Seismic Field Tests of a Distributed Acoustic Sensor

I.A. Ershov[1], O.V. Stukach[1,2]

[1] *Novosibirsk State Technical University, Novosibirsk, Russia*
[2] *National Research University Higher School of Economics, Moscow, Russia*

***Abstract* – This research is some contribution to advancing acoustic sensing, offering long-range monitoring of boreholes. High sensitive distributed acoustic sensor is required in oil and gas exploration, pipeline detection, and various practical applications. In this paper, a high sensitive quasi distributed acoustic sensor was tested in borehole. The waveforms are presented and distributed audio signal and spatial acoustic imaging are demonstrated. The field test results of the sound detection illustrate a good sensitivity within the flat frequency range up to 5 kHz up to 900 m depth. The partial results obtained further developments and applications in various fields.**

***Keywords*–DAS, fading suppression, OTDR, petroleum geophysics, vibration analysis.**

I. INTRODUCTION

The design of distributed fiber-optic sensors has possible to use systems for observation the condition of extended industry facilities such as oil and gas pipelines, railways, subways, production wells and cable routes [1]. A sensing element is optical fiber. In addition, it is used to transmit an information signal, which significantly reduces the size and weight of the system [2–4]. The use of electrical sensors in the systems described above is either economically impractical or physically impossible because the electric sensor is capable of making measurements at a single point. So, a large number of point sensors are required to monitoring of the extended object. At the same time, each fixed sensor will create electromagnetic hindrances. It is invisible with a small number of elements, but impact to operation of compact tools. If the size of the system is limited, for example, for well monitoring, it is impossible to place electrical sensors along the length. Distributed fiber-optic sensors are placed in the well using flexible tubing.

It is the possibility of non-standard placement to cover a certain surface, or wrapping around objects with a circular cross-section, such as pipes due to the flexibility of fiber [5–6]. To obtain advanced information about the condition of an object, a combination of a distributed acoustic sensor and a distributed temperature sensor is usually used [7].

II. STATE-OF-THE-ART

Nowadays distributed fiber-optic acoustic sensors (DAS) have wide fields of application: petroleum industry, railway, cable communications etc. [8–10].

An improved DAS using a waveguide electro-optic phase modulator and a novel phase demodulation on homodyne detection is proposed in [11]. The signal-to-noise ratio (SNR) 20 dB is achieved, and the spatial resolution is about 10 m at 5 km sensing fiber.

Paper [12] devoted to suppress the interference fading effect of OTDR system, a multi-frequency detection fading recognition and suppression method based on SVM classification. This method shows a good performance and simple structure is used to construct the classifier.

Authors [13–15] use DAS Transducer for Enhanced Acoustic Sensitivity. Some papers propose methods for signal processing for DAS. For example, a deep learning approach for the separation of multi-source signals in the UW-FBG DAS system was design in [16]. The effectiveness and robustness of the method were verified by comparing of other methods and different signals. It is providing a valuable solution for the signal separation in complex environments using DAS [17].

III. MEASUREMENTS

We use DAS based on an advanced ϕ-OTDR for the field test results [13–15, 18–20].

A borehole seismic device was used for the first stage of testing. This device generates shocks of a given energy in Joules. The test scheme is shown in Fig. 1. The device was lowered into the 5 m well from the ground surface. Also there were 135 m of fiber in the well.

The seismic device generated an impact with energy of 0.1 kJ, 0.5 kJ, 1.0 kJ, and 1.5 kJ (Fig. 2). The measurement results are shown in Figs. 3–6. The graphs correspond to the part of the fiber and the time where the effect was observed.

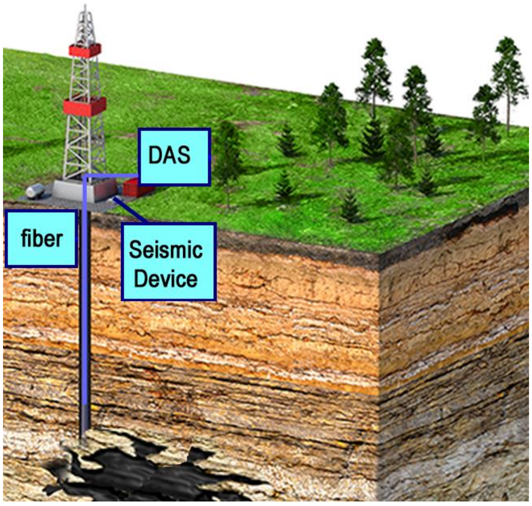

Fig. 1. Measurement chart

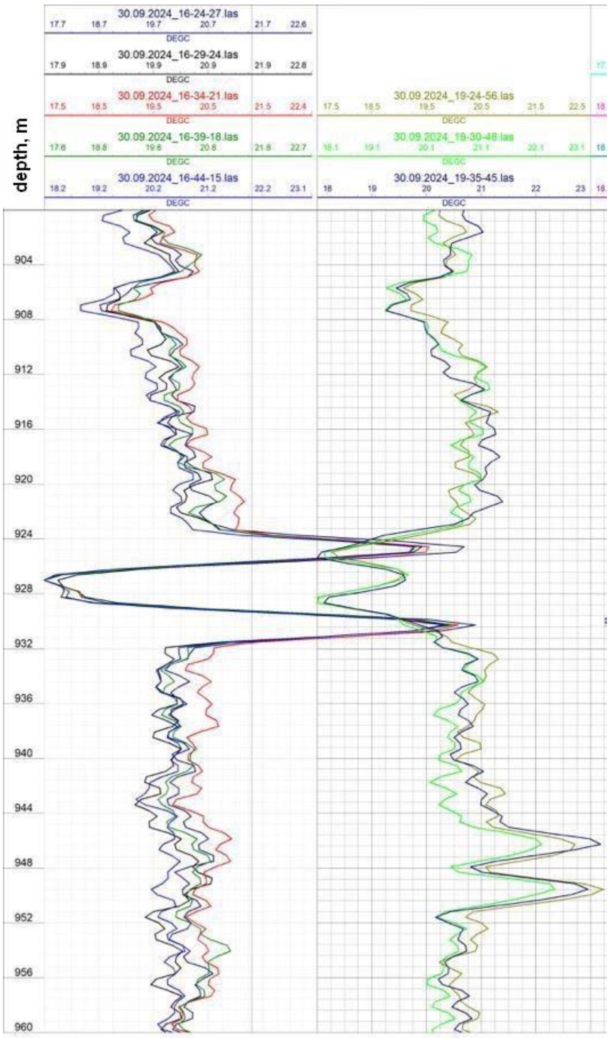

Fig. 2. Detection of signal from fiber.

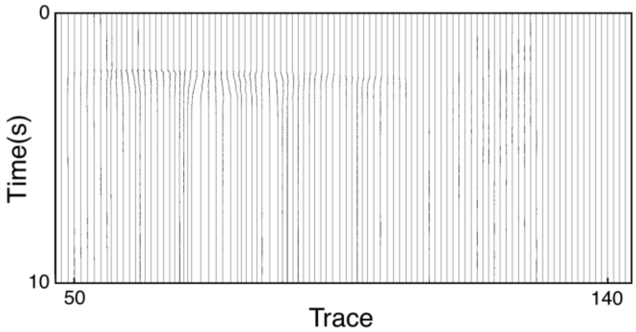

Fig. 3. Acoustic impact with energy of 0.1 kJ.

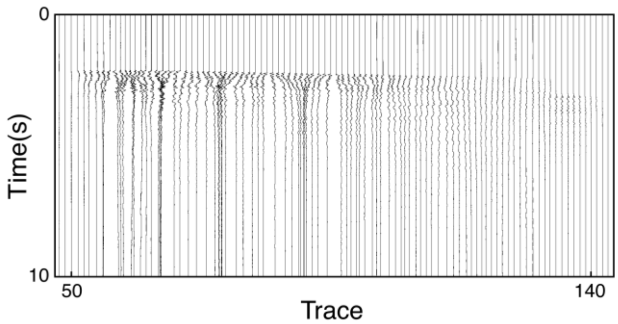

Fig. 4. Acoustic impact with energy of 0.5 kJ.

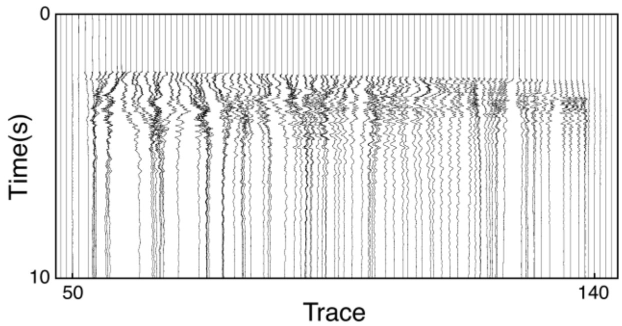

Fig. 5. Acoustic impact with energy of 1.0 kJ.

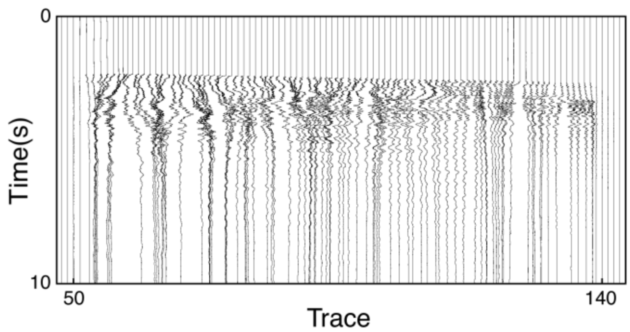

Fig. 6. Acoustic impact with energy of 1.5 kJ.

It is difficult to find exactly where the seismic device is on this diagrams, but from [21] follows that where there is one white stripe in Fig. 3.

IV. DISCUSSION

Each track is a point on the fiber. The distance between the tracks is 0.8 m. the 1.5 kJ. Impact vibration spread to a depth of 62 m from the seismic device in 3 sec from the seismogram data. This corresponds to the expected results. It seems we need some detection of vibration without fading-noise [22]. If we transform the graphs into black and white characterizing the intensity of seismic vibrations, interference is clearly visible when the impact energy increases to 1.0 kJ (Fig. 7).

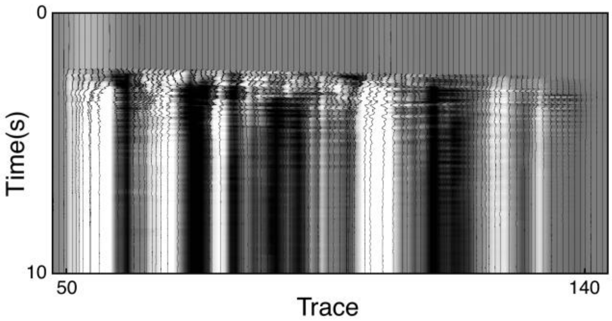

Fig. 7. Interference with acoustic impact with energy of 1.0 kJ.

V. CONCLUSIONS

Fiber-optic DAS can obtain locations and waveforms of vibrations occurring at any section of the optical fiber. In this paper we propose visualization of the acoustic impact for define distance from surface to point of fiber. Nevertheless, field test resulted that fading noise caused by interference makes DAS unable to detect vibrations correctly without fading suppression.

REFERENCES

[1] J.C. Juarez, E.W. Maier et al, "Distributed fiber-optic intrusion sensor system," Journal of Lightwave technology, 2005, no. 23(6), p. 2081.

[2] Q. Liu, X. Fan, and Z. He, "Time-gated digital optical frequency domain reflectometry with 1.6-m spatial resolution over entire 110-km range," Opt. Express, 2015, no. 23(20), pp. 25988-25995.

[3] O.V. Stukach, I.A. Ershov, I.V. Sychev, "Towards the Distributed Temperature Sensor with Potential Characteristics of Accuracy", 2018 XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE), October 2-6, 2018, Novosibirsk, Russia. DOI: 10.1109/APEIE.2018.8546271.

[4] D. Chen, Q. Liu, X. Fan, and Z. He, "Distributed fiber-optic acoustic sensor with enhanced response bandwidth and high signal-to-noise ratio," Journal of Lightwave technology, 2017, no. 35(10), pp. 2037-2043.

[5] R.Zh. Aimagambetova, A.D. Mekhtiyev, O.V. Stukach, "Experimental Studies of Laboratory Samples of Fiber-Optic Sensors within Reinforced Concrete Building Construction. Part 1: Overview", International Seminar on Electron Devices Design and Production (SED), 2024 October 02-03, Sochi, Russian Federation, Publisher: IEEE. DOI: 10.1109/SED63331.2024.10741063.

[6] R.Z. Aimagambetova, A.D. Mekhtiyev, O.V. Stukach, "Experimental Studies of Laboratory Samples of Fiber-Optic Sensors within Reinforced Concrete Building Construction. Part 2: The Experiment," Dynamics of Systems, Mechanisms and Machines (Dynamics), 2024, 12-14 Nov., Omsk, Russian Federation, pp. 1-8, DOI: 10.1109/Dynamics64718.2024.10838662.

[7] I.A. Ershov, O.V. Stukach and R.Z. Aimagambetova, "The Peculiar Measure Identifying of the Temperature Leap in the Distributed Raman Sensors", Dynamics of Systems, Mechanisms and Machines (Dynamics), 2021, 9-11 Nov., Omsk, Russian Federation, pp. 1-4, doi: 10.1109/Dynamics52735.2021.9653721.

[8] Q. Sun, C. Fan, H. Li et al, "Progress of research on optical fiber distributed acoustic sensing technology in petroleum industry", Geophysical Prospecting for Petroleum. 2022, no. 61(1), pp. 50-59, DOI: 10.3969/j.issn.1000-1441.2022.01.005.

[9] H. Wu, Z. Chen, L. Lv, et al, "Novel pressurized water pipe leak monitoring method based on the distributed optical fiber vibration sensor", Chin. J. Sci. Instrum. 2017, no. 38(1), pp. 159-165, DOI: 10.19650/j.cnki.cjsi.2017.01.0 21.

[10] J. Tejedor, J.M. Guarasa, H.F. Martins, et al, "A contextual GMM-HMM smart fiber optic surveillance system for pipeline integrity threat detection", Journal of Lightwave Technol., 2019, no. 37(18), pp. 4514-45225, DOI: 10.1109/JLT.2019.2908816.

[11] F. Ma, X. Wang, Y. Wang, R. Zhu, Z. Yuan et al, "An improved device and demodulation method for fiber-optic distributed acoustic sensor based on homodyne detection", Optical Fiber Technology, 71(2022), p. 102925, DOI: 10.1016/j.yofte.2022.102925.

[12] Y. Wang, J. Wang, Y. Fan, Y. Gao et al, "Interference fading suppression for distributed acoustic sensor using frequency-shifted delay loop", Optics & Laser Technology 171(2024), p. 110441, DOI: 10.1016/j.optlastec.2023.110441.

[13] D.F. Gomes, G.H. Weber, D.R. Pipa, M.J. Silva et al., "DAS Transducer for Enhanced Acoustic Sensitivity", IEEE Sensors Letters, 2023, vol. 7, no. 9, p. 5001204, DOI: 10.1109/LSENS.2023.3309262.

[14] H. Li, Q. Sun, T. Liu, C. Fan, et al, "Ultra-High Sensitive Quasi-Distributed Acoustic Sensor Based on Coherent OTDR and Cylindrical Transducer", Journal of lightwave technology, 2020, vol. 38, no. 4, February 15, pp. 929-938, DOI: 10.1109/JLT.2019.2951624.

[15] D.F. kandamali, X. Cao, M. Tian, Z. Jin, et al, "Machine learning methods for identification and classification of events in phi-OTDR systems: a review", Appl. Optics, 2022, no. 61(11), pp. 2975-2997., DOI: 10.1364/AO.444811.

[16] Z. Luo, Z. Yang, X. Chen, C. Ran, J. Huang, Y. Ye, "Separating method for multi-source vibration signals in ultra-weak fiber Bragg grating distributed acoustic sensors", Optical Fiber Technology, 2023, no. 81, p. 103501, DOI: 10.1016/j.yofte.2023.103501.

[17] Z. Luo, Z. Yang, B. Lu, B. Xu, J. Huang, "Modular DAS demodulation system based on ultra-weak fibre Bragg grating", J. Instrum., 2022, no. 17(10), p. 10037, DOI: 10.1088/1748-0221/17/10/P10037.

[18] D. Chen, Q. Liu, and Z. He, "Distributed fiber-optic acoustic sensor with sub-nano strain resolution based on time-gated digital OFDR", Asia Communications and Photonics Conference, Guangzhou(China), 2017, p. S4A.2.

[19] S. Wang, X. Fan, Q. Liu, and Z. He, "Distributed fiber-optic vibration sensing based on phase extraction from time-gated digital OFDR," Opt. Express, 2015, no. 23(26), pp. 33301-33309.

[20] L. Macedo, E. Pedruzzi, L. Avellar, et al, "High-resolution sensors for mass deposition and low-frequency vibration based on phase-shifted bragg gratings", IEEE Sensors Journal, 2023, no. 23 (3), pp. 2228-2235, DOI: 10.1109/JSEN.2022.3231434.

[21] I.A. Ershov, O.V. Stukach, N.V. Myasnikova, "Features of the Implementation of the Extremal Filtration Method in the Distributed Optic-Fiber Temperature Sensor", 2021 International Seminar on Electron Devices Design and Production (SED), Czech Republic, Prague, 27-28 April, 2021, IEEE Publisher, 5 p., DOI: 10.1109/SED51197.2021.9444514.

[22] D. Chen, Q. Liu, and Z. He, "Phase-detection distributed fiber-optic vibration sensor without fading-noise based on time-gated digital OFDR," Opt. Express, 2017, no. 25(7), pp. 8315-8325.

Информация об авторах:

Ершов Иван Анатольевич, ассистент кафедры Защиты информации Новосибирского государственного технического университета, г. Новосибирск, Россия, e-mail: ershov@corp.nstu.ru, ORCID: 0000-0003-1524-6508.

Стукач Олег Владимирович, д.т.н., профессор кафедры Защиты информации Новосибирского государственного технического университета, г. Новосибирск, Россия, профессор департамента Электронной инженерии Московского института электроники и математики им. А.Н.Тихонова Национального исследовательского университета «Высшая школа экономики», г. Москва, Россия, e-mail: tomsk@ieee.org , ORCID: 0000-0001-6845-4285.

Полевые испытания распределённого акустического датчика

И.А. Ершов[1], О.В. Стукач[1,2]

[1]*Новосибирский государственный технический университет, Новосибирск, Россия*

[2]*Национальный исследовательский университет «Высшая школа экономики», Москва, Россия*

***Аннотация* – Это исследование является вкладом в развитие акустического зондирования, предлагая мониторинг скважин на больших расстояниях. Высокочувствительный распределённый акустический датчик необходим при разведке нефти и газа, мониторинге трубопроводов и в других практических приложениях. В этой статье высокочувствительный квазираспределённый акустический датчик был испытан в скважине. Представлены формы волны, продемонстрированы распределённый аудиосигнал и пространственная акустическая визуализация. Результаты полевых испытаний обнаружения звука иллюстрируют хорошую чувствительность в пределах частотного диапазона до 5 кГц на глубине до 900 м. Частичные результаты получили дальнейшее развитие и применение в различных областях.**

Ключевые слова – DAS, подавление затухания, OTDR, нефтяная геофизика, анализ вибраций.

Список литературы

[1] J.C. Juarez, E.W. Maier и др. Distributed fiber-optic intrusion sensor system // Journal of Lightwave technology. – 2005. – № 23(6)? – С. 2081.

[2] Q. Liu, X. Fan, Z. He. Time-gated digital optical frequency domain reflectometry with 1.6-m spatial resolution over entire 110-km range // Opt. Express. – 2015. – № 23(20). – С. 25988-25995.

[3] Стукач О.В., Ершов И.А., Сычев И.В. О распределенных датчиках температуры с потенциальными характеристиками точности / 14-я Межд. науч.-техн. конф. "Актуальные проблемы электронного приборостроения" (АПЭП-2018). Труды конф. 2–6 октября 2018. – Новосибирск, Россия. – DOI: 10.1109/APEIE.2018.8546271.

[4] D. Chen, Q. Liu, X. Fan, Z. He. Distributed fiber-optic acoustic sensor with enhanced response bandwidth and high signal-to-noise ratio // Journal of Lightwave technology. – 2017. – № 35(10). - С. 2037-2043.

[5] Аймагамбетова Р.Ж., Мехтиев А.Д., Стукач О.В. Экспериментальные исследования лабораторных образцов волоконно-оптических датчиков в железобетонных конструкциях зданий. Часть 1: Обзор / Международный семинар по проектированию и технологии производства электронных средств (SED), 02-03 октября 2024, Сочи, Россия. – Издатель: IEEE. – DOI: 10.1109/SED63331.2024.10741063.

[6] Аймагамбетова Р.Ж., Мехтиев А.Д., Стукач О.В. Экспериментальные исследования лабораторных образцов волоконно-оптических датчиков в железобетонных конструкциях зданий. Часть 2: Эксперимент" / Конф. Динамика систем, механизмов и машин, 12-14 ноября 2024, Омск, Россия. – С. 1–8. Издатель: IEEE. – DOI: 10.1109/SED63331.2024.10741063.

[7] Ершов И.А., Стукач О.В., Аймагамбетова Р.Ж. Своеобразная мера определения скачка температуры в распределенных рамановских датчиках / Динамика систем, механизмов и машин, 9-11 ноября 2021, Омск, Россия, – С. 1-4. – DOI: 10.1109/Dynamics52735.2021.9653721.

[8] Q. Sun, C. Fan, H. Li и др. Progress of research on optical fiber distributed acoustic sensing technology in petroleum industry // Geophysical Prospecting for Petroleum. – 2022. – № 61(1). – С. 50-59. – DOI: 10.3969/j.issn.1000-1441.2022.01.005.

[9] H. Wu, Z. Chen, L. Lv и др. Novel pressurized water pipe leak monitoring method based on the distributed optical fiber vibration sensor // Chin. J. Sci. Instrum. – 2017. – № 38(1). – С. 159-165. – DOI: 10.19650/j.cnki.cjsi.2017.01.021.

[10] J. Tejedor, J.M. Guarasa, H.F. Martins и др. A contextual GMM-HMM smart fiber optic surveillance system for pipeline integrity threat detection // Journal of Lightwave Technol. – 2019. – № 37(18). – С. 4514-45225. – DOI: 10.1109/JLT.2019.2908816.

[11] F. Ma, X. Wang, Y. Wang, R. Zhu, Z. Yuan и др. An improved device and demodulation method for fiber-optic distributed acoustic sensor based on homodyne detection // Optical Fiber Technology. – 71(2022). – С. 102925. – DOI: 10.1016/j.yofte.2022.102925.

[12] Y. Wang, J. Wang, Y. Fan, Y. Gao и др. Interference fading suppression for distributed acoustic sensor using frequency-shifted delay loop // Optics & Laser Technology. – 171(2024). – С. 110441. – DOI: 10.1016/j.optlastec.2023.110441.

[13] D.F. Gomes, G.H. Weber, D.R. Pipa, M.J. Silva и др. DAS Transducer for Enhanced Acoustic Sensitivity // IEEE Sensors Letters. – 2023. Т. 7. – № 9. – p. 5001204. – DOI: 10.1109/LSENS.2023.3309262.

[14] H. Li, Q. Sun, T. Liu, C. Fan и др. Ultra-High Sensitive Quasi-Distributed Acoustic Sensor Based on Coherent OTDR and Cylindrical Transducer // Journal of lightwave technology. – 2020. – Т. 38. – № 4. – С. 929-938. – DOI: 10.1109/JLT.2019.2951624.

[15] D.F. kandamali, X. Cao, M. Tian, Z. Jin и др. Machine learning methods for identification and classification of events in phi-OTDR systems: a review // Appl. Optics. – 2022, no. 61(11), pp. 2975-2997., DOI: 10.1364/AO.444811.

[16] Z. Luo, Z. Yang, X. Chen, C. Ran, J. Huang, Y. Ye. Separating method for multi-source vibration signals in ultra-weak fiber Bragg grating distributed acoustic sensors // Optical Fiber Technology. – 2023. – № 81. – С. 103501. – DOI: 10.1016/j.yofte.2023.103501.

[17] Z. Luo, Z. Yang, B. Lu, B. Xu, J. Huang. Modular DAS demodulation system based on ultra-weak fibre Bragg grating // J. Instrum. – 2022. – № 17(10). – С. 10037. – DOI: 10.1088/1748-0221/17/10/P10037.

[18] D. Chen, Q. Liu, and Z. He. Distributed fiber-optic acoustic sensor with sub-nano strain resolution based on time-gated digital OFDR / Asia Communications and Photonics Conference, Guangzhou(China), 2017. – С. S4A.2.

[19] S. Wang, X. Fan, Q. Liu, and Z. He. Distributed fiber-optic vibration sensing based on phase extraction from time-gated digital OFDR// Opt. Express. – 2015. – № 23(26). – С. 33301-33309.

[20] L. Macedo, E. Pedruzzi, L. Avellar и др. High-resolution sensors for mass deposition and low-frequency vibration based on phase-shifted

bragg gratings // IEEE Sensors Journal. – 2023. – № 23 (3). – С. 2228-2235. – DOI: 10.1109/JSEN.2022.3231434.
[21] Ершов И.А., Стукач О.В., Мясникова Н.В. Особенности использования метода экстремальной фильтрации в распределённой оптической термометрии / Международный семинар по проектированию и технологии производства электронных средств (SED). – Прага, Чехия, 27-28 апреля 2021. – Издатель: IEEE. – DOI: 10.1109/SED51197.2021.9444514.
[22] D. Chen, Q. Liu, and Z. He. Phase-detection distributed fiber-optic vibration sensor without fading-noise based on time-gated digital OFDR // Opt. Express. – 2017. – № 25(7). – С. 8315-8325.