Distributed fiber-optic acoustic sensing for petroleum geology exploration

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Abstract—Using seismic geophones to get stratum information is a common method of petroleum geophysical exploration technology. Optical fibre distributed acoustic sensor (DAS) is one of the most advanced sound field detection technologies. It has most advantages of distributed continuous monitoring, such as deployment, high cost performance ratio, wide range measurement and so on. In this paper, a distributed acoustic sensing technology using interferometric demodulation is researched. Basic principal of the DAS, demodulation algorithm, and parameter test are introduced in detail. Ground geophysical prospecting test for petroleum is designed and carried out and a very clearly seismic section image is drawn out. DAS system performance and test data are discussed in detail. The research provides a new approach to petroleum geophysical prospecting using optical fiber sensor technology. Convenient, big coverage and large data make it potentially better suited for geophysical prospecting applications.

1. Introduction

Acoustic wave detection technology is a sensing technique that focuses on the detection and monitoring of acoustic signals propagating within an object or structure. Acoustic detection based on optical fibre sensing technology has very conspicuous technical advantages, such as wide frequency bandwidth, high sensitivity, high temperature resisting, no electromagnetic interference. It has now been used for natural gas, oil exploration and development, bridges, large buildings and other civil engineering health monitoring, as well as military, national defence and so on. It has significant economic value and social significance.

One of the most advanced optical fibre field reduction technology that based on OTDR principle is fibre distributed acoustic sensing (DAS). It is a novel technology that uses an optical fibre cable as a sensor for acoustic signals and can simultaneously detect the acoustic information of almost any point along the fibre cable by detecting the change of Rayleigh backscattering in the fibre.

φ-OTDR has gradually become an active research area since φ-OTDR with narrow injecting linewidth than that of conventional OTDR was proposed by H.F.Taylor in 1993[1]. Then Juan J. C. Juarez[2], Rao Yunjiang[3,4], Xiaoyi Bao[5,6], Qinzheng Sun[7], A. Masoudi[8], H. F. Martins[9], Chen Wang[10] and L. Zhou[11] improved the performance of φ-OTDR in extending monitoring distances, improving spatial resolution and expanding frequency response range and so on.

For the application, the major companies include QinetiQ, OptaSense and Silixa, Qorex and Ziebel in Norway, are all interested in researching and developing DAS market-system. They have worked with oil and logging companies such as Shell and Weatherford to develop equipment for the oil...
detection. and they have got many publish research results over the past two years. For example, Shell have finished a three-component vertical seismic profile (VSP) detect in Schoonebek of Netherlands using fibre DAS technology at the end of 2012. Complete P-wave, S-wave reflection signals were got. Weatherford uses fibre DAS technology to measure oil and gas moisture content. Institute of Laser Research, Shandong Academy of Sciences \cite{10}, had completed two earthquakes experiment in Shengli Oilfield Yingkou Dongfeng Port oil recovery area in 2013 and 2015, and made a series of seismic cross-section results.

2. Principle

Sound waves can be considered as pressure waves. The refractive index or other parameters of the optical fibre that exposed in the sound field will be affected by the sound pressure.

![Fig. 1. Principle diagram of DAS System.](image)

The diagram of the optical fibre distributed acoustic sensor system is shown in figure 1. A distributed feedback laser diode (DFBLD) is used as pump laser to generate a 1.5 um continuous laser. Acoustic-optical modulator (AOM) makes continuous laser in to pulse which width is about 10 ns. Two optical fibre amplifiers (OFA) are used to increase laser pulse’s power and reflected laser’s power. Considered spontaneous emission noise will be increased after OFA, filter is necessary to used. The pump laser pulse is increased into optic-fibre sensing cable from one port of circulator, and the reflected backward Rayleigh light is backed from another port. The reflected light is too weak to need amplified. Considered using EDFA to amplifier laser pulse will induce spontaneous emission noise, filters are needed to eliminate light noise. Backward Rayleigh light which carrying acoustic sensing information is separated a beam as reference light. While Others are injected into an interferometer. A Michelson interferometer is set up by a coupler and two Faraday rotation mirror (FRM).

Difference of the two arms is d. The reflected backward Rayleigh light $e_r(t)$ is processed by the Michelson Interferometer. The interference signal contains phase information that induced by the acoustic waves, so as long as phase information can be demodulated. Therefore, the DAS system can quantitatively inverse the acoustic field such as the acoustic signal amplitude, phase and frequency.

When the interference intensity is demodulated via phase demodulation (As figure1, the typical $3\times3$ passive demodulation algorithm with $3\times3$ coupler\cite{10}). PD1, PD2, PD3 and the digital acquisition card are used to be photoelectric conversion and input it into computer. I1, I2, I3 are intensities of the three signals. As processing algorithm of I1, I2, I3, it can obtain the disturbance information of the phase at the certain position.
3. Field experiment and result

In order to verify the feasibility of the system in geophysical exploration, field experiment was conducted in an oil production field which located in Shengli Oilfield, Dongying, Shandong Province, China. The layout of the on-site experiment sensing system is shown in figure 4. The test site is located in a farmland. An about 2000 m long optical sensing cable is fixed on the surface of the field with metal vertebras. Interval of the vertebras is 2.5 m. Explosive sources are employed in oil seismic exploration to active reflect wave. When explosive sources are detonated in turn, the reflect wave signals are obtained from the sensing optical cable and DAS system.

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To adapt to geophysical engineering, the reflected wave is formatted in to SEG-D (The latest nine and a half inches tape record format recommended by the Society of Exploration Geophysicists (SEG) which is the international society of applied geophysicists). One of a frame of Data which include reservoir distribution is shown in figure 4. Horizontal axis is position of the cable (meters), and the vertical axis is time (milliseconds).
From the above data we can see, seismic reflection signals can be well captured through the fibre DAS system. Due to the large workload of on-site construction using traditional point sensors, conventional seismic experiments usually use 10 meters intervals or even farther to place sensor head to improve work efficiency. The entire image has a clear texture which represents the clear geological structure. As figure 5 shows, a seismic section image with single shot is drawing out. 1100 channels data with 0.8 m group interval makes the seismic section have a high resolution.

4. Conclusions
Seismometers are the primary technical problems that restrict the exploration of deep geological formations and exploitation of resources. Wide broadband and high sensitive distributed optical fibre geophone is a new technology with great potential for the acquisition of deep formation reflection sound waves and also the key equipment to further improve the level of oil and gas exploration and development. Optical fibre distributed acoustic sensor system that used in seismic geophysical is studied in this paper. It realizes distributed seismic detection technology. The experiment proves that it can obtain a complete and clear stratigraphic section, which is the oil and gas resources exploration and development of the necessary technical means.

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