Enhanced Brillouin Distributed Strain and Temperature Sensing for Structural Health Monitoring in Industrial Applications

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ENHANCED BRILLOUIN DISTRIBUTED STRAIN AND TEMPERATURE SENSING FOR STRUCTURAL HEALTH MONITORING IN INDUSTRIAL APPLICATIONS

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ABSTRACT

The quest for energy is pushing fibre based monitoring into new frontiers. Similarly, structural health monitoring is also demanding advanced monitoring solutions. The combination of Brillouin optical time domain analyzers with specifically designed sensing cables and proper analysis tools is shown to be a perfect match for these challenging applications.

KEYWORDS: *Distributed sensing, Brillouin, Remote monitoring,*

INTRODUCTION

The global energy demand is constantly growing. It forces major actors in the field to access new resources which can be remote, in harsh environment or deeper water depth, and which need to be transported over longer distances. Despite extremely challenging environmental conditions, energy transport structures must show reliability and efficiency. Similarly, civil engineering is also facing monitoring challenges, to survey the evolution and guarantee the safety of existing structures aging beyond their original design life time or to closely monitor the long term stability of surrounding neighbourhood during new sites construction.

Nowadays, fibre optic distributed sensing, based on temperature and strain dependence of optical fibre parameters, is seen as an effective, viable and reliable solution for asset integrity monitoring. Using specifically designed sensing cables together with stimulated based Brillouin optical time domain analyzers (BOTDA), fibre based monitoring solutions provide functionalities such as flow assurance, thermal management and leak detection as well as ground movement, pipeline deformation and vibration or structural deformation of large structures in different industries.

In this paper, following a short description of the physical principle beyond BOTDA and the associated sensing cables and software tools, we described a few typical applications that took place recently. It includes pipeline monitoring (Sakhalin-Khabarovsk-Vladivostok and Péru LNG transandean pipeline), power cable monitoring, subsea umbilical, riser and flowline monitoring (SURF) and structural health monitoring. In addition, it provides an insight into the coming novelties in terms of Brillouin technology for field deployment.

1 BRILLOUIN SENSING PRINCIPLE

1.1 Backscattering properties

When a powerful light pulse, known as the pump, propagates through an optical fibre, a small amount of the incident power is scattered in all directions due to local non-homogeneities. Backscattering is of particular interest since it propagates back towards the pump and therefore can be analysed as a function of time/distance and other relevant parameters to provide distributed sensing.

Scattering processes originate from material density inhomogeneity (Rayleigh), thermally excited acoustic waves (Brillouin) or molecular vibrations (Raman), as shown in Figure 1.

Rayleigh scattering, the largest of the three, is the interaction of a light pulse with material impurities; it is the principle of Optical Time Domain Reflectometer (OTDR) as well as of most Distributed Acoustic Sensing (DAS) systems.

Brillouin scattering is the interaction of the light pulse with thermally excited acoustic waves (acoustic phonons). Acoustic waves, through the elasto-optic effect, slightly and locally modify the index of refraction. The corresponding moving grating reflects back a small amount of the incident light and shifts its frequency due to the Doppler Effect. The frequency shift, which is temperature and strain dependant, depends on the acoustic velocity in the fibre and the propagation direction of the acoustic wave, resulting in two backscattering frequencies (Stokes and Anti-Stokes components) close to the incident light (around 10GHz for silica at 1550nm). Brillouin scattering in single-.mode fibre is the principle of Brillouin Optical Time Domain Reflectometer or Analyser (BOTDR or BOTDA) used for strain sensing and long distance distributed temperature sensing (DTS) systems.

Raman scattering, the smallest of the three, is the interaction of a light pulse with thermally excited molecular vibrations (optical phonons). It exhibits a large frequency shift of typically 13THz (around 100nm in silica at 1550nm). The Raman Anti-Stokes component intensity is temperature dependent. Raman scattering in multi-mode fibres is the principle of short distance DTS.

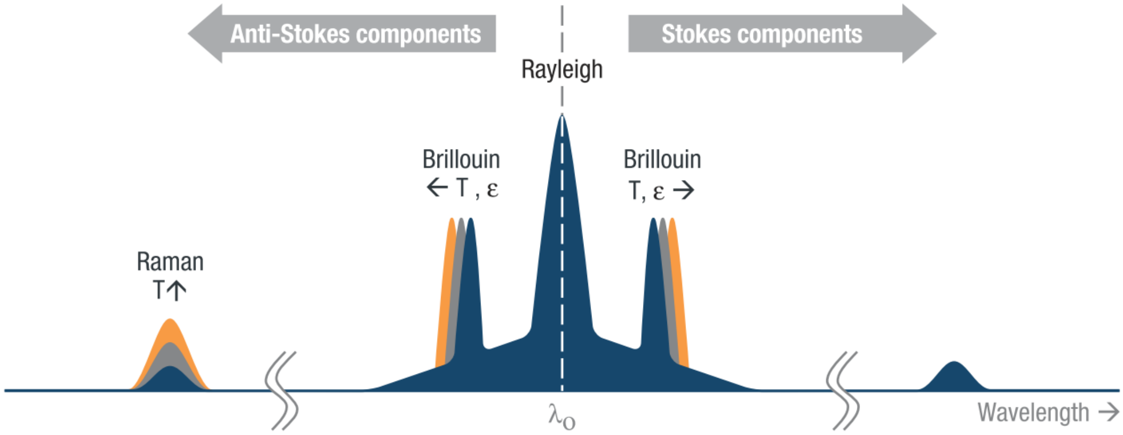

Figure 1 : Backscattered light components of a single mode laser (λ_o) launched in a single mode optical fibre.

1.2 Brillouin optical time domain analyser

The frequency information of Brillouin backscattered light can be exploited to measure the local temperature or strain information along an optical fibre whilst the use of properly designed sensing cable allows for the separation of the temperature and the strain contribution. This frequency-based technique is inherently more reliable and more stable than any intensity-based technique, which is prone to drifts of attenuations. Thus, Brillouin based techniques offer long term stability, are largely immune to spatial and temporal changes of attenuation and can manage large optical budget.

The Brillouin scattering process can be stimulated by using a probe signal, counter-propagating with respect to the pump direction. This can be understood as a resonant phenomenon where an amplification of the probe power occurs at the expense of the pump when the resonant condition is fulfilled, i.e. when the frequency difference between pump and probe matches the local Brillouin frequency. Scanning the probe frequency with respect to the pump whilst monitoring the intensity of the backscattered signal as a function of time allows the Brillouin shift along the fibre to be found, from which the local temperature or the strain can be computed [1]. Instrument based on Stimulated Brillouin Backscattering (SBS) are known as BOTDA; the stimulation requires a fibre loop so that BOTDA are also known as dual-end instrument.

The OMNISENS DITEST interrogator is a unique BOTDA instrument for distributed measurement of strain and temperature over several tens of kilometres, allowing the measurement of thousands of locations in just one shot by means of a single optical fibre sensor It is a powerful diagnostic instrument for the identification and localization of potential problems, and its inherent stability and reliability guarantees an optimal security for the long term surveillance of large structures

1.3 Sensing cable

The easiest way to completely separate temperature and strain is to work with specifically designed cables.

A loose tube fibre design, as a Fibre in Metal Tube (FIMT) design is an excellent temperature sensor when the excess fibre length (EFL) is well controlled and larger than typically 0.1% and the tube is filled with a jelly. This ensure strain decoupling from the structure.

At the opposite, a tight buffer design in which the fibre is locked in some precisely manufactured upper buffering is a perfect candidate for elongation/compression sensing. The thermal effect, if any, can be compensated by measuring the nearby temperature.

More elaborate design integrate both loose tube and tight buffer into a single cable design; half the sensing loop corresponds to temperature, the other half to strain so that both temperature and strain are measured in a single operation whilst thermal compensation is applied to the later one. Such a cable is shown in Figure 2 (see [2]).

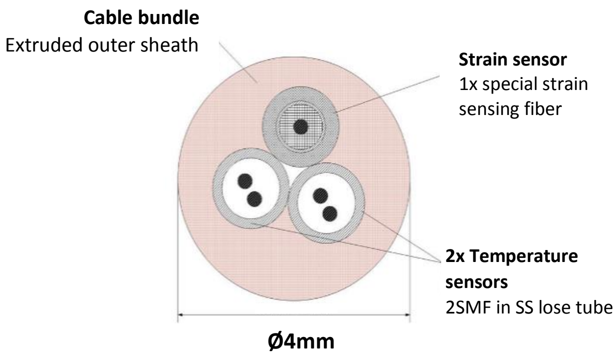

Figure 2: Combined temperature and strain sensing cable based on stainless steel FIMT.

1.4 Monitoring solution

Field applications require a complete solution, comprising dedicated sensing cable, integration methods and means of installing and commissioning systems in environments as diverse as offshore platforms or arctic conditions. But beyond the cables and the sensing methods, the key is the analysis algorithms that ultimately provide the alarms necessary to the asset monitoring. This is of prime importance, especially when multiple analysers are deployed in the field, each providing a portion of the final data used to monitor a particularly long or complex asset (for instance in [3], [4], [5] and [6]).

2 PIPELINE MONITORING

2.1 Sakhalin-Khabarovsk-Vladivostok pipeline

The 1800km long Sakhalin-Khabarovsk-Vladivostok pipeline route across Siberia is subject to considerable geohazards, including swamp areas, soil freezing and thawing as seasons change and unstable ground areas due to high seismic activity in Active Tectonic Faults (ATF) zones. Distributed monitoring is the only solution for such elongated asset. In this particular case, it combines ground movement measurement and pipeline 3D deformation [7].

Ground movement results in potentially large induced strain on the pipeline so that its monitoring provides early warning for buckling [8]. It is monitored based on a tight buffer FIMT with corrugated outer sheath and metal wire reinforcement regularly anchored in the soil. For highest risk zones, pipeline deformation (3D pipe positioning) is monitored using three strain sensors attached to the tube whilst a temperature sensor located on top of the pipeline provides thermal compensation for the strain measurement.

Altogether, strain sensors were deployed over a total of 26km of the pipe itself, using a specifically designed installation machine, in order to measure its 3D deformation, whilst more than 90km of ground movement sensors were buried to monitor no less than 32 ATF zones (Figure 3).

Figure 3: a) Automated machine for simultaneous integration of 3 sensors on a pipeline and b) example of field installation of 3D deformation monitoring.

2.2 Peru LNG transandean pipeline

The Peru LNG Pipeline Project is a transandean pipeline transporting natural gas from the production fields in the Peruvian jungle to a liquefaction plant on the Peruvian coast. Its route crosses region with high geohazard risks. The nature of terrain and the pipeline length is such that patrolling is difficult, making more acute the need for remote techniques. Since the beginning of the operation in 2010, several events have been detected by the fiber optic monitoring system (Figure 4, left) and correlated with field observations (Figure 4, right). Field work was performed to stabilise soil in different locations [6]; thanks to early detection, there was no damage to the natural gas pipeline.

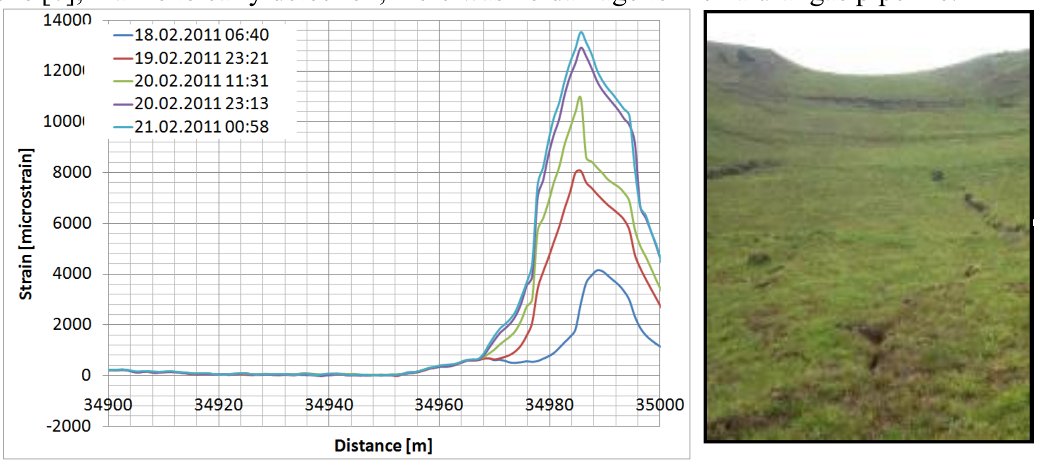

Figure 4: Near KP35, settlement and soil movement measurement (left) and effect in the field (right).

3 POWER CABLE MONITORING

Many offshore windfarms are now built at significant distances from the onshore substation (50km or more), requiring long HV export cables. Such cables are at risk of being covered with mud/sand resulting in local hot spot at constant load; similarly they are subject to threats such as dropped objects, anchor drag, etc. which may damage them and dramatically change their performance. In addition, as the load varies dynamically with the wind, monitoring temperature allows optimising the cable operation. As soon as an unplanned change in the temperature is logged, action can be taken; the load can be adjusted and/or that part of the cable can be investigated.

Omnisens DITEST Brillouin based technology has been installed on many projects, using a sensing fibre integrated within the energy cable using a loose FIMT design. Distances of over 65km can be monitored from a single interrogator located on shore, with accurate temperature information available every meter.

In autumn 2012, data were gathered on a power cable installed in shallow water. The temperature distribution was measured for different levels of generated energy, resulting in different temperatures, as shown in Figure 5 on the first 6km. On this section, two noticeable points showing sharp temperature transition were identified. They were correlated with a change in the burial depth (Figure 5, 2700m) and a variation of the water depth (Figure 5, 4750m). In other experiments, power cable crossings, resulting in local hot spots, have also been clearly identified.

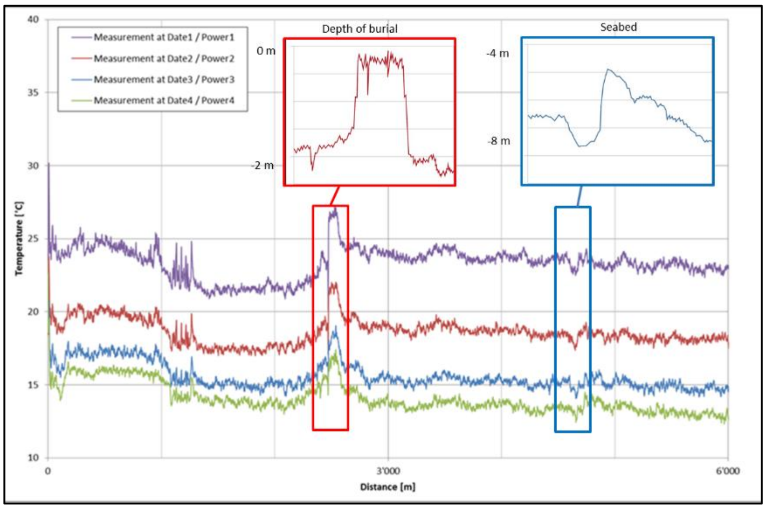

Figure 5: the effects of cable exposure and water depth on wind farm export cable temperature.

4 SUBSEA UMBILICAL, RISER AND FLOWLINE MONITORING

4.1 Heated flowline temperature monitoring

To prevent hydrates and waxes formation within subsea flowline during shutdowns or to maintain fluid temperature above certain critical levels during operation in the case on long tie-backs, the oil industry has developed electrically heated flowlines (Direct Electrical Heating DEH) and thermally insulated pipe in pipe (PiP) technology as an alternative to chemical hydrate inhibitors.

DEH cables are attached to the pipeline and supply large AC currents through the tube, resulting in the desired heating process. In the PiP approach, electrical heater are spread around the inner tube underneath the insulation material.

Two long DEH (23 and 43km) have been installed in the North Sea and monitored with OMNISENS DITEST Brillouin interrogators; several energization campaign allowed the identification of different heating behaviour [9].

An electrical trace heat PiP (6km long with a possible 19m tieback) was also installed in the North Sea; during test campaign, good matching between DTS measurement and theoretical modelling were found [10].

4.2 Umbilical dynamic fatigue monitoring

The Jack and St. Malo oil fields are located in the Gulf of Mexico; they have a water depth of around 2100m and are about 40km away from the closest platform. Due to this increased distance and depth, more power is required for subsea equipment, resulting in a 35kV power umbilical containing 2 circuits, each featuring three power conductors. The umbilical incorporate a monitoring system that improves construction validation, provides installation feedback, and allows permanent on-line temperature and strain monitoring.

The cable shown in Figure 2 was specifically designed for this project; it was integrated within PVC spacers in the centre of the umbilical (Figure 6, left) and provided tensile and temperature information. Multiple tests were carried out before, during and after manufacturing of the umbilical resulting in accurate measurement during the complete umbilical qualification testing and particularly during the flex fatigue test and the elongation test as shown in Figure 6, right.

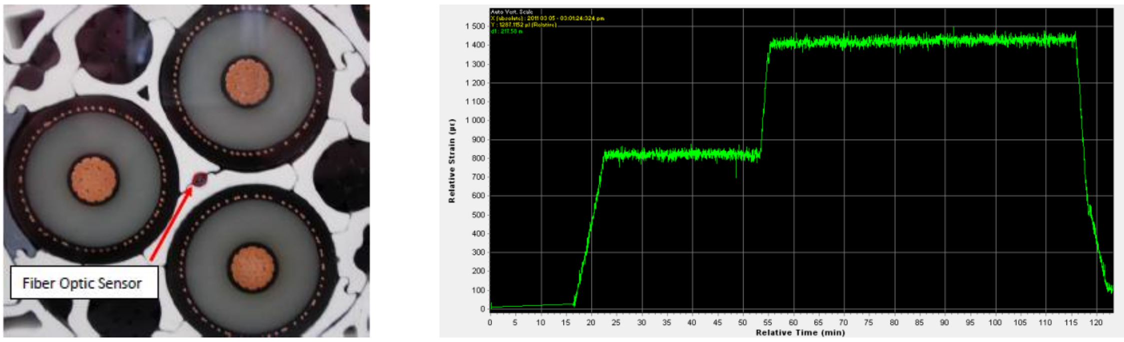

Figure 6: Fibre optic sensor embedded in PVC spacers (left) and tensile test strain measurement (right).

Thanks to a systematic approach to the design, integration, and validation, an effective distributed strain and temperature monitoring solution was successfully designed and qualified according to strict optical and mechanical criteria [2].

5 STRUCTURAL HEALTH MONITORING

The Götaälvbron bridge is a more than 1000m long combined road and light-rail bridge in Sweden; it was built in 1939. The bridge is reaching the end of its design lifetime and must be replaced. Prior to replacement, a fibre based monitoring has been installed to measure total change in strain along the whole structure whilst a specific algorithm was design to look for cracks in concrete (namely to find sub spatial resolution event). The system allows detecting 10.5mm cracks over 10cm, using a spatial resolution of 1m (Figure 7).

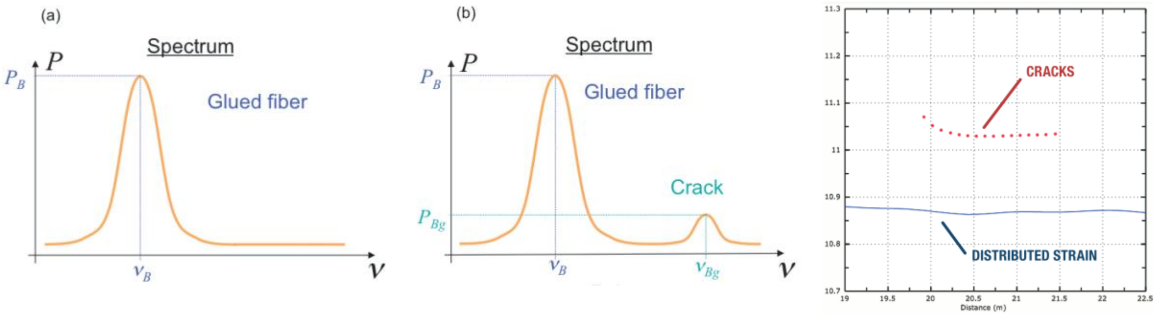

Figure 7: Crack effect on Brillouin spectrum (left) and results in the measured values (right).

Strain sensor in a thin tape like shape were designed, produced and integrated onto the bridge featuring a total of 5km fully instrumented. Thanks to the instrumentation, bridge usage is permanently monitored until a replacement is in place ([11] [12]).

6 UPCOMING CHALLENGES

6.1 Ultra long distance

Remote offshore oil fields characterized by deeper deployments, longer tiebacks and subsea completion are now under investigation. These developments are located for instance in tropical regions subject to stormy weather or in extreme arctic conditions, thus requiring leak detection and flow assurance over distances exceeding hundreds of kilometres. Single topside equipment is the only reliable approach but is facing the challenge of reaching more than 300km sensing. A BOTDA is a good candidate due to its compatibility with optical amplification. A patent pending scheme, taking into account BOTDA specificities has been recently proposed featuring 330km linear sensing (on a 660km loop configuration) with 3m spatial resolution at the far end and a 2°C repeatability [13].

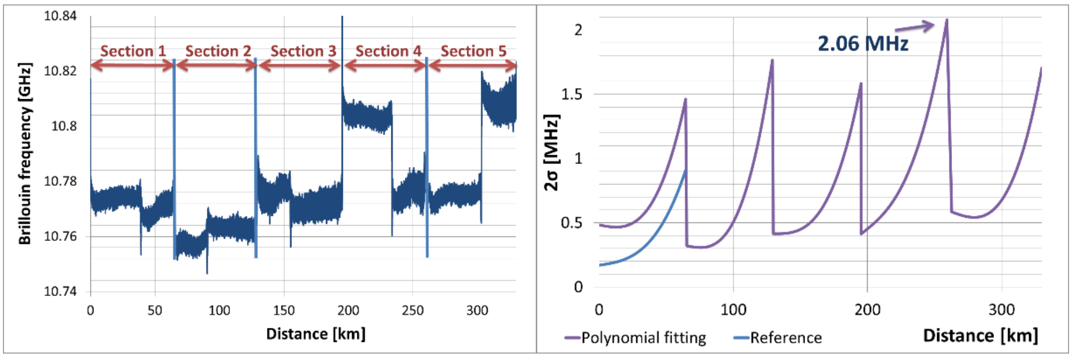

Figure 8: Evolution of the Brillouin frequency (left) over the 330km (different spools) and 2-standard deviation (2σ, fit over the measured deviation) over the measuring distance (right) for 3m spatial resolution.

The temperature variation of a 10m long hot spot could be clearly measured at the end of the fibre span.

6.2 High optical budget

Test have been carried out with optical fibres cables specifically designed to address temperature up to 350°C. Due to the cable concept (undisclosed), loss was temperature dependent so that during the trial, as much as 47dB total optical budget (the loop configuration) was reached.

Thanks to the compatibility of the DITEST with amplification and using a method similar to the approach described in §6.1, it was possible to perform accurat measurement in this case. Using 3m spatial resolution, a repeatability better than 2°C (2σ) was achieved, despite the loss.

6.3 Enhanced spatial resolution

There is a need for sub meter spatial resolution (of the order of 10cm) both for civil engineering and for fatigue monitoring of subsea structures. Unfortunately, it is not possible to simply shorten the pulse duration of a BOTDA; the acoustic waves response time involved in the corresponding stimulated Brillouin process limits this approach to around 1m. Several methods were proposed, amongst which the use of multiple pump pulses.

Recently, a double-pulse configuration was demonstrated [14]; two 2ns pulses separated by 2ns where launched into the fibre, resulting in a 20cm spatial resolution at 11km with a repeatability (2σ) of 1°C (corresponding to 20με for strain measurement).

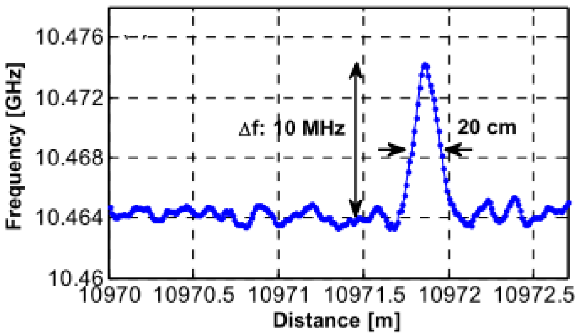

Figure 9: 20 cm hot-spot detection at 11 km distance using the double-pulse BOTDA configuration.

CONCLUSION

Distributed sensing of large oil and gas and energy industry structures using BOTDA with dedicated cable together with monitoring software for event detection, identification of abnormal trends and alarming has been successfully and reliably deployed in the field. It allows the operator to maintain their structure's integrity through efficient condition monitoring and to optimize their asset's performance over an extended period of time. The technology has also been successfully deployed for structural health monitoring.

In particular, a number of pipelines were instrumented for leak detection, ground movement monitoring and 3D deformation. Subsea umbilical riser and flowlines were instrumented, providing heat tracing, thermal response and fatigue monitoring. And large civil engineering structures were also instrumented, targeting crack detection and stability.

In many cases, new solutions were developed in terms of fibre optic cable designs, integration methods and monitoring algorithms. Due to the more and more challenging project, the technology is still being developed with significant steps towards longer distance, increased measurement speed and enhanced spatial resolution.

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