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Prospects for the Application of Wavelet Analysis in the Problems of Classification of Hydroacoustic Signals

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ABSTRACT Wavelet transformation is widely used for signal analysis, which, unlike the classical Fourier transform, make it possible to simultaneously detect low-frequency and high-frequency characteristics of signals on different time scales (i.e., it is feasible to examine how the frequency spectrum of signals varies over time). The theory of wavelet transformation relies on the concept of multi-scale analysis, which involves examining the signal at various frequencies and resolutions. At the same time, it increases the flexibility of signal processing methods and expands the scope of their application. Wavelet transformation is also widely used in information and telecommunication systems, physics and astrophysics, mathematics, seismology, image compression, speech recognition, medicine etc. Moreover, based on wavelet analysis of non-stationary and nonlinear echoes of underwater objects, it is possible not only to classify and identify objects, but also to solve these problems in highly noisy and complex conditions for detecting hydroacoustic signals. Further research using wavelet analysis opens up new perspectives for the development and improvement of systems used to monitor and analyze complex signals in various environments. Wavelet transformation open up new horizons for scientific research, become an integral part of modern signal analysis technologies, contribute to a more effective solution of complex problems in different fields of technology and science, which ensures high accuracy and reliability of the results obtained. In addition, due to the ability to localize in the time-frequency domain and resistance to interference, wavelet transforms are used in highly efficient modern systems for detecting and identifying underwater objects. Further development of scientific research in this area will certainly further expand the possibilities of wavelet analysis, making it an even more powerful tool in the field of signal and information processing.

KEYWORDS hydroacoustic signal, information and telecommunication systems, wavelet transformation, digital signal processing, Fourier transform.

I. INTRODUCTION

Although there is a substantial amount of literature on the practical use of wavelet transformation in digital signal processing, some problems still remain unsolved. First of all, it concerns the evaluation of the parameters of the wavelet transform itself during the study of objects, namely: the choice of parameters for pre-processing of data and the selection of the parent wavelet (wavelet basis). Determination of the optimal parent wavelet is an important stage in wavelet analysis, since it is from this basic function that all functions will be obtained by the operations of its shifts and stretches.

The Fourier transform has long been utilized for spectral analysis of signals because of its frequency domain localization, but it has the drawback of lacking time domain localization. The aim of this research is to examine and compare current wavelet transformation methods and identify optimal wavelet bases based on criteria such as time-frequency localization, computational efficiency, and noise resistance.

Wavelet transformations are usually divided into the following types [1]:

1. Discrete wavelet transform;
2. Packet wavelet transform;
3. Continuous wavelet transform;
4. Modified discrete wavelet transform.

A discrete wavelet transform (DWT) is performed to divide a signal into low-frequency (approximate) and high-frequency (detailing) coefficients. After the first level, the approximations are crushed into higher levels.

Packet wavelet transformation (PWT) extends the discrete wavelet transform by further decomposing both the approximation and detail coefficients of the signal at each level, providing a more refined representation of the signal across all decomposition levels. PWT is convenient to use for detailed analysis of signals with complex structures, such as underwater noise and vibrations.

A continuous wavelet transforms (CWT) scales and shifts the wavelet across the entire domain of the analyzed signal during calculation, i.e. it works at any scale [2]. CWT is one of the most straightforward transformations to visualize and is somewhat analogous to the Fourier transform, where any time-based function can be expressed as an infinite series of sinusoidal functions with corresponding coefficients. However, in wavelet analysis, sinusoidal functions are substituted with wavelet functions. The basic idea is to find the coefficients that are necessary to accurately represent the time function. A wavelet is a mathematical function that usually depends on time.

The Modified Discrete Wavelet Transform (MDWT) is also a DWT, but with enhanced capabilities in the form of modified wavelet bases and additional levels of decomposition, as well as additional algorithms that allow the processing of non-stationary signals without limiting the sample size and has proven itself in the analysis of non-stationary underwater signals [3] that change over time, for example: vibrations from underwater vehicles, sounds from marine mammals, etc.

II. ANALYSIS OF STATIONARY AND NON- STATIONARY SIGNALS

Wavelet theory covers both continuous and discrete cases, offering versatile methods applicable to a wide range of signal processing tasks. It is particularly useful for analyzing non-stationary signals, providing an alternative to the short-time Fourier transform (STFT) or Gabor transform. The key distinction lies in the fact that, unlike STFT, which relies on a single analysis window, the wavelet transform employs short windows for high frequencies and longer windows for low frequencies. In some cases, it is beneficial to view wavelet transformation as the decomposition of a signal into a series of basis functions, known as wavelets. These wavelets are derived from a single prototype through scaling and shifting.

The goal of signal analysis is to extract valuable information from a signal through transformation. This process enables a unique representation of the signal, allowing for more advanced tasks such as parameter estimation, encoding, and pattern recognition to be conducted on the transformed data, where relevant properties may be clearer. These transformations are particularly useful for stationary signals, which are characterized by having consistent properties over time. For such $x(t)$ signals, the natural "steady-state transformation" is the well-known Fourier transform [4]:

$$X(f) = \int_{-\infty}^{+\infty} x(t) e^{-j\pi f t} dt. \quad (1)$$

The analysis coefficients $X(f)$ characterize the global frequency of the signal f. As illustrated in equation (1), these coefficients are calculated by projecting the signal onto sinusoidal basis functions of infinite length. Fourier analysis is effective when $x(t)$ is composed of multiple stationary components. However, for non-stationary signals, where abrupt changes occur over time, these changes are spread across the entire frequency spectrum $X(f)$. Consequently, analyzing non-stationary signals necessitates methods beyond the traditional Fourier transform. One approach involves incorporating a time-dependent element into Fourier analysis while preserving its linear nature. This means introducing a "local frequency in time" parameter so that the "local" Fourier transform examines the signal within a window where it can be considered nearly stationary. Alternatively, sinusoidal basis functions in Fourier transform can be replaced with basis functions that are more temporally focused, as seen in continuous wavelet transformation. To address the resolution limitations of STFT, consider allowing the resolution Δt and Δf to vary across the frequency-time plane. [5]:

$$\frac{\Delta f}{f} = c, \quad (2)$$

where c is a constant.

The analysis filter bank is made up of bandpass filters that maintain a constant relative bandwidth. When equation (2) is applied, the resolution Δt will vary with the central frequency of the analysis filter Δf . In continuous wavelet transformation, the impulse responses of the filter bank are defined as scaled (i.e., stretched or compressed) versions of a single prototype $h(t)$:

$$h_\alpha(t) = \frac{1}{\sqrt{|\alpha|}} h\left(\frac{t}{\alpha}\right), \quad (3)$$

where: α – a scaling factor (it is used to normalize energy); $h_\alpha(t)$ – represents a scaled version of the basic wavelet $h(t)$, utilized for analyzing the signal at various scales. Then:

$$\mathrm{CWTx}(\tau, \alpha) = \frac{1}{\sqrt{|\alpha|}} \int x(t) h^*\left(\frac{t-\tau}{\alpha}\right) dt, \quad (4)$$

where: $h^*(t)$ – complex conjugation of the base wavelet $h(t)$, which will be used to correctly compute the convolution in a continuous wavelet transform.

The prototype $h(t)$ referred to as the basic wavelet, is employed for all impulse responses within the filter. Consequently, the wavelet analysis remains consistent across different scales. The relationship to the modulated window used in STFT can be written as follows $h(t)$ [5]:

$$h(t) = g(t) e^{-2j\pi f_0 t}, \quad (5)$$

where: $g(t)$ – this is a window function that defines the temporal localization of the wavelet; f_0 – this is the center frequency or carrier frequency of the wavelet. It defines the fundamental frequency of the harmonic function that modulates the window $g(t)$.

III. THEORY OF HYDROACOUSTIC SIGNAL PROCESSING BY WAVELET ANALYSIS

To classify hydroacoustic signals effectively, they must undergo pre-processing first. The quality and accuracy of the classification process are heavily dependent on the effectiveness of this initial processing. The processing of hydroacoustic signals involves the preparation of data and the use of subsequent algorithms that allow useful signals to be extracted. Pre-processing involves several steps, including removing noise from signals, evaluating randomness, emphasizing short-term local features, and applying preliminary filtering, among others. Methods and methods of pre-treatment affect the process of further analysis in the hydroacoustic monitoring system [6].

It's important to recognize that while methods for pre-processing hydroacoustic signals have been explored for a significant period, several challenges remain unresolved, including:

1. Handling signal parameter uncertainties;
2. Processing complex, non-stationary hydroacoustic signals with numerous local features;
3. Analyzing multi-component signals.

Modern advances in digital signal processing, as well as the development of hardware, make it possible to effectively apply a significant number of mathematical methods, combining continuous and discrete wavelet transformation. Such a solution is an effective tool for signal preprocessing due to the presence of fast computational algorithms and a variety of wavelet bases, as well as adaptability [7].

Therefore, using wavelet analysis during the processing of hydroacoustic signals, the following possibilities will be obtained [8, 9]:

1. Detection of objects in the aquatic environment;
2. Detection and classification of sea targets based on the analysis of local features of signals;
3. Selection of hydroacoustic signals in the presence of background noise;
4. Visualization and processing of hydroacoustic signals based on wavelet spectrograms of different scales.

The wavelet transform uses wavelets as basis functions, so consider the basis of harmonic wavelets whose spectra are rectangular in a given frequency band [10]. Harmonic wavelets are typically expressed in the frequency domain.

The wavelet function can be written as [11]:

$$\varphi(\omega) = \begin{cases} \frac{1}{2\pi}, 2\pi \leq \omega < 4\pi \\ 0,\ \omega < 2\pi, \omega \geq 4\pi \end{cases}, \qquad (6)$$

where: $\boldsymbol{\varphi(\omega)}$ – a wavelet function in the frequency domain, describes how the frequency components are represented in a signal after a wavelet transformation has been applied. The values of $\varphi(\omega)$ determine the amplitude of the frequency components in a particular frequency range $(\boldsymbol{\omega})$.

Because $\boldsymbol{\varphi(\omega)}$ not zero within $\boldsymbol{2\pi \leq \omega < 4\pi}$, the integral can be calculated within:

$$\varphi(\omega) = \int_{2\pi}^{4\pi} \frac{1}{2\pi} e^{j\omega x}\, d\omega, \qquad (7)$$

then:

$$\varphi(x) = \int_{-\infty}^{+\infty} \varphi(\omega) e^{j\omega x} d\omega = \frac{e^{j4\pi x} - e^{j2\pi x}}{j2\pi x}, \qquad (8)$$

where: $\boldsymbol{\varphi(x)}$ – represents the inverse Fourier transform of $\boldsymbol{\varphi(\omega)}$, which converts the function from the frequency domain back to the time domain. This means that $\boldsymbol{\varphi(x)}$ is a function that describes a signal in the time domain recovered from the frequency representation $\boldsymbol{\varphi(\omega)}$.

That is, with the help of formulas (6-8) it is possible to describe the function $\boldsymbol{\varphi(\omega)}$ in the frequency domain and its inverse Fourier transform, which gives $\boldsymbol{\varphi(x)}$ in the time domain.

IV. SIMULATION OF HYDROACOUSTIC SIGNALS USING WAVELET TRANSFORM

In the field of engineering, for the purpose of computer modeling, analysis and signal processing, the Matlab software package was widely used. Distortion and noise are key factors impacting the accuracy of results in signal measurement systems and also constrain data transmission capacity in telecommunications networks.

Simulations focused on removing noise and distortion are central to both the theoretical and practical elements of signal processing and communication. It should also be noted that the problem of reducing noise and distortion levels is a major challenge in areas such as mobile communications, speech recognition, image processing, medical signal processing, sonar systems, etc. [12]. Wavelets are convenient to use to remove noise from information signals.

With the help of the functions of the built-in wavelet package in Matlab, you can use Daubechies wavelet and many others [13, 14]. The Daubechies wavelet provides temporal localization and form an orthogonal basis.

An analysis of the sound signal from the vessel propagated on the surface of the sea using the Wavelet Signal denoiser was carried out. Fig. 1 illustrates the outcome of isolating a useful signal from background noise, which consists in using a discrete wavelet transform to compare the initial data (data) and the noise-free signal (data1).

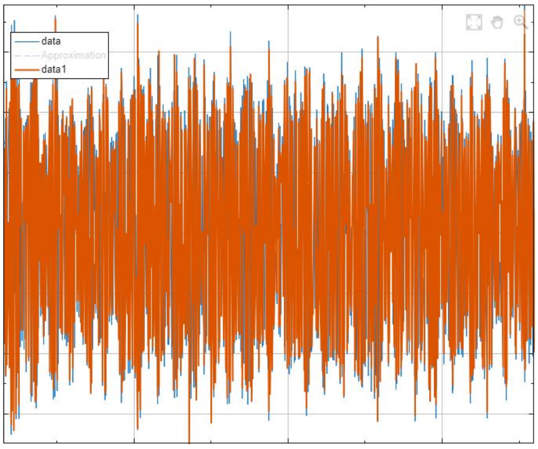

FIG. 1. Isolation of noise from the useful signal of the vessel's movement on the sea surface.

Due to the fact that each wavelet is displayed and executed differently, a comparative analysis is provided when using Daubechies wavelet (in this case, third-order wavelet) and Biorthogonal wavelet.

The coefficients of Daubechies wavelet and Biorthogonal wavelet make it possible to compare the efficiency of signal cleaning from noise, which includes differences in the retention of useful signal information and the degree of noise suppression.

The results of signal purification from noise using Daubechies wavelet and Biorthogonal wavelet with the corresponding coefficients are shown in Fig. 2 and Fig. 3.

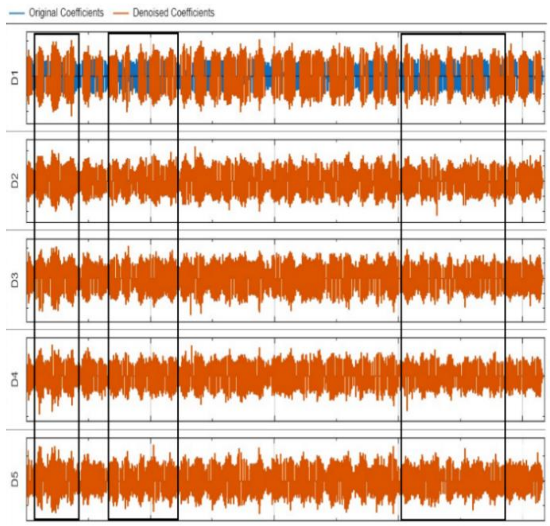

FIG. 2. Results of signal clearance from noise using Daubechies wavelet with D1-D5 coefficients.

Based on the analysis of the obtained results of signal processing, it can be noted that Daubechies wavelet provides better compression and isolation of signal components, while Biorthogonal wavelet has the property of preserving the symmetry of the signal after its processing.

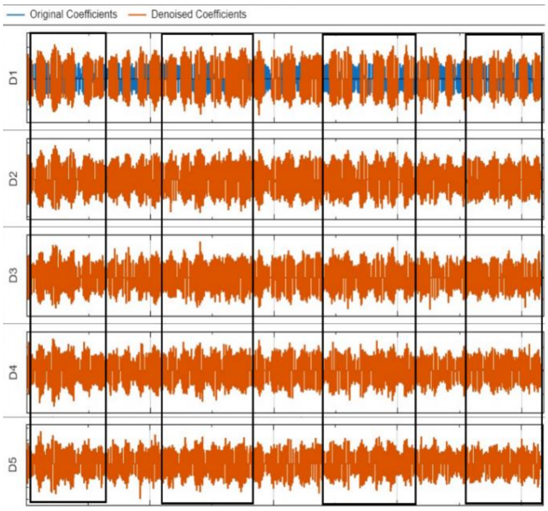

FIG. 3. Results of signal cleaning from noise using Biorthogonal wavelets with D1-D5 coefficients.

It should be noted that the use of wavelet transformation is an effective tool for signal preprocessing, especially in conditions of significant noise, and the obtained dependencies of the amplitude of the studied hydroacoustic signals on frequency and time can be further used for more in-depth analysis and study.

V. CONCLUSION

Wavelet transforms are an effective means of analyzing and processing non-stationary signals with variable frequency responses. Unlike the Fourier transform, the wavelet transform provides a more adaptive approach to signal analysis on different time scales, which is critical for hydroacoustic signal processing. The use of wavelet analysis opens up new opportunities for more accurate classification and processing of hydroacoustic signals. Due to its property for localization in the frequency-time domain and resistance to noise, wavelet transformation significantly increases the efficiency of modern underwater monitoring systems. Further research and innovation in this area will certainly contribute to the creation of more reliable and accurate systems for detecting and identifying underwater objects.

AUTHOR CONTRIBUTIONS

Y.P., O.L. – writing (original draft preparation), conceptualization, methodology, investigation; H.L. – methodology, investigation, writing (review and editing).

COMPETING INTERESTS

The authors declare no competing interests.

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Перспективи застосування вейвлет аналізу в задачах класифікації гідроакустичних сигналів

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АНОТАЦІЯ Широкого застосування для аналізу сигналів отримали вейвлет-перетворення, що, на відміну від класичного Фур'є-перетворення, дозволяють виявляти одночасно низькочастотні та високочастотні характеристики сигналів на різних часових масштабах (тобто є можливість аналізу часової зміни частотного спектру сигналів). В основу теорії вейвлет-перетворення покладено підхід кратномасштабного аналізу, тобто аналізу сигналу на різних частотах і з різною роздільною здатністю одночасно, що підвищує гнучкість методів обробки сигналів та розширює сферу їх застосування. Тож вейвлет-перетворення набули широкого використання в інформаційно-телекомунікаційних системах, фізиці та астрофізиці, математиці, сейсмології, стисненні зображень, розпізнаванні мови, медицині та інших галузях. Більше того, на основі вейвлет-аналізу нестаціонарних та нелінійних ехосигналів підводних об’єктів можна здійснювати не тільки класифікацію та ідентифікацію об'єктів, а й вирішення цих завдань у сильно зашумлених та складних умовах виявлення гідроакустичних сигналів. Подальші дослідження з використанням вейвлет-аналізу відкривають нові перспективи для розробки та вдосконалення систем, які використовуються для моніторингу і аналізу складних сигналів у різних середовищах. Вейвлет-перетворення відкривають нові горизонти для наукових досліджень, стають невід’ємною частиною сучасних технологій аналізу сигналів, сприяють ефективнішому вирішенню складних завдань у різних галузях науки і техніки, що забезпечує високу точність і надійність отриманих результатів. Крім того, завдяки здатності локалізації в частотно-часовій області та стійкості до завад, вейвлет-перетворення знаходять застосування в високоефективних сучасних системах виявлення та ідентифікації підводних об'єктів. Подальший розвиток наукових досліджень цієї галузі неодмінно ще більше розширить можливості вейвлет-аналізу, роблячи його ще більш потужним інструментом у сфері оброблення сигналів та інформації.

КЛЮЧОВІ СЛОВА гідроакустичний сигнал, інформаційно-телекомунікаційні системи, вейвлет-перетворення, цифрове оброблення сигналів, перетворення Фур’є.