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Filtration Methods in Sonar Systems

Yevhen Parkhomenko*, Halyna Lastivka, Oleksandr Lastivka and Andrii Samila

Department of Radio Engineering and Information Security, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine

*Corresponding author (E-mail: parkhomenko.yevhen@chnu.edu.ua)

ABSTRACT The paper considers the main methods of hydroacoustic signal filtering used to extract useful information from natural and anthropogenic noise. The reliability and accuracy of sonar systems depend on the ability to suppress interference while preserving the useful components of the received acoustic signals. Particular attention is paid to wavelet smoothing, the Wiener filter, adaptive filtering algorithms based on the Least Mean Squares (LMS) method, and a variety of frequency-selective filters, including bandpass, low-pass, high-pass, and notch filters. The effectiveness of each method is discussed in the context of typical underwater acoustic environments, where noise sources vary in origin and spectral characteristics. As part of the study, a real hydroacoustic signal recorded using a broadband hydrophone in natural aquatic conditions was used to evaluate and compare the filtering techniques. The signal contained both low-frequency and high-frequency interference components, as well as impulsive noise typical of biological and anthropogenic sources. MATLAB R2024a software was used to simulate and visualize the filtering process, including wavelet decomposition and thresholding. Based on the results obtained, a combined approach to filtering is proposed, which integrates several complementary methods to enhance signal clarity. This hybrid strategy enables more accurate detection and identification of underwater objects by adapting to specific noise scenarios. The simulation results confirm that a multi-stage filtering scheme significantly improves the signal-to-noise ratio and preserves informative features of the hydroacoustic signal. The proposed approach is applicable to sonar systems used for marine research, underwater navigation, and environmental monitoring.

KEYWORDS hydroacoustic, wavelet transformation, Fourier transform, Wiener filter.

I. INTRODUCTION

Hydroacoustic plays an important role in the development and research of sonar technologies and systems, which in turn are important for ensuring underwater communication, monitoring, detection of surface and underwater objects of both natural and man-made origin, as well as in the study of the marine environment, including its physicochemical properties, geological structure and biological activity. In addition, hydroacoustic is used to map the bottom, observe the migration of marine organisms, measure noise levels, comprehensively assess the technical condition of underwater infrastructure, etc. The research data is based on the analysis of large arrays of hydroacoustic data, which in turn require high-precision mathematical processing, identification of informative features, identification of hidden patterns and construction of models to describe complex physical phenomena. Such phenomena include, in particular, the propagation of acoustic waves in media with random spatial inhomogeneities, the emission of signals by sources of different configurations and apertures, interference phenomena, scattering of waves at inhomogeneities, as well as diffraction effects. Especially important is the use of the low-frequency sound range, which allows you to reach significant depths of signal penetration and effectively probe geological structures that are located at great depths. However, acoustic signals propagating in the aqueous medium are affected by a large number of factors, including reflection from the boundaries of the medium, refraction on density gradients, scattering on suspended particles and bubbles, absorption of energy in the water column, as well as the presence of acoustic interference. A large number of these factors significantly complicate the selection of a useful signal, reduce the signal-to-noise ratio and lead to information distortion. Thus, efficient processing of sonar signals using modern methods of filtering, statistical analysis, adaptive spectral decomposition processing and machine learning is extremely important to ensure the reliability, accuracy and efficiency of the functioning of sonar systems in real conditions.

II. FILTERING METHODS FOR HYDROACOUSTIC SIGNAL PROCESSING

Hydroacoustic systems play a key role in detecting and identifying underwater objects, in particular when searching for minerals located in them. Due to the ability of low-frequency sound vibrations to penetrate to considerable depths, effective probing of geological structures is ensured. In addition, the analysis of sound scattering characteristics in the water column makes it possible to detect acoustically active layers of biological origin, also called sound scattering zones. This makes it possible to estimate the size and density of small fish aggregations, which in turn is of practical importance for fisheries research and marine bioecology [1].

Signals propagating in water are often affected by a variety of factors, including reflection, refraction, and absorption, which complicates their analysis and interpretation. Efficient processing of hydroacoustic signals is critical to improving the accuracy and reliability of such systems.

The main purpose of filtering hydroacoustic signals is to extract useful information that may be contained in the amplitude, frequency or spectral composition, as well as the phase of the signal or the relative time dependencies of several signals. Due to the presence of background noise in the underwater environment, the extraction of a useful acoustic signal is one of the problems in the field of hydroacoustic signal processing.

The sources of background noise are both natural (biological sounds and seismic phenomena) and anthropogenic factors. Moreover, the interpretation and refinement of hydroacoustic data is further complicated by the presence of noise of various origins, such as turbulent pulsations, wave noise, biological and anthropogenic interference, and therefore the correct choice of filtering methods is of particular importance, to effectively extract the informative component of the signal

The most effective filtering methods include wavelet smoothing, which provides a representation of the signal in the time-frequency domain and allows to extract components characteristic of the useful signal by thresholding the coefficients [2].

This approach is especially effective for processing nonstationary signals that are often encountered in hydroacoustic studies, and the process itself is realized through a discrete wavelet transform (DWT) that can be formally written in the form:

$$DWT(s(t)) = \sum_j \sum_k c_{j,k} \Psi_{j,k}(t), \qquad (1)$$

where: $s(t)$ – input signal; $\Psi_{j,k}(t)$ – wavelet functions (scaled and time-shifted versions of the basic wavelet function); $c_{j,k}$ – wavelet coefficients that reflect the contribution of the corresponding function $\Psi_{j,k}(t)$ to the formation of the output signal.

After the wavelet transformation, the threshold zeroing of the coefficients is applied as follows:

$$\hat{c}_{j,k} = \begin{cases} 0, & |c_{j,k}| < \lambda \\ c_{j,k,} & |c_{j,k}| \geq \lambda \end{cases}, \qquad (2)$$

where: λ – threshold value, which is selected according to the noise level.

This operation makes it possible to suppress or entirely eliminate high-frequency components induced by noise, while preserving useful information in the original signal.

Another effective tool is the Wiener filter, which demonstrates high performance in the presence of Gaussian noise. It allows for optimal signal recovery, provided that at least some partial information about the spectral characteristics of the signal under study and the interference is available. The main goal of this method is to minimize the root mean square error between the recovered signal and its real but unknown form [3].

In the frequency domain, the Wiener filter has the form:

$$H(f) = \frac{s_{xx}(f)}{s_{xx}(f)+S_{nn}(f)}, \qquad (3)$$

where: $H(f)$ – frequency response of the Wiener filter; $s_{xx}(f)$ – is the power spectral density of the input signal; $S_{nn}(f)$ – is the spectral density of the noise power.

The application of the filter to the observed signal $Y(f)$ is as follows:

$$\hat{X}(f) = H(f)Y(f), \qquad (4)$$

where: $\hat{X}(f)$ – evaluation of the filtered signal spectrum. The inverse Fourier transform will be used to further restore the signal.

In cases where the signal has a limited spectrum, it is advisable to use bandpass filters that enable the isolation of the frequency range necessary for the study. This is especially true for echolocation and underwater object detection tasks.

In turn, low-pass and high-pass filters should be used to pre-clean the signal from frequency components that are most likely to be noise [4]. It is also possible to use notch filters to selectively suppress narrowband interference, which is often caused by man-made sources such as engines or electromagnetic generators [5].

For tasks in which noise characteristics change over time, it is advisable to use adaptive filters based on the least mean squares algorithm, which allow real-time changes in filter parameters in accordance with current conditions [6].

In the presence of a reference signal, it is useful to use correlation analysis methods, in particular cross-correlation, which allows to identify signals similar to the reference and suppress the background [7].

In general, in the practice of hydroacoustic analysis, a combined approach is usually used when pre-filtering methods are combined with wavelet analysis and adaptive processing, which allows for high accuracy of detection and identification of underwater objects.

III. SIMULATION RESULTS AND VISUAL ANALYSIS

Modeling with distortion and noise removal is at the heart of theoretical and practical aspects of signal processing. The problem of noise and distortion reduction is a serious issue in such areas as speech recognition, image processing, sonar systems, etc. [8].

The functions of the built-in wavelet package in Matlab provide access to Daubechies wavelets and many others [9, 10].

Figure 1 obtaining a useful signal using a discrete wavelet transform. The figure presents a comparison between the original signal (labeled "Data") and the filtered signal (labeled "Data1") after applying a DWT. The signal was processed in MATLAB. The horizontal axis represents time, while the vertical axis shows amplitude. The transformation allows suppression of noise components and highlights the useful part of the signal.

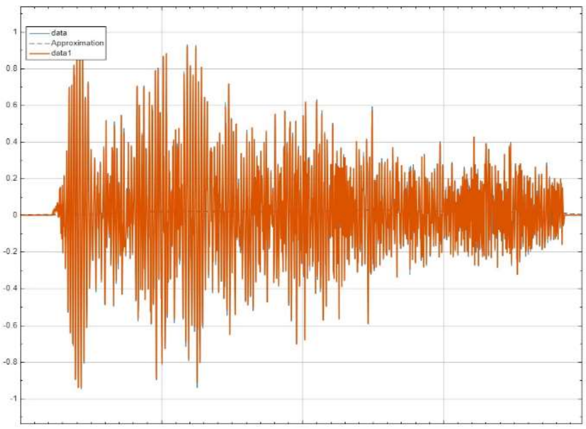

FIG. 1. Obtaining a useful signal using a discrete wavelet transform.

Figure 2 presents the wavelet decomposition coefficients of the noisy signal (`Data`) and the target denoised signal (`Data1`) before denoising. The signal is decomposed into five detail levels: D1, D2, D3, D4, and D5. Each level corresponds to a specific frequency band, from highest (D1) to lowest (D5). The plots show how noise manifests across multiple scales.

a) X-axis – Time (sample index).

b) Y-axis – wavelet detail coefficients.

High-amplitude fluctuations in D1–D3 represent high-frequency noise components, while lower levels (D4, D5) contain useful structural information.

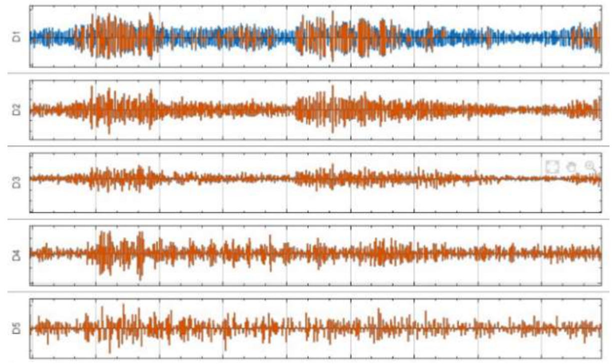

FIG. 2. Wavelet transformation coefficients before noise cleaning.

Figure 3 is similar in structure to Figure 1 but emphasizes the final cleaned signal after reconstruction. Data shows the noisy input. Data1 is the clean output after applying DWT and inverse transformation. The successful extraction of the useful part of the signal is visually confirmed. The difference from Figure 1 lies in more pronounced contrast between signal and background.

a) X-axis – Time.

b) Y-axis – Signal amplitude.

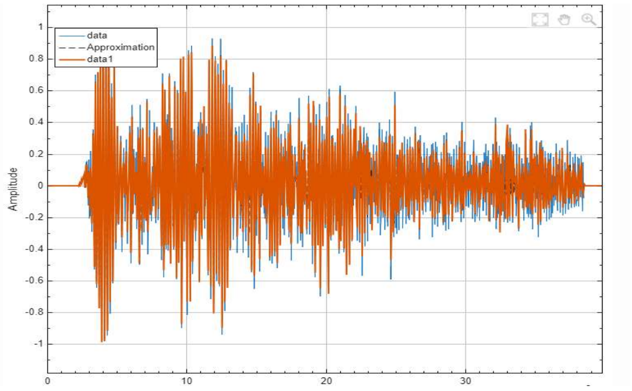

FIG. 3. The result of cleaning the useful signal from noise.

Figure 4 displays the wavelet decomposition coefficients after thresholding and noise reduction. The underlying signals are the same `Data` (original) and `Data1` (denoised) signals used in Figure 3.

a) The same levels D1 – D5 are shown.

b) Many of the small, noisy coefficients are reduced or set to zero.

c) X-axis – Time.

d) Y-axis – Denoised detail coefficients.

The suppression of high-frequency noise is evident, especially in the upper levels. The useful signal is preserved primarily in the lower-frequency bands.

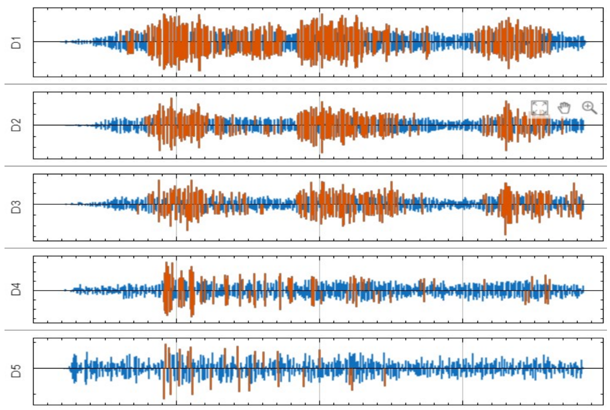

FIG. 4. Wavelet transformation coefficients after noise cleaning.

IV. CONCLUSION

Filtering of hydroacoustic signals is critical to ensure reliable extraction of informative characteristics in noisy environments. The choice of filtering methods depends on the type of signal, the nature of the interference, and the accuracy requirements of the analysis. Wavelet smoothing has proven to be particularly effective for non-stationary signals due to its operation in the frequency-time domain. The Wiener filter provides high efficiency in the presence of Gaussian noise and the ability to estimate statistical parameters a priori. General frequency filters are used for basic signal cleaning, while notch filters are applied to suppress specific narrowband interferences. Adaptive filters based on LMS algorithms allow you to adjust to changes in the spectral composition of noise in real time. Cross-correlation methods provide effective detection of hydroacoustic signals in the presence of a reference. Thus, the best results are achieved by combining several filtering methods, which in turn allows to adapt the hydroacoustic signal processing system to the underwater environment and increase the efficiency of hydroacoustic surveys. Simulation results (Figures 1 – 4) confirm the effectiveness of discrete wavelet transform in isolating useful signal components across multiple decomposition levels. Visual comparison before and after denoising (Figures 2 and 4) illustrates the removal of noise-dominant coefficients, while Figures 1 and 3 demonstrate the quality of reconstructed signals. These results validate the applicability of wavelet-based smoothing for processing hydroacoustic data in complex environments.

AUTHOR CONTRIBUTIONS

Y.P. – writing (original draft preparation), conceptualization, methodology, investigation; O.L – writing (original draft preparation), conceptualization, methodology, investigation; G.L., A.S. – writing (original draft preparation), conceptualization, methodology, investigation.

COMPETING INTERESTS

The authors declare no competing interests.

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Yevhen Parkhomenko

Received MS degrees in Radio Engineering from Yuriy Fedkovych Chernivtsi National University, Ukraine. Is currently studying at a postgraduate course in Electronic Communications and Radio Engineering. His research interests include network and cyber security.

ORCID ID: 0009-0006-1805-1932

Halyna Lastivka

Received BS and MS degrees in Radio Engineering from ChNU, Ukraine. She received a Ph.D. in solid state electronics from ChNU. She is currently an associate professor of the Radio Engineering Department of ChNU. Her research interests include methods and means of radio spectroscopy, their application for research of sensory properties, structures, defects of layered and organic semiconductors.

ORCID ID: 0000-0003-3639-3507

Oleksandr Lastivka

Received MS degrees in Electronic Communications and Radio Engineering from Yuriy Fedkovych Chernivtsi National University, Ukraine. His research interests include electronic communications and radio engineering, network and cyber security.

ORCID ID: 0009-0002-6232-3270

Andrii Samila

Yuriy Fedkovych Chernivtsi National University. D.Sc. (Engineering), Full Professor, Head of Radio Engineering and Information Security Department of Yuriy Fedkovych Chernivtsi National University. Research interests: IoT, Microelectronics & Electronic Packaging, Signal Processing, Computer Hardware Design, Robotics, High Energy & Nuclear Physics. Author of nearly 200 publications in this research area.

ORCID ID: 0000-0001-8279-9116

Методи фільтрації в гідроакустичних системах

Євген Пархоменко*, Галина Ластівка, Олександр Ластівка, Андрій Саміла

Кафедра радіотехніки та інформаційної безпеки, Чернівецький національний університет імені Юрія Федьковича, м.Чернівці, Україна

*Автор-кореспондент (E-mail: parkhomenko.yevhen@chnu.edu.ua)

АНОТАЦІЯ У статті розглянуто основні методи фільтрації гідроакустичних сигналів, що використовуються для виділення корисної інформації з природних та антропогенних завад. Надійність і точність гідроакустичних систем залежать від здатності придушувати завади зі збереженням корисних складових прийнятих акустичних сигналів. Особливу увагу приділено вейвлет-згладжуванню, фільтру Вінера, алгоритмам адаптивної фільтрації на основі методу найменших квадратів, а також різноманітним частотно-селективним фільтрам, зокрема смуговим, низькочастотним, високочастотним і режекторним. Ефективність кожного методу обговорюється в контексті типових підводних акустичних середовищ, де джерела шуму відрізняються за походженням і спектральними характеристиками. В рамках дослідження для оцінки та порівняння методів фільтрації використовувався реальний гідроакустичний сигнал, записаний за допомогою широкосмугового гідрофона в природних водних умовах. Сигнал містив як низькочастотні, так і високочастотні завади, а також імпульсні шуми, характерні для біологічних та антропогенних джерел. Для моделювання та візуалізації процесу фільтрації, включаючи вейвлет-розкладання та порогове значення, було використано програмне забезпечення MATLAB. На основі отриманих результатів запропоновано комбінований підхід до фільтрації, який інтегрує кілька взаємодоповнюючих методів для підвищення чіткості сигналу. Ця гібридна стратегія дозволяє більш точно виявляти та ідентифікувати підводні об'єкти, адаптуючись до конкретних шумових сценаріїв. Результати моделювання підтверджують, що багатоступенева схема фільтрації значно покращує відношення сигнал/шум і зберігає інформативні характеристики гідроакустичного сигналу. Запропонований підхід може бути застосований до гідроакустичних систем, що використовуються для морських досліджень, підводної навігації та екологічного моніторингу.

КЛЮЧОВІ СЛОВА гідроакустика, вейвлет-перетворення, перетворення Фур'є, фільтр Вінера.