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LONG-RANGE PIPELINE MONITORING BY DISTRIBUTED FIBER OPTIC SENSING

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ABSTRACT

Distributed fiber 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 fiber 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, 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 fiber 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 present 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, including leakage detection on brine and gas pipelines, strain monitoring on gas pipelines and combined strain and temperature monitoring on composite flow lines and composite coiled-tubing pipes.

INTRODUCTION

Flowlines – pipelines or gas-lines often cross hazardous environmental areas, from the point of view 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 damaging, 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 the 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,m structural monitoring of full extent is an issue itself. The use of the discrete sensors, short- or long-gage 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 the 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 fiber strain and temperature sensing techniques based on Brillouin scattering effect promise to provide a cost-effective tools allowing monitoring over kilometric distances. Thus, using a limited number of very long sensors it is possible to monitor structural

and functional behavior 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 was a comparatively modest advancement in the development of the distributed strain sensors and their installation techniques.
The aim of this paper is to present an 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 represent 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 fiber 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 (see Figure2). [4]. A scheme of the DiTeSt system is given in Figure 1 and typical performances in Table 1.

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 με (0.002 mm/m)
Strain range (typical)	-1.25% to 1.25%
Acquisition time (typical)	2 minutes

Table 1: Performances of DiTeSt system

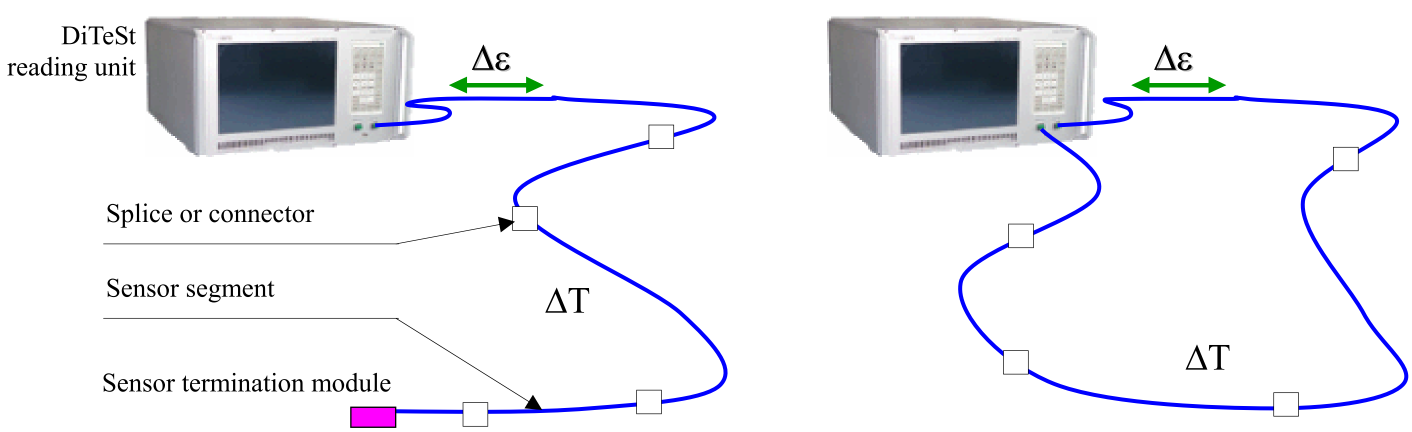

Fig. 1: Schema of DiTeSt® system configurations, left: single-end configuration; right: loop configuration

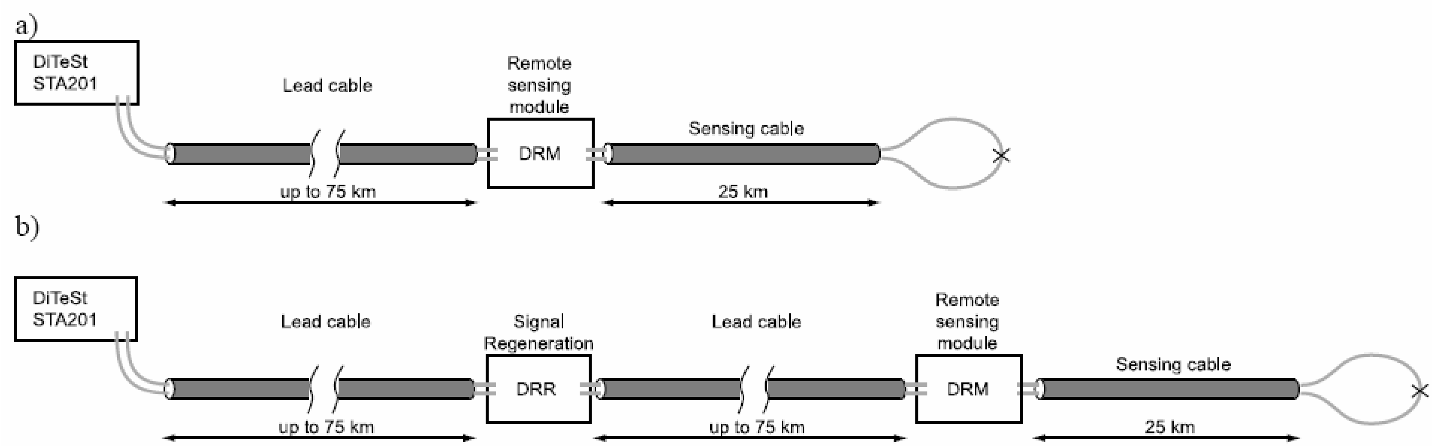

Fig. 2: Range Extender Configurations, allowing the monitoring of long pipeline sections with a single instrument

Sensing Cable 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 effectiveness 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 form 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 cables in parallel. It would be therefore desirable to combine the two functions into a single packaging.

Extreme temperature sensing cable

The extreme temperature sensing cables are designed for distributed temperature monitoring over long distances. They consist of up to four single mode or multimode optical fibers contained in a stainless steel loose tube, protected with stainless steel armoring wires and optionally a polymer sheath. These components can be differently combined in order to adapt the cable to the required performance and application. The use of appropriate optical fibre coating (polyimide or carbon/polyimide) allows the operation over large temperature ranges, the stainless steel protection provides high mechanical and additional chemical resistance while the polymer sheath guarantees corrosion protection. The carbon coating offers improved resistance to hydrogen darkening. The over-length of the optical fibers is selected in such a way that the fiber is never pulled or compressed, despite the difference in thermal expansion coefficients between glass and steel. The total cable diameter is only 3.8 mm (see figure 3).

These cables can be used in a wide range of applications that require distributed temperature sensing, such as temperature monitoring of concrete in massive structures, waste disposal sites, onshore, off-shore and downhole sites in gas and oil industry, hot spots, cold spots and leakage detection of flow lines and reservoirs, fire detection in tunnels and mapping of cryogenic temperatures, just to name a few.

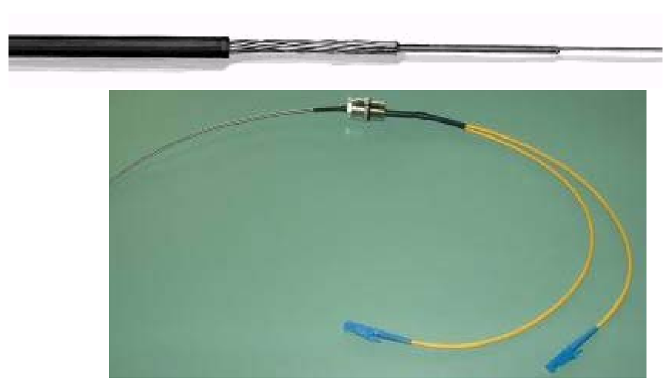

Figure 3: Extreme temperature sensing cable design and termination

Strain sensing tape: SMARTape

When strain sensing is required, the optical fiber must be bonded to the host material over the whole length [2]. 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 to integrate the optical fiber within a tape in the similar manner as the reinforcing fibers are integrated in composite materials. 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 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 fit 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 tape material remains on top or bottom of the optical fiber, with the risk that the optical fiber will emerge from the tape. The scheme of the sensing tape cross-section, with typical dimensions, is presented in Figure 4.
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.

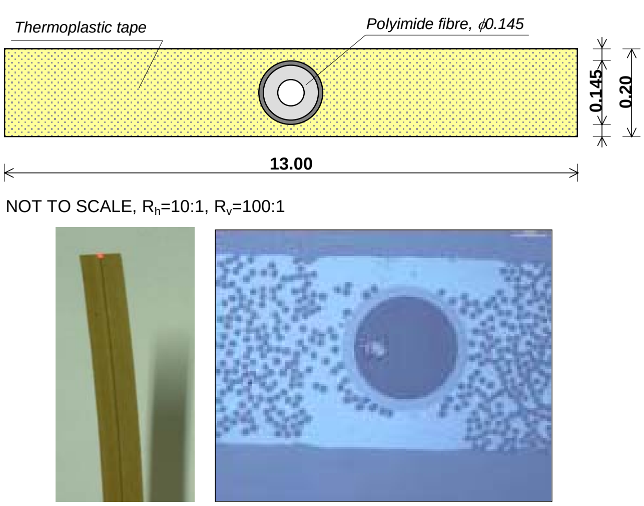

Figure 4: Cross-section picture and micrograph of the sensing tape (SMARTape)

Combined Strain and temperature sensing: SMARTprofile

The SMARTprofile sensor design combines strain and temperature sensors in a single package.
This sensor consists of two bonded and two free single mode optical fibers embedded in a polyethylene thermoplastic profile. 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 5) 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).

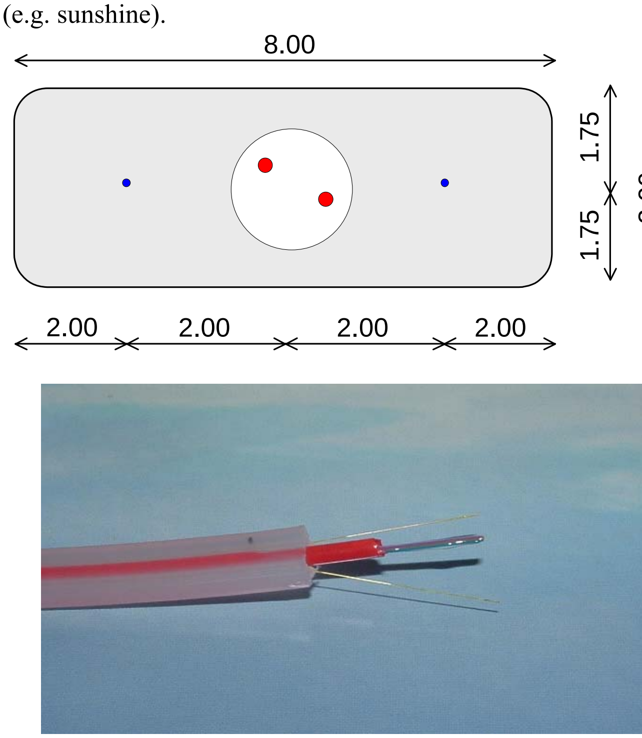

Figure 5: SMARTprofile cross-section and sample. The red tube contains the free fibers

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.

Leakage detection in a Brine Pipeline

In 2002 the construction of a natural gas storage facility some 1500m under the ground surface was started in the area of Berlin in Germany. Using mining technology the building of underground caverns for gas storage in large rock-salt formation requires hot water and produces large quantities of water saturated with salt, the so-called brine. In most cases the brine cannot be processed on-site and must be transported by a pipeline to the location where it can either be used for chemical processes, or injected back safely into the ground. Because the brine can be harmful for the environment, the pipeline shall be monitored by a leakage detection system.
In the Berlin project a 55km pipeline was built and the company GESO was selected for the development and the installation of the leakage detection system [3]. In order to cover the whole pipeline distance, it was decided to use two DiTeSt analyzers although one instrument would have been theoretically able to cover the whole distance with its two channels. However the installation of the fiber cable required some 60 splices (that correspond to a additional loss of up to 3 dB) which reduces the distance range of the instrument accordingly and justified the use of two instruments, since the range extender technology was not yet available.
During the construction phase the temperature sensing was first placed in the trench and buried in the sand some 10 cm underneath the pipeline. The pictures in Fig. 6 show the construction of the pipeline before and after the pipeline was put in the trench.

Figure 6. Construction phase of a buried brine pipeline in the north-east area of Berlin. The fiber optics cable is placed in the sand at the 6 o'clock position about 10 cm underneath the pipeline.

The temperature profiles measured by both DiTeSt instruments are transferred every 30 minutes to a central PC and further processed for leakage detection. A dedicated software performs the leakage detection through a comparison between recorded temperature profiles, looking at abnormal temperature evolutions and generates alarm in the case of the detection of leakage. The system is able to automatically transmit alarms, generate reports, periodically reset and restart measurements, and requires virtually no maintenance.

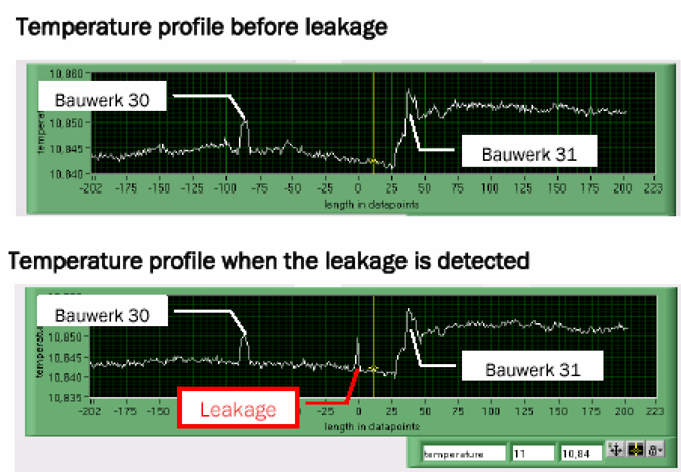

Figure 7. Measured profiles before and after the leakage

The pipeline construction phase was completed in November 2002 and the pipeline was put into operation in January 2003. In July 2003, a first leakage was detected by the monitoring system. It was later found that the leakage was accidentally caused by excavation work in the vicinity of the pipeline. Fig. 7 shows the occurrence of the leakage and its effect on the temperature profiles showing a local temperature increase of 8°C. An alarm was immediately and automatically triggered and the flow was eventually stopped.

Gas Pipeline Monitoring

About 500 meters of a buried, 35 years old gas pipeline, located in Italy, lie in an unstable area. Distributed strain monitoring could be useful in order to improve vibrating wire strain gauges monitoring system, actually used in the site. The landslide progresses with time and 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 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 8). The lengths of segments were 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 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 με/m. The diagram showing the strain distribution over all the length of the pipeline after the burring measured by SMARTapes is presented in Figure 9. The normal cross-sectional strain distribution as well as the curvature distribution in horizontal and vertical plane are calculated from the measurements and presented in Figure 10.

Figure 8: SMARTape on the gas pipeline.

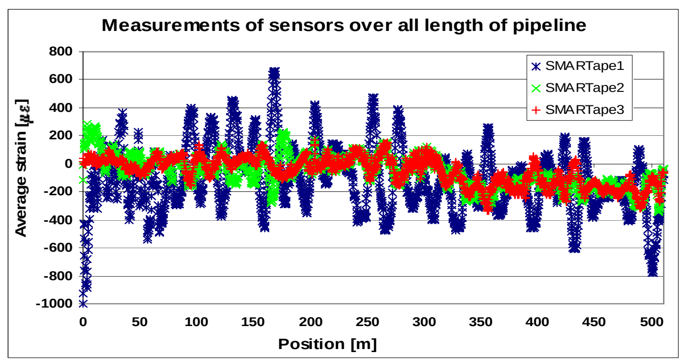

Figure 9. Strain distribution over the monitored part of the pipeline measured by SMARTape sensors

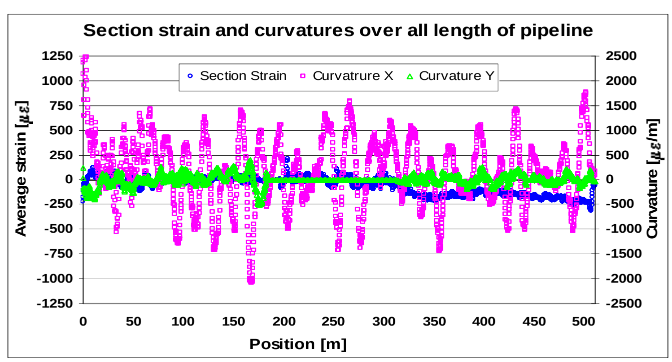

Figure 10. Cross-section strain and curvatures distribution measured by SMARTape sensors

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 far 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 11.

Figure 11. Leakage simulation test

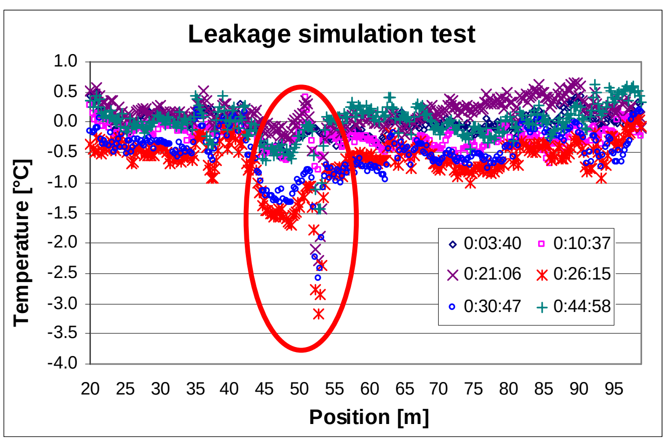

Figure 12. Results of leakage test; leakage is detected as temperature change

A reference measurement was performed before the tube was cooled down. After the carbon dioxide was inserted, the temperature measurements are performed every 2 to 10 minutes and compared with reference measurement. The results of the test are presented in Figure 12. The test was successful and point of simulated leakage was clearly observed in diagrams (encircled area in Figure 12).

Composite High-Pressure Pipe Monitoring: SmartPipe

Smart Pipe is a high strength, light weight, monitored reinforced thermoplastic pipe that can be used for the rehabilitation of an existing pipeline, or as a stand alone replacement. The key feature of the technology that underlies Smart Pipe is the use of ultra high strength fibers that are wrapped onto a high density polyethylene core pipe (see figure 13). Through the selection of the fibers, the lay angles, and their sizes, Smart Pipe can be specially tailored for any given condition in terms of design pressure, pull-in length (for a rehabilitation), and safe operating duration.

In urban and environmentally sensitive areas it delivers significant savings in the costs of access to and permitting for difficult locations using its trenchless installation methods. It is simultaneously manufactured and installed as a tight fit liner in up to 50,000 feet of an underground pipeline without any disruption of the surface areas covering the pipeline (except for a small opening at the entry and exit points of the pipeline section being lined). It can restore the subject pipeline to its full pressure service rating, renewing the projected service life of the subject pipeline to like new or better than new condition, and in most cases does so without reducing the flow rates through the line despite the nominal reduction in inside diameter of the pipeline that occurs due to the presence of the liner.

The integrated SMARTprofile sensors (see Figure 14) provide the operator of the pipeline with continuous monitoring and inspection features to assure safe operation of the line throughout the renewed operating life of the pipeline and to provide compliance with the regulations now emerging under the various Pipeline Safety Acts.

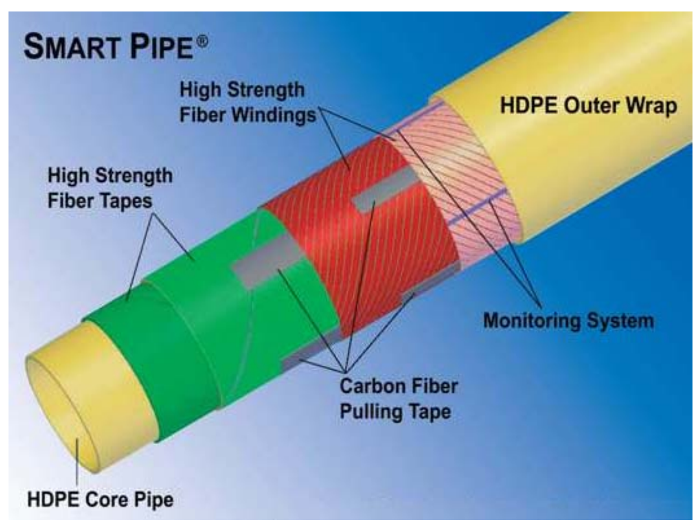

Figure 13. SmartPipe design, including SMARTprofile Monitoring system.

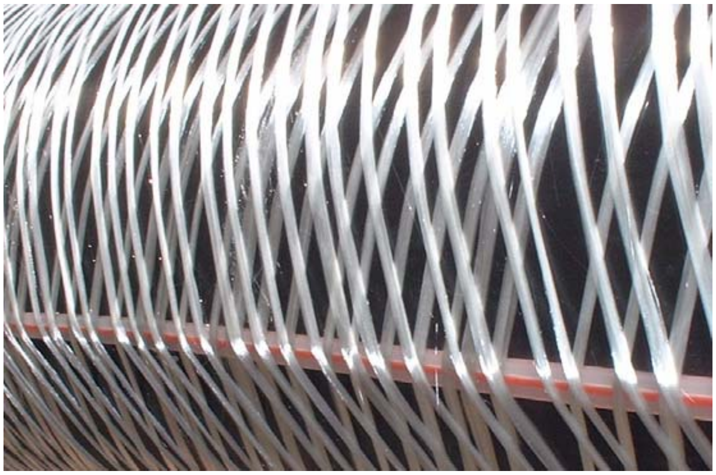

Figure 14. SMARTprofile integration with high-strength fiber windings.

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 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 15).

The embedded optical fiber 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 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 and torsion tests are presented in Figures 16 and 17.

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 18.

Figure 19 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.

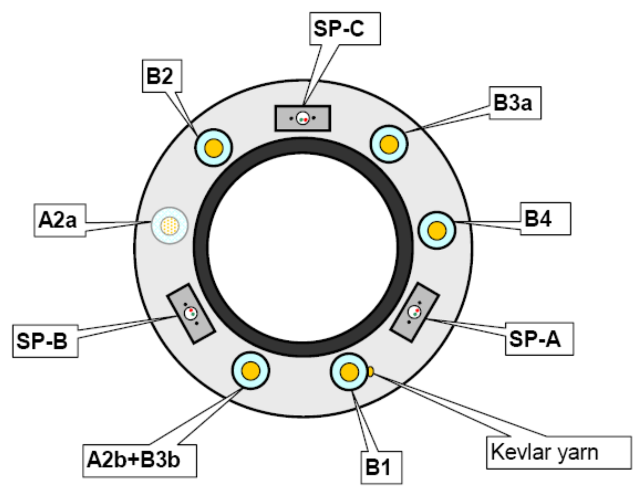

Figure 15. PDT-Coil Cross-section. The fiber optics sensing SMARTprofiles are designated by SP-A, SP-B and SP-C.

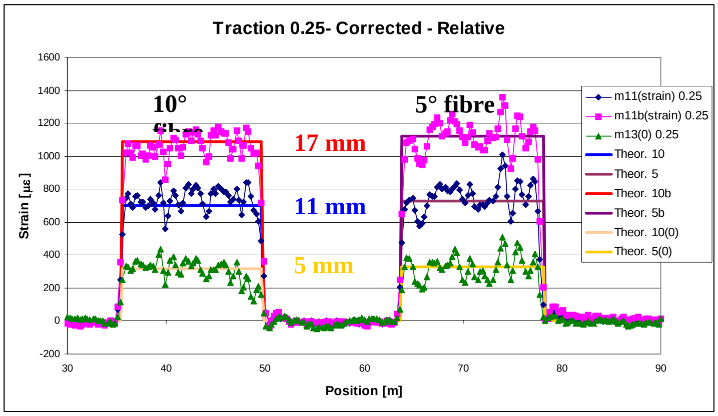

Figure 16. Results of the traction test and comparison with theoretical prediction

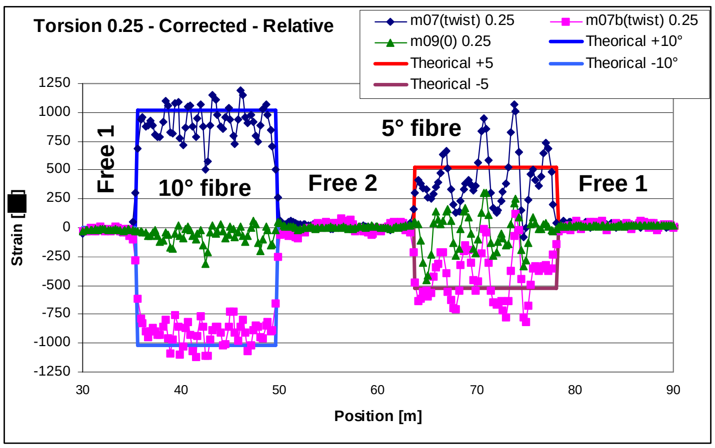

Figure 17. Results of the torsion test and comparison with theoretical predictions; higher winding angles provide more sensitivity and accuracy for torsion measurements

Figure 18. Liner heating test by electrical current injection

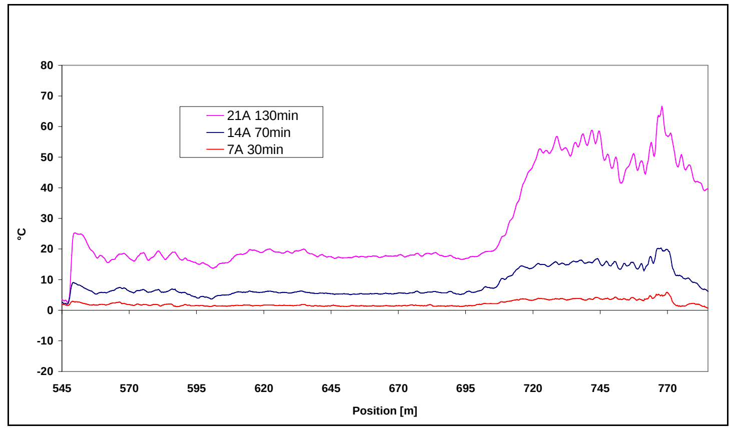

Figure 19. Liner temperature changes for different current levels and heating times. The first 545 m of optical fiber are not integrated in the liner and not shown

CONCLUSIONS

The use of distributed fiber optic monitoring system allows a continuous monitoring and management of pipelines, increasing their safety and allowing the pipeline operator to take 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 fiber optic system allows the following monitoring tasks:

Distributed temperature monitoring: allows the measurement of the temperature profile along the pipe and therefore of the temperature changes of the transported fluid. This information can be used for optimizing operational parameters and for the identification and location of hydrate, ice, and wax accumulations. These may be detected by sensing changes in temperature on either side of the accumulation.

Leakage detection: through the identification of temperature anomalies, it is possible to detect and localize leakages of small entity, that cannot be detected by conventional volumetric techniques. Furthermore, the ability to pinpoint the exact location of the leak allows an immediate reaction at the event location, minimizing downtime and ecological consequences.

Intrusion detection: based on a similar approach, focusing on localized strain and temperature changes, the presence and location of an accidental or intentional intrusion can be detected. This enables preventive action before the intruder can damage the pipeline.

Distributed strain and deformation monitoring: Provides information on the strain evolution along the pipeline. This is particularly useful at critical locations, where movements caused by earthquakes, landslides, settlements or human activities can introduce potentially dangerous strain conditions to the pipeline. Distributed strain monitoring allows the early detection of such conditions, allowing an intervention before a real damage is produced. This is an useful tool for pipeline management and for on-demand maintenance. Distributed strain monitoring also has the potential of detecting wall-thickness changes along the pipe, resulting form corrosion or abrasion.

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 e.g. pigging operations. The method can also be applied to non-piggable pipes.

Recent developments in distributed fiber 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 fiber optic telecommunication lines installed along a pipeline for temperature monitoring and leakage detection.

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