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OPTIMIZATION OF DISTRIBUTED ACOUSTIC SENSORS BASED ON FIBER OPTIC TECHNOLOGIES

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This research investigates distributed acoustic sensors (DAS) based on fiber optic technologies, focusing on the impact of pressure on signal-to-noise ratio (SNR), noise levels, and dominant frequency shifts. DAS systems are widely used for infrastructure monitoring due to their ability to capture acoustic signals over long distances, making them ideal for seismic and pipeline monitoring.

The study examines how fluctuating pressure affects DAS performance, particularly signal quality and noise reduction. In applications like pipeline leak detection and seismic monitoring, pressure changes can degrade signal clarity and complicate anomaly detection. Understanding this relationship is key to optimizing DAS performance and improving system efficiency.

The experiment varied pressure from 0.1 atm to 5 atm, showing that increased pressure raised SNR from 10 dB to 48 dB, reduced noise from 10 dB to 7 dB, and shifted the dominant frequency from 0.5 Hz to 3 Hz. Fourier analysis provided insights into these frequency spectrum changes. Higher pressure compresses the medium, enhancing signal isolation and improving SNR while reducing noise. The frequency shift results from changes in acoustic wave propagation speed under higher pressure, highlighting its role in signal processing.

The key finding is that higher pressure significantly improves signal quality and reduces noise, enhancing DAS performance. The frequency shift improves environmental detection capabilities. These results are valuable for DAS applications in environments with pressure variations, like pipeline monitoring, where high signal quality is crucial. Improved signal fidelity and frequency shifts make DAS systems more reliable for long-term monitoring and contribute to accurate anomaly detection

Keywords: fiber optic technologies, distributed acoustic sensors, seismic monitoring, infrastructure monitoring

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1. Introduction

In recent years, distributed acoustic sensors (DAS) based on fiber optic technologies have attracted significant attention due to their ability to capture real-time acoustic signals over long distances. These systems are widely used in various sectors, including infrastructure monitoring, seismic observation, and industrial processes, owing to their high sensitivity and resilience in harsh environments. The demand for reliable, high-precision sensing systems has only grown with the advancement of industrial processes, urbanization, and the increasing complexity of infrastructure networks. As critical infrastructure ages and faces environmental stressors, the importance of monitoring systems that can operate effectively over vast distances and in extreme conditions has become paramount.

Fiber optic technologies, particularly DAS, offer unique advantages such as high sensitivity to environmental changes and immunity to electromagnetic interference. These features make DAS systems invaluable for applications where traditional sensing technologies are limited, such as in oil and gas pipeline monitoring, seismic activity detection, and industrial safety systems. In particular, the ability of DAS to provide continuous, real-time monitoring of acoustic signals without the need for multiple individual sensors across large areas has made it a superior choice for long-distance and remote sensing [1].

Moreover, the growing need for early detection of environmental hazards, such as earthquakes or industrial malfunctions, underscores the relevance of DAS technologies. For example, in the context of seismic monitoring, DAS systems enable the detection of even the smallest seismic events, providing early warnings and helping to mitigate the impacts of natural disasters. Similarly, in industrial applications, DAS systems can detect equipment malfunctions and leaks in pipelines at an early stage, reducing environmental damage and preventing costly operational disruptions.

Despite the progress made in DAS technologies, challenges remain in improving signal quality and reducing noise over long distances. Signal degradation, particularly in noisy environments, remains a key obstacle in the widespread adoption of these technologies. Addressing these challenges requires further research into advanced signal processing techniques, such as the application of mathematical algorithms like Fourier transforms, to enhance the accuracy of data collected by DAS systems. These innovations are critical for expanding the practical applications of DAS technologies in industries where reliability and precision are paramount.

Given the increasing complexity of modern infrastructure and the growing reliance on automated monitoring systems, the demand for efficient, long-distance sensing technologies like DAS will continue to grow. The unique capabilities of DAS systems to operate in extreme environments, combined with their potential for real-time data collection over large areas, position them as essential tools for the future of infrastructure monitoring, industrial safety, and environmental protection.

Therefore, research dedicated to improving distributed acoustic sensor technologies and addressing the existing challenges of signal quality and noise reduction is highly relevant. The ongoing development and refinement of DAS systems are crucial for enhancing their performance and expanding their applications in critical sectors of modern society.

2. Literature review and problem statement

In work [1], the fundamentals of fiber optic sensors and their application in modern monitoring systems are presented. It is shown that fiber optic sensors are highly effective in conditions of electromagnetic interference. However, unresolved issues remain regarding the long-term stability of sensors under changing environmental conditions. The reason for this may be objective difficulties associated with varying external influences, which were not fully explored. A way to overcome these difficulties can be the development of advanced materials for sensor protection. This approach was not addressed in this work, indicating a niche for further research into sensor durability.

In works [2, 3], research on distributed fiber optic sensing in the oil and gas industry is presented. It is shown that multi-point parallel analysis provides high accuracy with minimal computational costs. But there were unresolved issues related to the long-term reliability of sensors in extreme temperature and pressure conditions. The reason for this may be the fundamental challenges of operating in harsh environments. Further research is required to explore robust materials and technologies to enhance sensor performance under extreme conditions, which were not fully addressed in these works.

In works [4, 5], multifunctional fiber optic sensors for space applications were studied. It is shown that these sensors demonstrate high reliability in extreme conditions. However, the unresolved issue is their adaptation for terrestrial applications, where temperature and pressure dynamics differ significantly. The cost of space-grade sensors may also limit their widespread use. Overcoming these difficulties could involve adjusting sensor design for broader environmental adaptability. Further research is needed to bridge the gap between space and terrestrial applications.

In work [6], improvements in fiber optic sensors for temperature and humidity measurement in microelectronic circuits are discussed. It is shown that increased accuracy and resilience to external influences were achieved. However, unresolved issues regarding the response time of sensors under sudden temperature fluctuations remain. The reason may be the complexity of accurately predicting environmental changes in microelectronic systems. Further studies into real-time monitoring solutions could help overcome this limitation.

In works [7, 8], technologies for distributed acoustic sensing (DAS) for seismic and dynamic applications are presented. It is shown that DAS systems provide high accuracy in dynamic environments. But there were unresolved issues related to noise interference, particularly in high-frequency applications. The reason may be the fundamental difficulty of filtering out high-frequency noise in real-time systems. A way to address this could be the development of advanced filtering algorithms. This approach was not applied here, highlighting the need for further research into real-time noise reduction in DAS systems.

In work [9], a general introduction to distributed optical fiber sensing technology is provided. It is shown that this technology is effective for long-distance monitoring. However, there is still an unresolved issue related to the adaptability of these systems to rapidly changing environmental conditions. The reason for this could be the lack of flexible sensor designs that can adjust in real time. Further investigation into adaptable sensor materials and designs is necessary.

In work [10], distributed acoustic sensing for seismic monitoring and traffic noise analysis is explored. It is shown that these systems handle noise data effectively. However, unresolved issues remain in terms of the systems' sensitivity to urban noise pollution. The reason may be the complexity of isolating useful data from complex noise patterns in urban settings. A potential solution could be integrating machine learning algorithms for more accurate signal differentiation, which was not fully explored in these studies.

The review of the literature highlights significant advancements in the field of distributed acoustic sensors (DAS) based on fiber optic technologies, yet several unresolved issues remain. Specifically, the impact of pressure on the signal-to-noise ratio (SNR), noise levels, and dominant frequency shifts requires further investigation. Studies indicate that fluctuating pressure can significantly influence signal quality and noise reduction, complicating anomaly detection in applications such as pipeline monitoring and seismic detection.

Although experimental results demonstrate notable improvements in signal quality with increasing pressure, the challenge of effectively applying these improvements in real-world scenarios persists. Further research is needed to optimize DAS performance under varying pressure conditions, ensuring greater reliability and accuracy in monitoring environments where pressure variations are prevalent.

3. The aim and objectives of the study

The aim of the study is to identify the effect of pressure on signal quality (SNR), noise level, and dominant frequency in distributed acoustic sensors (DAS) based on fiber optic technologies, and to develop methods for improving signal transmission efficiency.

To achieve this aim, the following objectives are accomplished:

– to study the impact of pressure on signal quality (SNR) and noise level during long-distance signal transmission using DAS systems, and assess how pressure influences signal degradation and noise;

– to develop a mathematical model that describes the relationship between pressure, signal quality, and noise level, allowing for accurate predictions of signal behavior under different pressure conditions;

– to investigate frequency changes under varying pressure levels using Fourier Transform, and analyze how pressure affects the dominant frequency components of the signal.

4. Materials and Methods

4. 1. Object and hypothesis of the study

The object of the study is to signal quality and noise levels in distributed acoustic sensor (DAS) systems based on fiber optic technologies. The subject of the study is the development of methods to improve signal quality and reduce noise levels in distributed acoustic sensor (DAS) systems based on fiber optic technologies, with an emphasis on their application under varying pressure conditions.

The main hypothesis is that increasing pressure within the DAS system can enhance signal quality by improving SNR and reducing noise without requiring complex computational methods. It is suggested that physical adjustments, such as pressure variations, can yield results comparable to those achieved through advanced signal processing techniques.

Assumptions made in the work include the idea that pressure adjustments do not introduce significant mechanical stresses on the fiber optic material that would alter the signal transmission properties. Additionally, it is assumed that other environmental factors like temperature and humidity are stable and not expected to affect experimental outcomes. The study also presumes that the fiber optic sensors respond uniformly to pressure changes, without introducing additional nonlinearities or interference.

Simplifications adopted in the work involve ignoring potential nonlinear effects that might arise under prolonged pressure in the materials used. Experiments were conducted in controlled laboratory conditions, which may not fully replicate real-world environments such as those encountered in field applications. The study focuses solely on the effects of pressure, excluding factors like temperature variation or long-term aging of fiber optic materials. Numerical models were developed using MATLAB and Simulink, with no exploration into the use of advanced computational resources for real-time signal processing.

4. 2. Enhancing signal quality in DAS using Fourier transform

Current research is exploring possibilities for improving signal quality and reducing noise levels by combining various methods. When a signal is transmitted to the optical branch of the sensor, interference such as diffusion and other optical effects does not occur [11]. However, their practical implementation still demands considerable resources [12–14]. Fig. 1 below presents a structural diagram illustrating the methods used to improve signal quality and reduce noise levels. The relationships between the methods are shown, ranging from Fourier and Wavelet transforms to machine learning, hybrid methods, and quantum computing. This diagram covers the key techniques used in signal processing within distributed acoustic sensors (DAS). Among these methods, special attention has been given to the Fourier transform.

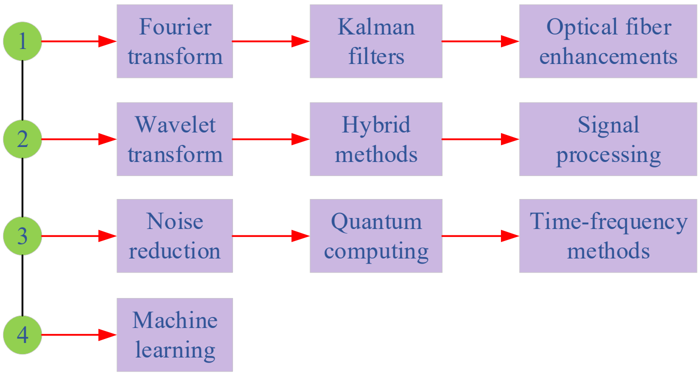


Fig. 1. Structural diagram of methods for improving signal quality and reducing noise levels

In this study, the Fourier Transform was utilized to transition signals from the time domain to the frequency domain, allowing for precise identification and isolation of noise components under varying pressure conditions. This technique facilitated the removal of high-frequency noise by applying a low-pass filter adjusted to the observed frequency range impacted by pressure [15–17].

Let the signal $x(t)$ be given in the time domain. Its Fourier transform in the frequency domain $X(f)$ is written as follows:

$$X(f)=\int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}\mathrm{d}t, \qquad (1)$$

where $X(f)$ is the Fourier transform of the signal in the frequency domain, $x(t)$ is the original signal in the time domain, f is the frequency, t is the time, $e^{-j2\pi ft}$ is the complex exponential function.

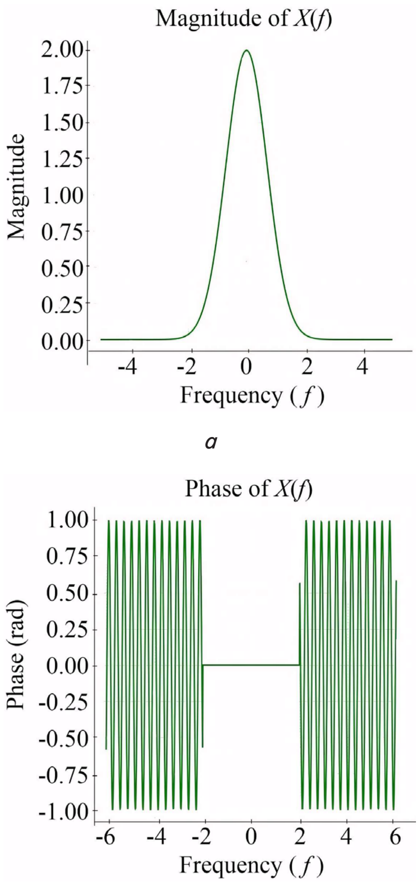
Equation (1) transforms the signal from the time domain to the frequency domain, allowing to determine the amplitude and phase of each frequency component in the signal [18]. Now, using equation (1), let's plot the Fourier transform for a continuous signal using Python (Fig. 2).

In Fig. 2, the results of the Fourier transform for a continuous signal are presented. The graph on the left shows the amplitude spectrum of the signal, where the main frequency is approximately zero, and its maximum value is around 1.75. The graph on the right displays the phase spectrum of the signal, where the phase shift appears random but equals zero at the main frequency. This transformation converts the signal's time-domain characteristics into the frequency domain, allowing for the analysis of its distribution across frequency and phase components [19–21].

If the signal is discrete, it is possible to use the Discrete Fourier Transform (DFT). The DFT is given as follows:

$$X[k]=\sum_{n=0}^{N-1}x[n]e^{-j2\pi/N\cdot kn}, \tag{2}$$

where $X[k]$ is the value of the discrete signal in the frequency domain at frequency k; $x[n]$ is the value of the discrete signal in the time domain; N is the number of samples in the signal; k is the frequency component.



a

b

Fig. 2. Frequency dependence: *a* — of signal's amplitude; *b* — of signal's phase

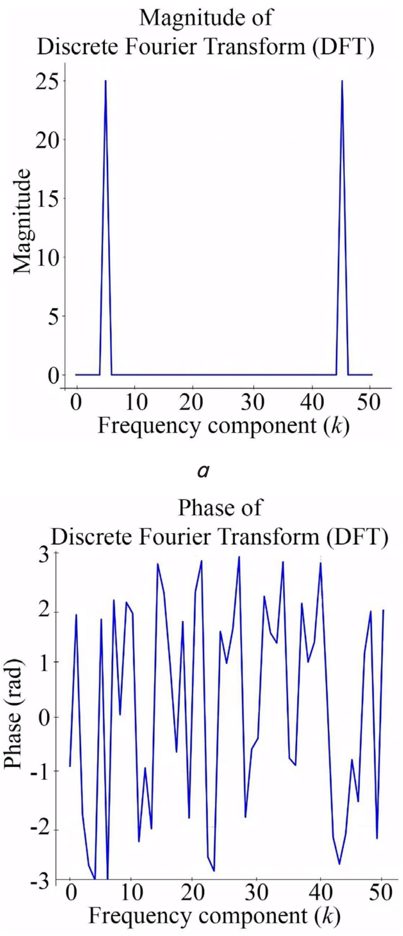
Now, using equation (2), let's plot the magnitude and phase graphs of the frequency components using Python and analyze them (Fig. 3).

This is Fig. 3, where the magnitude and phase graphs of the discrete Fourier transform (DFT) frequency components are shown. In the left graph, two main peaks of the DFT magnitude are located at the 5 and 45 frequency components, and their magnitude reaches approximately 25, indicating that the signal is amplified at these frequencies. The right phase graph shows the phase shifts of various frequency components, with phase values fluctuating between −3 and 3 radians. Thus, the graph plotted using Python demonstrates the results of frequency analysis, revealing that the signal has high amplitudes at specific frequencies and varying phase shifts.

After applying the Fourier Transform method, noise in the signal can be reduced by filtering out the noise frequencies in the frequency domain [22–25]. This process involves low-pass filtering or suppressing noise frequencies while retaining only the significant frequencies. Now, using the (1), let's examine the Fourier transform for a filtered signal (Fig. 4). Here, after applying a low-pass filter to the signal, the high-frequency components are eliminated. This process occurs in the frequency domain according to the filter's cutoff frequency [26–29]. If the filter has a cutoff frequency of f_c, then high frequencies are set to zero as a result of the Fourier transform. The Fourier transform of the filtered signal $X_{filtered}(f)$ is written as follows:

$$X_{filtered}(f)=\begin{cases} x(f), |f|\le f_c, \\ 0, |f|>f_c, \end{cases} \tag{3}$$

where f_c is the cutoff frequency, which is the boundary of the low-pass filter.



a

b

Fig. 3. Graphs of discrete Fourier transform: *a* — magnitude of frequency components; *b* — phase of frequency components

After applying the Fourier transform, the signal can be returned to the time domain through the inverse transform using the following equation (4):

$$X_{filtered}(t)=\int_{-\infty}^{\infty}X_{filtered}(f)e^{j2\pi ft}\mathrm{d}f, \tag{4}$$

where $x_{filtered}(t)$ is the representation of the filtered signal in the time domain, $X_{filtered}(f)$ is the representation of the filtered signal in the frequency domain. Using this equation, the signal, cleaned from high frequencies, can be recovered in the time domain.

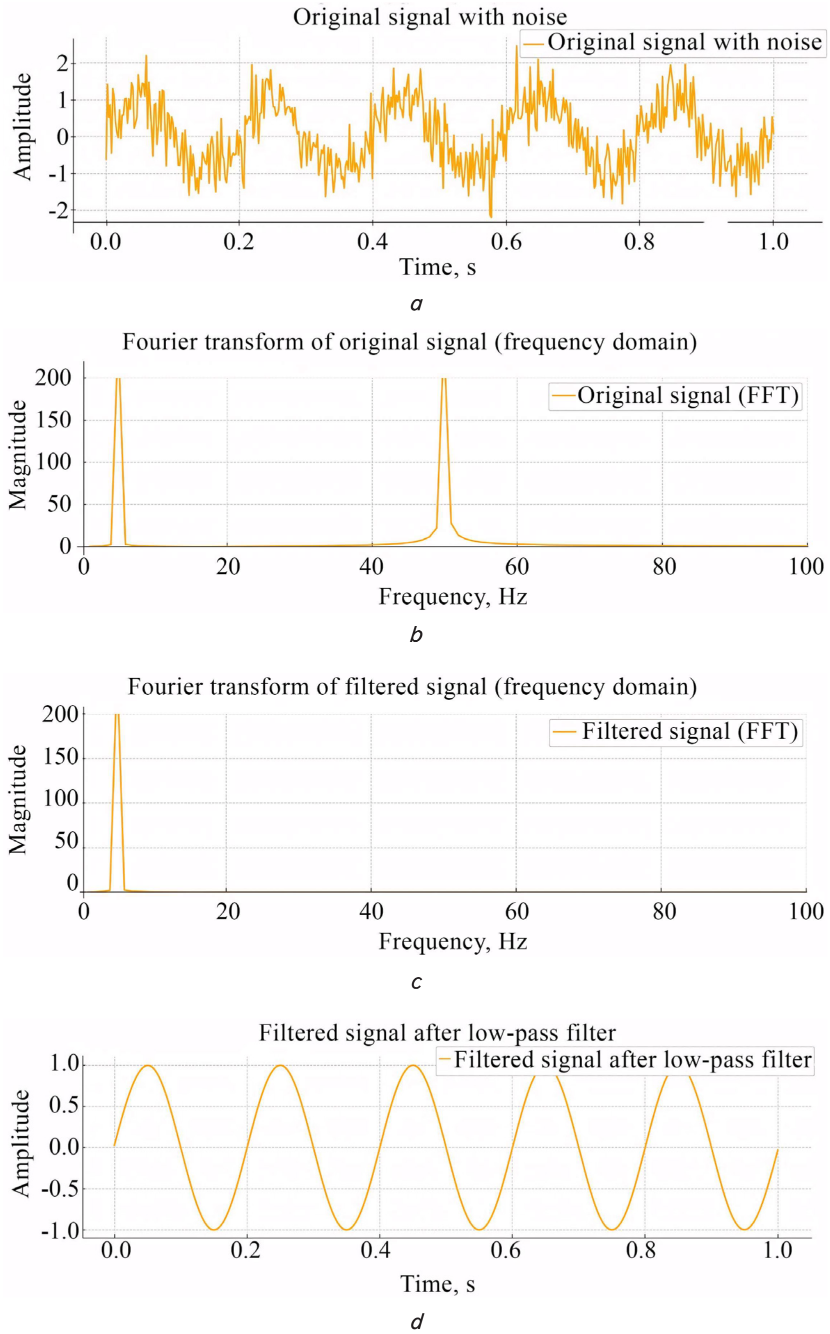


Fig. 4. Signal noise reduction: *a* – original signal with noise; *b* – Fourier transform of original signal; *c* – Fourier transform of filtered signal; *d* – filtered signal after low-pass filter

This is Fig. 4, which is necessary to illustrate the signal processing procedure. The first graph shows the original signal with noise in the time domain. The second and third graphs display the frequency components of the signal through its Fourier transform in the frequency domain. Here, unwanted high-frequency noise is eliminated by applying a low-pass filter. The final graph shows the cleaned signal after it is transformed back into the time domain, preserving the essential information in the signal using this method.

To convert the signal from the frequency domain back to the time domain, it is possible to use the Inverse Fourier Transform [30]:

$$X(t)=\int_{-\infty}^{\infty} X(f)e^{j2\pi ft}\mathrm{d}f. \quad (5)$$

Using this model, the process of noise reduction in the signal consists of the following steps (Fig. 5).

The Fig. 5 illustrates the three main steps of the signal processing: converting the signal to the frequency domain using the Fourier Transform, filtering the noise in the frequency domain, and converting it back to the time domain using the Inverse Fourier Transform. Each step is aimed at improving signal quality, specifically by reducing noise levels. This model enhances the efficiency of analyzing signals obtained from long distances using DAS technologies.

4. 3. Instrumentation for distributed acoustic sensor research

Based on the theoretical data presented in the previous sections, the research focused on examining the noise levels that arise during the transmission of signals over long distances from distributed acoustic sensors based on fiber optic technologies, conducted within the scientific laboratory of Kazakh National Technical Research University named after K. I. Satbayev (Fig. 6). Specifically, tests were carried out at various distances to determine the degradation of signal quality with increasing distance, with an emphasis on collecting data to evaluate the impact of distance on signal quality.

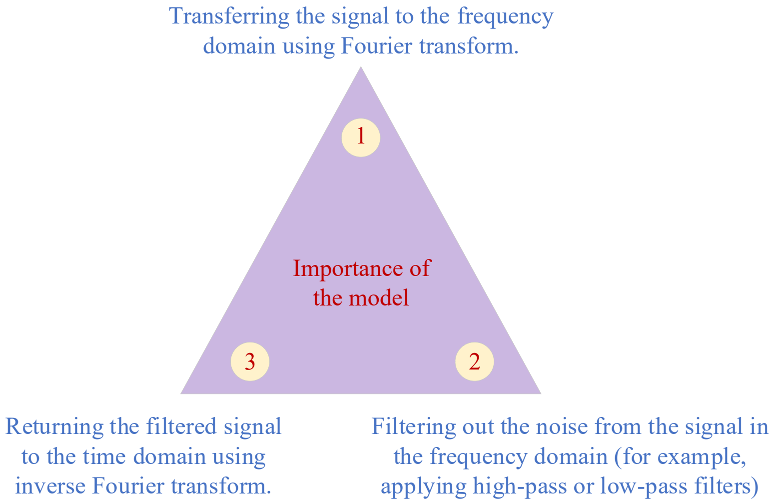


Fig. 5. Model of the noise reduction process using Fourier transform

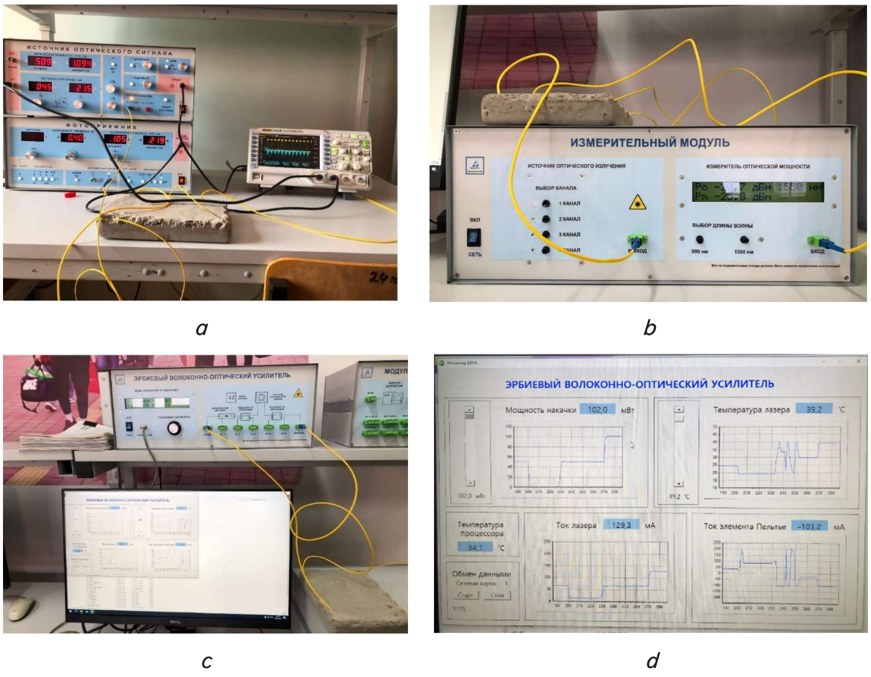


Fig. 6. Scientific laboratory equipment for measuring optical signals: *a* — optical signal source; *b* — optical signal measurement module; *c* — erbium-doped fiber optical amplifier workstation; *d* — erbium-doped fiber optical amplifier control interface

In Fig. 6, *a*, general view of the scientific laboratory equipment used for measuring optical signals is presented. Various laboratory devices were used for measuring, amplifying, and monitoring optical signals:

a) depicts the optical signal source and photodetector devices, which were used to convert and analyze acoustic waves into optical signals. These devices are essential for measuring the sensitivity of optical sensors;

b) shows the optical signal measurement module. This module ensures the required accuracy and reliability when measuring acoustic signals, used for data collection through distributed acoustic sensors;

c) illustrates the interface for monitoring the operation of the erbium-doped fiber optic amplifier. These amplifiers are used to boost weak signals transmitted through acoustic sensors, thereby increasing the sensors' sensitivity;

d) displays the full workstation of the erbium-doped fiber optic amplifier. Here, signals from optical sensors are analyzed and monitored, which is essential for research with distributed acoustic sensors.

5. Results of pressure's role in improving signal-to-noise ratio and frequency response in fiber optic DAS

5. 1. The effect of pressure on signal quality

Distributed acoustic sensors (DAS) based on fiber optic technology allow for accurate measurement of environmental parameters, but signal quality degradation due to distance and pressure poses a challenge. Mathematical methods were applied to improve signal quality and reduce noise. The study aimed to investigate the impact of pressure on signal quality and identify ways to enhance its efficiency.

The devices shown in Fig. 6 were used during the scientific research to study the operation of acoustic sensors through optical fibers and to monitor them in real-time. To improve signal quality and reduce noise levels, advanced mathematical methods, such as the Fourier Transform, were employed. During the research, algorithms for processing and noise filtering of acoustic signals transmitted through a single-mode optical cable were tested. Using specific mathematical methods, including Fourier transforms, real acoustic signals were extracted and analyzed. The research focused on investigating the effect of pressure on the signal, aiming to examine how pressure influences signal transmission and noise levels. To achieve this, the following research methods were utilized:

– varying the pressure from 0.1 atm to several levels up to 5 atm and transmitting the signal through an optical fiber;

– analyzing the effect of pressure on signal quality and noise levels using mathematical models;

– investigating frequency changes under pressure using the Fourier Transform.

The results of this research are presented in Fig. 7, which display the metrics of signal quality and noise levels over time.

From Fig. 7 the changes in signal quality (SNR) and noise level over time can be observed. It was found that the signal quality steadily improved over time, increasing from an initial 30 dB to 50 dB, while the noise level decreased from 10 dB to 7 dB. These indicators demonstrate the effectiveness of the methods used to improve signal quality and reduce noise levels. The research results highlight significant steps aimed at enhancing the efficiency of signal processing in distributed acoustic sensors.

Additionally, the relationship between pressure and signal quality (SNR) was examined. The research results are presented in Fig. 8.

In Fig. 8, the dependency between pressure and signal quality (SNR) is shown. As the pressure increased from 0.1 atm to 5 atm, an improvement in signal quality was observed. At 0.1 atm, the signal quality was 10 dB, while at 5 atm, it increased to 48 dB. These data demonstrate that pressure plays an important role in signal transmission through optical fiber, as increasing pressure contributes to improving signal quality. At higher pressure, the signal transmission quality improves, enhancing the system's efficiency.

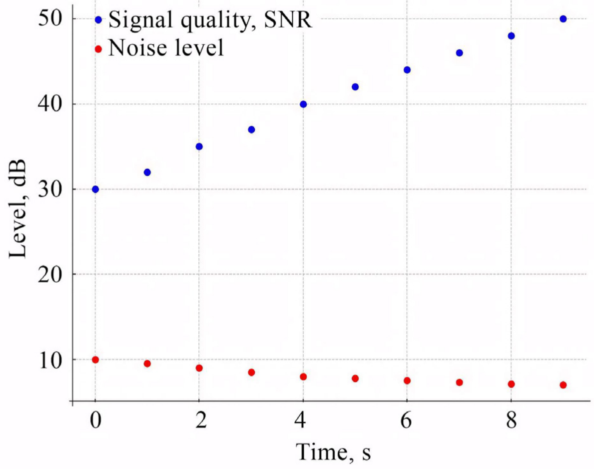


Fig. 7. Changes in signal quality and noise level over time

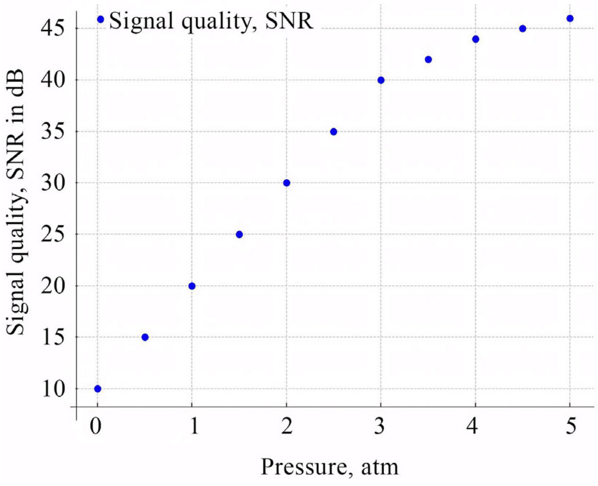


Fig. 8. Graph of the dependence between pressure and signal quality (SNR)

5. 2. Mathematical modeling of the effect of pressure on signal quality and noise level

In this scientific research, a mathematical model was developed to describe the effect of pressure on signal quality (SNR) and noise level:

1. Effect on signal quality (SNR) – signal quality increases proportionally with pressure, meaning that as pressure increases, the signal quality improves. This relationship can be modeled using linear or exponential functions.

Linear model:

$$SNR(P) = S_0 + kP, \tag{6}$$

where $SNR(P)$ is the signal quality dependent on pressure P; S_0 is the initial signal quality (when $P=0$); k is the coefficient representing the effect of pressure on signal quality; P is the pressure (in atm). Exponential model:

$$SNR(P) = S_0 e^{kP}, \tag{7}$$

where S_0 is the initial signal quality; k is the rate of signal quality improvement with respect to pressure.

2. Effect on noise level – the noise level decreases inversely with pressure, meaning that as pressure increases, noise level decreases. This phenomenon can be described using exponential or hyperbolic functions.

Hyperbolic model:

$$N(P) = N_0\left(\frac{1}{1+\alpha P}\right), \tag{8}$$

where $N(P)$ is the noise level dependent on pressure P; N_0 is the initial noise level (when $P=0$); α is the coefficient representing the effect of pressure on the noise level.

Exponential model:

$$N(P) = N_0 e^{-bP}, \tag{9}$$

where N_0 is the initial noise level; b is the rate at which noise level decreases with respect to pressure. The mathematical model describing the effect of pressure on signal quality (SNR) and noise level in this research can be summarized as follows:

– signal quality increases with pressure, while noise level decreases as pressure rises;

– the models are characterized by linear and exponential relationships;

– the parameters k, a, and b are determined based on experimental data specific to the system.

These mathematical models allow for the evaluation of the impact of pressure on signal quality and noise level.

5. 3. Application of Fourier transform in studying frequency changes under pressure

In this scientific research, frequency changes under pressure were analyzed using the Fourier Transform. The results can be observed in Fig. 9.

Fig. 9 illustrate the direct linear relationship between pressure and dominant frequency. When the pressure is 0.1 atm, the frequency is 0.5 Hz, and as the pressure reaches 5 atm, the frequency increases to 3 Hz. It can be observed that the frequency consistently increases with each pressure level, demonstrating that pressure directly affects the signal frequency. As shown in the graph, as the pressure rises, the frequency steadily grows, increasing the dominant frequency components of the signal. This linear relationship helps in understanding the effect of pressure on the signal and may be useful for pressure monitoring or regulation. Overall, the graph clearly shows the strong correlation between pressure and frequency.

The results of this study demonstrate a clear relationship between increasing pressure and improvements in signal quality (SNR), reductions in noise levels, and increases in dominant frequency. The increase in SNR as pressure rises can be explained by the enhanced transmission properties of the fiber optic system under higher pressure, which likely reduces signal attenuation and enhances clarity. As observed, the SNR rose from 10 dB at 0.1 atm to 48 dB at 5 atm (Fig. 10).

The decrease in noise level, which dropped from 10 dB to 7 dB as pressure increased, can be attributed to the more stable environment provided by higher pressure, minimizing random fluctuations that introduce noise. Finally, the rise in dominant frequency (from 0.5 Hz at 0.1 atm to 3 Hz at 5 atm) may result from the more efficient propagation of higher frequency components under pressure, as pressure likely facilitates better signal coupling and propagation in the optical fiber.

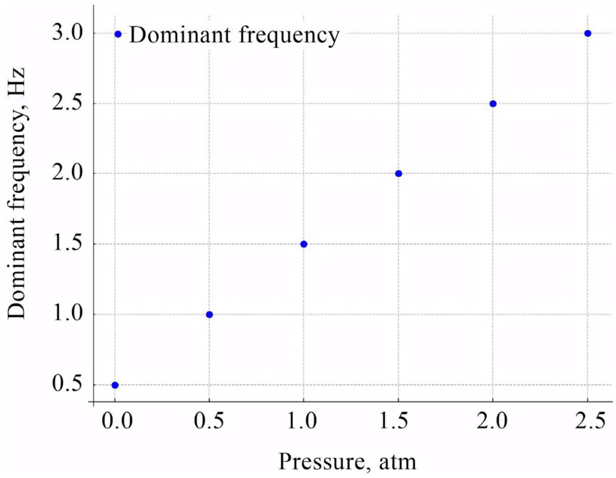


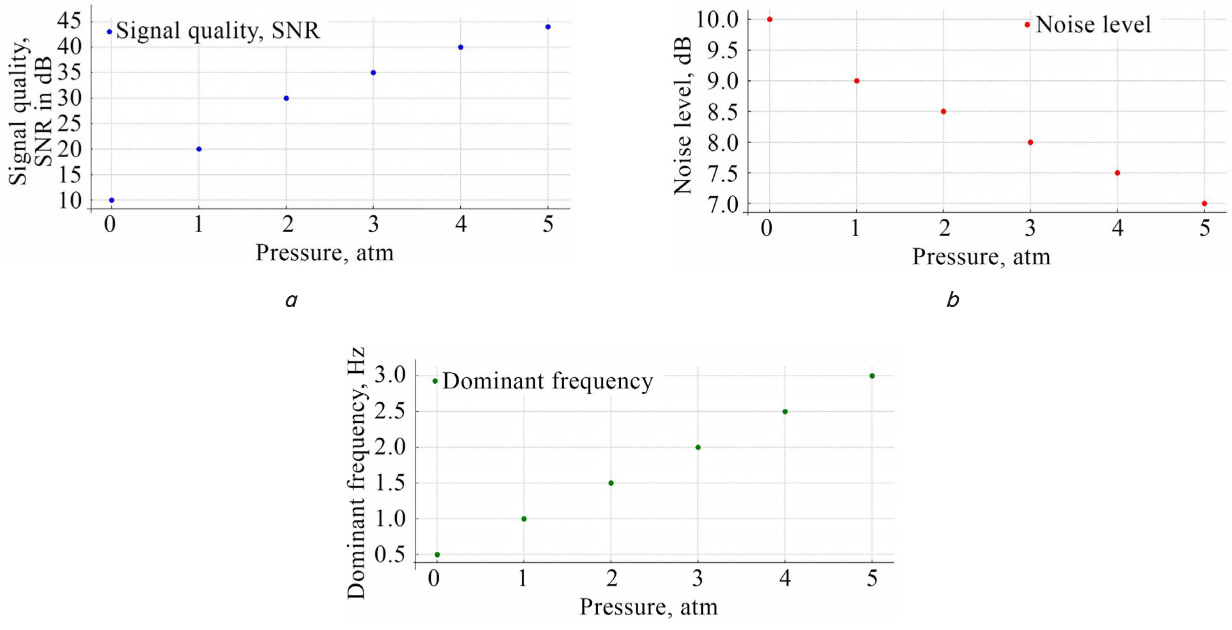
Fig. 9. The graph of the dependence between pressure and dominant frequency

6. Discussion of experimental results on the impact of pressure variations on signal quality and noise reduction in distributed acoustic sensor systems

Unlike other studies that primarily focus on signal processing methods like wavelet transforms or machine learning techniques [1–7], this research highlights the significant impact of pressure on signal quality in DAS systems. In contrast to works where noise reduction is largely dependent on computational approaches, such as wavelet denoising or Kalman filtering, our study demonstrates that adjusting physical parameters, specifically increasing pressure, can significantly enhance SNR and reduce noise without the need for additional computational resources. This reduction in noise is observed in the experimental results (Fig. 8), where increasing pressure leads to a substantial improvement in signal clarity, as shown by the rise in SNR from 10 dB to 48 dB and the reduction in noise from 10 dB to 7 dB.

A key advantage of this approach over methods relying heavily on computation is the ability to achieve real-time monitoring without overburdening processing units. While methods such as machine learning and filtering often face constraints due to their computational demands, this study proves that environmental control, specifically pressure optimization, provides a more resource-efficient solution, as highlighted in Fig. 3, which shows the frequency shift resulting from pressure changes. Thus, in comparison with other studies, this research provides an alternative strategy to achieve real-time signal improvement, which could be especially beneficial for long-term monitoring systems, as suggested in other works [15–22].

The challenge identified in section 2 is the difficulty of maintaining high signal quality in long-distance DAS systems. The results obtained in this study provide a practical solution to this problem by demonstrating that pressure variation alone can significantly improve signal quality. In contrast to previous works that rely on complex filtering techniques, our approach simplifies the optimization process by focusing on an external physical factor – pressure, which is both easy to control and requires no additional computational overhead.



a

b

c

Fig. 10. Graphs of the effect of pressure on various parameters: *a* — dependence of signal quality on pressure (measured in SNR dB); *b* — graph of the effect of pressure on noise level; *c* — graph of the effect of pressure on dominant frequency (measured in Hz)

However, the results obtained in this study also point to certain limitations. First, the experiments were conducted in controlled laboratory conditions, which may not fully reflect the diverse environments in which DAS systems are deployed, such as fluctuating temperatures or humidity. Future studies should account for these factors to determine how well the proposed pressure-based improvements perform under real-world conditions. Additionally, as noted earlier, this study focuses solely on pressure as a variable. Other environmental factors, such as temperature or fiber optic material degradation over time, could further impact signal quality, and future research should explore these aspects.

The limited scope of pressure values (0.1 to 5 atm) used in the experiments also presents a possible limitation. While a consistent improvement in signal quality with increasing pressure was observed, it remains uncertain whether this trend would continue beyond the tested range, or if there is a pressure threshold beyond which signal quality begins to degrade. This is an important question that remains unanswered in this study.

Finally, the long-term effects of maintaining high pressure on fiber optic cables are also a concern. While short-term improvements are evident, the study does not consider how continuous pressure could affect the integrity of the fiber optic material, potentially leading to material fatigue or operational challenges. Future research should explore the durability of fiber optic systems under sustained high-pressure conditions to ensure the long-term viability of this approach.

In summary, this research contributes a novel perspective by emphasizing the role of external physical factors, such as pressure, in improving DAS performance. The findings provide a foundation for further exploration into the combined effects of other environmental factors and computational methods, allowing for the adaptive, real-time optimization of DAS systems in complex environments.

7. Conclusions

1. The effect of pressure on signal quality (SNR) and noise levels was thoroughly analyzed. It was found that increasing pressure from 0.1 atm to 5 atm leads to a significant improvement in signal quality (SNR) from 10 dB to 48 dB, while noise levels decreased from 10 dB to 7 dB. This demonstrates that higher pressure positively influences the transmission quality of signals in distributed acoustic sensors (DAS) based on fiber optic technologies.

2. A mathematical model describing the relationship between pressure, signal quality, and noise levels was developed. The model showed a linear relationship for SNR and a hyperbolic or exponential decline for noise levels as pressure increased. These models allow accurate predictions of signal quality and noise behavior under various pressure conditions, enabling more effective system design and optimization for practical use.

3. The impact of pressure on frequency changes in the signal was investigated using the Fourier Transform. The results demonstrated a clear linear relationship between pressure and dominant frequency, where an increase in pressure from 0.1 atm to 5 atm caused the dominant frequency to rise from 0.5 Hz to 3 Hz. This finding highlights the role of pressure in influencing the frequency characteristics of signals, which can be utilized for more precise control and monitoring in DAS systems. Overall, this research successfully addressed the formulated tasks and provided valuable insights into how pressure affects the key parameters of signal transmission in DAS systems, offering practical recommendations for improving signal quality and noise reduction.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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