

Original paper

Spectral Features of Hydroacoustic Signals

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Abstract

The paper analyses spectral and time-frequency characteristics of hydroacoustic signals of animal and anthropogenic origin, as well as background signals. The study aims to classify and identify these signals to address ecological monitoring tasks in the marine environment and to develop effective criteria for signal differentiation for automated assessment of the acoustic situation in coastal and shelf zones. We used methods of spectral and time-frequency analysis along with comparative analysis based on a review of current scientific literature. Characteristic features of spectra and spectrograms for various groups of signal sources were identified. Signals were classified according to their acoustic origin, and key parameters for signal identification under high noise conditions were determined, including spectral shapes, presence of harmonics, pulse durations, and specific temporal patterns. A feature set in the form of numerical vectors was created for subsequent application in machine learning algorithms and automatic recognition systems. The developed approach can be integrated into ecological monitoring systems for coastal waters and advanced navigation solutions.

Keywords: spike, harmonic, sound localization, hydroecholocation, identification, natural noise, technogenic noise, pulse, broadband

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Спектральные особенности гидроакустических сигналов

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Аннотация

Анализируются спектральные и временно-частотные характеристики гидроакустических сигналов животного и антропогенного происхождения, также фоновые сигналы, с целью их классификации и идентификации для решения задач экологического мониторинга морской среды, а также формирования эффективных критериев дифференциации сигналов для автоматизированной оценки акустической обстановки в прибрежных и шельфовых зонах. Используются методы спектрального и временно-частотного анализа, а также сравнительного анализа на основе обзора современной научной литературы. Выделены характерные особенности спектров и спектрограмм для различных групп источников сигналов. Проведена классификация сигналов по типу акустического происхождения, определены ключевые параметры идентификации сигнала в условиях высокой шумовой нагрузки – форма спектров, наличие гармоник, длительность импульсов и специфические временные паттерны. Сформирован набор признаков в виде числовых векторов для последующего применения в алгоритмах машинного обучения и системах автоматического распознавания. Разработанный подход может быть интегрирован в системы экологического мониторинга прибрежных акваторий и перспективные навигационные решения.

Ключевые слова: всплеск, гармоника, идентификация сигналов, естественный шум, техногенный шум, импульс, широкополосность, акустический сигнал, спектр

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Introduction

Hydroacoustic underwater monitoring systems play a key role in modern marine science and technology, enabling effective research and monitoring of the ocean environment. The development of these systems is driven by the need to obtain accurate and timely information about the underwater environment, which is crucial for both scientific research and ensuring the safety of maritime operations ¹⁾. Modern hydroacoustic technologies, based on digital signal processing and spectral analysis methods, allow various underwater sound sources to be identified and classified with high accuracy, which is critical for underwater navigation, communication, and environmental monitoring tasks [1, 2].

¹⁾ Zakharov, I.S., 2004. [Development of National Hydroacoustic Means: The Early 1920s–The Late 1950s. Doctoral Thesis]. Saint Petersburg, 390 p. (in Russian).

The development of domestic hydroacoustic equipment began in the mid-20th century, when the fundamental principles of acoustic signal research in aquatic environments were established. The subsequent decades, particularly the late 20th and early 21st centuries, saw significant progress in spectral and time-frequency analysis of hydroacoustic data, greatly improving the efficiency of signal processing and interpretation [3]. Modern research focuses on optimizing processing algorithms, including the use of discrete and fast Fourier transforms, vector-phase methods and trajectory-space filtering, aimed at enhancing the extraction of informative features from noise sources and improving the accuracy of determining their coordinates and directionality [4, 5].

Despite the availability of a wide range of specialized methods for analyzing hydroacoustic signals, many are tailored to highly specific tasks and limited in their application to particular classes of sound sources. Existing methods often fail to adequately provide a unified description of the spectral characteristics of signals varying in nature and origin, including both anthropogenic and bioacoustic sources. This creates a gap in digital processing technologies, hindering the broader application of hydroacoustic systems in areas such as automated eco-monitoring of marine ecosystems and comprehensive classification of underwater objects [2, 4–6].

The increasing anthropogenic impact on the underwater environment and the growing volume of information from underwater sources necessitate the development of precise methods for analyzing and identifying acoustic signals to enhance the reliability of underwater navigation and communication systems [1, 3, 7]. Environmental monitoring tasks are becoming increasingly critical, as they require simultaneous recording and analysis of both bioacoustic signals and anthropogenic noise, complicating the interpretation of the acoustic environment.

Although effective algorithms for processing hydroacoustic signals have been developed in recent years, including optimized Fourier analysis methods [4] and vector-phase approaches [8, 9], they typically focus on highly specialized tasks and do not provide a comprehensive description of both spectral and time-frequency characteristics of heterogeneous signals. Specifically, there are no universal methods that enable a uniform description of both bioacoustic and anthropogenic signals, limiting data integration in environmental monitoring and navigation systems [9–12].

The study aims to systematically analyze the spectral and time-frequency characteristics of various hydroacoustic signals, focusing on identifying unique features that enable reliable source identification and classification. The proposed approach facilitates a unified description of the spectral properties of both anthropogenic and bioacoustic signals, expanding the applicability of standard digital processing methods and enhancing the accuracy and versatility of hydroacoustic monitoring systems.

Materials and methods

The first stage of the study involved data collection and filtering. The analyzed signals were sourced from the AXDS Portals open database of hydroacoustic recordings, containing data from bottom stations, hydrophones, and other sensors deployed in coastal and oceanic areas²⁾. The recordings were in WAV format with sampling rates ranging from 4 to 64 kHz, depending on the source type and equipment. For analysis, sound fragments of 5 to 60 s were selected, representing typical samples of each signal class – biological, anthropogenic, and natural background noise. The total number of independent recordings for each signal type was 20–30, enabling the derivation of averaged spectra with acceptable statistical stability.

The recorded signals underwent preliminary processing to remove external interference and artifacts caused by equipment limitations. Digital filtering methods were applied to isolate significant frequency ranges and reduce the impact of background noise [3].

The fast Fourier transform was used to identify the primary frequency components of each signal. This method enabled the derivation of power spectra, characterizing the distribution of signal energy across frequencies. The signal spectrum is defined as the set of amplitudes and initial phases of harmonic oscillations at various frequencies, which collectively reconstruct the original signal. The spectra were analyzed to identify dominant frequencies, harmonics, and patterns characteristic of specific signal groups. The basis of spectral analysis was the discrete Fourier transform, defined for a discrete signal $x[n]$ with N samples by the formula:

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-j \frac{2\pi kn}{N}},$$

where $k = 0, 1, \dots, N-1$ is the frequency index.

To investigate changes in the spectral structure over time, time-frequency analysis methods, including spectrogram construction, were employed. This enabled the identification of unique temporal structures, such as burst periodicity, pulse duration, and signal attenuation dynamics.

A comparative analysis of different signal types was conducted to identify unique features distinguishing animal, anthropogenic, and natural background noise signals. Key parameters included spectral shape, presence of harmonics, pulse duration, and specific temporal patterns. The spectra presented reflect typical characteristics of each signal class but do not account for variability due to species differences, seasonal and hydrometeorological conditions, or technical device characteristics.

²⁾ Axiom Data Science. *Data Portal Documentation*. 2025. Available at: <https://help.axds.co/portals/overview.html#data-views-overview> [Accessed: 22 August 2025].

The algorithm for analyzing spectra and spectrograms involved performing a Fourier transform, constructing spectrograms, analyzing peak frequencies, estimating signal bandwidth, calculating the spectral centroid to detect periodicities, and evaluating the signal autocorrelation function [4].

For use in machine learning algorithms, formalized spectral and temporal features (dominant frequency, bandwidth, harmonic amplitude parameters) were extracted and represented as numerical vectors, serving as input features for machine learning models [5]. These features are designed for classifying hydroacoustic signals by source type, including bioacoustic and anthropogenic noise. Such signals exhibit consistent structure and reproducibility in their spectral patterns, enabling their use in training datasets for developing recognition models without requiring manual labeling of the original signals.

To implement all stages of the analysis, general-purpose software tools were used, including digital signal processing libraries in MATLAB and Python, as well as data visualization tools. The reliability of the results was evaluated using cross-validation techniques, which involve repeatedly partitioning the dataset into training and test subsets to minimize the impact of random factors in the analysis.

The effectiveness of the developed methods was evaluated using independent datasets from the publicly available AXDS Portals database, which contains verified examples of the investigated noise types, confirming their applicability to a wide range of hydroacoustic signal identification tasks ²⁾.

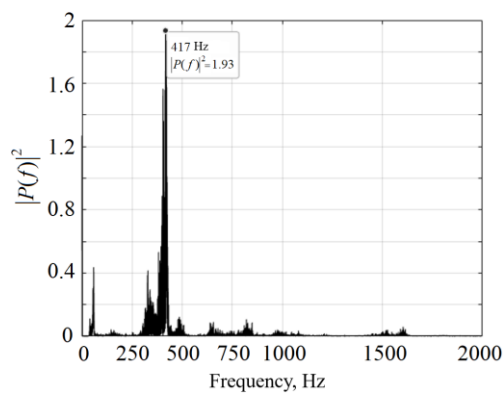
Results and discussion

The signals *sea lion barking* and *killer whale singing* are examples of animal sounds with relatively complex frequency structures [6, 7]. The spectrum of the *sea lion barking signal* (Fig. 1, *a*) exhibits a prominent peak at approximately 400 Hz, reaching a spectral power density value of 1.93. Attenuated bursts at frequencies of 60 and 330 Hz indicate the presence of harmonics, contributing to the characteristic low timbre, resembling a hoarse bark.

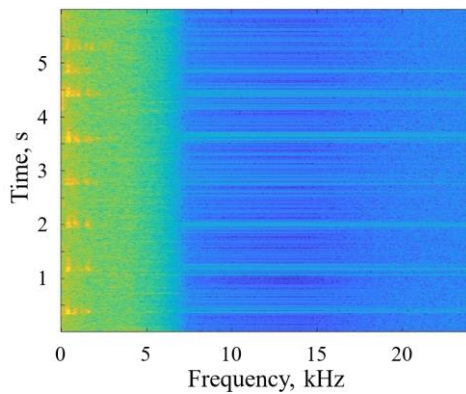
The signal spectrogram (Fig. 1, *b*) clearly illustrates the concentration of primary sound energy in the low-frequency range.

The spectrum of the *killer whale singing* signal (Fig. 2, *a*) exhibits the clearest signal structure among the signals analyzed in the study. It spans a broad frequency range, reflecting a complex harmonic structure and diverse acoustic elements in killer whale vocalizations. Multiple peaks occur between 0 and 11 kHz, with the most prominent at frequencies of 1.3, 2, and 2.1 kHz. These frequency components of the signal are associated with communication and environmental orientation [6].

The signal spectrogram (Fig. 2, *b*) is characterized by a number of bright bands located within the 0 to 11 kHz range. High-frequency components manifest as additional vertical bands, highlighting the broadband nature of the signal.

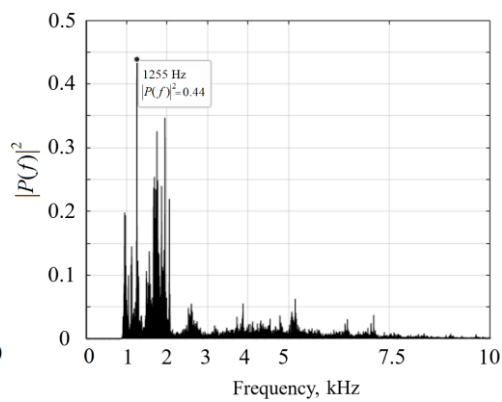


a

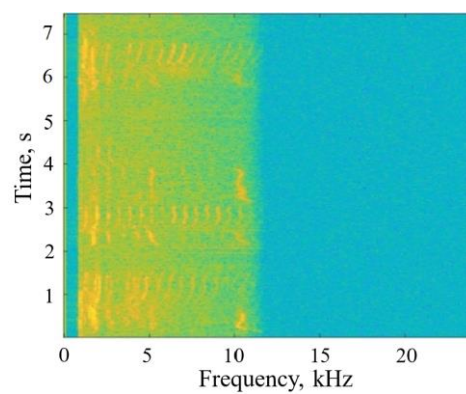


b

Fig. 1. Spectral analysis of the *sea lion barking* signal: *a* – spectrum; *b* – spectrogram



a

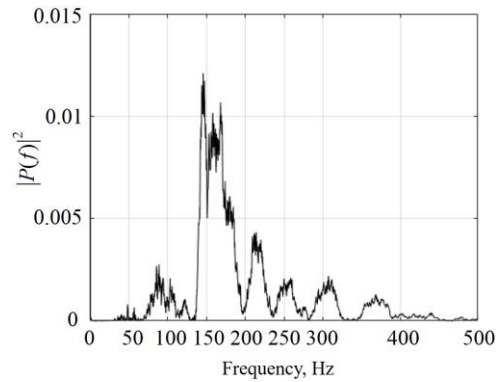


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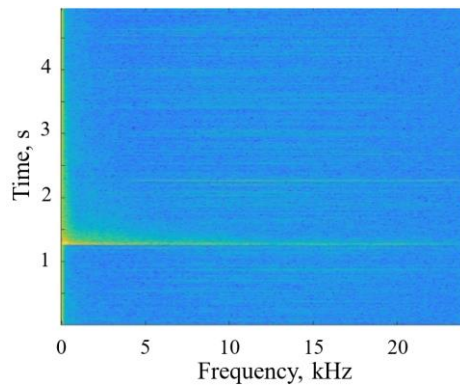
Fig. 2. Spectral analysis of the *killer whale singing* signal: *a* – spectrum; *b* – spectrogram

The *explosion* and *sonar* signals are characterized by distinct narrowband peak frequencies. The *explosion* signal exhibits a different frequency power distribution compared to the *sonar* signal, as evidenced in both the obtained spectrum (Fig. 3, *a*) and the spectrogram (Fig. 3, *b*). The maximum spectral power density (0.88) was observed in the 140–180 Hz range [8, 9].

The spectrum of the *sonar* signal (Fig. 4, *a*) exhibits a series of narrowband peaks within the 2.3 to 3.3 kHz range. In the spectrogram (Fig. 4, *b*), these appear as recurring bright horizontal bands. Their periodicity, consistent width, and intensity highlight the stability and predictability of the signal. This frequency composition is characteristic of signals employed by sonar devices [9].

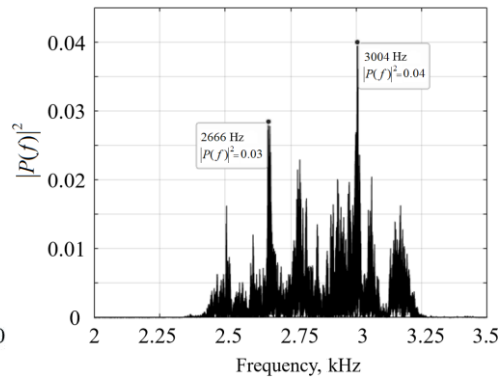


a

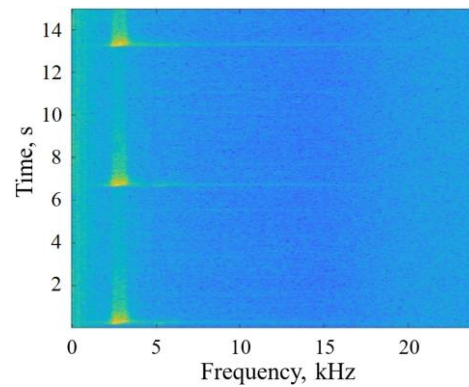


b

Fig. 3. Spectral analysis of the *explosion* signal: *a* – spectrum; *b* – spectrogram



a

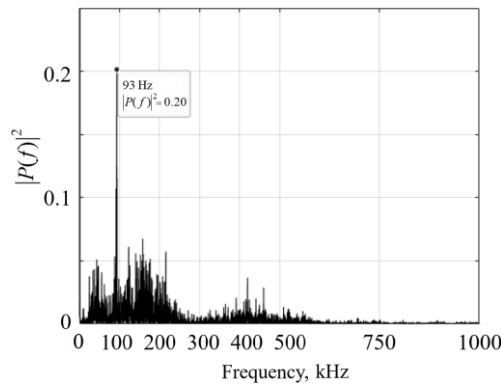


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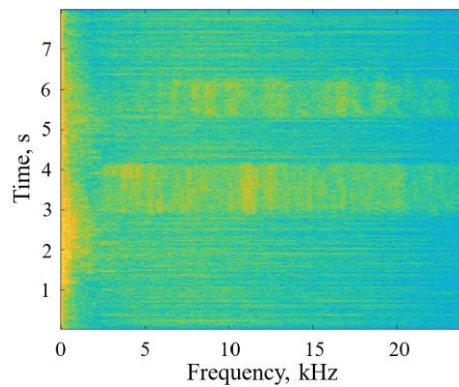
Fig. 4. Spectral analysis of the *sonar* signal: *a* – spectrum; *b* – spectrogram

The described structure enables identification of this signal type. Specifically, stable frequency peaks facilitate accurate determination of the signal source. For instance, the power peak at a frequency of 3 kHz serves as a key indicator of sonar activity, as this frequency range is not typical of natural sound sources. Unlike the short-term explosion signal, sonar produces consistent radiation, allowing for reliable identification and precise measurement in noisy conditions [10].

The signals *scuba diver's breathing* and *cruise ship noise* exhibit a significant constant component. The *scuba diver's breathing* signal is characterized by a dominant peak at near-zero frequency with a spectral power density of 18 (Fig. 5, *a*),

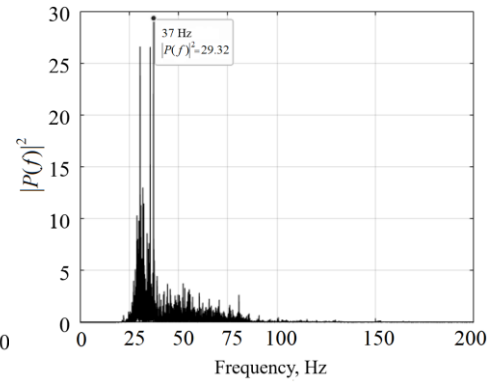


a

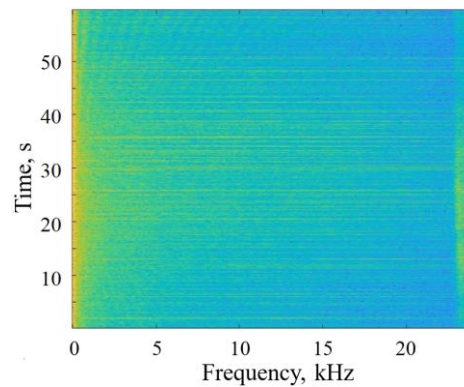


b

Fig. 5. Spectral analysis of the *scuba divers breathing* signal: *a* – spectrum; *b* – spectrogram



a



b

Fig. 6. Spectral analysis of *cruise ship noise* signal: *a* – spectrum; *b* – spectrogram

appearing as a bright vertical band with an irregular right edge in the spectrogram (Fig. 5, *b*). This indicates a zero-frequency component, likely due to the continuous exhalation of air bubbles. A minor peak at a frequency of about 100 Hz may reflect the periodicity of breathing cycles or turbulence from exhaled air flow. The constant component results from the continuous breathing process, ensuring spectral stability.

The spectrum of the *cruise ship noise* signal (Fig. 6, *a*) exhibits a prominent peak at a frequency of about 40 Hz with a spectral power density of 29.3, indicating a significant constant component, likely due to the operation of the ship's engines. A peak at a frequency of 37 Hz results from low-frequency hull vibrations, while a peak at a frequency of 80 Hz may correspond to auxiliary mechanisms or cavitation processes. The spectrogram (Fig. 6, *b*) displays a persistent bright band at near-zero

frequency throughout the recording. Analysis of phase shifts between signal components enables identification of time delays and relationships, facilitating determination of the location and nature of noise sources [11].

The *water noise* and *bottlenose dolphin's whistle* signals exhibit characteristic stability and harmonic components. The spectrum of the *water noise* signal (Fig. 7, *a*) and its spectrogram (Fig. 7, *b*) reveal a broad frequency range, with dominant power concentrated in the low-frequency band (up to 8 kHz), beyond which intensity rapidly decreases with increasing frequency. The signal's homogeneous nature is evidenced by its spectral power density.

The *bottlenose dolphin's whistle* shows two distinct peaks in its spectrum (Fig. 8, *a*), appearing as two well-defined structures in the spectrogram (Fig. 8, *b*). The first peak (1.26 kHz) corresponds to the fundamental frequency of background noise. The second peak (7.5 kHz) represents the average frequency of the "whistle" band (6–10 kHz), with variations in intonation depending on the message transmitted by the bottlenose dolphin through the hydroacoustic channel [6]. This peak also reflects the fundamental tone of the whistle and its first harmonic. The first harmonic, visible in the spectrogram (Fig. 8, *b*), displays uniform intensity and clear boundaries. These acoustic features serve as identifiers that can be classified as anomalies in the signal [12].

The spectral analysis demonstrates that each studied signal possesses a distinct spectral profile. Biological signals exhibit complex frequency structures with prominent harmonics, anthropogenic signals display distinct peaks at specific frequencies, and natural noise shows a uniform energy distribution in the low-frequency range [10, 12].

Signals of animal origin demonstrate significant variability in their spectral characteristics. The *sea lion barking* signal is characterized by energy concentration in the low-frequency range with prominent, stable harmonics. The *killer whale singing* signal displays a complex structure, reflecting a broad frequency range of vocalizations and diverse echolocation clicks. These features facilitate the study of marine mammal communicative behavior. The *bottlenose dolphin's whistle* signal, distinguished by two pronounced peaks, possesses a unique temporal structure that is readily distinguishable in the aquatic environment [6, 9].

Anthropogenic signals exhibit more predictable spectral characteristics. The *explosion* signal manifests as a short-term pulse with a sharp peak at near-zero frequency and rapid attenuation, enabling precise event timing. The *cruise ship noise* signal features a zero-frequency component at near-zero frequency and periodic peaks at higher frequencies. This structure helps to identify such signals when assessing the environmental impact of anthropogenic noise and developing methods to enhance signal clarity. The *sonar* signal exhibits a series of narrowband peaks,

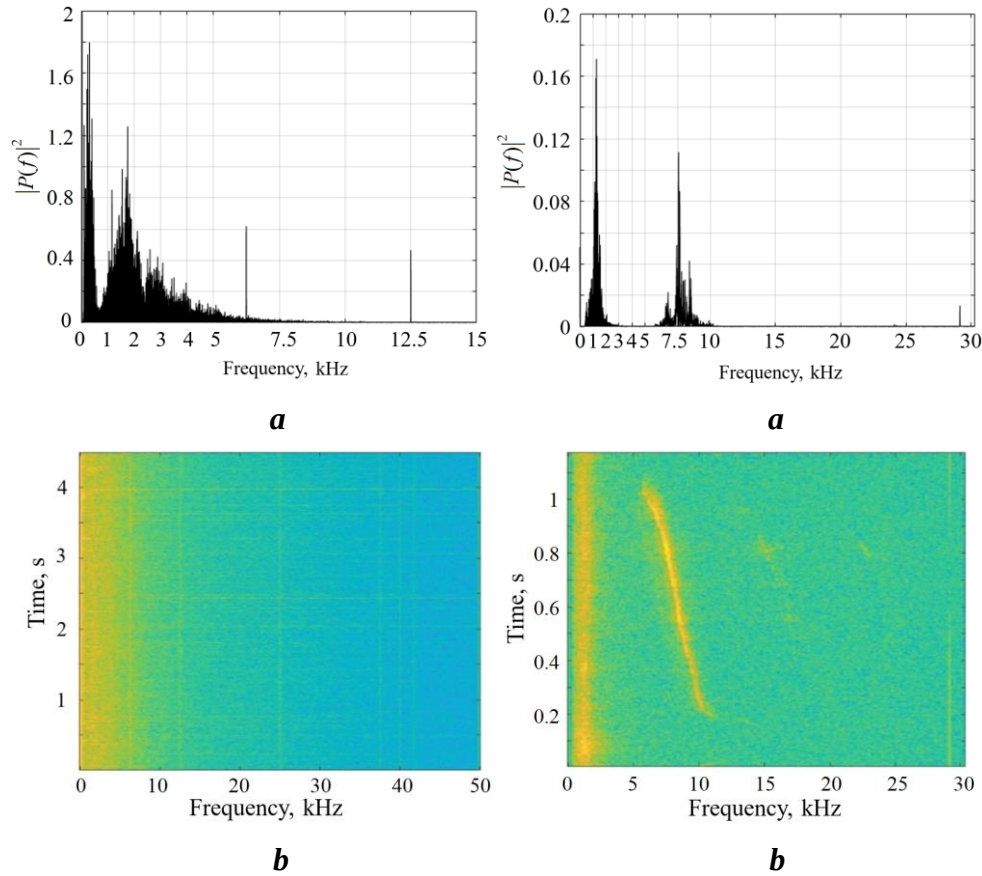


Fig. 7. Spectral analysis of *water noise* signal: *a* – spectrum; *b* – spectrogram

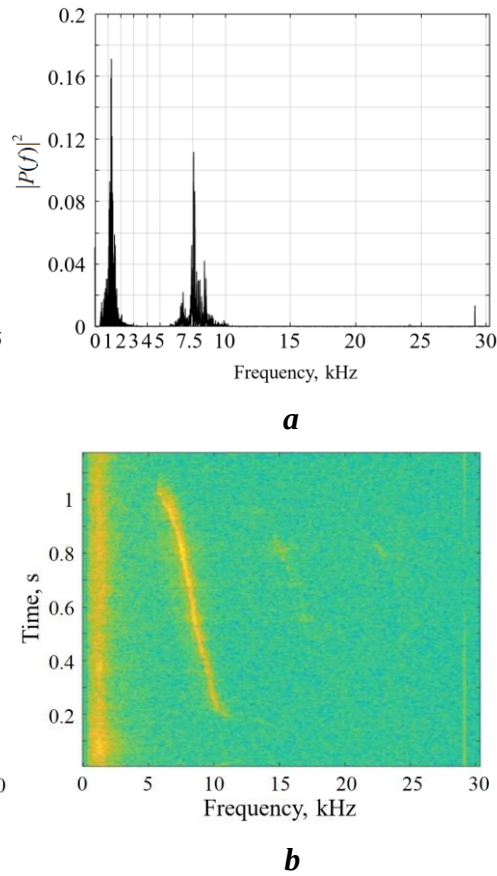


Fig. 8. Spectral analysis of *bottlenose dolphin's whistle*: *a* – spectrum; *b* – spectrogram

ensuring high accuracy in sounding and resistance against external interference, which is critical for underwater navigation and communication systems [9, 10].

Natural background noises exhibit distinct characteristics. The *water noise* signal displays a uniform spectrum in the low-frequency range and remains stationary over time, making it a reference signal for calibrating hydroacoustic devices and systems. The spectrum of the *scuba diver's breathing* signal is concentrated in the lowest frequency range, reflecting the slow variation of breathing sounds synchronized with inhalation and exhalation. Frequencies associated with turbulence and the consistency of breathing, influenced by immersion depth, are valuable for analyzing human physiological processes in underwater environments and designing diver life support systems.

The distinct spectral-temporal profiles of animal-derived signals enable the study of marine mammal behavior and communication. The characteristics of anthropogenic signals are used to evaluate their impact on marine fauna and develop measures to reduce it. The stability and predictability of natural background noise spectral characteristics provide a foundation for calibrating hydroacoustic instruments and systems, ensuring measurement accuracy [12, 13].

The analysis of spectrograms enables the development of algorithms for automatic recognition of sound sources, which is essential for the operation of passive acoustic surveillance and ecological monitoring systems. These data play a critical role in studying the acoustic ecology of marine ecosystems, developing underwater navigation and communication systems, and monitoring anthropogenic impacts on the marine environment and its inhabitants [14, 15].

Conclusion

Analysis of hydroacoustic signals revealed distinct spectral and time-frequency characteristics, enabling accurate identification of animal, anthropogenic, and natural background noise sources. A comparative evaluation of the signals highlighted their unique features, which can enhance the effectiveness of ecological monitoring and navigation systems.

Formalized features are represented as numerical vectors, suitable for machine learning tasks, particularly for classifying signals by source type. This approach enhances the detection of acoustic sources and broadens the application of hydroacoustic technologies in underwater environmental monitoring and anthropogenic impact assessment.

The research findings are highly relevant, providing a foundation for advancing underwater navigation technologies and developing new approaches to acoustic data analysis.

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Alena V. Nerush – critical analysis of materials, processing and describing the study results, preparing the text, drawing conclusions

Nikolai A. Tuzov – experiment conduction, literature analysis on the study topic, analysis and discussion of the results, preparing graphic materials for the article

Igor N. Kartsan – problem statement, analytical research on the content, preparation of the article text and graphic materials

All the authors have read and approved the final manuscript.