Integration of distributed strain and temperature sensors in composite coiled tubing

Daniele Inaudi and Branko Glisic
SMARTEC SA, Via Pobiette 11, CH-6928 Manno, Switzerland, www.smartec.ch

ABSTRACT

Composite coiled tubing is an emerging technology in the oil & gas sector that presents important advantages compared to the steel coiled tubing and conventional drilling. The composite tube has reduced weight, allowing extended reach and improved fatigue life. An additional advantage resides in the fact that the coiled tube wall can contain and protect additional functional elements, such as electrical conductors and fiber optics for sensing and data communication. Sensing systems based on Brillouin and Raman scattering can be used to verify the pipe operational parameters, prevent failure, optimize oil production from the well, provide strain distribution along the tubing and detect hot-spots in high-power cables. The integration of such sensing elements into composite tubing presents additional advantages and challenges. On one hand the embedded sensors are protected by the composite material and can be installed during production, avoiding external installation that could interfere with the tubing operations. In the other hand, the integration of optical fiber sensors into the composite structure requires the development of appropriate packaging and installation techniques that allow easy handling during production and avoid and damage to the sensor and the composite structure itself. This contribution presents the sensing cable designs for temperature and strain sensing in a composite coiled tubing as well as testing results form initial field demonstrations.

Keywords: Distributed Fiber Optic Sensors, Composites, Coiled Tubing, Brillouin Scattering

1. DISTRIBUTED FIBER OPTIC SENSING SYSTEMS

In the past few years, innovative distributed strain and temperature monitoring techniques using optical fibers have demonstrated to be an efficient way to measure these two parameters at thousands of locations along a single optical fiber cable [1]. These techniques use a concept similar to Optical Domain Reflectometry (OTDR) for the localization, whereas the strain and temperature information is extracted from the analysis of the scattered light through Raman or Brillouin scattering processes. Raman-based systems were first proposed for temperature sensing [2] and used in practical applications, while the Brillouin-based technique has been introduced in the early nineties [3, 4] and offers longer distance ranges [5, 6] while allowing the measurement of strain and temperatures.

Figure 1 schematically shows the spectrum of the scattered light in optical fibers assuming that a single wavelength \( \lambda_0 \) is launched in the fiber. Both scattering effects are associated to different moving non-homogeneities in the silica and have therefore completely different spectral characteristics.

Figure 1: Schematic representation of the scattered light spectrum from a single wavelength signal propagating in optical fibers. An increase of the fiber temperature has an effect on both Raman and Brillouin components.
The Raman scattered light is caused by thermally influenced molecular vibrations. Consequently the backscattered light carries the information on the local temperature where the scattering occurred. In fact the Raman backscattered light has two frequency shifted components: the Stokes and the Anti-Stokes components. The amplitude of the Anti-Stokes component is strongly temperature dependent whereas the amplitude of the Stokes component is not. Therefore Raman sensing technique requires some filtering to isolate the relevant frequency components and consists in recording the ratio between Anti-Stokes amplitude by the Stokes amplitude, which contains the temperature information. Since the magnitude of the spontaneous Raman backscattered light is quite low, high numerical aperture multimode fibers are used in order to maximize the guided intensity of the backscattered light. However, the relatively high attenuation characteristics of multimode fibers limit the distance range of Raman-based systems to approximately 10 km.

Brillouin scattering occurs as a result of an interaction between the propagating optical signal and the thermal acoustic waves in the GHz range present in the silica fiber giving rise to frequency shifted components. It can be seen as the diffraction of light on a moving grating generated by an acoustic wave (an acoustic wave is actually a pressure wave which introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift since the grating propagates at the acoustic velocity in the fiber. The acoustic velocity is directly related to the medium density and depends on both temperature and strain. As a result the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fiber. Furthermore, Brillouin-based sensing techniques rely on the measurement of a frequency as opposed to Raman-based techniques which are intensity based. Brillouin based techniques are consequently inherently more accurate and more stable on the long term, since intensity-based techniques suffer from a higher sensitivity to drifts.

Brillouin scattering has the particularity that it can become a stimulated interaction provided that an optical signal called the probe signal is used in addition to the original optical signal usually called the pump. This interaction causes the coupling between optical pump and probe signals and acoustical waves when a resonance condition is fulfilled, i.e. when the frequency difference between probe and pump light corresponds to the Brillouin frequency shift. It turns out that the resonance condition is strain and temperature-dependent, so that determining the resonance frequency directly provides a measure of temperature or strain. The advantage of measuring the interaction of two optical signals instead of recording the low intensity spontaneously scattered light is that the signal-to-noise ratio is much more comfortable. As a result, the measurement of spontaneous backscattered light required long integrating time, whereas the pump-probe technique doesn’t and is therefore suitable for rapid measurements.

Brillouin-based sensing techniques operates only with singlemode optical fibers and thanks to the low loss characteristics of singlemode fibers, measurements over several tens of kilometers can be achieved.

The localization of the strain and temperature information along the fiber is possible by using a radar-like concept. Optical laser pulses are launched into the sensing fibers, while their interaction with the propagating medium is recorded as a function of time. Provided that the velocity of light in the fiber is known, the time information can be converted into distance and an actual temperature profile of the fiber can be computed. Thanks to the high speed of light, fiber lengths of several kilometers can be scanned within a fraction of second, yielding several thousands of measurement points. The spatial resolution is set by the pump pulse width or the equivalent distance occupied by half of optical pulse within the fiber (for instance a 10ns pulse yields a 1 meter spatial resolution along the fiber). Both Raman and Brillouin systems have demonstrated spatial resolution in the meter range.

In general, Raman systems operates well with multimode fibers, but have a limited distance range (up to 10km) whereas Brillouin-based sensing techniques works only with singlemode fibers and present much longer distance capabilities (beyond 50 km [6]). Both techniques can achieve accuracies below 1°K provided that the averaging time is properly set. Stimulated Brillouin scattering has demonstrated to offer a higher signal-to-noise ratio and higher quality measurements can be performed in shorter periods of time and therefore is more suitable for rapid measurements. Finally Brillouin-based systems can measure both strain and temperature, while Raman scattering is sensitive only to temperature. An example of a Brillouin distributed sensing system is shown in Figure 2.
2. SENSING CABLES DESIGN

Traditional fiber optic cable design aims to the best possible protection of the fiber itself from any external influence. In particular it is necessary to shield the optical fiber from external humidity, side pressures, crushing and longitudinal strain applied to the cable. These designs have proven very effective in guaranteeing the longevity of optical fibers used for communication and can be used as sensing elements for monitoring temperatures in the –20°C to +60°C range, in conjunction with Brillouin or Raman monitoring systems.

Sensing distributed temperature below 20°C or above 60°C requires a specific cable design, especially for Brillouin scattering systems, where it is important to guarantee that the optical fiber does not experience any strain that could be misinterpreted as a temperature change due to the cross-sensitivity between strain and temperature.

On the other hand, the strain sensitivity of Brillouin scattering prompts to the use of such systems for distributed strain sensing, in particular to monitor local deformations of large structures such as pipelines, landslides or dams. In these cases, the cable must faithfully transfer the structural strain to the optical fiber, a goal contradicting all experience from telecommunication cable design where the exact opposite is required.

Finally, when sensing distributed strain it is necessary to simultaneously measure temperature to separate the two components. This is usually obtained by installing a strain and a temperature sensing cable in parallel. It is therefore appreciated to combine the two functions into one single packaging.

These really practical requirements have lead to the development of cables specifically designed for sensing applications.

1.1. General Requirements

All cable designs share common goals independently from the used sensing technique (Brillouin or Raman scattering) and application domain:

- The optical fibers must be compatible with the selected sensing system: singlemode fibers for Brillouin scattering or multimode fibers for Raman scattering systems.
- The fibers must be protected from external mechanical actions during installation and while in use. In particular the cable design must allow easy manipulation without the risk of fiber damage.
- The cable design must allow sufficient shielding of the optical fibers against chemical aggression of water and other harmful substances.
- All optical losses must be kept as low as possible in order not to introduce degradations to the native instrument’s distance range.
- Installation of connectors and repair of damaged sensors should be compatible with field operations.

The next paragraph will describe cable designs for distributed strain and combined strain and temperature sensing.
1.2. Strain Sensing Tape: Smartape

When strain sensing is required, the optical fiber must be bonded to the host material over the whole length. The transfer of strain is to be complete, with no losses due to sliding. Therefore an excellent bonding between strain optical fiber and the host structure is to be guaranteed. To allow such a good bonding it has been recommended that the optical fiber is integrated within a tape in the similar manner as the reinforcing fibers are integrated in composite materials [8]. To produce such a tape, we selected a glass fiber reinforced thermoplastic with PPS matrix. This material has excellent mechanical and chemical resistance properties. Since its production involves heating up to high temperatures (in order to melt the matrix of the composite material) it is necessary for the fiber to withstand this temperature without damage. In addition, the bonding between the optical fiber coating and the matrix has to be guaranteed. Polyimide-coated optical fibers meet these requirements and were therefore selected for this design.

The typical cross-section width of the thermoplastic composite tape that is used for manufacturing composite structures is in the range of ten to twenty millimeters, and therefore not critical for optical fiber integration. The thickness of the tape can be as low as 0.2 mm, and this dimension is more critical since the external diameter of polyimide-coated optical fiber is of 0.145 mm approximately. Hence, only less than 0.03 mm of the tape material remains on top or bottom of the optical fiber, with the risk that the optical fiber emerges from the tape. The scheme of the sensing tape cross-section, with typical dimensions, is presented in Figure 3.

![Cross-section picture and micrograph of the sensing tape: SMARTape](image)

Figure 3: Cross-section picture and micrograph of the sensing tape: SMARTape

The use of such sensing tape (called SMARTape) is twofold: it can be used externally, attached to the structure, or embedded between the composite laminates, having also a structural role.

1.3. Combined Strain And Temperature Sensing: SMARTprofile

The SMARTprofile sensor design combines strain and temperature sensors in one single package. This sensor consists of two bonded and two free single mode optical fibers embedded in a polyethylene thermoplastic profile [9]. The bonded fibers are used for strain monitoring, while the free fibers are used for temperature measurements and to compensate temperature effects on the bonded fibers. For redundancy, two fibers are included for both strain and temperature monitoring. The profile itself provides good mechanical, chemical and temperature resistance. The size of the profile makes the sensor easy to transport and install by fusing, gluing or clamping. The SMARTprofile (see Figure 4) sensor is designed for use in environments often found in civil geotechnical and oil & gas applications. However, this sensor cannot be used in extreme temperature environments nor environments with high chemical pollution. It is not recommended for installation under permanent UV radiation (e.g. sunshine).
3. COMPOSITE COILED TUBING MONITORING

The larger hydrocarbon reservoirs in Europe are rapidly depleting. The remaining marginal fields can only be exploited commercially by the implementation of new ‘intelligent’ technology, such as electric Coiled Tubing drilling or Intelligent Well Completions. Steel CT with an internal electric wire line is the current standard for such operations. Steel CT suffers from corrosion and fatigue problems, which dramatically restrict the operational life. The horizontal reach of steel CT is limited due to its heavy weight. The inserted wire line results in major hydraulic power losses and is cumbersome to install. To address these issues a joint research project supported by the European Commission was started in the year 2000. The project aims to solve these problems by researching and developing a high-temperature, corrosion and fatigue resistant thermoplastic Power & Data Transmission Composite Coiled Tubing (PDT-COIL) for electric drilling applications. This PDT-COIL contains embedded electrical power and fibre-optics for sensing, monitoring and data transmission. The PDT-COIL consists of a functional liner containing the electrical and the optical conductors and a structural layer of carbon and glass fibers embedded in high performance thermoplastic polymers. The electric conductors provide electric power for Electric Submersible Pumps or Electric Drilling Motors. A fibre-optic Sensing and Monitoring System, based on the SMARTprofile design is also integrated in the liner thickness over its whole length and is used to measure relevant well parameters, monitor the structural integrity of the PDT-COIL and can be used for data transmission (see figure 5).

The embedded optical fiber system was tested for measuring strain, deformations and temperatures of the coil.

Figure 4.- SMARTprofile cross-section and sample. The red tube contains the free fibers.

Figure 5.- PDT-Coil Cross-section. The fiber optics sensing SMARTprofiles are designated by SP-A, SP-B and SP-C.
1.4. Strain and deformation measurements

Testing of distributed strain and deformation measurements was performed on a 15m long section of polyethylene liner with integrated stain sensing fibers. The diameter of the tube was 56 millimeters. Four optical fibers were installed with the angles of -2.5°, -5°, 5° and 10° with respect to the tube axis, in order to evaluate performance of fibers installed with different angles. Two sensors with angles of -5° and 10° were connected one after the other and a closed loop was created with the reading unit. The temperature was measured on coils with free optical fibers installed before, between and after the strain sensing sections.

The aim of this test was to verify the performance of the monitoring system and algorithms. The following tests were performed: traction test, torsion test, combined traction and torsion test, bending test, half tube bending test, double bending test and, combined bending and torsion test.

The results of this test confirmed the excellent performance of the DiTeSt reading unit, providing a resolution compatible with the requirements (better than ±30µε) and short measurement time (better than 5 minutes). Resolution of temperature was better than 1°C. As examples, the results of traction, torsion and bending tests are presented in Figures 6 to 8. Figure 9 shows the full-bending loading case and the DiTeSt system in the foreground.

![Traction 0.25- Corrected - Relative](image)

Figure 6.- Results of the traction test and comparison with theoretical prediction.
Figure 7.- Results of the torsion test and comparison with theoretical predictions; Higher winding angles provide more sensitivity and accuracy for torsion measurements.

Figure 8.- Results of bending test and comparison with theoretical predictions; only half tube was bended, and bending radius of the tube could not be fully controlled; the theoretical line is not valid for whole length of the tube and shows only the maximal value and strain period.
1.5. Temperature measurements

To test the temperature sensing capabilities of the PDT-Coil sensing system, a 150 m section of integrated liner was heated by injecting different levels of current in the electrical conductors as shown in Figure 10.

Figure 11 shows the recorded temperature profile for different current levels. It can be noticed that the temperature is not constant along the liner, since one part of the liner was in direct contact with the metallic winding drum that acted as a heat sink, while further sections were wound on a second layer that was essentially surrounded by air and therefore thermally insulated. In real applications the PDT-Coil tubing would be cooled by the fluids circulating inside and outside the pipe.
1.6. Field Testing

A section of PDT-Coil tubing with carbon reinforcement over wrap was field tested in the Netherlands. The test consisted in powering a submersible pump to circulate water in the coiled tubing and to verify the operation of the fiber optic sensors and connection. In particular the test served to validate the design of a field-matable connector transmitting mechanical solicitations, electrical power and fiber optic signals. Figure 12 shows the testing setup.

Figure 11.- Liner temperature changes for different current levels and heating times. The first 545 m of optical fiber are not integrated in the liner and not shown.

Figure 12.- Field testing setup to demonstrate transmission of electrical power to a submersible pump and fiber optic signals through a field-matable connector.
CONCLUSIONS

Sensing systems based on Brillouin scattering have been demonstrated to be an effective method to monitor integrity and operational parameter of a composite coiled-tubing in laboratory and field demonstrations. In order to guarantee a reliable and practical embedding procedure, the optical fiber sensors have been pre-packaged in a novel sensing cable design, combining strain- and temperature-sensing fibers in a single profile, called SMARTprofile.

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