13. Liu, X.; Centeno, J.; Alvarado, J.; Tan, L. One dimensional convolutional neural networks using sparse wavelet decomposition for bearing fault diagnosis. *IEEE Access* **2022**, *10*, 86998–87007. [[CrossRef](#)]
14. Antoniadis, I.; Glossiotis, G. Cyclostationary analysis of rolling-element bearing vibration signals. *J. Sound Vib.* **2001**, *248*, 829–845. [[CrossRef](#)]
15. Stockwell, R.G.; Mansinha, L.; Lowe, R.P. Localization of the complex spectrum: The S transform. *IEEE Trans. Signal Process.* **1996**, *44*, 998–1001. [[CrossRef](#)]
16. Guo, Y.; Jin, X.; Wei, Y.; Wei, Y.; Yang, Y. Fault diagnosis method of rotating machinery using variational mode extraction guided by S transform. *J. Vib. Eng.* **2022**, *35*, 1289–1298.
17. Liu, X.; He, K. A new scheme for extracting fault features of rolling element bearings. *Eng. Comput.* **2022**, *39*, 3038–3057. [[CrossRef](#)]
18. Xia, J.; Liu, Y.; Len, Y.; Ge, J. Analysis of Methods of Weak Signal Detection. *Noise Vib. Control* **2011**, *31*, 156–161.
19. Cai, J.; Tang, J.; Lei, L.; Wang, X. Time frequency analysis of magnetotelluric data. *Geol. Explor.* **2009**, *45*, 462–467.
20. Meng, Z.; Liu, Z.; Lyu, M. Fault Diagnosis for Rolling Bearings Based on Improved Singular Value Decomposition and Spectral Kurtosis. *China Mech. Eng.* **2020**, *31*, 2420–2428.
21. Jiang, H.; Chen, J.; Dong, G.; Liu, T.; Chen, G. Study on Hankel matrix-based SVD and its application in rolling element bearing fault diagnosis. *Mech. Syst. Signal Process.* **2015**, *52–53*, 338–359. [[CrossRef](#)]
22. Zhao, X.; Ye, B. Similarity of signal processing effect between Hankel matrix-based SVD and wavelet transform and its mechanism analysis. *Mech. Syst. Signal Process.* **2009**, *23*, 1062–1075. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.