Open Access Library Journal
2022, Volume 9, e9552
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Development and Application of Distributed Optical Fiber Instruments

Jian Li[1,2], Mian Zhang [1,2], Shuaiyu Song[1,2]

[1]School of Earth Science and Engineering, Xi'an Shiyou University, Xi'an, China
[2]Shaanxi Key Laboratory of Petroleum Accumulation Geology, Xi'an Petroleum University, Xi'an, China
Email: 903699901@qq.com

How to cite this paper: Li, J., Zhang, M. and Song, S.Y. (2022) Development and Application of Distributed Optical Fiber Instruments. *Open Access Library Journal*, **9**: e9552.
https://doi.org/10.4236/oalib.1109552

Received: November 9, 2022
Accepted: December 25, 2022
Published: December 28, 2022

Abstract

At present, the Brillouin Optical Time Domain Reflectometer (BOTDR) sensor has been widely used in oil and gas pipeline monitoring and maintenance, and the ability to resist cross-interference is weak for the BOTDR sensor system, and it cannot process interference data at the same time. A Polarized Optical Time Domain Reflectometer (POTDR) based on the polarization effect is designed, which is based on the traditional POTDR sensor system and combined with the fiber grating, by using the fiber grating to enhance the intensity of the reflected signal light, effectively improve the signal-to-noise ratio of the sensor system, make the vibration measurement more accurate, and achieve the purpose of monitoring different fault points at the same time. Solve the limitation that BOTDR can only monitor the fault point individually. The fully distributed optical fiber sensor combined with the fiber grating gets rid of the limitation that BOTDR and POTDR can only monitor a single physical quantity parameter, and can monitor multiple physical quantity parameters at the same time, and the system is low cost, stable and feasible, and can be applied to the field of oil and gas pipeline monitoring on a large scale.

Subject Areas

Chemical Engineering & Technology, Geochemistry

Keywords

Oil and Gas Pipeline Monitoring, BOTDR, POTDR, Fiber Grating

1. Introduction

Along with the rapid development of oil and gas industry, people have higher and higher requirements for the safety of long-distance oil pipelines. Leakage or explosion of oil and gas pipelines can cause irreparable damage to people's lives and properties, so it is urgent to strengthen the monitoring and management of long-distance oil pipelines.

At present, the common leak detection techniques for oil and gas pipelines mainly include cable leak detection method, negative pressure wave method, acoustic wave method, etc. Leak detection cable method and negative pressure wave method have the disadvantages of low positioning accuracy, short detection distance, and poor real-time, while the acoustic method is expensive for post-maintenance and has a lag.

This paper introduces the technical principle and workflow of Brillouin Optic Time Domain Reflectometer (BOTDR) and Polarized Optical Time Domain Reflectometer (POTDR) sensors and makes a comparison; the Brillouin Optical Time Domain Reflectometer (BOTDR) system sensor is based on the Brillouin frequency shift principle, its connection with the fiber strain and temperature, according to the scale of the optical wave frequency shift inverse derivation of the strain and temperature information in the fiber, so as to achieve the safety evaluation of oil and gas pipelines. Conventional BOTDR detection is limited to special devices with built-in FBGs, which cannot provide temperature and stress information distributed in the direction of the fiber, and the cost of system configuration increases rapidly as the number of built-in FBGs increases. Moreover, its ability to resist cross- interference influence is weak, and it can only monitor the fault point separately. The sensor system based on Polarized Optical Time Domain Reflectometer (POTDR) principle is to use the polarization state property of the optical wave to identify and judge the disturbance behavior of the optical fiber such as vibration and temperature change, and to transmit the optical wave while sensing the external disturbance information for real-time monitoring [1]. The Polarized Optical Time Domain Reflectometer (POTDR) technique is used to extract external events by measuring the change in Rayleigh backscattered light SOP in optical fibers, which has the advantages of fast response, high sensitivity, and distribution monitoring, and is generally used for vibration and weak strain detection [2]. However, when the fiber is disturbed by two or more vibrations at the same time, Polarized Optical Time Domain Reflectometer (POTDR) is difficult to extract the vibration after the first vibration, because the polarization state of the light after the first vibration is modulated by the first vibration, and in practice, the fiber is often disturbed by two or more events at the same time. In this paper, we propose a Polarized Optical Time Domain Reflectometer (POTDR) sensing system with fiber grating, which can effectively improve the signal-to-noise ratio of the sensing system and make the measurement of vibration more accurate by enhancing the intensity of the reflected signal light with fiber grating [3].

2. Technology Principle

2.1. Principle of Brillouin Optical Time Domain Reflectometer (BOTDR) Based Sensor

When the oil and gas pipeline is disturbed by external signals such as vibration, stress deformation, or temperature change, the incident light generates back-scattered light inside the optical fiber, along with the frequency shift of the light wave, the signal is transmitted to the strain monitoring system, and the specific content and location of the physical changes are deduced from the frequency shift of the light, thus realizing the real-time monitoring of the oil and gas pipeline.

By measuring the frequency shift of the Brillouin scattered light and the optical power of Brillouin scattering, the temperature and stress magnitude of the measured point can be inferred.

The Brillouin frequency varies linearly with temperature and strain, and the mathematical expressions are:

$$f_B = f_{BO} + f_T T\left({}^{\circ}\mathrm{C}\right) + f_\varepsilon \varepsilon\left(\mu\varepsilon\right) \quad (1)$$

The rise of temperature and the increase of strain increase and decrease the Brillouin power, and the mathematical expression is:

$$P_B = P_{BO} + P_T T\left({}^{\circ}\mathrm{C}\right) + P_\varepsilon \varepsilon\left(\mu\varepsilon\right) \quad (2)$$

In reality, coherent detection is generally used to enhance the signal-to-noise ratio of Brillouin scattering signals. Single-frequency Brillouin fiber lasers with stable power and single-mode output can collect low-noise vibrational optical signals with similar optical frequencies to those of the sensing fiber STOCKS. BOTDR systems using Brillouin fiber lasers as signal generators have a wide range of applications in fiber optic sensing as well as coherent optical communication systems due to their good coherence [4].

2.2. Sensor Principle of Polarized Optical Time Domain Reflectometer (POTDR)

Rayleigh scattering is caused by the elastic collision of incident light with particles in the medium, where the scattered light and incident light have the same frequency. Polarized Optical Time Domain Reflectometer (POTDR) system sensor work based on the principle of Rayleigh scattering optics, the polarized light is coupled into the fiber, and the fiber state is monitored by detecting changes in the polarization state of the scattered wave in the fiber. This sensor system uses Optical Time Domain Reflectometer (OTDR) structure, which enables spatial localization of the object under test. **Figure 1** shows the basic system block diagram of a backscattering distributed fiber optic sensor [5].

According to the modulation effect of Rayleigh scattering in optical fibers, the technique can be divided into polarization modulation type and intensity modulation type. In this paper, we introduce the polarization modulation type, namely Polarized Optical Time Domain Reflectometer (POTDR) method.

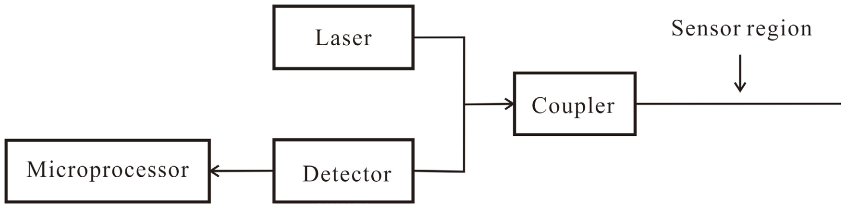

Figure 1. Basic block diagram of backscattered distributed fiber optic sensor system.

Since the polarization of light is a function about position, the spatial and temporal distribution characteristics of polarization in light can be obtained by detecting the polarization of backscattered light [6]. When the transmission medium fiber senses a perturbed signal, the content of the external signal acting on the fiber can be inverted by comparing the content and extent of the change in beam properties due to the influence of the sensing fiber on the external signal resulting in a change in beam characteristics, such as phase and wavelength.

Because electromagnetic fields, stress and temperature can modulate the polarization state of the optical signal, as this technique can measure many physical parameters.

3. System and Workflow Introduction

3.1. Using Brillouin Distributed Fiber Optic Sensing Technology

The overall BOTDR system can be divided into five parts, including 1) optical transmitter subsystem; 2) Brillouin outlier receiver subsystem; 3) signal acquisition and processing subsystem; 4) down-converter subsystem; 5) optical pulse modulation subsystem.

In this paper, a new BOTDR sensing system is proposed to use multi-wavelength detection light as the excitation signal and aberration-free BOTDR sensing system for uninterrupted distributed measurement of two parameters, strain and temperature, in oil and gas pipeline fibers. Compared with the previous common BOTDR sensing system, this system effectively improves the signal-to-noise ratio of the system without the influence of nonlinear effects, which makes the measurement results more accurate; due to the aberration-free BOTDR technique, the two-parameter continuous distributed measurement results of strain and temperature can be obtained without Brillouin scattering spectral scanning, which makes the measurement process more convenient and efficient [7].

Figure 2 shows a zero-difference BOTDR sensor system with multi-wavelength detection light as the excitation signal, which can perform uninterrupted distributed measurements of both parameters of fiber strain and temperature [8].

The working process of BOTDR sensing system: The multi-wavelength detection light signal emitted by laser emitter and microwave particles emitted by microwave emitter are synthesized in the electro-optical modulator and then amplified by the amplifier. The amplified optical signal is divided into two channels through a coupler. The first optical signal is processed by the computer and meets the pulse signal emitted by the pulse transmitter in the second electro-optical modulator. The modulated optical signal reaches the circulator and is sent out merged with the changing optical signal at the other end of the fiber.

The second optical signal distributed by the coupler is processed by the computer 2 and combined with the microwave particles emitted by the microwave transmitter 2 in the electro-optical modulator 3. And then the optical signal is processed by a balanced detector and the information about parameters such as strain and temperature in the optical signal is transmitted to a network computer to achieve the detection of parameters such as fiber strain and temperature for real-time monitoring of oil and gas pipelines [9].

3.2. Adopting Polarized Light Time-Domain Reflection Technology

The polarization state of light waves in optical fiber is particularly sensitive to changes in temperature, deformation, frequency and other parameters. Ordinary POTDR sensing systems use polarization instruments to convert the polarization state of light waves into changes in parameters such as power, which has the advantages of fast response time and easy parameter acquisition, but it is difficult to distinguish multiple events and accurately locate multiple change points that exist simultaneously [10]. **Figure 3** shows a novel POTDR sensing system that combines a basic POTDR system with a fiber grating array. The system uses a combination of fiber grating to enhance the intensity of the reflected signal light, which can effectively improve the signal-to-noise ratio of the sensing system, resulting

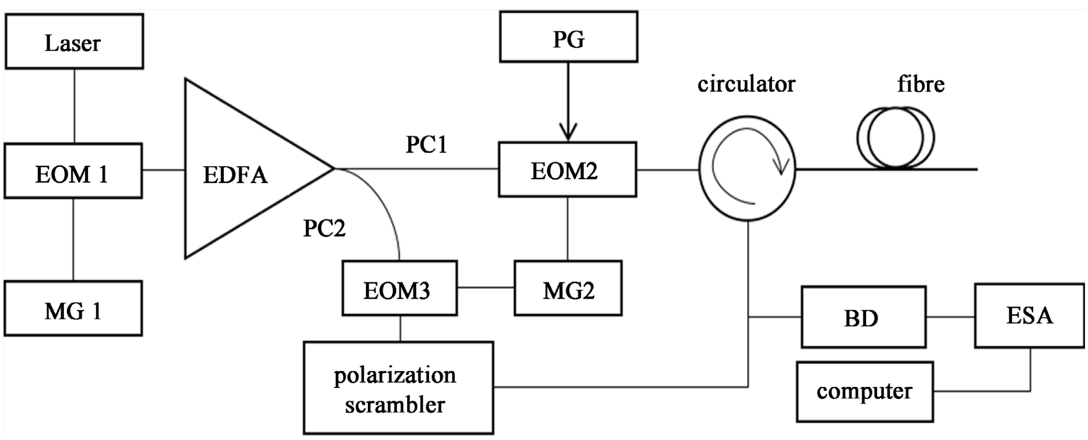

Figure 2. Multi-wavelength differential-free BOTDR sensing system.

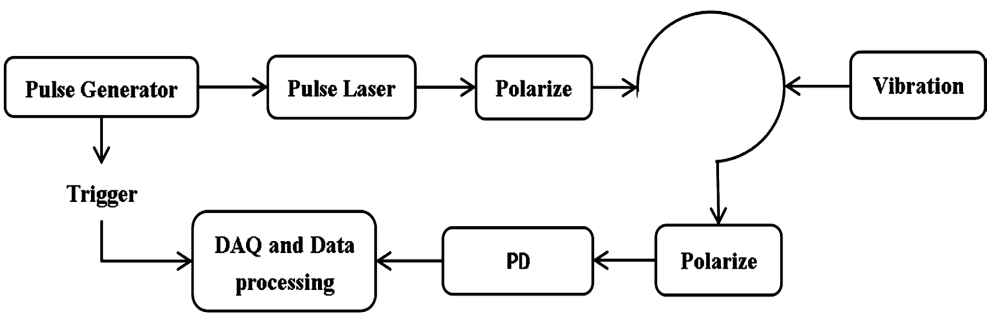

Figure 3. POTDR sensing system combined with fiber grating.

in more accurate measurement of vibration [11].

The working process of POTDR sensing system: the laser excites the light pulse to the polarization instrument, the polarization instrument outputs the polarization light pulse signal to reach the measured fiber, the signal is cyclically modulated back to the polarization instrument, and then the polarization light signal is output to the polarization detector, the modulated signal output from the detector enters the signal processing system, and then the signal processing system decodes the information of the received signal and displays the detection results.

In oil and gas related fields, where pipeline applications are very common, a proper monitoring system that collects structural safety information and provides early warning for future catastrophic failures that may result (such as pipeline explosions, leaks and corrosion) appears to be essential. Oil and gas pipelines are typically hundreds of kilometers or more in length, and real-time monitoring of oil and gas pipelines using the POTDR sensor system combined with fiber optic grating proposed in this paper allows for timely collection and analysis of any possible external signals for the purpose of monitoring oil and gas pipeline safety [12] [13].

4. Comparison of Sensors Based on the BOTDR Principle and Sensors Based on the POTDR Principle

Due to the high viscosity of oil, relay heating or heat tracing is required during the oil transmission process to prevent the pipeline from becoming sticky and clogged due to the low oil temperature. When there is an oil leak, the temperature around the leak point will be significantly higher than the temperature elsewhere in the pipeline. By laying optical fibers along the oil pipeline and monitoring the temperature change of the pipeline with the help of fiber optic sensing technology, leak information can be received in a timely and accurate manner.

A good fiber optic sensor can be evaluated in terms of its accuracy, spatial resolution and backscattered power level. Due to the weak backscattering signal in the Brillouin scattering mechanism, various techniques have been proposed to increase the excited Brillouin scattering threshold power to mitigate the nonlinear effects that lead to degraded sensor performance. Nowadays, the research field has started to use wavelet transform-based methods to improve the signal-to-noise ratio and achieve information amplification.

4.1. Conventional BOTDR System Sensor Monitoring Oil and Gas Pipeline

BOTDR uses the same one-dimensional closed-circuit radar principle as conventional optical time domain reflectometer systems. The difference is the backscattered light produced when pulsed light is transmitted in the fiber, and BOTDR is Brillouin scattered light; the distance test of the scattering point can be achieved by measuring the time difference between the incident light and the scattered light, and then calculating the speed of light of the medium. The change of sound wave velocity caused by the change of optical fiber stress and temperature is reflected as the change of Brillouin frequency shift, and the frequency shift and intensity of the Brillouin scattered signal are measured, and the time difference positioning can be added to realize point-by-point distributed temperature and strain measurement.

1) The laser emits continuous light, which is modulated into pulsed light and then turned into scattered light after being shot into the fiber.

2) The scattered light is directed to the gathering pipeline and the reflected light is received by the detector.

3) The emitted light becomes Brillouin scattered light with a certain frequency shift from the incident light, and then the frequency shift of the Brillouin scattered signal and the relationship between power consumption change and temperature are used to obtain the specific situation of temperature on the fiber, so as to achieve the monitoring of the gathering pipeline [14] [15].

4.2. POTDR System Sensor Monitoring Oil and Gas Pipeline

When the optical fiber of the POTDR system is modulated by the external physical quantity, the polarization state of the light will change accordingly, and the polarization direction of its Rayleigh scattered light at the scattering point is the same as the incident light, and the distribution of the external physical quantity can be obtained by detecting the polarization state of the backward Rayleigh scattered light and the delay time of the optical signal at the incident end of the optical fiber; Since magnetic fields, electric fields, transverse pressures, and temperatures all modulate the polarization state of light in an optical fiber, this technique can be used to measure multiple physical quantities.

1) Some optical fibers are placed on the oil and gas pipeline to receive the physical quantity changes associated with the pipeline. The optical fibers need to be tightly sealed, otherwise they will bring out toxic gases such as hydrogen sulfide.

2) Temperature, pressure and other physical quantities modulate the optical fiber, thus changing the polarization state of the light, and the polarization state of the backward Rayleigh scattered light and the delay time of the optical signal are identified and detected, which can be inferred to obtain the specific external physical quantities.

3) The polarization state of light is modulated by multiple physical quantities, so this technique can achieve the measurement of multiple physical parameters [16].

5. Example Analysis

There are a variety of distributed fiber optic temperature measurement instruments sold on the market, mostly temperature-sensitive fire detectors, divided into two devices for firefighting and non-firefighting, the following shows a distributed fiber optic line type temperature-sensitive fire detector (DTS), and based on its technical analysis.

The product is based on the principle of POTDR distributed fiber optic sensing technology, which uses the sensitive relationship between the intensity of scattered light (Raman) signals in optical fiber and temperature to achieve accurate feedback on temperature changes. It is mainly divided into three parts, one is the fiber optic host, which is the central brain of information processing, with built-in fiber optic temperature module, touch display and DC24V power supply, with the following functions: temperature measurement, information display and storage; the second is the temperature sensing fiber, which is the information sensing of the whole device, using the structure of metal spiral armor situation, can work stably in the environment of minus 40˚ to above zero 120˚, with strong ability to carry interference; and the POTDR distributed fiber optic sensing technology. The third is the user software, the user software is self-developed, running using WINDOWS control system, with: Chinese interface, simple operation, support for keyboard and mouse and touch screen operation, etc., can achieve: real-time data acquisition and display, partition measurement, multi-level alarm and other functions.

Its overall structure model is shown below in **Figure 4**.

The working principle flow chart is shown in **Figure 5**.

The device has the following advantages: 1) system temperature measurement and positioning speed; 2) monitoring distance is wide, the length can reach more than ten kilometers, the interval set by themselves; 3) high accuracy, temperature resolution in 0.1˚C up and down, temperature accuracy between ±1˚C, positioning accuracy between ±0.5 m; 4) distributed fiber optic sensing system using open communication protocol, good compatibility; 5) high security, detection of fiber

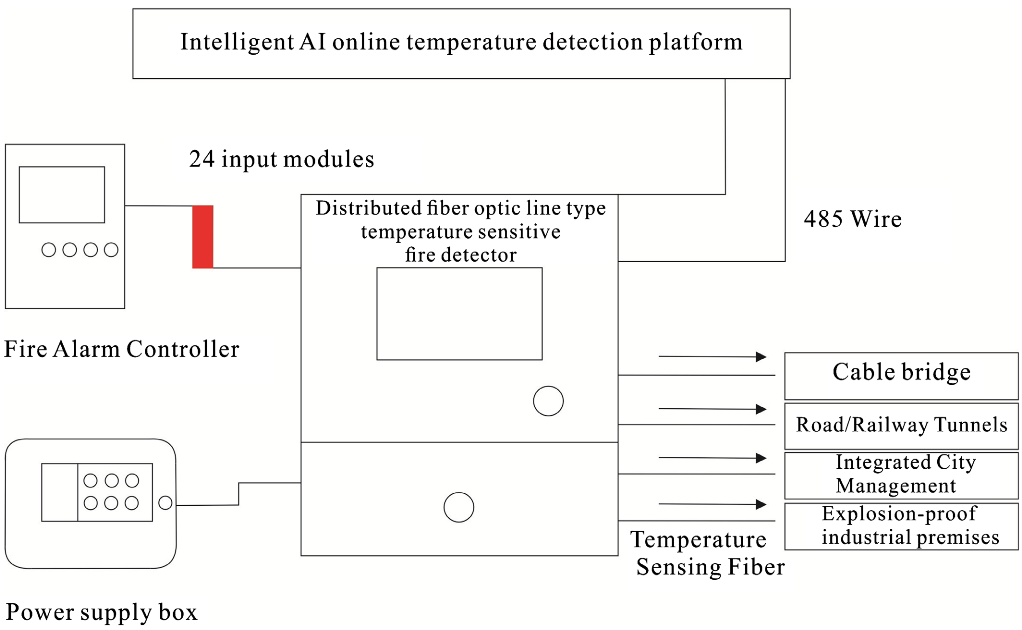

Figure 4. The overall construction model of the implementation.

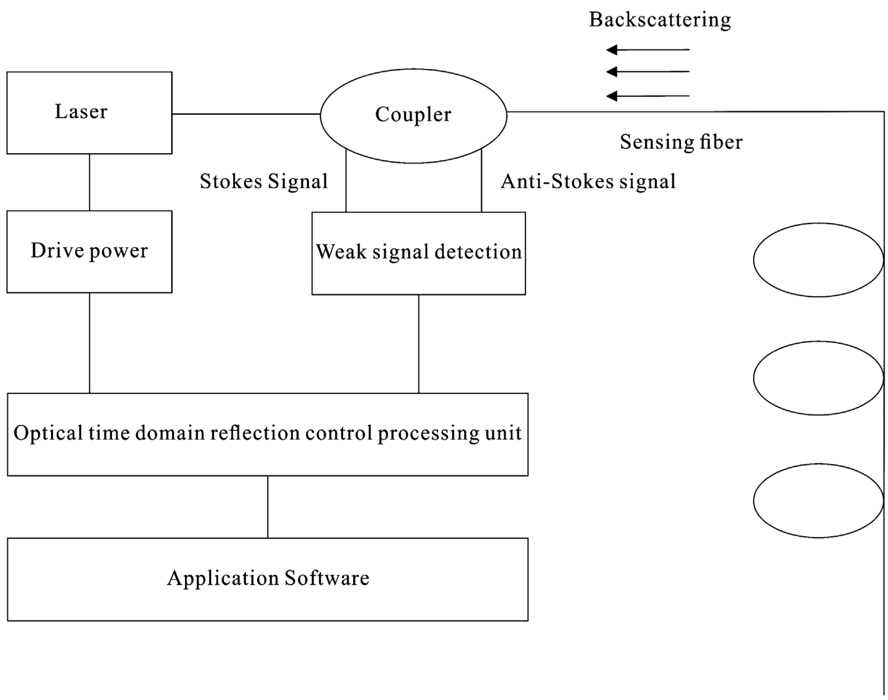

Figure 5. Flow chart of the working principle of the implementation.

optic nature of safety and reliability.

This product design is inspired by distributed fiber optic sensing technology, which is based on the sensitive characteristics of scattered light (Raman) signal strength to temperature, and has many advantages over other similar products. But also has its disadvantages, such as: weak Raman scattering signal, Rayleigh scattered light signal on the Raman signal interference, etc., so this product design needs to focus on expanding the signal-to-noise ratio of the Raman scattered light signal, and needs to exclude Rayleigh scattered light signal interference, so as to effectively collect the Raman signal, so that the product instrumentation is better [17] [18].

6. Conclusions

1) A fully distributed fiber optic sensor based on the polarization effect uses only ordinary optical fibers as sensors; due to its polarization principle, every part of the fiber has sensing capability. Therefore, the POTDR sensor can respond to perturbations such as temperature changes, temperature variations, and any point on the fiber, identify and judge signals such as vibrations, and because the polarization state of the optical signal is a vector signal, it can filter, filter, and identify changes caused by different perturbations, identify the type and location of the perturbation, and process multiple sets of data simultaneously.

2) In practice, sensors based on the BOTDR principle have been applied to oil and gas pipeline monitoring, while sensors based on the POTDR principle are mainly used in cable protection systems, etc. In this research, we learned that POTDR sensors are also widely used in oil and gas pipeline monitoring. The

analysis technology of the polarization state principle is not very sensitive to small external disturbances, so it is not suitable for detecting environments with small disturbances and high accuracy of external force identification. However, when oil and gas pipelines are damaged and the temperature changes are large, POTDR sensors can fully sense and easily identify them, so POTDR is also suitable for oil and gas pipeline monitoring.

Acknowledgements

This work was supported by a grant from the Xi'an University of Petroleum (Grant YCS21112058) and the Shaanxi Province Key Research and Development Program: (2022GY-130). Many thanks to the reviewers and editors for their insightful comments, which significantly improved the original version of this paper.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Yan, S.Z. and Chyan, L.S. (2010) Performance Enhancement of BOTDR Fiber Optic Sensor for Oil and Gas Pipeline Monitoring. *Optical Fiber Technology*, **16**, 100-109. https://doi.org/10.1016/j.yofte.2010.01.001

[2] Chen, M.M., Wang, F., Zhang, Y.X., *et al.* (2018) Measurement of Multiple Vibration Points by Using POTDR. *International Conference on Optical Instruments and Technology*, Vol. 10618, Article ID: 1061803.

[3] Hu, J.T., Wang, X.C. and Pan, S.L. (2018) Application of the Probe Pulse with Ergodic SOPs in Detecting Multi-Vibrations Using POTDR. *International Conference on Optical Instruments and Technology*, Vol. 10618, Article ID: 1061805.

[4] Wang, X.C., Zhang, X.P., Wang, F., *et al.* (2011) Application of Frequency Spectrum Analysis in Measuring Multi-Vibrations by Using POTDR. *International Conference on Optical Instruments and Technology*, Vol. 8198, Article ID: 819808. https://doi.org/10.1117/12.910376

[5] Chi, Y.G., Bai, Q., Wang, Y., *et al.* (2018) Pipeline Stress Hazard BOTDR Distributed Fiber Optic Detection System. *Journal of Sensing Technology*, **31**, 1775-1780.

[6] Sun, Q.Z. (2008) Research and Application of Distributed Optical Fiber Sensing and Information Processing Technology. Ph.D. Thesis, Huazhong University of Science and Technology, Wuhan.

[7] Geng, J.P., Xu, J.D., Wei, G., *et al.* (2002) Advances in Distributed Fiber Optic Sensors Based on Brillouin Scattering. *Journal of Testing Technology*, No. 2, 87-91.

[8] Zhao, X.F., Lu, J. and Wang, Y.H. (2010) Experimental Study of a BOTDR Fiber Optic Temperature Sensor. *Journal of Disaster Prevention and Mitigation Engineering*, **30**, 247-250.

[9] Zhao, L.J. and Li, Y.Q. (2015) Fast Extraction of Temperature Features of BOTDR System Based on Wavelet Transform. *Electrical Measurement and Instrumentation*, **52**, 19-23.

[10] Su, Y., Zhao, C., Long, X., *et al.* (2013) Distributed Generation Application in the Rural Areas of West China. *Energy & Power Engineering*, **5**, 167-170.

https://doi.org/10.4236/epe.2013.54B032

[11] Li, J.H., Wang, R., Xu, Z.Y., *et al.* (2007) A New Direct Detection BOTDR System with Wavelet Transform Application. *Proceedings of the* 13*th National Conference on Fiber Optic Communication and* 14*th Academic Conference on Integrated Optics*, 349-353.

[12] He, J. and Wang, E.W. (2017) Coherent Detection-Based Polarized Optical Time-Domain Reflection Fiber Optic Vibration Sensing System. *Journal of Sensing Technology*, **30**, 1017-1021.

[13] Yang, F., Tang, S.-L., Yin, W.-G., *et al.* (2022) Analysis of Wind Vibration Monitoring of Overhead Transmission Lines Based on Multiparameter Distributed Fiber Optic Sensing. *Power System Protection and Control*, **50**, 169-177.

[14] Yin, G.L., Jiang, R., Xu, Z., *et al.* (2022) Fast, High Spatial Resolution Distributed Fiber Optic Sensing Technology and Its Application to Mechanical Deformation and Temperature Monitoring. *Journal of Mechanical Engineering*, **58**, 96-104.

[15] Zhang, Y.H., Jiang, Z.Q., Ran, Y.D., *et al.* (2022) Distributed Optical Fiber Sensing Data Encoding and Storage Method. *Laser Journal*, **43**, 148-153.

[16] Jiang, T.W., Wang, S.J., Zhu, S.B., *et al.* (2022) Experimental Research and Application of Distributed Optical Fiber Acoustic Sensing System in Downhole Fault Activity Monitoring in Developed Gas Fields in Western China. *Progress in Geophysics*, **37**, 1960-1968.

[17] He, J. and Wang, E.W. (2017) A Polarized Optical Time-Domain Reflection Fiber Optic Vibration Sensing System Based on Coherent Detection. *Journal of Sensing Technology*, **30**, 1017-1021.

[18] Zhou, Y., Jin, S.J., Zhang, Y.C., *et al.* (2005) Research on Distributed Fiber Optic Sensing Technology for Pipeline Leak Detection. *Optical Laser*, No. 8, 935-938.