Fiber Optical Sensors for Upstream Hydrocarbon Industry

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Summary

The Distributed Temperature Sensing (DTS) technique using an optical fiber sensor is a relatively new method in temperature logging.The key technique is optical time domain reflectometry (OTDR). A laser pulse is launched into an optical fiber. As the pulse passes through the fiber, energy is lost owing to scattering. The intensity of the backscattered light decays exponentially with time, given uniform losses within the fiber. Therefore, knowing the speed of the light in the fiber, it is possible to convert this intensity against distance. Among the scattered light components, Raman scattering due to molecular vibrations is temperature sensitive. Raman back-scattering is used for distributed temperature sensing (DTS), while Brillouin waves are used for distributed temperature and strain sensing (DTSS). General wireline logging practice, this method is referred to as the “wireline DTS installation. Nevertheless, in contrast to conventional wireline logging, where the logging tool(sonde)is moved along the section of the borehole to be scanned, the DTS cable remains in place during the measurement of the temperature profiles. For long-term monitoring or in cases when full access to the interior of the borehole is needed, the sensor cables are installed behind the borehole casing Because it is not necessary to move point sensor during measurement, the DTS technique enables us to make simultaneous monitoring of the temperature profile of the well at a time interval of a few to several minutes. This feature of the DTS temperature logging system is suitable for detecting temporal change of the temperature profile of a geothermal well such as during injection and production tests. Optical-fibre sensors have become an indispensable tool in the oil and gas industry, helping engineers to not only locate wells, but also get the most out of them. Rayleigh scattering based distributed acoustic sensing (DAS) systems use fiber optic cables to provide distributed strain sensing. A fibre-optic ocean-bottom seismic system. Thousands of sensors are trenched in the seafloor and connected back to topside facilities for monitoring.A fibre-optic four-component seismic station. Three identical accelerometers are placed orthogonal to each other inside a sensor package together with a hydrophone. The sensor package is spliced into the cable, and several thousands of these stations are connected in a full-scale OBC system.Distributed optical fiber temperature sensors adopting optical fiber scattering theory can overcome the shortcomings of traditional point electronic sensors that cannot work inenvironments of high temperature, high pressure, corrosion, strong geomagnetic disturbances etc.It is not sensitive to electromagnetic interference and is able to withstand extreme conditions,including high temperature, high pressure and strong shock and vibration environment. However, monitoring temperature data obtained by the distributed optical fiber temperature sensing monitoring system is inevitably adulterated with noise, thus affecting the accuracy of monitoring data.DTS, the signal is so weak that the signal is very difficult to be detected. The noise level in the acquired signal is very high, and the temperature error is not little. A wavelet transform modulus maxima de-noising method is employed to decrease the temperature error by denoising DTS signal.Distributed acoustic sensing:Rayleigh scattering based distributed acoustic sensing (DAS) systems use fiber optic cables to provide distributed strain sensing. In DAS, the optical fiber cable becomes the sensing element and measurements are made, and in part processed, using an attached optoelectronics device. Such a system allows acoustic frequency strain signals to be detected over large distances and in harsh environments. Hilbert transform is employed to enhance precision in Brillouin scattering distributed temperature sensor.

Introduction

In Rayleigh scatter based distributed fiber optic sensing, a coherent LASER pulse is sent along an optic fiber, and scattering sites within the fiber cause the fiber to act as a distributed intetferometer with a gauge length approximately equal to the pulse length. The intensity of the reflected light is measured as a function of time after transmission of the laser pulse. When the pulse has had time to travel the full length of the fiber and back, the next laser pulse can be sent along the fiber. Changes in the reflected intensity of successive pulses from the same region of fiber are caused by changes in the optical path length of that section of fiber. This type of system is very sensitive to both strain and temperature variations of the fiber and measurements can be made simultaneously at all sections of the fiber. The sensitivity and speed of Rayleigh-based sensing allows distributed acoustic monitoring over distances of up to 50 km from each laser source. With suitable analysis software, continuous monitoring of pipelines for unwanted interference, as well as leaks or flow irregularities is possible. Roads, borders, perimeters etc. can be monitored for unusual activity with the position of the activity being determined to within approximately 10 metres. Due to the ability of the optic fiber to operate in harsh environments, the technology can also be used in oil well monitoring applications, allowing real-time information on the state of the well to be determined.Recently, Applications of DTS & DTSS Techniques: Locations of fractures can be detected clearly by the temporal change of the temperature. Fractures are more clearly detected during injection than recovery.. The DTS logging can show the fracture locations more clearly andeasily than conventional temperature logging systems. The water level can be traced by the DTS logging. The pressure profile of a borehole can be calculated from the water leveland the temperature profile data.Comparison between the calculated pressure value from temperature profile and the measured pressure value suggests that it may be possible to evaluate the amount or rate of inflow into the borehole from the reservoir.. To ensure this comparison is valid, precise calibration of the single-ended fiber sensor is required.The DTS technique has an advantage over a conventional point probing logging system in that it enables us to make simultaneous monitoring of the temperature profile of thewell at a time interval of a few to several minutes. This feature is suitable for detecting temporal changes in the temperature profile of a geothermal well such as during temperature recovering after drilling, injection tests and production tests. Distributed temperature sensing (DTS) is a valuable tool used to understand the dynamics of oil and gas production and injection rates.

Theory and/or Method

Among the scattered light components, Raman scattering due to molecular vibrations is temperature sensitive. Raman scattering signal is split into two "bands" displaced approximately symmetrically about the incident wavelength: the Stokes band and the Anti-Stokes band . The intensity of the Stokes band is only little temperature sensitive, whereas the intensity of Anti-Stokes band is strongly temperature dependent.Raman back-scattering is used for distributed temperature sensing (DTS), while Brillouin waves are used for distributed temperature and strain sensing (DTSS).

$$\frac{I_a}{I_s} = \frac{\left(\bar{\gamma}_0 + \bar{\gamma}_k\right)^4}{\left(\bar{\gamma}_0 - \bar{\gamma}_k\right)^4} \exp\left(\frac{-hc\,\bar{\gamma}_k}{KT}\right)$$

where

$I_a \Rightarrow$ intensity of the Anti -Stokes band

$I_s \Rightarrow$ intensity of the Stokes band

$\overline{\gamma_0} \Rightarrow$ wave number of the incident light

$\overline{\gamma_k} \Rightarrow$ shift amount of the wave number

$T \Rightarrow$ temperature (K)

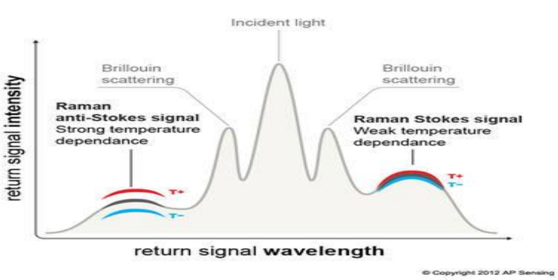
$K \Rightarrow$ Boltzman' s constant

$h \Rightarrow$ Plank' s constant

$c \Rightarrow$ light velocity

Using OTDR technique and temperature dependency of the Raman backscattering light, it is possible to measure the temperature along the entire length of the optical fiber. In actual measurement, signals must be stacked (or averaged) for several tens of seconds to several minutes because the intensity of the Raman scattering is very weak. In the case of temperature sensing, the phenomenon of Raman scattering (where light is scattered through an interaction with molecular vibrations within the glass) provides a convenient, temperature-dependent signal. The early workers in the field used the well-known temperature dependence of the ratio between the powers in the upper and lower sidebands of the Raman signal as the sensing mechanism. Later on, the instrumentation was simplified by using only the anti-Stokes (high-frequency) signal, as this is the more sensitive of the two sidebands Fibre-optic distributed temperature monitoring offers special advantages for remote measurements in hazardous environment or in a situation where there is a large amount of electromagnetic noise and possibility of data corruption. It also offers particular advantage in places where there is risk of sparking due to atmospheric volatility, such as oil refineries. Distributed anti-Stokes Raman thermometry (DART) is becoming a major technology for measurement of temperature along optical fibres. The distributed temperature sensing (DTS) method, based on optical time domain reflectometry (OTDR) using Raman effect, represents a powerful breakthrough in temperature measurements by providing fast, accurate and highresolution information. In the DTS technique, a pulse laser is coupled to an optical fibre through a directional coupler. The light is backscattered through the fibre due to changes in density and composition as well as due to molecular and bulk vibrations. The backscattered light consists of a Rayleigh component, a Brillouin component and a Raman component. Thermally influenced molecular vibrations cause the Raman backscattered component to change and therefore it is sensitive to temperature. The anti-Stokes component is strongly dependent upon temperature, while the Stokes component is weakly dependent on temperature. Therefore, the ratio of anti-Stokes to Stokes signal provides an absolute value of temperature irrespective of laser power, launch conditions and fibre geometry. Combining the temperature measurement technique of Raman backscatter with distance measurement through time-offlight of light, DTS provides temperature measurements along the length of the fibre. It may be noted that all intensity signals are recorded at a fixed wavelength (Raman anti-Stokes) in OTDR mode and peaks represent increase in backscattered light of anti- Stokes component due to temperature changes.

Raman Optical Time Domain Reflectometry (**OTDR**) technology- An optical laser pulse propagating through the fiber gets partially scattered back to the transmitting end, where it is analyzed. The backscattered light consists of different spectral components:Rayleigh Backscattering; Brillouin Backscattering; Raman Backscattering.The **Raman backscattering** intensity depends on temperature and can be used as a measure for the temperature along the fiber. The Raman backscattered light has two components above and below the incident light: the Raman **Stokes** and Raman **Anti-Stokes** peak.The backscattered light is spread across a range of wavelengths. Some of these wavelengths are affected by temperature changes while others are less affected. Using a very accurate detector the difference in the signal strength is measured and the temperature is derived from these measurement results.



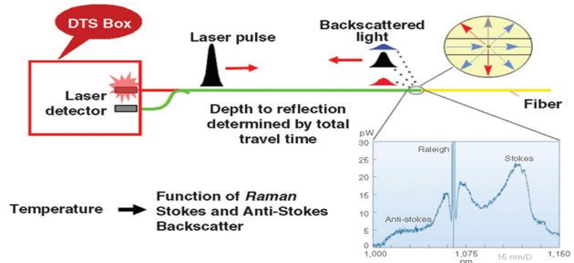


Fig1(left): Distributed Temperature Sensing (DTS) principle (Courtesy http://www.apsensing.com)

Fig2(right): Fiber Optics-Based Distributed Temperature Sensing System

The Raman signal is comprised of the so-called “Stokes” and “anti-Stokes” bands. The Stokes band at the higher wavelengths (red shifted) is stable with little temperature sensitivity. The anti-Stokes band at the lower wavelengths (blue shifted) exhibits a temperature sensitivity, where the higher the energy within the band, the higher the temperature and vice versa. A ratio of the energy or area within the Anti-

Stokes band to that of the Stokes band can be simply related to the temperature of the fiber optic line at the depth where the signal originated.

Wavelet Analysis: Wavelet analysis and mathematical microscope are excellent techniques to check health & wealth of petroleum reservoir. WT analysis is their property of being localized in time (space) as well as scale (frequency). This provides a timescale map of a signal, enabling the extraction of features that vary in time. This makes wavelets an ideal tool for analyzing signals of a transient or non-stationary nature. Complex Wavelet Transform is used to rectify and pacify limitations; shift sensitivity, poor directionality, and absence of phase information. Based on wavelet transform multi-resolution analysis, spectrum is determined. Using relationship between wavelet transform modulus maxima and singular point, it can determine location of signal singular point and singular exponent of singular signal. The signal singular point location can be analyzed, the local singularity is prescribed by Lipschitz index. Wavelet analysis is an effective tool for detecting signal singularity. In each singularity point *t*, the coefficient of wavelet transform *Wx*(*s*, *t*) is expressed as: *Wx*(*s*, *t*) ≤ *A*sv, where *s* is the transform scale, *v* the Lipschitz index, and *A* is a constant. Wavelet coefficient is closely related to the local singularity of a signal. Wavelet transform can analyze the signal elements at certain frequency band and time section, which has good time frequency localization and can seize character of instantaneous changing signals accurately and focus any details of signal for frequency through gradually meticulous sampling step of time field and frequency field.

The function $f(t)\epsilon L^2(R)$) is square integrated function; Ψ (t) is basic wavelet or mother wavelet. Series of wavelet functions $\Psi_{ab}(t) = \frac{1}{\sqrt{|a|}}\Psi(\frac{t-b}{a})\,dt$ are called wavelet function family. Wavelet transformation of *f* (*t*) is

$$Wf(a,b) = \frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty} f(t)\,\overline{\Psi\left(\frac{t-b}{a}\right)}\,dt$$

In the Ψ_{ab}(t) the parameter "*a"* governs frequency of the wavelet; parameter "*b"* gives its position. In actual signal processing, discrete wavelet transform and multi resolution analysis are often used. Hilbert transform,Laplace Transform,DFT Discrete Fourier Transform,,Hadamard Transform,Wavelet Transform ,etc. are employed for analysis of sensors signals.

Conclusions

Optical-fibre sensors have become an indispensable tool in the oil and gas industry, helping engineers to not only locate wells, but also get the most out of them. Rayleigh scattering based distributed acoustic sensing (DAS) systems use fiber optic cables to provide distributed strain sensing**.** Plasma Pulse Technology (PPT) is an environmentally friendly technology that allows producers to obtain sustained higher productivity from their oil wells. A fibre-optic ocean-bottom seismic system. Thousands of sensors are trenched in the seafloor and connected back to topside facilities for monitoring.A fibre-optic four-component seismic station. Three identical accelerometers are placed orthogonal to each other inside a sensor package together with a hydrophone. The sensor package is spliced into the cable, and several thousands of these stations are connected in a full-scale OBC system.Analysis of the geothermal conditions and the derivation of the stability field for methane hydrate are often based on the interpolation of single, thermally disturbed bottom-hole temperature measurements and drill-stem test data from petroleum exploration wells and about the thermal properties of the formation regarding formation evaluation . Nanosensor (fibre optics) can be made fashionable by using DTS ,Spatial and temporal variation of temperature during a Gas Hydrate production. Knowledge about the thermal properties of hydrate bearing rocks (i.e. thermal conductivity, specific heat, and latent heat of phasetransition) is therefore of crucial importance. Advantages of the deployment of fibre-optic distributed temperature sensing proved to be successful for temperature monitoring in boreholes under a wide range of conditions. One of the main advantages of DTS technology is, that continuous temperature profiles can be registered with high spatial and temporal resolution. This favours theobservation of dynamic subsurface processes involving temperature changes.Real Time Fiber Optic Casing Imager

(RTCI) provides a 3- dimensional image of the casing or sand control screens as they are stressed during production by shifting formations such as salt or unconsolidated sandstones Although most fibre-optic sensors for the oil and gas industry have been made for in-well sensing, there is growing interest in fibre-optic monitoring systems for subsea and sea-bottom applications. These include ocean bottom seismic cable (OBC) systems, for example, where the large-scale multiplexing capability and passive nature of fibre-optic sensing systems can be fully exploited. An OBC system comprises thousands of seismic stations placed in trenches at the bottom of the ocean. Each station (commonly called a 4C station) includes four components: one fibre-optic hydrophone and three fibre-optic accelerometers for the measurement of pressure waves and vibrations. The sensors are installed on the seafloor in a regular pattern, and seismic signals are generated using an airgun in the water. Each sensor measures the direct pressure wave from this airgun as well as the reflection of this wave from the rock formation underneath the sensor. Differing physical properties of the formation affect the reflected signals. By appropriate signal processing and interpretation it is possible to predict the location of oil and gas reservoirs and, by repeating these surveys over time, it is possible to monitor dynamically the effect of oil production on the reservoir, so-called 4D monitoring. With thousands of sensors installed on the seafloor it is possible to cover a large area of the subsurface, providing the reservoir engineer with a global view of the reservoir. Hydrocarbons can be detected using *electronic* "noses" called *sniffers* & Electronic Acoustic Receiver/EAR.

Acknowledgements

My best salute to the galaxy of Nobel Laureates(Sir C V Raman)
http://www.unesco.org/new/en/brasilia/about-this-office/prizes-and-celebrations/2015-international-year-of-light/the International Year of Light and Light-based Technologies (IYL 2015)
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http://www.mit.edu/~demiller/ I am thank ful to Prof DOUGLAS E. MILLER

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