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DISTRIBUTED FIBRE-OPTIC SENSING FOR LONG-RANGE MONITORING OF PIPELINES

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Abstract

Distributed fibre-optic sensing presents unique features that have no match in conventional sensing techniques. The ability to measure temperatures and strain at thousands of points along a single fibre is particularly interesting for the monitoring of elongated structures such as pipelines, flow lines, oil wells and coiled tubing. Sensing systems based on Brillouin and Raman scattering are used for example to detect pipeline leakages, verify pipeline operational parameters, and prevent failure of pipelines installed in landslide areas, optimize oil production from wells and detect hot-spots in high-power cables. Recent developments in distributed fibre sensing technology allow the monitoring of 60 km of pipeline from a single instrument and of up to 300 km with the use of optical amplifiers. New application opportunities have demonstrated that the design and production of sensing cables is a critical element for the success of any distributed sensing instrumentation project. Although some telecommunication cables can be effectively used for sensing ordinary temperatures, monitoring high and low temperatures or distributed strain presents unique challenges that require specific cable designs. This contribution presents advances in long-range distributed sensing and in novel sensing cable designs for distributed temperature and strain sensing. The paper also reports a number of significant field application examples of this technology.

INTRODUCTION

Flowlines, pipelines or gas-lines often cross hazardous environmental areas, from the point of view of natural exposures such as landslides and earthquakes, and from the point of view of third-party influences such as vandalism or obstruction. These hazards can significantly change the original structural functioning of the flowline, leading to damage, leakage and failure with serious economic and ecologic consequences. Furthermore, the operational conditions of the pipeline itself can induce additional wearing or even damage.

The structural and functional monitoring can significantly improve pipeline management and safety. Providing regularly with parameters featuring the structural and functional condition of the flowline, monitoring can help (1) prevent the failure, (2) in time, detect the problem and its position and (3) undertake maintenance and repair activities in time. Thus the safety is increased, maintenance cost optimized and economic losses decreased. Typical structural parameters to be monitored are strain and curvature while the most interesting functional parameters are temperature distribution, leakage and third-party intrusion. Since the flowlines are usually tubular structures with kilometric lengths, structural monitoring of full extent is an issue itself. The use of discrete sensors, short- or long-gauge is practically impossible, because it requires installation of thousands of sensors and very complex cabling and data acquisition systems raising the monitoring costs. Therefore, the applicability of discrete sensors is rather limited to some chosen cross-sections or segments of flowline, but not extended to full-length monitoring. Other current monitoring methods include flow measurements at the beginning and end of the pipeline, offering an indication of the presence of a leak, but no information on its location.

Recent developments of distributed optical fibre strain and temperature sensing techniques based on Brillouin scattering effect promise to provide a cost-effective tool allowing monitoring over kilometric distances. Thus, using a limited number of very long sensors it is possible to monitor structural and functional behaviour of flowlines with a high measurand and spatial resolution at a reasonable cost.

Even if the development of Brillouin scattering based sensing techniques, as well as their application for temperature and leakage monitoring is presently well advanced, there has been a comparatively modest advancement in the development of the distributed strain sensors and their installation techniques.

The aim of this paper is to present on-site applications of a newly completed distributed sensing system called DiTeSt [1].

DITEST MONITORING SYSTEM

Basics on distributed sensing

A distributed sensor is, conventionally, a device with a linear measurement basis, which is sensitive to measurand at any of its points. Optical fibre-distributed sensors consist of a single optical-fibre sensitive over all its length. A single distributed fibre optic sensor could therefore replace thousands of discrete (point) sensors. The low fibre attenuation allows a monitoring over extremely long distances (up to 25 kilometres), which representS an impressive number of measuring points. This makes distributed sensing technique a very attractive solution when the monitoring of a large number of locations is required.

DiTeSt Reading Unit

The development of a fibre-optics distributed sensor system relies upon using a known and reproducible method by which the measurand can interact with the light travelling within the fibre. The DiTeSt (Distributed Temperature and Strain monitoring system) is based on a detection scheme using a non-linear optical effect named Stimulated Brillouin Scattering [1]. This scattering process is an intrinsic property of the propagation of light in the silica material from which the sensing fibre is made. The Brillouin scattering effect exhibits a well-known and reproducible response to external measurands such as temperature and strain.

The Brillouin interaction results in the generation of scattered light which experiences a frequency shift through the scattering process. This frequency shift depends linearly on the fibre strain and temperature. As a consequence, the scattered light has a slightly different wavelength than the original light and the departure from the original wavelength is directly dependent on the strain and temperature of the fibre. A system based on the analysis of the Brillouin scattered light in optical fibres is naturally devoted to perform strain and temperature measurement.

The main components of the DiTeSt system are the Reading Unit and the Sensor Cable. The Reading Unit is connected to the proximal end of the sensor and can be placed remotely from the sensing area, since a section of optical fibre cable could be used to link the Reading Unit to the sensor itself without any performance degradation. The other sensor-end can be either connected to the Sensor Termination Module (single-end configuration), which could be placed remotely from the sensor area as well, or brought back and connected to the Reading Unit (loop configuration). The selection of the configuration (single-end or loop) depends on the application. The use of optical amplifier modules (range extenders) allows the monitoring of up to 300 km of pipeline from a single instrument [2]. The typical performances of the DiTeSt system are summarized in Table 1.

Table 1. Performances of DiTeSt system

Measurement range	30 km (standard) 150 km (extended)
Number of channels	2 (standard) max. 60 (with channel switch)
Spatial resolution	1 m over 5 km 2 m over 25 km
Temperature resolution	0.1°C
Temperature range (depends on type of sensing cable)	-270°C to +500°C
Strain resolution	2 □□ (0.002 mm/m)
Strain range (typical)	-1.25% to 1.25%
Acquisition time (typical)	2 minutes

Sensing Cable Design

Traditional fibre-optic cable design aims to the best possible protection of the fibre itself from any external influence. In particular it is necessary to shield the optical fibre from external humidity, side pressures, crushing and longitudinal strain applied to the cable. These designs have proven effectiveness guaranteeing the longevity of optical fibres 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 fibre 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 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 fibre, 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 strain and temperature sensing cables in parallel as shown in Figures 1, 2, and 3.

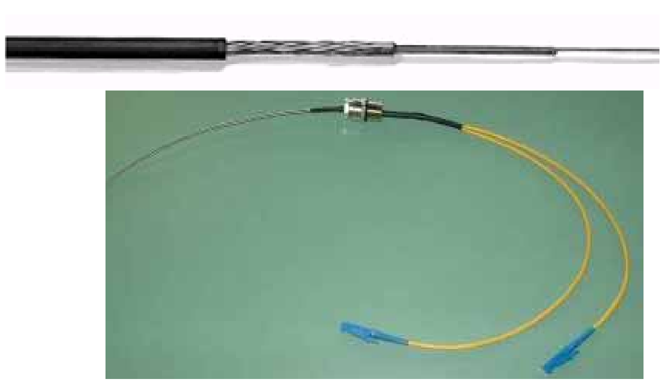

Figure 1. Extreme temperature sensing cable design and termination [3].

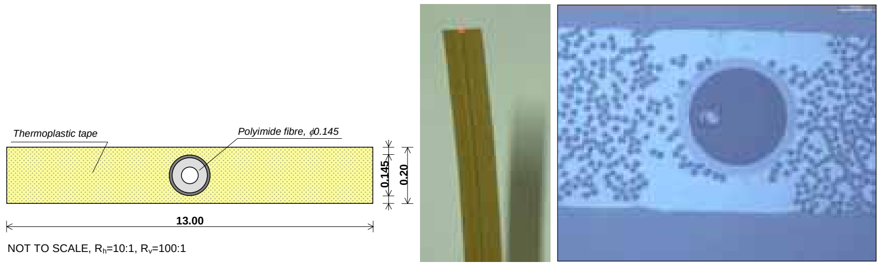

Figure 2. Cross-section picture and micrograph of the sensing tape (SMARTape) [1].

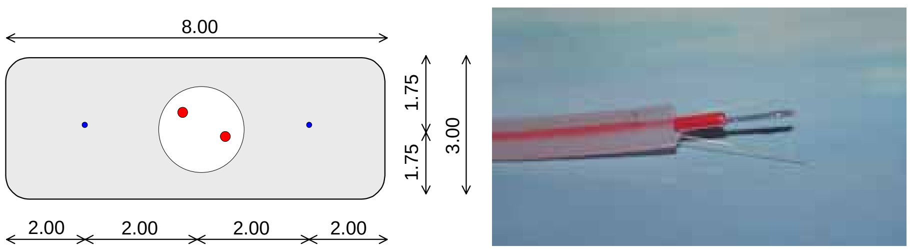

Figure 3. SMARTprofile cross-section and sample. The red tube contains the free fibres [3].

PIPELINE MONITORING APPLICATIONS

In the following sections we will introduce application examples showing how different pipeline monitoring tasks can be addressed with the presented system.

Gas Pipeline Monitoring

About 500 metres of a buried, 35-year-old gas pipeline, located in Italy, lies in an unstable area. Distributed strain monitoring could be useful in improving vibrating wire strain gauges monitoring system, used in the site. As the landslide progresses with time, it could damage pipelines up to be put out of service. Three symmetrically disposed vibrating wires were installed in several sections at a distance typically of 50/100 m chosen as the most stressed ones according to a preliminary engineering evaluation. These sensors were very helpful, but could not fully cover the length of the pipeline and only provide local measurements.

Different types of distributed sensors were used: SMARTape and Temperature Sensing Cable. Three parallel lines constituted of five segments of SMARTape sensor were installed over the whole concerned length of the pipeline (see figure 4). The lengths of segments ranged from 71 m to 132 m, and the position of the sensors with respect to the pipeline axis were at 0°, 120° and –120° approximately. The strain resolution of the SMARTape is 20 micro-strains, with spatial resolution of 1.5 m (and an acquisition range of 0.25m) and provides the monitoring of average strains, average curvatures and deformed shape of the pipeline. The Temperature Sensing Cable was installed onto the upper line (0°) of the pipeline in order to compensate for the strain measurements for temperature. The temperature resolution of the sensor is 1°C with the same resolution and acquisition of the SMARTape. All the sensors are connected to a Central Measurement Point by means of extension optical cables and connection boxes. They are read from this point using a single DiTeSt reading unit. Since the landslide process is slow, the measurements sessions are performed manually once a month. In case of earthquake, a session of measurements is performed immediately after the event. All the measurements obtained with the DiTeSt system are correlated with the measurements obtained with vibrating wires. At present stage, the sensors have been measured for a period of two years, providing interesting information on the deformation induced by burying and by the landslide progression. A gas leakage simulation was also performed with success using the temperature sensing cable.

During the works the pipe was laid on the soil supports every 20 – 30 m. Therefore, its static system can be considered as a continuous girder. After the burring, the pipe was loaded with soil and therefore deformed. The pipe cross-sections located on the supports have been subject to negative bending (traction at the top part) and the section between the supports to positive bending (traction at the bottom part). The maximal allowed strain in the elastic domain is 1750 με, and maximal curvature without normal forces 5303 kN/m. The diagram showing the strain distribution over all the length of the pipeline after the burring measured by SMARTapes is presented in Figure 5. The normal cross-sectional strain distributions as well as the curvature distribution in horizontal and vertical plane are calculated from these measurements.

Figure 4. SMARTape on the gas pipeline.

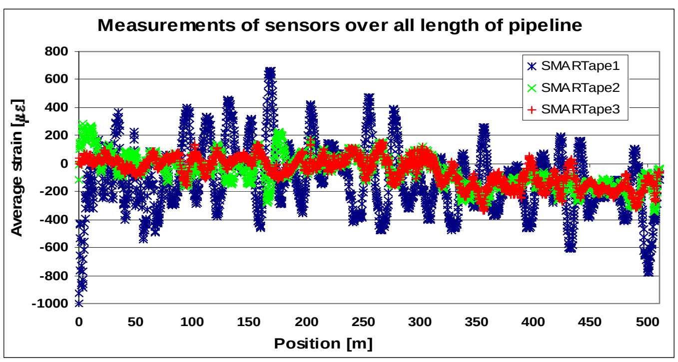

Figure 5. Strain distribution over the monitored part of the pipeline measured by SMARTape sensors.

During the putting of the sensors in place and burring of the pipe, an empty plastic tube was installed connecting the upper part of the pipe with the surface, 50 m from the beginning of the first monitored segment. This tube was used to simulate a leakage of the gas. Carbon dioxide was inserted in the tube, cooling down the pipe end, due to pressure relaxation, and making the thermal conditions surrounding the contact between the pipe and the tube similar to conditions expected in case of leakage. This process is presented in Figure 6.

A reference measurement was performed before the tube was cooled down. After the carbon dioxide was inserted, the temperature measurements were performed every 2 to 10 minutes and compared with reference measurement. The results of the test are presented in Figure 7. The test was successful and point of simulated leakage was clearly observed in diagrams (encircled area in Figure 7).

Figure 6. Leakage simulation test.

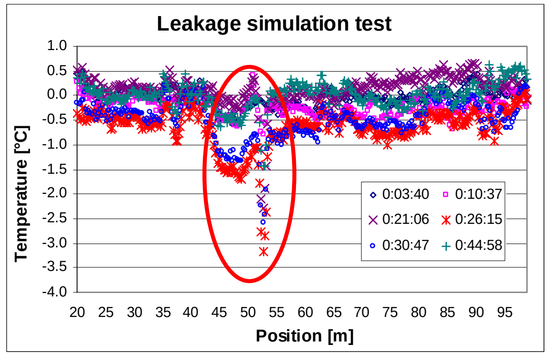

Figure 7. Results of leakage test; leakage is detected as temperature change.

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 issue 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 fibres 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 8).

The embedded optical fibre system was tested for measuring strain, deformations and temperatures of the coil. Testing of distributed strain and deformation measurements was performed on a 15m long section of polyethylene liner with integrated strain sensing fibres. The diameter of the tube was 56 mm. Four optical fibres were installed with the angles of -2.5°, -5°, 5° and 10° with respect to the tube axis, in order to evaluate performance of fibres 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 fibres 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 torsion tests are presented in Figure 9.

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.

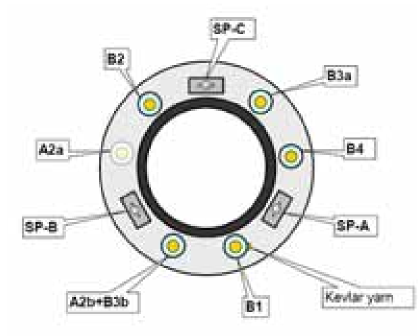

Figure 8. PDT-Coil Cross-section. The fiber optics sensing SMARTprofiles are designated by SP-A, SP-B and SP-C.

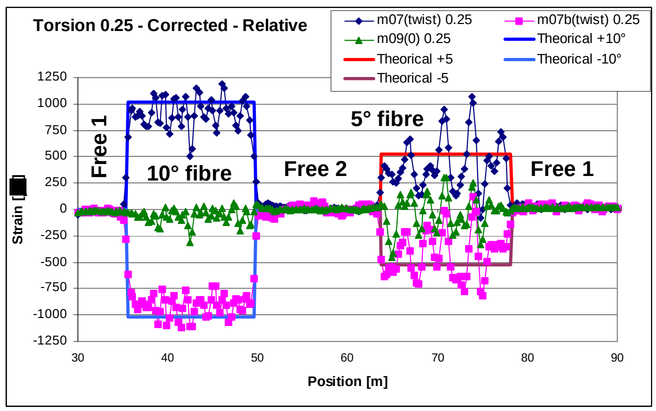

Figure 9. Results of the torsion test and comparison with theoretical predictions; higher winding angles provide more sensitivity and accuracy for torsion measurements.

CONCLUSIONS

The use of distributed fibre-optic monitoring system allows a continuous monitoring and management of pipelines, increasing their safety and allowing the pipeline operator to make informed decisions on the operations and maintenance of the pipe. The presented monitoring system and the application examples shown in this paper demonstrate how it is possible to obtain different types of information on the pipeline state and conditions. In particular a distributed fibre-optic system allows the following monitoring tasks: distributed temperature monitoring, leakage detection, intrusion detection, distributed strain and deformation monitoring.

In general, distributed strain/deformation and temperature sensing is a useful tool that ideally complements the current monitoring and inspection activities, allowing a more dense acquisition of operational and safety parameters. The measurements are performed at any point along the pipeline and not at specific positions only. Furthermore, the monitoring is continuous and does not interfere with the regular pipeline operation, contrary to pigging operations, for example. Recent developments in distributed fibre-sensing technology allow the monitoring of 60 km of pipeline from a single instrument and of up to 300 km with the use of optical amplifiers. To achieve the above-mentioned goals and take full advantage of the described sensing technology, it is however fundamental to select and appropriately install adequate sensing cables, adapted to the specific sensing need. While it is generally easier to install sensing cables during the pipeline construction phases, it is also possible to retrofit existing pipelines. In some cases it is even possible to use existing fibre-optic telecommunication lines installed along a pipeline for temperature monitoring and leakage detection.

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