Distributed Fiber- Optic Sensing for Hydraulic-Fracturing Monitoring and Diagnostics

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Abstract. Fiber-optic sensing (FOS) are an emerging technology in hydraulic fracture diagnosis. Fiber-optic sensing technologies mainly include distributed temperature sensing (DTS) and distributed sound sensing (DAS). During hydraulic fracturing, the perforation cluster efficiency for cemented plug and perforation (PnP) wells, points of fracture initiation for packer and sleeve (PnS), and fluid channelling between fractured intervals caused by either tubular or annular leaks could be quantitatively evaluated by DTS data. Combined with DAS data, fluid distributions for each fracturing stage along the entire horizontal wellbore could be obtained. The roles of DTS and DAS in different hydraulic fracture stages are comprehensively analyzed in this paper. It provides a guidance for application of FOs in oil industry.

1 Introduction

Fiber-optic sensing technology has long been used in single-well hydraulic fracturing analysis, and its focus has been on the advantages of distributed temperature sensing (DTS) and distributed sound sensing (DAS) technologies and how these technologies have evolved from qualitative interpretation to quantitative interpretation. Recently, the industry has carried out a more in-depth study and application [1].This paper will review the application of fiber optic sensing technology during and after fracturing. This type of sensing technology is the most widely used in hydraulic fracturing operations. In the past 10 years, with the improvement of cable reliability, the feasibility of long-term sensing of transient production logging has been ensured [2].

This paper argues that the fiber optic sensing technology used in hydraulic fracturing is limited to monitor the near wellbore zone. However, integrated the fiber optic sensing data with far field monitoring results, the characterization of fracturing fluid into formation far away from the wellbore and fracture parameters (such as fracture length and orientation) can be determined more accurately. Combining fiber optic sensing results with micro-seismic, micro-deformation and inter-well pressure parameters, they can not only help to understand how fluid flows from the wellbore to the reservoir, but also understand the influence of fracture initiation location on the geometry of far-field fractures. The use of integrated sensing diagnostic models, such as combined near-well data monitored by fiber optic sensing with far-field monitoring data, can provide additional constraints for fracture and reservoir modelling.

2 Multi-parameter sensing mechanism of distributed fiber

The light source signal transmitted by the optical fiber generally adopts a laser with high directivity and high coherence, and the sensing information collected by the sensing process is mainly the change state of light wave. After the light emitted by the laser, it is driven into the fiber connected thereto, the refractive index of the fiber at different positions varies depending on the complexity of the transmission core material and the fluctuation of the internal density.

2.1 Sensing mechanism of optical signals in optical fibers

The sensing process of the sensing technology optical signal is microscopically, the laser particle and the fiber molecule collide with each other to generate momentum change and energy transfer, and the external manifestation is the change of the corresponding laser characteristic parameter. From the aspect of light wave characteristics, if there is energy migration or loss in the interaction between photon and fiber particles, several scattered light waves with different characteristic parameters of light wave will be formed [3]. Depending on the difference in the wavelength of the scattered light, these light waves can be roughly classified into three categories: Raman, Brillouin, and Rayleigh (Figure1) [4].

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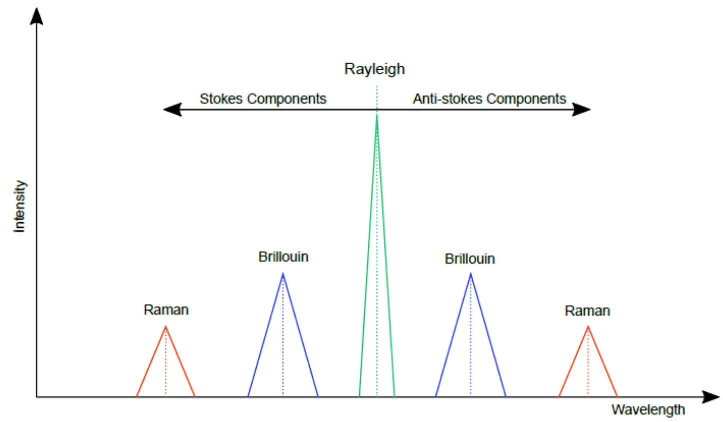

Figure.1. Schematic displaying Rayleigh, Raman, and Brillouin peaks in the electromagnetic spectrum.

Rayleigh scattering is an elastic process due to the random non-uniformity of the refractive index of the fiber core. Since no energy is transmitted in the glass, the Rayleigh scattering has the same frequency as the incident light pulse. Rayleigh backscattered light has a time delay for spatial distribution sensing along the length of the fiber (Figure 2). In general, Rayleigh scattering provides a constant temperature and strain reference attenuation profile that is useful when sensing these parameters along the fiber using Raman scattering or Brillouin scattering [5–7].

Figure.2. Schematic of a spontaneous Rayleigh backscattering process through the core of an optical fiber cable.

2.2 Multi-parameter sensing system based on Brillouin scattering

The distributed optical fiber sensing system uses the optical signal to transmit continuous optical light in a linear relationship with temperature, strain and other parameters [8]. The demodulation device demodulates and analyzes the received optical signal. The conversion calculation of high-performance computers directly reflects the temperature and strain around the fiber on the monitoring host, thus realizing distributed measurement and abnormal positioning along the line.

In the standard optical time domain reflectometry (OTDR), a broadband incoherent light source is used to detect anomalies along the length of the fiber. However, the phase information of the return light is not available in the standard OTDR. In general, FOS technology for distributed parameter detection spans from interferometry-based systems to Rayleigh and/or Brillouin scattering-based phase-OTDR and polarization-OTDR systems, using either coherent or direct detection methods [9-11].

3 Fiber-optic Diagnostic Technologies

Distributed fiber-optic sensing is a technology that offers the possibility to overcome most of these significant challenges. Distributed fiber sensing relies on an uphole electronic device attached to a passive fiber-optic telecommunications cable placed downhole, usually attached directly to the outside of the casing. With fiber-optic sensing, the optical fiber itself is the sensor, allowing for simultaneous measurements at up to tens of thousands of locations with a spatial resolution typically as small as one meter. Several distributed sensing technologies for use in oil field applications are already commercially available. However, downhole fiber sensing is not widely implemented because of installation costs along with some uncertainties in interpreting sensor results [12].

3.1 Hydraulic fracturing monitoring

3.1.1 DTS Fiber-optic Monitoring

Fiber-based DTS data acquisition and analysis technology is quite mature in oil and gas upstream industry applications. At the same time, it is also used in the fields of injection profile, production profile and leak detection. In the past few years, fracturing engineers have achieved the perforation cluster efficiency of PnP wells and PnS wells through the developed thermal hydraulic injection profile model. Quantitative evaluation of fluid channelling between fractured sections caused by either tubular or annular leaks can be realized. The information collected is mainly from the DTS temperature profile after completing fracturing operation. Based on the temperature data, the quantitative distribution of fracturing fluid in the PnP wells along the wellbore, the actual number of fracture per unit foot in the fracturing section of the PnS well, and the turbulent flow ratio between the fracturing sections caused by the column or annulus leakage can be grasped. It can be seen from Fig.3 that there is no fractures initiation at the perforation cluster 2, and the temperature monitored by the optical fiber during the injection process is continuously lowered. Once the injection is stopped, the temperature begins to rise. Therefore, the perforation cluster efficiency can be obtained by comparing the temperature variation curves of the injection phase and the temperature recovery phase [13,14].

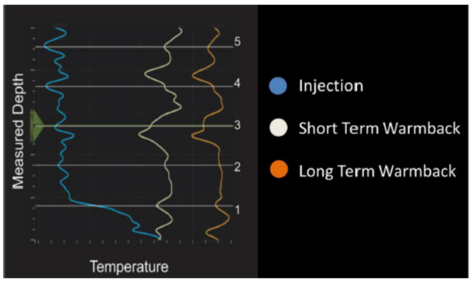

Fig.3. Temperature data and temperature return curve of inverse mapping hole cluster efficiency when PnP is completed.

3.1.2 DAS Fiber-optic Monitoring

The DAS can be used as a noise log to monitor fluid injection points and production intervals. In addition, it can be used to monitor the ball seat, the position of the perforating gun and the ignition, the bridge plug and the seal between the bridge plug or packer. Combined with the combination of DAS and DTS analysis, the accuracy of the fracturing monitoring results can be improved, which contributes to well completion optimization and better completion results[15,16].

Although the quantitative analysis of DAS fluid profile is more and more widely used in the fracturing injection process, there is still a lot of work to be done to improve the credibility of its quantitative results. After obtaining the DAS sound wave result, the cumulative DAS flow can be calculated by using the perforation cluster acoustic wave response data of a given fracturing section, and the total flow rate and the corresponding flow rate of each perforation cluster with time can be identified. The DAS results are combined with the DTS modelling results to obtain the fluid distribution of each fracturing section in the entire horizontal section. Figure 4 shows the DAS monitoring results for this example. The black dashed line in the figure represents the perforation cluster in the current fracturing section. It can be seen from the figure that the acoustic wave activity at the perforation clusters in the bridge plug and the front fracturing section is relatively strong.

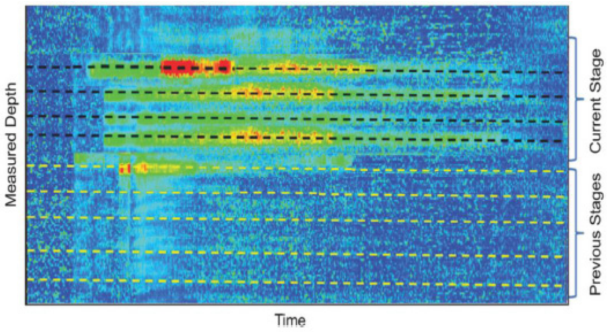

Fig.4. Fluid leakage during the injecting phase monitored by DAS.

Fiber monitoring can also be used to determine the interaction of wells in the same well site. Communication between multiple wells can also be determined through DAS data. This interaction generally results from the presence of fracturing operations, faults or other geological formations in adjacent wells. In addition, multi-well connectivity in the same well site can also be determined by DAS data. When a well in two connected wells is fracturing, the corresponding sound wave response signal will appear in the other well.

3.2 Post-fracturing production monitoring

For reservoir engineers, understanding the location of oil and gas production throughout the production interval is critical, and this information is often obtained through production logging, which is not only expensive but also less credible. Therefore, it is of great significance to use a permanent installation method to determine which areas contribute to production. DAS offers the possibility for this idea. To use DAS for production analysis, we need to understand the acoustic response characteristics of different flow regimes. For example, the generation of gas usually occurs in the high frequency range, and the frequency of the oil flow is lower than the frequency at which the water is produced. This interpretation becomes complicated when two or more fluids flow simultaneously. Engineers have developed a noise distribution library that can be associated with each flow state. By referring to this noise distribution library, engineers can accurately predict the flow contribution rate and flow regime of fluid passing through the perforation. Since the gas has a very pronounced sound response characteristic, the flow analysis of the gas is the simplest. When gas and liquid flow together, the DAS can be used as multiphase flow meter, but it is still in the developing stage [17]. Figure 5 shows the DAS reading of gas wells. It is clear there is one primary productive zone in the well, zone 7. The noise around zones 9 and 8 is actually gas flowing over water in slump in the well.

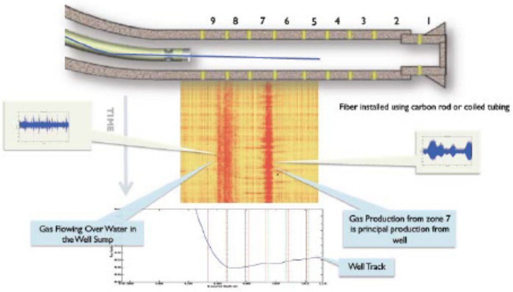

Fig.5. Flow profile in a gas well

4 Conclusions

The optical fiber sensing technology in hydraulic fracturing is limited to monitor near wellbore zone. However, integrated optical fiber monitoring data with far field monitoring results, a more accurate characterization of fracturing fluid into formation in far away from the wellbore and fracture parameters can be obtained. Combining optical fiber monitoring results with micro-seismic, micro-deformation and inter-well pressure parameters can not only help to understand how fluid flows from the wellbore to the reservoir, but also understand the influence of fracture initiation location on the geometry of far-field fractures.

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