Pipeline Leak Detection using Distributed Fiber Optic Sensing

By J. Frings and T. Walk

Based on continuously improved state of the art for design and operation of pipelines the number of pipeline leak incidents could be reduced considerably. However, quick leak detection and localization still are the key to minimize the impact on population and environment. Various leak detection systems for enhancement of the standard computational monitoring systems are available. Out of these distributed fiber optic sensing has proven to be very well suited for pipeline monitoring, as a single sensor cable can cover up to 30 kilometers of pipeline and a leak can be detected with a few meters precision. Short overviews of the basic principles for distributed fiber optic sensing systems as well as about their application to pipelines are provided.

Introduction

Pipelines for oil, gas and other mediums are an indispensable part of modern world's infrastructure. Although being well known for high efficiency and safety, potential pipeline leaks and their influence on population and environment are still a major concern.

In consequence today all countries have regulations and policies to ensure safe pipeline operation (e.g. [1], [2]). In all cases the following two lines of defense are required:

1. Prevention of any leakage or pipeline damage due to high quality standards and procedures during pipeline construction and operation (primary pipeline safety)
2. Minimized impact on population and environment in an unlikely case of leakage due to reliable, sensible and prompt leak detection systems (secondary pipeline safety)

To ensure secondary pipeline safety, it is required typically that two independent continuously working leak detection systems are active during steady state operation. One of these systems needs to detect leaks also during transient and standstill conditions. Furthermore a system needs to be in place which can identify the leak location quickly to allow precise deployment of remedial activities.

Today Computational Pipeline Monitoring (CPM) systems are state of the art and analyze real-time SCADA information like pressure, flow and temperature to estimate the hydraulic behavior of the transported medium as a basis for identification of leak related anomalies and leak location. However, although widely applied these systems are challenged during transient process situations.

In addition to these intrinsic leak detection systems various types of extrinsic systems have been developed during recent years out of which distributed fiber optic sensing is considered to be a highly promising technology. This is because it is possible to detect various physical effects of pipeline leaks over monitoring sections of up to 30 kilometers with localization accuracy down to a few meters.

When considering improving leak detection systems it is important to know the most frequent leak causes. Thus, the next section will focus on leak statistics for oil and gas pipelines.

Recent Oil & Gas Pipelines Leakage Incident Statistics

The oil companies' European association CONCAWE for environment, health and safety in refining and distribution is collecting spillage data on European cross-country oil pipelines since 1971 (**Table 1**). Approximately seventy companies and agencies operating oil pipelines in Europe currently provide data for the CONCAWE annual survey [3]. These organizations operate over 150 pipeline sys-

Table 1: Oil pipeline incidents derived from CONCAWE report [3]

cold pipelines	1971-1980		1981-1990		1991-2000		2001-2006		2007	
	spillages per 1.000 km	% of total	spillages per 1.000 km	% of total	spillages per 1.000 km	% of total	spillages per 1.000 km	% of total	spillages per 1.000 km	% of total
external Third Party	0,31	41%	0,19	38%	0,14	40%	0,14	44%	0,20	77%
Natural	0,04	5%	0,02	4%	0,01	3%	0,01	2%	0	0%
Corrosion	0,12	16%	0,12	24%	0,07	20%	0,06	20%	0,06	23%
Operational	0,06	8%	0,06	12%	0,03	9%	0,01	3%	0	0%
Mechanical	0,23	30%	0,11	22%	0,10	29%	0,10	31%	0	0%
	0,76		0,5		0,35		0,31		0,26	

Table 2: Classification and occurrence of gas pipeline incidents within EGIG report [4]

Cause	Overall Percentage [%]
external third party interference	49,6
construction defect / material failure	16,5
corrosion	15,4
ground movement	7,3
hot-tap made by error	4,6
other and unknown	6,7

tems, which, at the end of 2007, had a combined length of 34.721 km.

CONCAWE is reporting 9 spillage incidents in 2007, corresponding to 0,26 spillages per 1000 km of line, just under the 5-year average and well below the long-term running average of 0,55. This has decreased continuously from a value of 1,2 in the mid 70s. Of the 9 reported incidents in 2007, 2 were related to corrosion and 7 were connected to third party activities either accidental or malicious. Within the previous CONCAWE report 12 spillage incidents have been registered in 2006, half of these were related to mechanical failure, 2 were related to corrosion and 4 were connected to third party activities.

Optimized design as well as technically advanced and improved maintenance and operation procedures according to the always improving state of the art contributed to this continuous reduction of leakage incidents for almost four decades. On the long run, third party activities are still the main cause of spillage incidents although many measures for improved protection of the pipeline right of way have been implemented.

A very similar statistic is provided regularly by the European Gas pipeline Incident data Group (EGIG) [4], (**Table 2**). Transmission companies of fifteen European countries collect incident data on almost 130.000 km of gas pipelines every year. Analysis of incident causes gives an insight to which causes effort should be focused.

One of the conclusions of the 7th EGIG report shows that the main cause of incidents remains to third party interference and this is true also for the past five years with 48 % of all incidents. The relatively high contribution of external third party interference emphasizes its importance to pipeline operators and authorities.

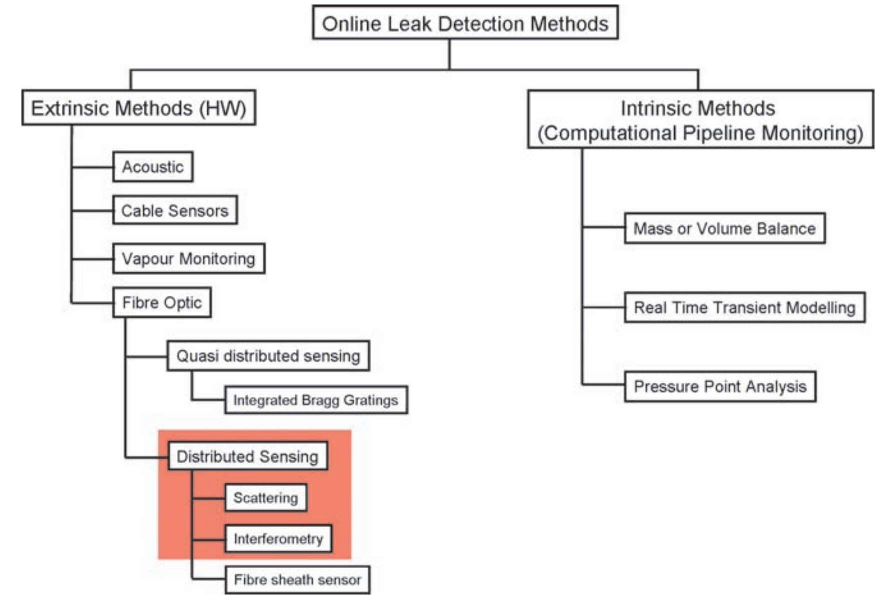


Fig. 1: Online Leak Detection Methods

Online Leak Detection Methods

Being part of secondary pipeline safety it is each leak detection system's target to minimize the leak impact to population and environment by detecting and locating the leak as soon as possible (within seconds and up to several minutes). Only online leak detection methods which can monitor the pipeline continuously are able to do so. In comparison other methods such as intelligent pigging and walking along the pipeline have comparatively high reaction times (days to weeks) and thus typically are applied for integrity status monitoring only.

In general intrinsic and extrinsic online leak detection methods can be distinguished (see **Figure 1**).

As already mentioned, it is state of the art to install intrinsic Computational Pipeline Monitoring Methods which utilize the available real time process data of the Control Center SCADA application software by using mathematical algorithms basis for identification of leak related anomalies and leak location. The intrinsic methods form an integrated part of the SCADA system and they are focused on mass or volume balance, do pressure point analysis or calculate a Real Time Transient Model.

On the other side extrinsic leak detection systems always require to install additional sensors and other hardware along the entire pipeline. All of them detect one or more effects of a pipeline leak: sound effects, leaking medium outside the pipeline and temperature effects caused by temperature difference between medium and soil or by the Joule-Thompson-Effect for relaxing gaseous mediums. All of them have to provide solutions for the stretched nature of the pipeline without the need for installation of a large multitude of sensors to keep the detection system affordable and maintainable.

Acoustic sensing methods use the sound waveguide features of the pipeline. Microphones are installed along the pipeline in large distance and thus can detect the sound of e.g. an excavator hitting the pipeline. Based on the runtime difference detected between the adjacent microphones the leak location can be calculated.

Cable sensors typically are metallic cables that are installed along the pipeline such that the emanating medium can touch the cable. Since the cable sheath reacts on the medium with local changes to the electro-magnetic features of the cable, the leak location can be detected. The same approach is available based on fiber optic technology.

Vapor monitoring systems are based on porous "sniffing" tubes which allow vapor gases of the emanated medium to enter and which are installed along the pipeline. In regular intervals the gas inside the tube is pumped into gas analyzers and thus the leak location can be detected.

All of these systems require the installation of sensors and analyzers together with power supply and communication facilities in distances between several hundred meters up to several kilometers.

In quasi distributed fiber optic sensors a series of individual Bragg gratings which themselves are point sensors are spliced into a fiber. Since the number of sensors in a fiber is

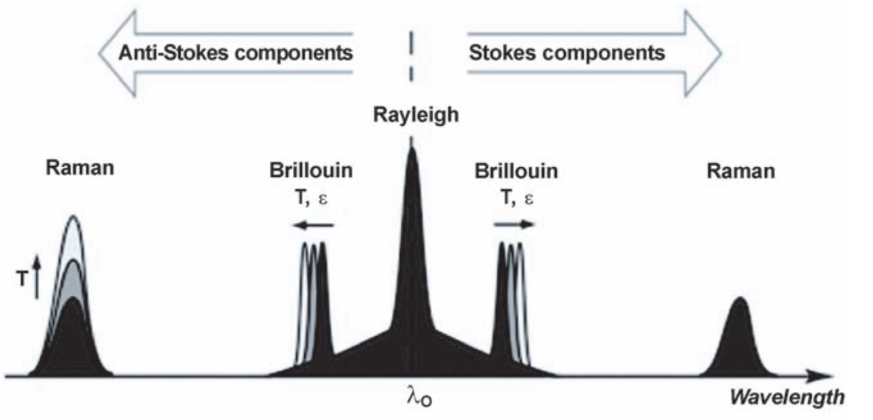


Fig. 2: Scattering effects within fiber optic cables caused by temperature [T] or strain [ε]

limited, they are not apt for leak detection of complete pipelines, although the sensor fibers can stretch for many kilometers.

Only distributed fiber optic sensing methods are suitable to cover typical distances between stations of pipelines (20 to 60 kilometers) without need for additional installations needing power supply and communication in between.

With distributed fiber optic sensing, physical effects of standard telecommunication fibers are applied to measure temperature and sound effects of leaks as will be presented in the next sections.

For an almost complete overview on leak detection methods be referred to [5].

Fiber Optic Cables as Distributed Sensors

Fiber optic cables are standard equipment for transmission of voice, video and other data and are frequently installed along pipelines to enable communication between and remote control of individual stations.

The same standard optical fibers (typically single mode) are suitable to measure several physical effects with high absolute and local accuracy.

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]) [6] as shown in **Figure 2**.

- Rayleigh scattering:
  Elastic scattering of light based on density and composition fluctuations within the cable material. Not sensible to ambient conditions.
- Raman scattering:
  Inelastic scattering of photons due to molecular vibration within the cable material. The magnitude of the molecular vibration and the scattered signal is influenced by the environmental temperature.
- 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.

To measure these effects advanced and specialized optical time domain reflectometers (OTDR) are applied. These measurement devices send short laser pulses into the fiber and analyze the time-distance related reflection/scattering signals with regards to frequency and amplitude of the desired scattering effect. In consequence it becomes possible to measure strain and temperature along the fiber, as shown in **Figure 3**.

Multiple products are available on the market. Typical temperature resolution is in the range of 0,10 K, while strain resolution can be in the area of 20 με, both with a local resolution in the range of 1m, 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 Brillouin based systems typically are in the range of 20 to 30 kilometers.

While for Brillouin scattering temperature measurement can be implemented with standard telecom cable constructions 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 e.g. the pipeline 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).

Interferometry

A fiber optic configuration according to the Mach-Zehnder Interferometer can detect sound waves or vibrations by analyzing signal interference between two separate fibers [7] and thus can act as a hydrophone (see **Figure 4**).

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. The intelligent signal analysis can identify and separate farming machines, underground construction works, digging, tapping and other events which are subject of a specific training phase.

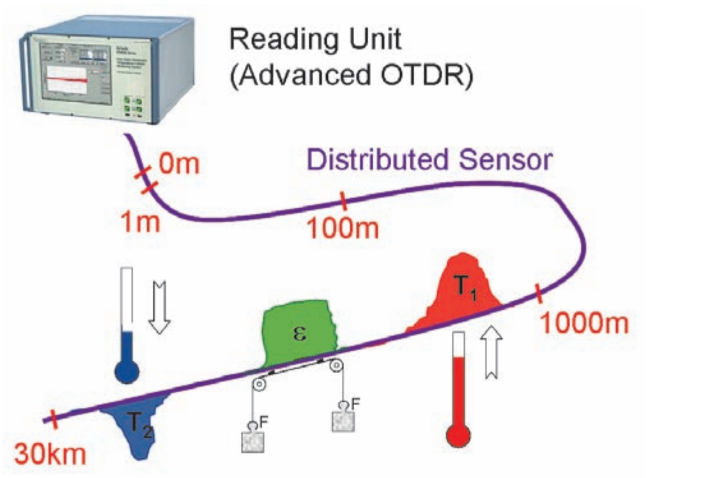


Fig. 3: Temperature and strain profiles along optical fiber

Application of distributed fiber optic sensors

Based on the above it becomes clear that distributed fiber optic sensors are almost ideal for pipeline applications. As a result various applications have been developed during recent years.

Leak Detection

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

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

Based on Raman or Brillouin scattering effects the temperature changes can be detected, if the medium temperature is different from the soil temperature. Hence distributed temperature sensing has been reported to be applied for natural gas, brine, phenol, sulfur, LNG, crude oil and other mediums and allows detecting even very small leaks [6, 10, 11]. Compared to the 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 sound detection is reported in [10] based on a Brillouin strain measurement system.

Distributed temperature sensing is used in all cases to improve the performance of computational monitoring systems. This is not only due to the fact that distributed temperature sensing has been installed at pipelines which already had computational monitoring systems. Although distributed temperature sensing is a well proven technology that has shown to be able to detect very small leaks in short time, it is very hard to calculate the minimum detectable leak size or to guarantee a maximum detection time which in many cases are necessary to receive pipeline operation licenses.

Ground Movement Detection

Geohazards like earthquakes, landslides and surface subsidence result into ground movement and thus put additional stress on the pipeline. Distributed fiber optic strain sensors have been applied in two ways to identify the endangering ground movements:

Strain sensing fibers have been attached directly to the pipeline to measure the pipeline walls strain and to conclude on the consequential pipeline movement [8] [9].

Strain sensing fiber optic cables are installed in parallel and close to the pipeline [13]. This method allows covering large route sections due to simplified cable installation method.

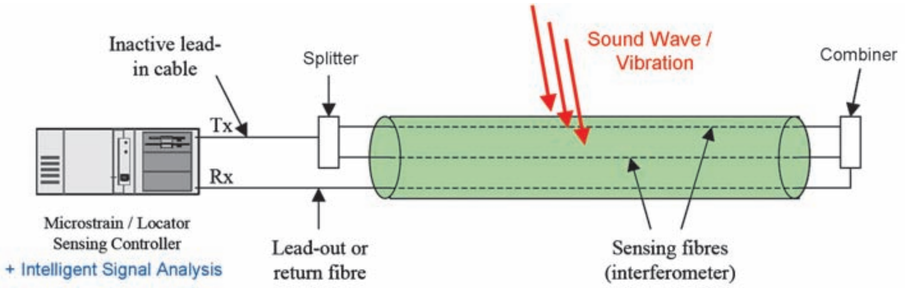


Fig. 4: System block diagram presenting fiber optic interferometer

Third Party Intervention

The majority of all reported leak incidents has been caused by third party intervention including construction and agricultural works, illegal tapping and intentional damaging. By applying distributed strain sensing (e.g. [10], [11]) or interferometer based hydrophones (e.g. [7]) along the pipeline, it becomes possible to detect approaching heavy earth working machines, actual digging (manual or machine supported), metallic contact with the pipeline and other sound and vibration signals. For example a Mach-Zehnder Interferometer according to [7] has been installed on the environmentally sensitive and remote Bolshomi Section of the BTC pipeline.

Cables and Cable Position

Since standard telecom cables are optimized for long distance signal transmission with protection of all fibers against strain (e.g. jelly filled tubes) or against environmental influences (e.g. multiple sheath layers), for measurement purposes these are not always the best solution. For example strain relieved fibers are not able to measure strain and thick multilayer sheaths increase measurement delay for temperature. In consequence various different measurement cable constructions are available in the market.

Typical locations of the sensor cables relative to the pipeline are indicated in the **Figure 5**. If the ground water level is below the pipeline, the sensor cable should be installed under the bottom to detect temperature changes due to leaking liquids and on top for leak detection of most 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 as well as for ground movement detection.

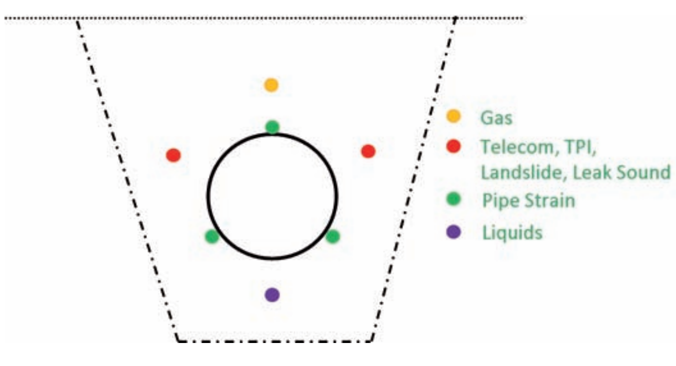
Conclusions

Distributed fiber optic sensing is well suited for surveillance and monitoring tasks along pipelines. This is because various physical effects like temperature, sound, strain and vibrations can be measured over long pipeline stretches with high location resolution and without need for intermediate power or communication services supply.

Distributed temperature and sound sensors have been successfully applied for leak detection purposes showing quick detection of small leaks and providing high location resolution, but can be applied only in addition to standard computational monitoring systems, since it is hard to provide absolute performance guarantees based on leak effects.

The additional features to detect vibration and sound can be used also to detect geohazards and other third party interventions and thus

Fig. 5: Application Specific Locations for Fiber Optic Cable



in time to intervene before the actual leak appears.

Like with all sensors and instruments careful system (sensor cable, signal analyzer) and solution design (cable position, cable fixation) are most important to measure and interprete the desired effects and require project specific engineering.

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Authors:

Tobias Walk
ILF Consulting Engineers GmbH, Munich

Tel. +49 89 255594-244
E-mail: Tobias.Walk@ilf.com

Jochen Frings
ILF Consulting Engineers GmbH, Munich

Tel. +49 89 255594-324
E-mail: Jochen.Frings@ilf.com