Review of Fiber-optic Distributed Acoustic Sensing Technology

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Abstract: A distributed optical-fiber acoustic sensor is an acoustic sensor that uses the optical fiber itself as a photosensitive medium, and is based on Rayleigh backscattering in an optical fiber. The sensor is widely used in the safety monitoring of oil and gas pipelines, the classification of weak acoustic signals, defense, seismic prospecting, and other fields.In the field of seismic prospecting, distributed optical-fiber acoustic sensing (DAS) will gradually replace the use of the traditional geophone. The present paper mainly expounds the recent application of DAS, and summarizes recent research achievements of DAS in resource exploration, intrusion monitoring, pattern recognition, and other fields and various DAS system structures. It is found that the high-sensitivity and long-distance sensing capabilities of DAS play a role in the extensive monitoring applications of DAS in engineering. The future application and development of DAS technology are examined, with the hope of promoting the wider application of the DAS technology, which benefits engineering and society.

Key words: Fiber-optic Distributed Acoustic Sensor, Rayleigh Backscatter, Geophone, Φ-optical Time-domain Reflectometry.

1 Introduction

The development of optical fiber sensors has advanced rapidly since Corning Corporation in the United States successfully developed the quartz glass optical fiber (simply known as the optical fiber) with a transmission loss as low as 20 dB/km. In 1976, Barnsen and Jensen first reported backscattering in an optical waveguide [1]. In 1981, Aoyama reported the application of optical time-domain reflectometry (OTDR) in a single-mode optical fiber [2]. In 1982, P. Hoaley proposed an OTDR system with heterodyne coherence [3]. In 1993, Taylor and Lee were awarded a patent on the amplitude measurement of coherent backscattering for intrusion detection[4]. In 2000, Posey at the US Naval Research Laboratory (NRL) demonstrated interferometric phase measuring based on coherent Rayleigh backscattering [5]. In 2009, British Shell first conducted DAS geophysical monitoring in Canada [6]. In 2011, Shanghai Optical Machine International first realized Rayleigh scattering distributed heterodyne coherent phase demodulation[7]. In 2015, Li Fang, at the Semiconductor Institute of the Chinese Academy of Sciences, used a Phase Generated Carrier (PGC) demodulation technology [8]. In 2016, Wang Zinan of the University of Electronic Science and Technology,proposed I/Q demodulation and homodyne detection technology [9]. In 2017, Zhang Min's team at Tsinghua University, adopted a dual-pulse monitoring frequency shifting technology [10]. In 2018, Chen Dian proposed a novel configuration of time-gated digital optical frequency domain rellectometry based on optical intensity modulator which solved fading problem and realized sub-meter spatial resolution in DAS [11]. In 2019, Peng Zhaoqiang reported a combined technique to enhance Rayleigh scattering signal in optical fiber and deep neutral network data analytics for DAS. By using ultrafast laser direct writing technique, over 45 dB of Rayleigh backscattering enhancement can be achieved in silica fibers [12]. It is found that, various technologies and applications related to DAS are developing rapidly.

Fiber-optic sensors can be categorized according to the types of point sensor and distributed sensor. Point sensors are not suitable for real-time monitoring over long distances. Distributed sensors can be further categorized into interferometric and reflection types. The main types of interferometric sensor are the Michelson interferometer[13], Mach - Zehnder-interferometer[14-15], Sagnac interferometer[16], dual Sagnac interferometer[17], and Sagnac - Michelson[18] interferometer with multiple composite structures. The interferometric sensor is sensitive to a phase change but also has disadvantages. Although the single-structure interferometric sensor has a relatively simple structure, it cannot detect multiple disturbance points at the same time, and it is prone to environmental interference. The structure and signal demodulation algorithm of the composite interferometric sensor are complex, and the sensor is thus difficult to produce. The fiber-distributed acoustic sensor can use Rayleigh backscattering, which is common in optical fibers, to realize multiple measurements that are more precise over a long distance. Compared with other sensors, the optical-fiber distributed acoustic sensor has high sensitivity and accuracy, good resistance against electromagnetic interference, high dielectric strength, good corrosion resistance, high heat resistance, integrated sensing and transmission, good safety, and good compatibility with digital communication systems. It is widely used in the safety monitoring of oil and natural gas pipelines, geophysical surveying; health monitoring of civil-engineering projects, such as bridges and large buildings; military, national defense, and aerospace applications; and process control systems[19]. Distributed acoustic sensing (DAS) has become a widely used technology in recent years. Recent surveys show that the DAS market has grown steadily over the past few years and is expected to exceed $2 billion by 2025. The field of application of this technology is becoming increasingly mature. The present paper systematically analyzes and summarizes the application of DAS in different fields and considers the future development of this technology.

2 Optical Time-domain Reflectometry (OTDR)

2.1 Basic principle of OTDR

As a new type of optical-fiber technology, the technology of interferometric distributed optical-fiber sensing based on OTDR can detect a vibration signal along an optical fiber remotely. The technology is based on sending incoherent light pulses into an optical cable. Owing to the inhomogeneity of the optical fiber medium and the effect of a high-power laser on the transmission medium, the pulsed light continuously produces backscattered light while propagating. When there is a loss, decay, break point, or vibration on the optical path, the intensity of backscattered light generated at the point changes accordingly, measuring the backscattered light intensity at the same end of the optical cable.

Letting P_1 be the input light power, α be the attenuation coefficient of pulse light transmission in the fiber, and L be the peak power when the pulse light propagates to the position of the fiber, it follows that:

$$PL = e\text{-}\alpha L\, P_1 . \tag{1}$$

According to the power relationship between Rayleigh backscattering and forward transmission, the Rayleigh backscattered light power at L is:

$$P_R(L) = e\text{-}\alpha L\, P_1 S\, \alpha_S W \frac{\nu}{2n} \tag{2}$$

When light enters the photoelectric detector, the detected light power is:

$$P_R(L) = e\text{-}2\alpha L\, P_1 S\, \alpha_S W \frac{\nu}{2n} \tag{3}$$

where $S = \lambda/4\pi nr$ is the Rayleigh scattering capture factor, λ is the wavelength of the Rayleigh backscattered light, r is the mode field radius of the fiber, α_S is the Rayleigh scattering coefficient, and W is the light pulse width. It is seen that the Rayleigh backscattering curve for the optical fiber measured by OTDR exponentially attenuates. If there is a core breakage, bending, optical fiber connection, or vibration in the optical fiber link, the attenuation coefficients of the forward transmission and backscatter increase sharply and the scattering curve has a cliff-type decline at that point. Corresponding pattern recognition and detection is carried out on the obtained OTDR curve to determine the location of the above events along the optical fiber.

According to the time difference between the incident signal and the reflected signal, the distance between an event point and the location of OTDR can be expressed as:

$$d = \frac{c\tau}{2n} \qquad (4)$$

where, c is the speed of light in a vacuum, n is the refractive index of the optical-fiber core, and τ is the delay. OTDR is widely used in measuring signal losses and detecting breakpoints along fiber-optic cables. Figure 1 presents a structural diagram of OTDR.

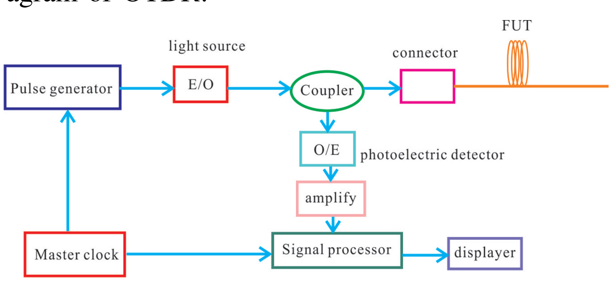

Fig. 1 Structural diagram of OTDR

2.2 Scattering signals in an optical fiber

There are three types of scattering of a signal in an optical fiber: Rayleigh scattering generated by fluctuation of the refractive index, Raman scattering generated by optical phonons, and Brillouin scattering generated by acoustic phonons. Raman scattering and Brillouin scattering are mainly used for the distributed measurement of stress and temperature, while Rayleigh scattering is mainly used for vibration detection. OTDR technology is a sensing technology based on Rayleigh backscattering. Rayleigh-scattering optical fiber vibration sensing uses the characteristics of the intensity, phase, frequency, and polarization state of Rayleigh backscattered light in the sensing fiber for vibration detection, thus realizing the positioning and reduction of vibration. The DAS system is based on OTDR technology.

2.3 OTDR performance indicators

2.3.1 Dynamic range

The dynamic range is an important parameter for OTDR system evaluation. The system can detect over a longer distance as the dynamic range increases. The dynamic range is the difference between the signal power obtained from the initial position of the fiber and the output noise power of the detector, which representing the maximum detection range of the system. The dynamic range can be expressed as:

$$R = \frac{1}{2}[P_1 - P_D - (Z + C) + SNR] \qquad (5)$$

where, P_1 is the optical power injected into the fiber, P_D is the minimum optical power of the detector response, C is the system loss, and SNR is the signal-to-noise ratio improved by the cumulative average algorithm. $Z = -10log10S\alpha S\nu gw/2$ is the optical fiber transmission loss, $S = 1/4(\lambda/\pi nr)^2$ is the backscattering light power capture factor, S is the optical fiber loss, g is the speed of light in optical fiber, and w is the light pulse width.

2.3.2 Spatial resolution

The spatial resolution is the minimum distance between two perturbation events. The spatial resolution is related to the pulse width of the injected fiber pulse, and the wider the pulse width of the injected fiber, the higher the spatial resolution of the system. The relation between the pulse width and the refractive index of the fiber can be expressed as:

$$\Delta Z = \frac{wc}{2\,n_f} \qquad (6)$$

where, w is the pulse width, c is the speed of light in a vacuum, and n_f is the refractive index of the fiber.

2.3.3 Detection sensitivity

The detection sensitivity represents the response ability of the system to perceive external disturbances. The line width of the laser, the sensitivity of the photodetector, and the repetition frequency of the light pulse are three factors that affect the sensitivity of the whole system. First, the interference effect becomes more obvious and the detection sensitivity increases as the line width of the laser decreases. Second, the sensitivity of the system and the sensing distance increase with the sensitivity of the photodetector. Third, the system can detect a higher maximum frequency of the disturbance signal as the repetition frequency of the light pulse increases.

3 Application of DAS System

3.1 DAS-based system for monitoring the security of an oil pipeline

DAS has unprecedented application prospects in the petroleum industry. Optasense and Silixa in the United Kingdom were the first companies to apply DAS to engineering, mainly applying DAS to the detection and analysis of seismic waves and the monitoring of the safety of oil pipelines, and thus covering the three processes of exploration, production, and transportation in the oil industry.

It is necessary to monitor a whole oil pipeline dynamically because many oil pipeline safety accidents are caused by thieves damaging an oil pipeline[20]. The theft of oil from pipelines results in not only the loss of petroleum products but also direct economic loss. More importantly, the damage caused by thieves is likely to cause environmental pollution and result in a serious ecological disaster. All activities carried out in the stealing of oil generate seismic waves in pipelines. At present, all communication between the boosting stations of domestic pipelines is transmitted along optical fiber, and the optical-fiber communication link and oil pipeline are laid in parallel and close to each other such that the seismic waves generated by third-party interference will be transmitted along the communication fiber. DAS can therefore be applied via the communication cable of a boosting station to realize long-distance intrusion monitoring. Rao Yunjiang's team[21] demonstrated the superior performance of a long-distance pipeline safety monitoring system based on DAS. In 2014, Xu Tuanwei et al.[22] invented a DAS system based on the phase generation carrier technology. Technology based on ϕ-OTDR can be used to monitor the safety of oil pipelines and thus effectively realize the dynamic measurement of large-phase signals and eliminate the problem of phase fading. Figure 2 presents a block diagram of the DAS system. In 2018, Ni Jiasheng et al.[23] from the Laser Institute of the Shandong Academy of Sciences, PR China, proposed a distributed acoustic sensing technology that is based on interference demodulation and provides a complete and clear formation profile. Their study provided a new method of oil exploration that uses optical-fiber sensing technology. This method has the advantages of convenience, wide coverage, and the acquisition of large quantities of data, making it more suitable for geophysical exploration applications.

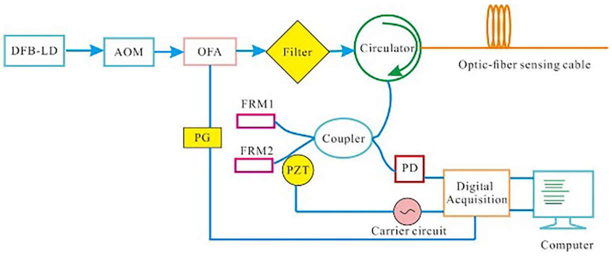

Fig. 2 Block diagram of the DAS system for oil exploration.

3.2 Detection of a weak underwater acoustic signal

In 2015, Shang Ying[24] used DAS technology based on Rayleigh backscattering to detect weak underwater acoustic signals. This scheme is different from previous schemes in that it amplifies the phase information of Rayleigh backscattering self-interference light of the sensing optical fiber that records the acoustic position, frequency, amplitude, and phase. The self-interference light phase of the Rayleigh backscattering recorded acoustic wave is generated by an underwater speaker. DAS technology and phase-generated carrier technology are used to restore acoustic wave information, such as the position, frequency, amplitude, and phase. Experimental results show that the acoustic information to be measured can be recovered using standard telecommunication single-mode optical fiber. The acoustic phase sensitivity of the DAS system at 600 Hz reaches about -151 dB (re rad/Pa), while the minimum measurable sound pressure is 6 Pa. Figure 3 presents a block diagram of the DAS system.

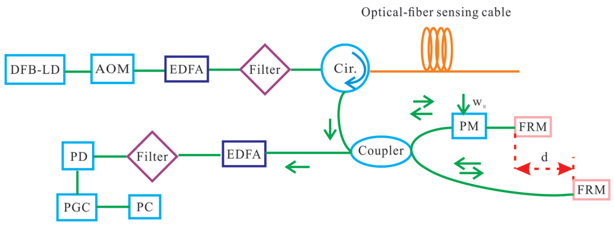

Fig. 3 Block diagram of the DAS system for detecting weak underwater acoustic signals.

In 2017, Dong Jie[25] proposed DAS technology based on Rayleigh-backscattering spatial differential interference to detect weak underwater sound waves over a long range. The Rayleigh backscattering light in single-mode sensing optical fibers is affected by acoustic vibration. Rayleigh backscattering light containing acoustic information is injected into an unbalanced Michelson interferometer, and the difference in arm lengths of the interferometer is adjusted to achieve Rayleigh backscattered light interference of adjacent spatial segments of different lengths. The output $V_{out} = \sqrt{3}\varphi(t) = \sqrt{3[\varphi(t) + \psi(t)]}$ $V_{out} = \sqrt{3}\varphi(t) = \sqrt{3[\varphi(t) + \psi(t)]}$ is then obtained through 3 × 3 coupling demodulation, and a high-pass filter is used to filter out $\psi(t)$, thereby demodulating the signal $\varphi(t)$ to be tested. The phase information is obtained and the acoustic signal is thus measured. At a frequency of 1 kHz, the phase sensitivity of underwater sound pressure reaches -148.8 dB, and the response flatness in the frequency range of 100 – 1500 Hz is less than 1.2 dB. The block diagram of the DAS system is shown in Figure 4.

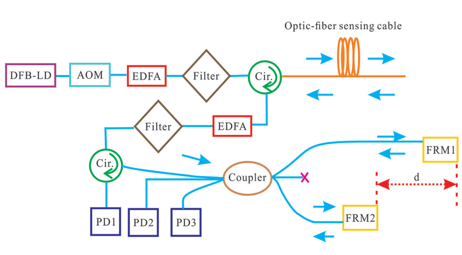

Fig. 4 Block diagram of the DAS system.

3.3 Artificial intelligence-based pattern recognition

Traditional OTDR data analysis and pattern recognition methods for monitoring potential threats and the signal processing of a large amount of data required by DAS application take a long time and are readily affected by the external environment[26]. It is thus impossible to correctly distinguish signals of similar phase. Methods of measuring amplitude, such as multi-scale wavelet decomposition[27], the use of the Gaussian mixture model[28], and the morphological feature extraction method[29], have been widely used in recent years. However, these methods are affected by the signal-to-noise ratio (SNR) of the OTDR system. Wen Hongqiao et al.[30] proposed a method that combines ultra-fast laser manufacturing and neural network pattern recognition, which improves the measurement efficiency of the DAS system to a certain extent. This method is a supervised learning method based on a neural network (NN). It classifies human motion from signals recorded by the DAS system, and can achieve a recognition accuracy of 80%. The convolutional neural network (CNN) is a type of neural network that is used to extract multiple local features from one layer to another[31]. It can be considered as an approach of artificial intelligence (AI). Feature extraction makes it easier for data to be processed with the CNN. The fast Fourier transform is used to obtain the frequency components of the data, so that the CNN can be used to directly access the global characteristics of the signal. At the same time, low-pass filtering is used to remove high-frequency components while sinc filtering is applied to smooth the representation in the frequency domain. In the CNN approach, convolution is adopted to process the data collected from the DAS system, which is particularly effective in revealing the spatial dependence of data. Figure 5 presents a block diagram of the DAS system.

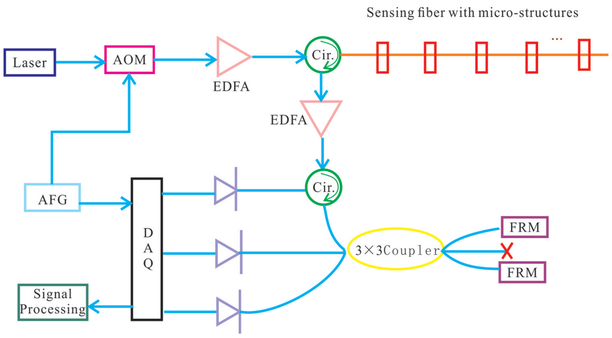

Fig. 5 Block diagram of the DAS system for AI-based pattern recognition.

3.4 Multi-threat classification

Another direction of DAS application is a linear asset protection system based on distributed acoustic sensing combined with new signal processing and threat classification technology. The sensing system is realized by direct detection phase-OTDR. In 2017, Metin Aktas et al. [32] proposed a new threat classification method based on deep learning to identify various types of threat. Their method adopts a deep CNN based on real sensor data training and extracts patterns from complex signals. An ITU-T G.652 cable buried 1 m underground was used in their experimental study. A comparison with preprocessing methods, such as time-difference and wavelet denoising methods that are commonly used in the literature, reveals that the application of the proposed signal processing, event detection, and classification methods provides a classification accuracy exceeding 93% for walking, digging with a pickaxe, digging with a shovel, digging with a harrow, strong wind, and facility noise generated by water pipes, generators, and air conditioning, and the maximum range of detection reaches 40 kilometers. Figure 6 presents a block diagram of the DAS system.

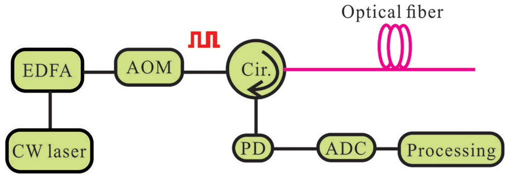

Fig. 6 Block diagram of the DAS system for multi-threat classification.

In 2018, Jiang Fei et al. [33] proposed a new method based on signal kurtosis to locate and distinguish disturbances in Φ-OTDR. First, the spatial kurtosis of the fiber is obtained by calculating the kurtosis of the acoustic signal at each position of the fiber within a short time. After moving the average of the spatial dimensions, the spatial-average kurtosis (SAK) is obtained, and its peak value accurately locates the center of the vibration segment. A comparison of the SAK value with a certain threshold value can distinguish the effects of system noise and environmental disturbance on the instantaneous destructive disturbance, to some extent. Experimental results show that, compared with the average results obtained using previous localization methods, the pencil-break rate and SNR of the SAK localization method are superior by 16.6 and 17.3 dB, respectively, and have a positioning standard deviation that is better by 7.3 and 9.1 m, respectively. For the instantaneous detection of destructive disturbances (pencil break and digging), the false alarm rate can be as low as 1.02% while the detection probability can be maintained at 95.57%. Figure 7 presents a block diagram of the DAS system.

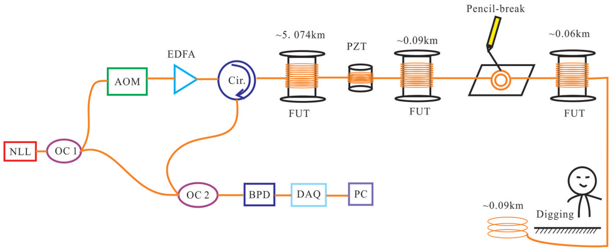

Fig. 7 Block diagram of the DAS system.

3.5 Borehole seismic exploration

DAS has developed rapidly in recent years to become a mature optical fiber technology, and is widely used in geophysics and well monitoring. Fiber-optic cables can be installed in any type of borehole. In the past, borehole intervention using conventional downhole detectors has been cumbersome and costly, making in-hole geophysical monitoring expensive and often infeasible. In recent years, the permanent installation of a low-cost downhole optical cable has become an ideal choice for noninvasive geophysical monitoring. There is no need for borehole intervention once the cable is installed.

DAS is increasingly being regarded as a feasible alternative to geophone arrays in the acquisition of borehole seismic data. DAS obtains in-hole seismic data without affecting the normal production, benefiting the operator. In 2018, Sun Qizhen et al. [34] of Huazhong University of Science and Technology, PR China, proposed a new distributed optical-fiber acoustic sensor with ultra-high sensitivity. The design and manufacture of a distributed microstructure optical fiber with a continuous longitudinal microstructure can improve the SNR of the backscattered light, while the technology of the coherent optical time-domain reflectometer can greatly improve the sensing performance of the acoustic signal. Experiments conducted on the surface and in boreholes of an oilfield in southern China showed that the scheme could achieve an ultra-high strain resolution of 0.16 nε along a 500-meter-long sensing fiber cable within a wide frequency range of 0.1 Hz to 45 kHz. Figure 8 presents a block diagram of the DAS system.

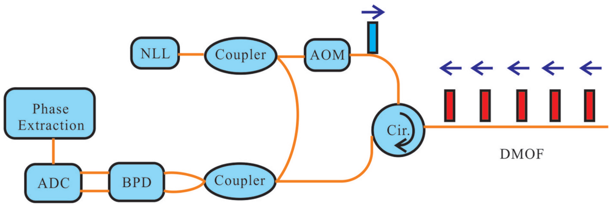

Fig. 8 Block diagram of the DAS system forborehole seismic exploration.

3.6 Protecting fiber links from third-party intrusion

A failure in a network system is a common scenario that must have minimal impact on the user. Today, link failures due to construction, weather events, and power outages are more likely to occur than internal equipment failures, and these problems often lead to more serious consequences, including severe service losses and extensive economic loss. OTDR is usually used to determine the exact locations of network cutting faults. However, this strategy does not prevent massive data loss or massive traffic blocking, especially in optical networks with a throughput of gigabits of terabits per second. Extensive research has been carried out to develop a survivable network and thus solve these problems [35]. One important function of survivable networks is to detect potential threats early and thus proactively route data traffic to links that do not have threats. In addition, the early detection of threats in optical networks may minimize the need for recovery methods, thereby extending the service life of deployed infrastructure [36] and increasing the efficiency of the infrastructure.

One main reason for the failure of optical communication links is an unintentional third-party invasion (usually related to civil/agricultural engineering) breaking fibers or damaging cables [37]. Distributed acoustic sensors can detect threats before the fiber optic infrastructure is threatened, and actively reroute traffic to links that are not threatened.

3.7 Measurement of the vertical seismic profile (VSP)

DAS is one of the most valuable techniques in the field of resource exploration. With the continuous advancement of science and technology in recent years, DAS has been used to obtain data of the VSP. Compared with the use of the conventional geophone, DAS has higher sensitivity, a deeper acquisition depth, better temperature and pressure resistance, a shorter well time, large-scale and long-term deployment, a higher downhole safety coefficient, better electromagnetic compatibility, and lower cost. DAS will gradually replace the use of the conventional geophone on the basis of economics, efficiency, and safety. DAS is compared with the use of a traditional geophone in Table 1. DAS data are increasingly used for seismic imaging rather than for estimating rock properties. Anton Egorov et al. [38] proposed a workflow for estimating the subsurface elastic properties through the full-waveform inversion of DAS VSP data. This method can be used to build an underground datum model.

Ran Zhou et al. [39] used DAS technology to provide whole-well seismic sensor coverage for in-well seismic applications. Using a DAS channel in a horizontal well, local horizontal slowness can be calculated directly from the VSP measurement. The slowness vector provides a measurement with which to detect and determine the local anisotropy around the well, when combined with the vertical slowness computed for a vertical well. Ran Zhou et al. proposed a model-based research method and discussed the feasibility of using the DAS asymptotic VSP to determine the local anisotropy parameters of vertical transverse anisotropic media. Results show that there are challenges in local slowness extraction and anisotropy estimation. The slowness vector can be obtained by combining horizontal wells with vertical wells (or vertical and horizontal parts of horizontal wells). The accuracy of the anisotropy estimates depends on the availability of the vertical DAS cable and the heterogeneity of the media around the well.

Figure 9 shows a photograph of a Silixa DAS unit. The unit has a fine sampling resolution of 25 cm, sampling frequency of 1 - 100 kHz, fine spatial resolution of 1 m, frequency range of 0.01 Hz - 50 kHz, dynamic range exceeding 120 dB, and a measuring range reaching 40 km.

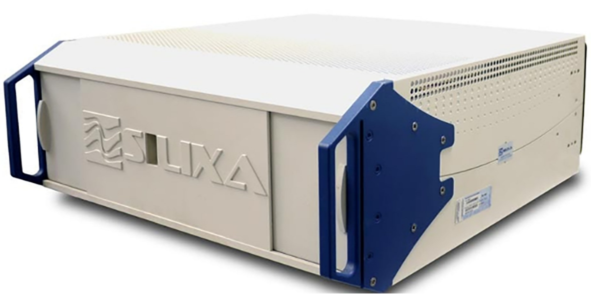

Fig. 9 Photograph of a DAS unit.

The intelligent DAS records the acoustic field at every 1 meter along the optical fiber in the well. This means that we can measure the amplitude, frequency, and phase of the incident energy including that associated with seismic surveying. Using single-mode fiber, He Xiangge obtained a response frequency band from 20 Hz to 20 kHz in a 400 m long sensing section [40] while a strain resolution of 80 nε with a 3 × 3 phase demodulation scheme has been demonstrated [41]. However, owing to the low signal-to-noise ratio of Rayleigh backscattered light in single-mode fiber, further improvement in the low-frequency range is hard to achieve. To enhance the signal-to-noise ratio of the sensing signal light, an FC/PC connector and ultra-weak fiber Bragg gratings are used in the sensing fiber[42]. The acoustic signal at 5 Hz has been demodulated[43] but DAS sensing under 1 Hz has not yet been reported. The sensing performance in the ultra-low frequency band has not been fully evaluated owing to the existence of low-frequency random optical noise.

Yu Gang et al. [44] acquired borehole seismic data using wireline conveyed fibers in an onshore well in China. They acquired a rich set of high-quality Walkaway VSP data over a previously producing well in northeastern China. A standard VSP data pre-processing workflow was applied, followed by prestack Kirchhoff time migration. Results were compared with a 327-level offset VSP data set acquired earlier with conventional 3C downhole geophones in the same well. The final pre-processed DAS walkaway VSP has a larger vertical aperture, resulting in a wider lateral image. The single-well DAS Walkaway VSP images provide a good result with higher vertical and lateral resolution than the surface seismicity in the objective area. The surface seismic image Walkaway VSP line with coarser shot density and its VSP image are inserted into the surface seismic section, as shown in Fig. 10. The Walkaway VSP images not only match well with the surface seismic image, but also show higher vertical resolution and more detailed structures.

3.8 Other applications

There are many other applications of DAS technology. DAS technology can, for example, be applied to online railway monitoring. A track circuit may fail in extreme weather events, such as strong

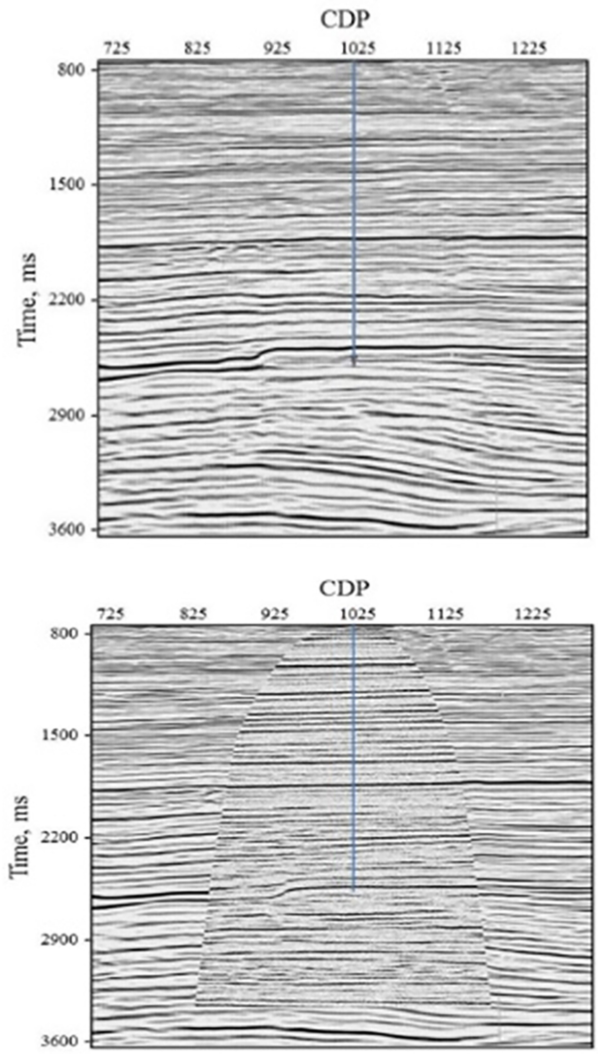

Fig. 10 Surface seismic profile (up) and DAS Walkaway VSP image inserted into the surface seismic profile (down) along the Walkaway VSP survey line with coarser VSP shots.

lightning events. This may cause a train to malfunction, but the DAS system can still work normally. The train can thus be positioned in real time and we get the speed of the train over time. DAS technology can also be used for building safety detection, where fiber in a building is arranged such that a person moving through the building can be located. DAS technology can be used for the identification of leakage signals of water supply pipelines, allowing such signals to be accurately and efficiently distinguished from other signals [45]. The technology can also be used in the ocean, for deep-sea seismic detection and

Table 1 Comparison of DAS and geophone results.

Contrast Content	Geophone	DAS
Sampling depth	<5000m	10000m
Series/level spacing	12-100 level/10-20m	1000-40000level/1-5m
Operating temperature range	<125°	>250°
Number of guns	depends on the level	dramatically reduced
Well time	depends on the level and the depth of the well	dramatically shortened
Electromagnetic compatibility	general	good
Cost performance	general	good
Sensitivity	general	good
Wavelength directivity	three-component vector wave field	single component vector wave field

the collection of seabed seismic information, allowing high-precision measurement and imaging.

4 Conclusion

This paper explored the recent application of DAS, and summarized recent research achievements of DAS in resource exploration, intrusion monitoring, pattern recognition, and other fields and various DAS system structures. Seismic exploration is gradually developing towards higher density and more channels in the field of petroleum resource exploration. The development of a million-channel land seismic acquisition system and the acquisition of large-channel seismic data are the main development directions and major targets of future seismic acquisition. The DAS system is expected to play an important future role in this field. In terms of pattern recognition, there remains great potential in combining the DAS system with advanced artificial intelligence; such as target monitoring and recognition combined with machine learning. The classification and analysis of the application of DAS in various fields reveals that a DAS system has the advantages of high sensitivity, a wide detection range, strong anti-interference, and low cost. DAS is the most promising technology among all known acoustic sensing technologies. Although the present study revealed great improvements of the detection ability of a DAS system, there remain many problems, such as the relatively low signal-to-noise ratio and coherent fading, to be solved before the system can be applied practically. The in-depth study of DAS will gradually reduce the cost, continuously improve the performance, and increasingly widen the application scope of DAS systems. It is believed that DAS systems will play an increasingly important role in the modernization of the relevant industrial sector.

Acronyms of the Block Diagrams

FUT: Fiber Under Test
DFB-LD: Distributed-Feedback Laser Diode
AOM: Acoustic-Optical Modulator
OFA: Optical Fiber Amplifier
PG: Pulse Generator
FRM: Faraday Rotator Mirror
PZT: Piezoelectric Ceramics
PD: Photoelectric Detector
EDFA: Erbium-Doped Fiber Amplifier
PM: Phase Modulator
PGC: Phase Generated Carrier
PC: Personal Computer
AFG: Analog Function Generator\
DAQ: Data Acquisition
CW: Continuous Wave
NLL: Narrow Line-Width Laser
OC: Optical Coupler
Cir.: Circulator
BPD: Balanced Photodetector
ADC: Analog-To-Digital Converter
DMOF: Distributed Micro-Structured Optical Fiber

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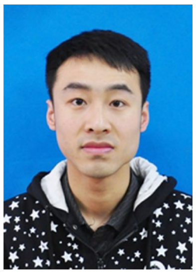

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