Distributed Fiber Optic Sensing Enhances Pipeline Safety and Security

*By J. FRINGS and T. WALK**

Abstract

Pipelines are efficient, highly reliable and safe means of transportation. However, despite intensive right of way surveillance by foot, car and out of the air, pipeline leaks and illegal tappings are a reality – sometimes with catastrophic results.
These events show a gap in real-time monitoring caused by the highly distributed nature of pipelines. Parts of this gap now can be closed with distributed fiber optic sensing technology.
Using various physical effects this technology is apt to detect temperature, strain, vibrations and sound with very good localization over spans up to 50 km with a single sensor cable.
Various field tested applications like leakage detection, third party activity monitoring and intrusion detection or ground movement detection as well as integrity monitoring proof that distributed fiber optic sensing can enhance pipeline safety and security.

1 Introduction

Pipelines are an important part of the infrastructure facilitating our modern communities' lifestyle and are indispensable for transportation of water, gas, oil and various other products.
As pipelines are often transporting large amounts of hazardous products any leakage of these systems does not only result in product and financial losses but may also cause environmental damages and even disastrous accidents.
In consequence, governments, industry associations and engineering companies have developed design, operation and maintenance standards for pipelines (e. g. TRFL [1] in Germany). Based on these standards the number of leak incidents dropped drastically since the 60's and early 70's of the last century. However, leaks and disastrous events still appear.
According to the European gas and oil transportation industries' recent statistics [2, 3] about 50% of all leak incidents are caused by third party activities followed by construction or material failure, corrosion and ground movement.
Since most of these third party activities would not result into leakages, if they are detected in time to intervene, it is clear that there is a gap in online monitoring along the complete pipeline's right of way.
Unfortunately this gap could not be closed with walking, driving or flying along the pipeline's right of way or classical point sensor technology like cameras and microphones due to prohibitive cost inclined with high number of required staff and literally thousands of point sensors including power and communication cabling along the pipeline route.
With the help of distributed fiber optic sensors at least parts of this gap can be closed. These systems are sensitive over their complete length (up to 50 km) and can detect temperature, strain, vibration and sound with good localization and absolute resolution. Since they are insensitive to EMC, designed for harsh environments and independent of additional field power supply or communication installations they are optimally suited for highly distributed pipeline monitoring applications and have been applied in a number of applications as will be shown below, after a short overview to the distributed fiber optic sensing technology.

Fiber Optic Cables are Distributed Sensors

Fiber optic cables are standard equipment for transmission of voice, video and SCADA data. They are frequently installed along pipelines and often used to enable communication between remote control units of individual stations of the system.
The same standard optical fibers (typically single mode type) are suitable to measure several physical effects with high absolute and local accuracy.

2.1 Scattering

Fiber optic cables are typically designed such that scattering effects are minimized to maximize transmission distance and data rate. However, it could be shown that some scattering effects of injected laser light depend on the fiber optic cable ambient conditions (temperature T, strain ε) [4] as shown in Figure 1.

1) *Rayleigh scattering:*
Elastic scattering of light based on density and composition fluctuations within the cable material. Scattering itself is not sensible to ambient conditions, but used for fiber integrity sensing and interferometric sensing applications.

2) *Raman scattering:*
Inelastic scattering of photons due to molecular vibration within the fiber material. The magnitude of the molecular vibration and the scattered signal is influenced by the environmental temperature.

3) *Brillouin scattering:*
Based on time dependent density variations of the fiber material. The wavelength of the scattered signal is depending on the ambient temperature and the strain or vibration of the optical fiber.

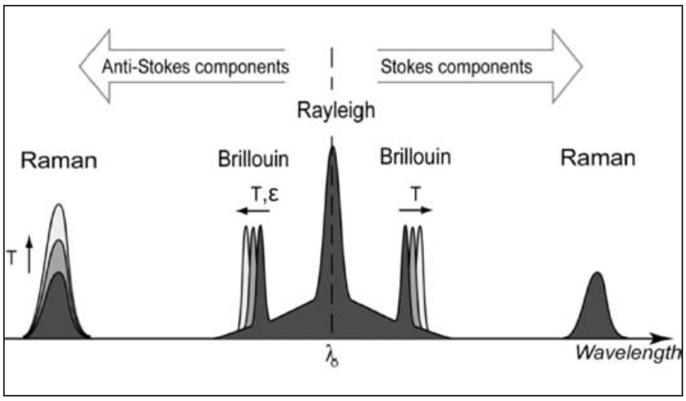

Fig. 1 **Scattering effects in fibre optic cables caused by temperature T or strain ε [4]**

To analyze the scattering signals, variations of the well known optical time domain reflectometer (OTDR) are applied. These devices send short laser pulses into the fiber and analyze the time-distance related scattering signals.
Although by itself not sensible for envi-

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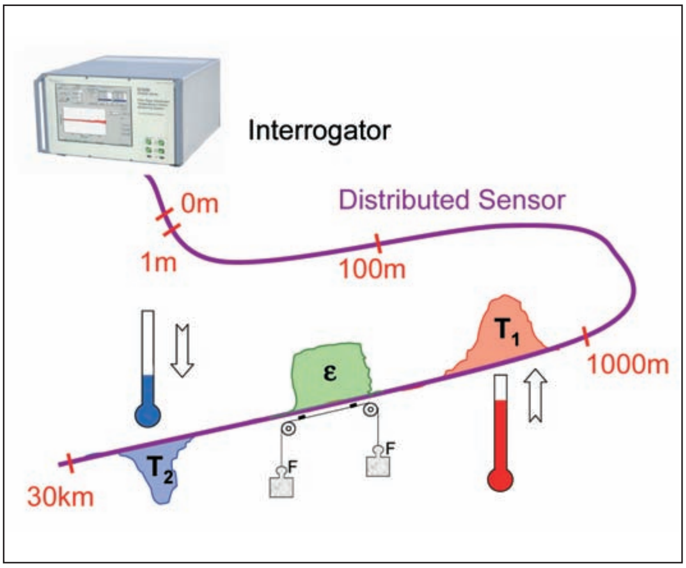

Fig. 2 Brillouin scattering: Temperature and strain profile along optical fiber [8]

ronmental conditions, Rayleigh scattering can be used for detection of strain and sound, if the highly increased sensitivity of the coherent OTDR (C-OTDR) [5, 6] is applied in combination with advanced computational algorithms. This way individual composition fluctuations (originally considered to be noise) can be detected thus creating a "fingerprint" of an individual fiber. As it can be assumed that the composition fluctuations do not move inside the fiber during the measurement any changes to this fingerprint can be interpreted as disturbances to the fiber which can be caused by strain, vibration or sound. As an example current implementations allow to have virtual microphones every 10 m of the fiber and to detect sound up to 1.25 kHz [7] e. g. from pedestrians, trucks, manual digging or excavators over distances up to 30 m from the cable.

In combination with spectrum analyzers (Brillouin) or frequency filters (Raman) it is possible to analyze frequency and amplitude of the scattering signal. Thus with Raman systems the temperature and with Brillouin systems temperature and strain can be detected (Fig. 2).

Multiple products are available on the market (e. g. [8–11]). Typical temperature resolution is in the range of 0.1 K, while strain resolution can be in the area of 20 με, both with a local resolution in the range of 1 m, while the absolute ranges largely depend on the cable construction. In all cases improvement of resolution corresponds to increased time for measurement and hence both have to be adapted application specific. Maximum sensor lengths for single mode fiber based Raman and Brillouin systems typically are in the range of 30 to 50 km, while multi mode fiber based Raman systems typically having a reach of up to 8 km.

While for Brillouin scattering temperature measurement can be implemented with standard telecom cable constructions (loose tube) which decouple the fiber from external strain as much as possible, for strain measurements temperature compensation has to be implemented. This can be achieved by using two fibers in parallel: One coupled to cable sheath or strength member to measure strain changes; the other fiber installed nearby and strain relieved to measure the temperature.

Based on strain sensing various vendors offer also detection of vibration (changing strain).

2.2 Interferometers

For more than a century interferometers have been a well known optical solution to detect very small changes of distances and the interferometer principles have been successfully applied to fiber optic measurement configurations since the early days of fiber optics.

With the advent of modern fiber optic components and using the constantly improving computing performance for improved measurement signal analysis research projects and several vendors developed configurations that can work as distributed microphones/hydrophones with high sensibility and good location accuracy.

For example a fiber optic configuration according to the Mach-Zehnder Interferometer can detect sound waves or vibrations by analyzing signal interference between two separate sensor fibers [12] and thus can act as a hydrophone (Fig. 3).

The interferometer can manage a sensing distance up to 40 km and its sensibility is at least up to 3 m radius around the fiber optic cable.

According to [13] another system sends two accurately timed pulses and analyses the interference of the Rayleigh scattering signals and thus is able to detect sounds in a range up to 9 kHz and over distances up to 50 m from the sensor. Sensitive cable length of up to 50 km is claimed to be possible.

Another approach to overcome the weak locating capabilities of standard interferometers is described in [14] were an interferometer is combined with Brillouin instrument. While the interferometer allows precise analysis of the event, the Brillouin instrument allows locating the event precisely.

3 Pipeline Applications for Distributed Fiber Optic Sensors

Based on the above it becomes clear that distributed fiber optic sensors are almost ideal for many types of pipeline monitoring applications and several of these applications have been implemented during recent years all over the industry. Unfortunately it is not possible to give a complete overview and thus the following should be considered as examples only.

3.1 Leak detection

Loss of transported medium due to pipeline leaks typically results into one or more of the following detectable effects:

– Local cooling due to Joule-Thomson effect (high pressure gas pipelines)
– Soil temperature change due to temperature difference between soil and emanated fluids and due to evaporation effects
– Especially in high pressure applications the emanating medium generates detectable sounds.

Based on Raman or Brillouin scattering effects these temperature changes in relation to soil temperature can be detected. Hence the application of distributed temperature sensing has been reported for natural gas, brine, phenol, sulfur, LNG, crude oil and other mediums. Even very small leaks (for example [4, 9, 10] can be detected, if the application configuration guarantees sufficient temperature effects. Compared to the conventional intrinsic Pipeline Monitoring methods this approach has the additional advantage to be completely independent of any process conditions. Even the periodical opening and closing of small leaks in gas pipelines due to freezing effects can be identified with modern signal analysis methods.

For offshore pipelines the application of leak

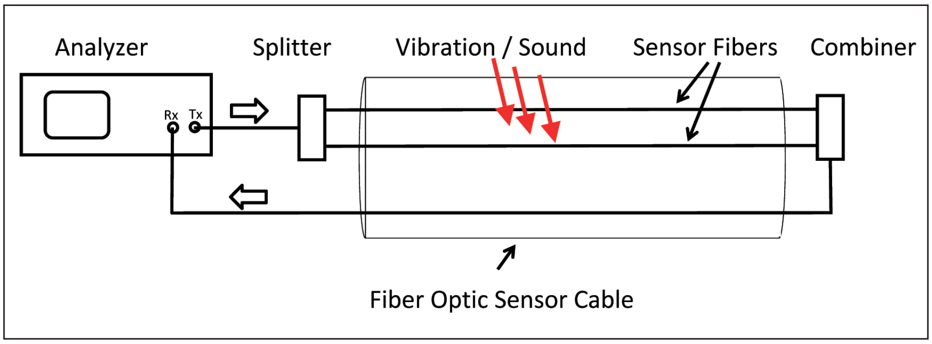

Fig. 3 System block diagram presenting fibre optic interferometer

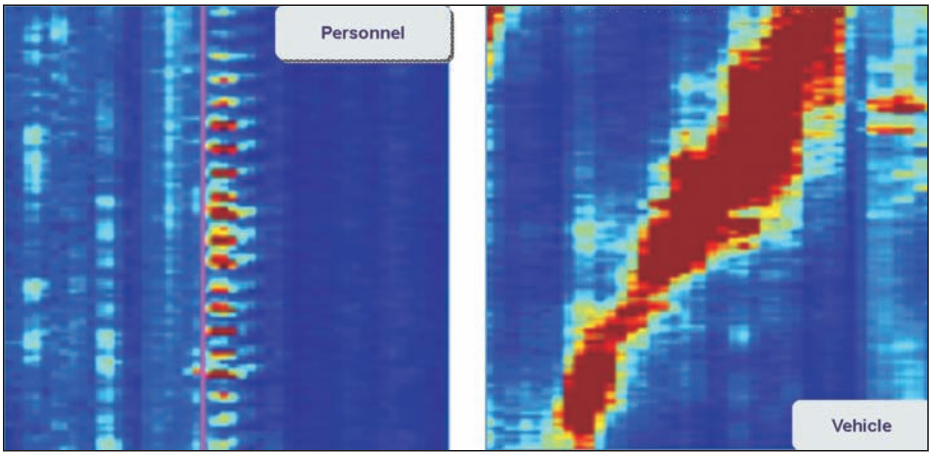

Fig. 4 "Waterfall" diagrams indicating patterns of walking person and SUV [7]

sound detection is reported in [9] based on a Brillouin strain measurement system.
Despite its good detection capabilities, distributed temperature sensing is used in all cases to improve the performance of computational monitoring systems and this is not only because these systems have been installed at pipelines which already had computational monitoring systems. It is because it is very hard to guarantee a minimum detectable leak size or a maximum detection time which in many cases are necessary to receive pipeline operation licenses.

3.2 Third party activities

The majority of all reported pipeline leak incidents has been caused by third party activities including construction and agricultural works, illegal tapping and intentional damaging. By applying C-OTDR based [15], distributed strain sensing based (e. g. [9, 10]) or interferometer based hydrophones (e. g. [12, 13]) along the pipeline or other buried infrastructure, it becomes possible to detect third party activities along the pipeline.
High performance computational signal analysis is necessary to identify and separate walking persons, farming machines, underground construction works, digging, tapping and other events which are subject of a specific training phase.
As shown in Figure 4 different attempts can be clearly separated visually and via the computational analysis (X-axis: length of sensor cable, Y-axis: time, color: signal strength). Based on this analysis it becomes possible to create alarms like "Manual digging at KP 71+290" or "Heavy Vehicle on the maintenance road at KP 52+340" on the pipeline operators screen via the SCADA alarm list.
It is emphasized that higher sensibility in terms of e. g. distance in which a pedestrian can be detected does not automatically proof to be an advantage as it might also increase the number of false alarms considerably.
As an example the system installed along the BTC pipeline [15] could detect a third party activity including manual digging. Because knowing the exact location of the event, immediate response could prevent illegal tapping and consequential environmental and financial damages.

3.3 Ground movement detection and structural health monitoring

Geohazards like earthquakes, landslides and surface subsidence damages result into ground movement and increase mechanical stress on pipelines, tunnels and other underground infrastructures. Distributed fiber optic strain sensors have been applied to identify the endangering ground movements:

– Strain sensing fibers have been attached directly to the pipeline walls to measure the walls' strain changes [16–18] or in parallel and close to the infrastructure [11] be warned on consequential movements and deformations. In case a sudden strain increase or movement is detected, the pipe's process pressure can be reduced to minimize the total stress and such to reduce the risk of a leakage until a stress relief solution can be implemented.
– To monitor entire slopes movements improved grip between sensor cable and soil is required. Solutions such as geo-textiles with integrated fiber sensors or clamp on grips have been applied successfully.

While pipeline sections known to have an increased risk of ground movements have been monitored with point sensors already during recent years, distributed fiber optic monitoring can be installed along longer stretches of the pipeline. Thus also strain changes and movements due to ground works (e. g. trenchless installation of crossing pipelines and cables) can be monitored or detected.

3.4 Status monitoring of water mains

Pre-stressed concrete cylinder pipes (PCCP) are widely used in water mains. However in several cases PCCP did not show to be as durable as expected, which resulted in several water main ruptures with considerable damages and a large number of smaller defects resulting into water losses. It has been shown [19] that the stability of PCCP correlates with the number of broken wires inside the pipe. As the breaking wire emanates a special sound this can be detected by an acoustic sensitive fibre optic sensor installed inside the pipeline. Based on the pipe book a software package can than count the number of broken wires per pipe and can issue an alarm in case the total number of broken wires or the number of wires broken within a certain time period exceeds a limit.
Since the wire break event is only very short the pulsed Brillouin based acoustic detectors often do not detect sufficient information for clear identification of the wire break event. On the other side interferometers such as Sagnac- or Michelson interferometer analyse the signal continuously and such receive all available information about the wire break sound – but they are weak in locating the signal. Thus a combined interferometer and Brillouin detector is described in [14] and has been applied to several water mains in the United States of America.

3.5 Scrapper position detection

Acoustic sensors for third party activities are also apt to detect the sounds created by and thus to identify the position of scrappers [7].

3.6 Fire detection

Distributed temperature sensing with fiber optic cables is used as heat detector for fire detection [20] in tunnels. Because the cable is sensitive along its complete length and because the temperature can be detected within a wide range it becomes possible to identify already the development of fires when fire fighting is still very effective and to monitor the position of the hot spots while the fire spreads. In consequence ventilation and other fire fighting measurements can be coordinated efficiently.

3.7 Power cable and transformer monitoring

Power cable isolation (XLPE) typically is rated for an operating temperature of 90 °C. Especially in power cable tunnels, when cables are bundled and mounted to cable trays it is possible that this temperature is exceeded in high load situations. To this end distributed fiber optic temperature sensors have been installed inside the cable isolation (e. g. [21, 22]), so that a direct temperature assessment becomes possible with high local resolution and thus countermeasures can be initiated easily.

Engineering Aspects

Standard telecom cables are optimized for long distance signal transmission with buffering against strain (e. g. jelly field tubes) and other environmental influences (e. g. multiple sheath layers) and thus not optimal for all kinds of measurements. In consequence various application specific cable constructions are available in the market. For example certain cable profiles ease mounting of the cable to the pipeline's or bridge's surface, un-buffered fibers support strain measurements and certain sheath constructions allow high temperature measurements.

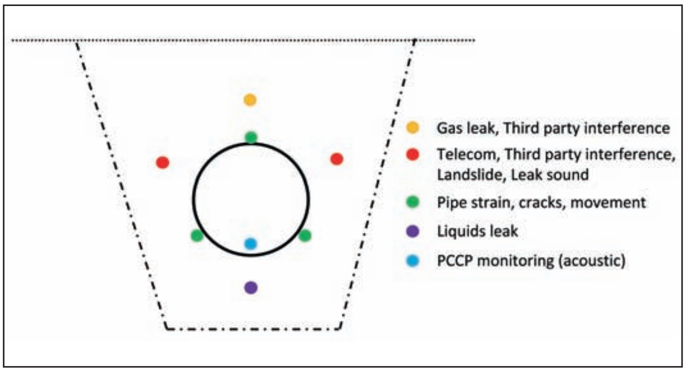

Fig. 5 **Application specific sensor location along pipeline**

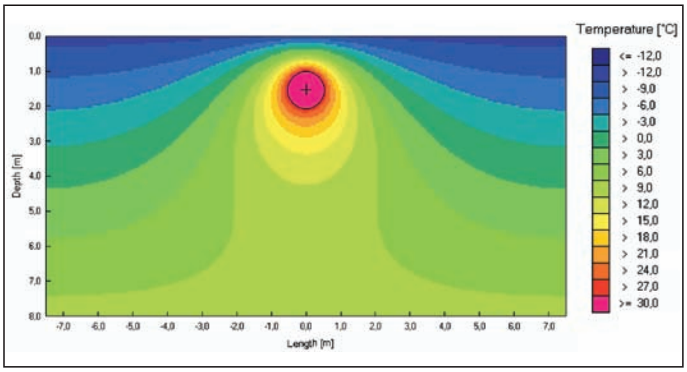

Fig. 6 **Soil temperature profile around oil pipeline (winter)**

Of course the sensor position is important for correct measurements. Typical locations of the sensor cables relative to a pipeline are indicated in Figure 5. For leak detection the sensor should be installed below the pipe for fluid and on top for gaseous mediums, while pipeline strain obviously can be measured only, if the fiber is directly bonded to the pipeline. Typical gas and telecom cable positions are suitable for third party interference (if the soil cover does not exceed 1.5 m) as well as for ground movement detection.

To achieve a clear leak detection signal for fluid mediums at least 2 to 5 K temperature difference between the medium and the soil temperature around the sensor are required and it has to be proven that this minimum temperature difference can be guaranteed throughout all seasons and for all pipeline operation states to avoid blind periods. Even in case that the medium temperature is much higher than the uninfluenced soil temperature this is not always given, as the following example shows. It shows the results of our analysis for a crude oil pipeline under the assumption of 33 °C medium temperature and –10 °C air temperature after several weeks of continuous operation and allows estimation of the minimum necessary distance between the pipeline wall and the sensor cable (Fig. 6).

Finally calibration or training of the sensing systems and their analysis algorithms are essential to ensure high quality detection with minimum false alarm rates.

Conclusion

Distributed fibre optic sensing is a field proven technology for online monitoring of temperature, strain, vibration and acoustic effects over long distances with good localization. Like any other part of pipeline instrumentation these systems require proper engineering and calibration or training to ensure the desired results.

Despite frequent release of new products with improved sensing technology and signal analysis methods there is no need to delay installation of distributed fiber optic systems. This is because future products most likely will use the same fibers and thus can be easily mounted on sensing cables installed today.

Finally it can be concluded that in case maintenance and intervention teams are well organized distributed fiber optic sensing can indeed enhance the pipeline's safety and security considerably.

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