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AGIFAMOR – Application of distributed acoustic and fibre optic sensors for continuous monitoring of pipes

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Abstract

Pipelines and industrial piping systems are particularly relevant regarding technical safety, availability and maintenance. Large flow rates of hazardous substances imply that even smallest leakages can lead to high environmental impacts. Therefore, and to ensure the availability of infrastructure, an early detection and localization of potentially hazardous degradations to the walls (e.g. cracks, pittings, sedimentation, etc.) of the containments is necessary. However, in many cases it is not feasible to equip pipelines with a large number of point sensors at reasonable expense.

The principle of distributed fibre optic sensing relies on one single optical fibre, which simultaneously acts as a spatially continuous sensor as well as the signal transducer. Therefore, extensive structures can be provided with this type of sensor with comparatively low efforts.

As a consequence, monitoring oil and gas pipelines using distributed fibre optic sensors is on the upswing. Besides the established methods to measure temperature and strain, distributed acoustic sensing (DAS) has lately received considerable attention as a means to detect and localize third party threats to pipelines (approach of vehicles, digging, mechanical manipulation).

The so far not utilized potential of DAS as a means for continuous condition monitoring of pipes by detecting and localizing acoustic signals that point to certain damage scenarios, is currently under investigation in an interdisciplinary research project at BAM (AGIFAMOR, Ageing Infrastructures – Fibre Optic Monitoring of Pipes).

In order to qualify distributed acoustic fibre optic sensors for this application area, we especially focus on detecting and identifying the relevant acoustic emissions of interesting degradations as well as on the optimal way of application of the optical fibres to the specimen to achieve an optimal signal transmission of acoustic signals.

1. The project AGIFAMOR

The interdisciplinary research project AGIFAMOR – “Application of distributed acoustic and fibre optic sensors for continuous monitoring of pipes” was initiated at BAM in 2015 in order to test and qualify distributed acoustic fibre optic sensing methods (commonly known as **d**istributed **a**coustic or **v**ibration **s**ensing DAS/DVS) towards their potential as a condition monitoring system for pipes. It bundles competences from different divisions at BAM, namely “Fibre Optic Sensors”, “Acoustic and Electromagnetic Methods”, “Sensors, Measurement and Testing Methods”, “Gases, Gas Plants”, “Constructive Fire and Explosion Safety for Gases”, “Tanks for Dangerous Goods and Accident Mechanics” as well as “Service Loading Fatigue and Structural Integrity”.

The project is laid out as a feasibility study and should open up new ways for an improved detection of potentially dangerous modifications to pipeline structure. Herein, the project does not only focus on detecting and localizing the relevant acoustic emissions of interesting degradations, but also investigates the way of application of the optical fibre sensors to the specimen for an optimal signal transmission.

Application boundaries and sensitivity of this sensor technology are validated by means of innovative acoustic emission analysis methods and are checked against other non-destructive testing procedures commonly used in pipeline monitoring. Once the suitability of the acoustic fibre optic method has been proven, verified measuring procedures could be developed for the continuous monitoring of pipelines.

As a starting point, three main scenarios were identified, which are relevant for the envisioned application and can potentially be detected by DAS/DVS:

(1) incidents causing (dynamic) circumferential changes of the pipe or initiating propagation of acoustic waves in the pipe wall (e.g. pressure shocks and cavitation, external mechanically induced shocks/vibrations),

(2) changes inside the pipeline causing altered flow generated noise (corrosion, sedimentation, clogging, in extreme cases also noise caused by leakage),

(3) crack formation and propagation in the wall with accompanying acoustic emissions – detection is aspired before macroscopic crack opening or leakage occurs.

Scenarios (1) to (3) impose increasing challenges on the condition monitoring system regarding measurement sensitivity, localization and unambiguous identification of damage.

2. Fibre optic sensing technologies on pipelines

Distributed fibre optic sensors are gaining more and more attention in a lot of application areas, specifically for monitoring of extended structures/infrastructure (e.g. pipelines, bridges, dams, tunnels) as they allow for spatially and temporarily continuous determination and localization of quantities such as temperature, strain, acoustic signals/vibrations, etc.

Optical fibre sensors combine several advantageous properties that make them highly interesting for a number of different applications:

(1) Since they are rather small (diameters of < 0.5 mm for standard silica fibres) they can be easily applied to or even integrated into structures and materials with very little reaction and can be used in otherwise inaccessible areas.

(2) They show a high durability and measuring capability under adverse environmental conditions such as extreme temperatures (< - 200 °C until > 1000°C), chemically aggressive or explosive environments or within electromagnetic fields.

(3) Distributed, i.e. spatially continuous, measurements are possible over large distances (up to 100 km) with a typical spatial resolution of about 1 m. No additional supply lines or sensing elements are needed as the optical fibre itself simultaneously acts as the spatially continuous sensor as well as the signal transducer.

Currently, three main groups of distributed fibre optic sensing schemes exist and are employed in the context of pipeline monitoring: distributed temperature sensing (DTS), distributed strain sensing (DSS) and distributed acoustic or vibration sensing (DAS/DVS). Table 1 gives an overview of these techniques and their properties in the context of the targeted condition monitoring system. An overview of current techniques in distributed fibre optic sensing for pipeline applications can be found in [1-3].

Table 1: Comparison of distributed fibre optic sensing systems used for pipeline monitoring

Measurement system	**Time scale**	**Application next to the pipeline**	**Application on the pipeline**
DTS	"static" ~ minutes	detection of leakages	detection of hot and cold spots
DSS	"static" ~ minutes	detection of ground movements	detection of pipe deformations
DAS/DVS	"dynamic" ~ ms ~ kHz	detection of intrusion	AGIFAMOR: detection of damages, critical operating conditions

The most well-known and established technology used on pipelines is DTS. It is employed for leak detection and localization by observing small temperature changes – usually in the ground next to the pipeline, which are caused by escaping medium (Joule-Thomson effect). However, leakages can only be detected after spilling of the medium. Furthermore, DTS is a so called "static" method, which requires averaging of the signal in the range of minutes before the leakage can be registered.

Another static method to observe slow changes on pipes is given by DSS, which is particularly utilized in areas with high risk for ground movements and accompanying pipe deformation. In order to observe these deformations optical fibres have to be applied directly onto the surface of the pipe.

In comparison, DAS/DVS is a relatively new, highly dynamic method that can capture strain changes in the kHz range and is therefore able to register acoustic or vibrational signals [4, 5]. This technology has been gaining more and more attention within the last few years. One of its most prominent applications is third party intrusion detection, specifically on pipelines [1, 3, 6]. For this purpose, optical fibres are usually deployed in the ground along the pipeline, and vibrations caused by approaching vehicles, digging or even footsteps as well as mechanical manipulation on the pipe can be detected and localized in real time. In many cases existing fibre optic telecommunication cables may be used for this purpose.

In addition to this, the project AGIFAMOR aims at extending the application field of DAS/DVS towards a global condition monitoring system for pipelines operating in real time. In this case, characteristic signals of potentially critical alterations originate from within the pipeline or the pipe wall, and are expected to be rather low in acoustic intensity. Therefore, it will be a prerequisite for a successful detection, localization and identification of these signals to apply the fibre optic sensors onto the pipe itself and optimize the application procedure towards an optimal acoustic signal transduction.

3. Sensing principle

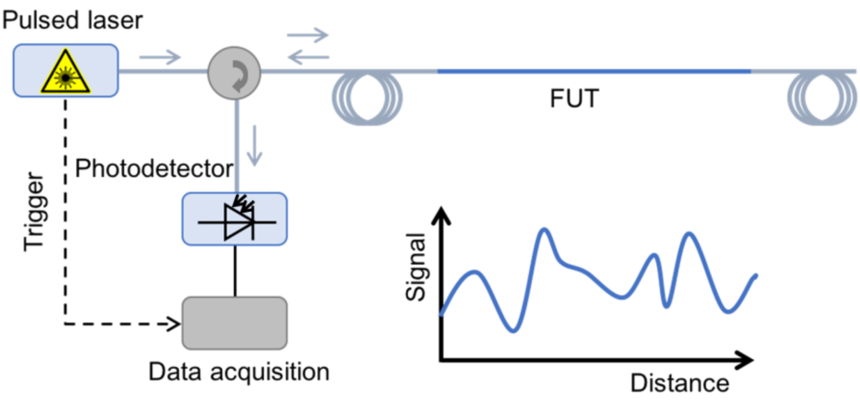
Besides a growing number of new developments of DAS/DVS systems on a research level, several commercial solutions are also available since recent years. These are mostly based on coherent Rayleigh time domain reflectometry (C-OTDR) [4].

The universal method of OTDR (optical time domain reflectometry) involves short laser pulses, which are launched into the optical fibre under test (FUT). Due to naturally occurring scattering processes (e.g. Rayleigh scattering caused by small variations of the refractive index in the fibre material) or also due to reflections on connectors or splices, light is reflected backwards and can be decoupled into a photodetector (Figure 1). The measured irradiance is recorded as a function of time, so that the corresponding position along the fibre can be deduced from the run time of the pulse. The resulting OTDR trace represents a “fingerprint” of the FUT. In conventional OTDR, these traces have to be averaged over a considerable span of time in order to receive sufficient signal-to-noise ratios; hence the term “static” method is used.

Coherent OTDR additionally exploits the coherence of the laser pulses. This leads to the detection of a Rayleigh backscatter induced speckle interferogram over time, which is very sensitive to small perturbations. Therefore, traces can be recorded and evaluated on a shot-to-shot basis and highly dynamic process along the optical fibre may be captured. As a consequence, the shortest detectable duration of impacts or rather the highest resolvable frequency is only limited by the technically settable pulse repetition rate and the total length of the FUT.

In the project AGIFAMOR, C-OTDR measurements are carried out using a Helios DAS system from Fotech Solutions.

Figure 1: Measuring principle of optical time domain reflectometry (OTDR)



4. Sensor application

One of the major tasks of the project AGIFAMOR is the development of a suitable application method for fibre-optic sensors adapted to industrial piping systems that will enable optimal signal transmission of highly dynamic acoustic signals and vibrations originating from the pipe. Besides influences of adhesives, fibre coating material and cable design as well as a possible interplay with temperature, different configurations of fibre sensor geometry on the pipe are explored. Lately, a number of studies have emerged addressing the latter in the context of geophysical applications [7-9].

Within the project, different alternatives for fibre application one-dimensionally along the pipe were investigated at first [10]. Here, a standard single-mode silica fibre (SMF 28, Corning) was fixed one-dimensionally along a laboratory scale (1 m length) stainless steel pipe using a two-component epoxy-resin adhesive (X280, HBM) in two sections. In one section, the optical fibre was glued to the steel surface along the entire length, while in the second section the fibre was only attached at nine specific positions equally spaced along the pipe (Figure 2a). An artificial signal was applied to the surface of the pipe using a piezo speaker embedded in silicone sending out bursts of 4 kHz signals and the response of the DAS system was tested for both cases. It was observed that attachment of the sensor to the surface of the pipe along the whole length of the fibre allows for an approximately 20fold more sensitive detection of the signal in this setup.

As the optical fibre is sensitive to (dynamic) strain changes only in the axial direction of the fibre, a very promising application geometry is given by a helical design, in which the pipe is enwound by the optical fibre. This should allow for an increased sensitivity towards circumferential changes as induced by pressure shocks or longitudinal sound modes propagating in the pipe wall. This design also entails an increase in spatial resolution. Possible disadvantages that should be balanced against this gain are a decrease in the total length of pipeline that can be monitored and a more complex instrumentation procedure. By using appropriate prestressing of the fibre, complete attachment to the pipeline surface can also be guaranteed for this design.

To test the performance of such geometry a different experimental setup was chosen, where an acryl glass cylinder was enwound densely by the optical fibre (38 m of fibre on 37 cm of pipe) (Figure 2b). In order to simulate a sound source from within the pipeline, the cylinder was filled with distilled water, into which the signal transducer was submerged. For comparison with the previous setup signals of 4 kHz were generated and transmitted in intervals of 1 s as well. However, due to the very high sensitivity of the setup, the voltage driving the piezo speaker had to be reduced by a factor 20.

Figure 2: a) Linear design: optical fibre glued to the surface of the pipe along the entire length and pointwise, b) helical design: optical fibre wound around the pipe

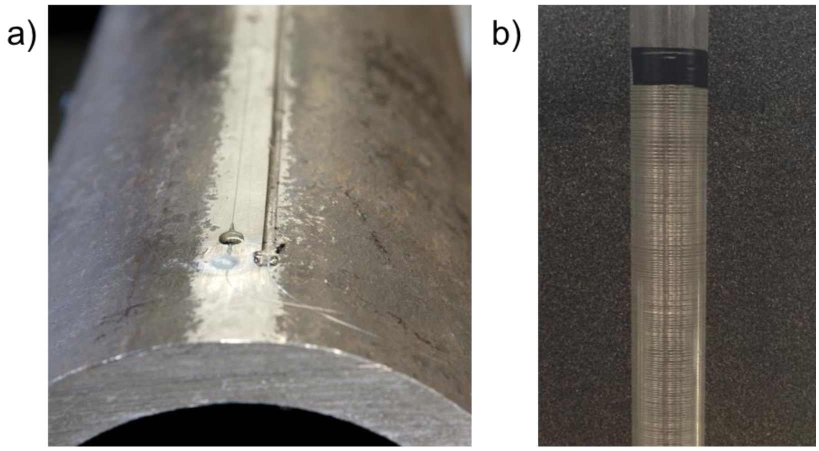
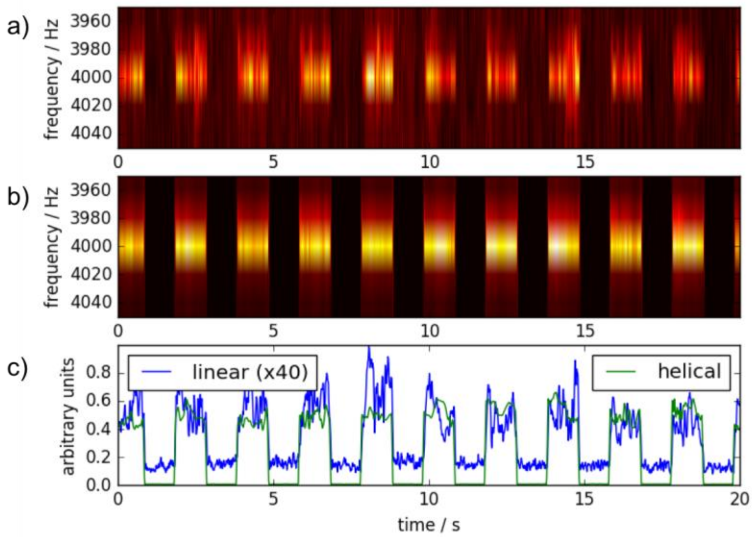


Figure 3: Total intensity of the recorded test signal around 4 kHz a s a function of time for a) linearly and b) helically deployed optical fibres, c) comparison of peak intensities acquired for the two setups after normalization according to total sensor length and transducer voltage



Figures 3 a) and b) show the total intensity of the recorded test signal around 4 kHz as a function of time for the setup with a linearly glued (as in [10]) and a helically wound optical fibre as described above, respectively. In each case the total intensity after summation over the whole length of the fibre, which was picking up the signal, is displayed.

For better comparison, the peak intensities are plotted after normalization according to total sensor length and transducer voltage in figure 3 c). It is clearly visible that even after correcting for the effect of more total sensor length in the case of the helical setup, this geometry still renders considerably higher signal intensities.

5. Loading tests and real-scale tests

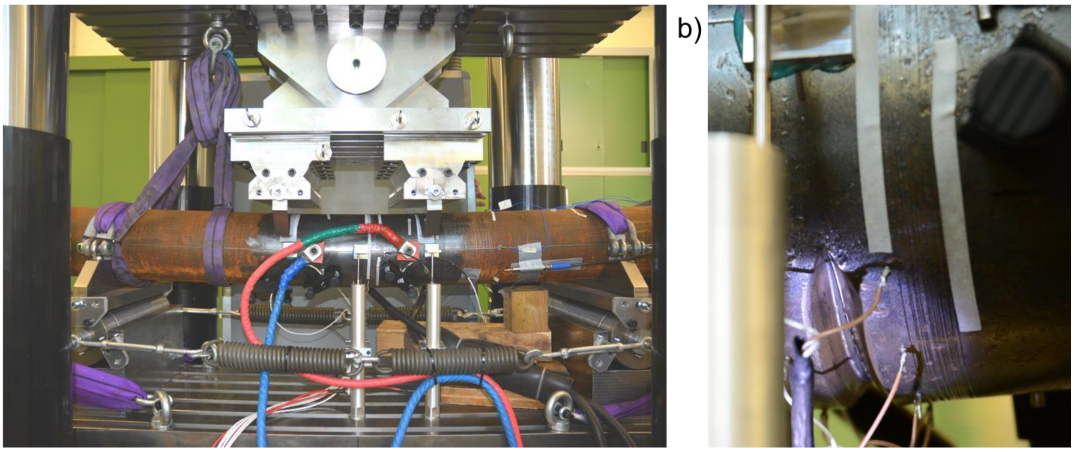
As a consequence from the laboratory experiments on the optimal sensor design, a helical geometry of the fibre optic sensor is pursued in subsequent loading tests on realistic models.

Loading tests were carried out in order to analyze the acoustic characteristics of ductile damage and cracks developing in the pipe material. Therefore, steel pipe segments (S355J2N, length: 2.5 m, outer diameter: 168 mm, wall thickness: 16 mm) were subjected to quasi-static loading within a 4-point bending test setup using a servo-hydraulic 4 MN test system. To induce stable crack growth, the pipes were initially damaged by a 90 °circumferential notch of 8 mm depth. During the tests, after plastic deformation and ductile damage in the ligament, a macroscopic crack grew through the wall until complete breakthrough (leakage).

The pipes were equipped with fibre optic sensors helically wound around the pipe close to the notch with a total applied sensor length of approximately 50 m. For comparison, acoustic emission analysis (AE), acceleration sensors and the DC potential drop technique were used to monitor acoustic activity in different frequency regimes as well as the crack growth. Figure 4 shows the fully instrumented pipe and the cracked pipe section at the end of the loading procedure.

Figure 4: a) Fully instrumented pipe segment under quasi-static loading in a 4-point bending setup, b) initial circumferential notch with macroscopic crack opening at the end of the bending test

a) b)



First results show that the time of crack initiation detected by the DC potential drop technique is in good agreement with results of former pipe test studies carried out at BAM and the first acoustic signals detected and localized in the vicinity of the notch by acoustic emission analysis. Although all three sensor systems used here for detecting acoustic activity are sensitive in a different frequency range, i.e. DAS up to 40 kHz, the employed acceleration sensors up to 25 kHz and AE from 20 kHz to 1 MHz, all of them were able to register strong acoustic events and an increased acoustic activity after reaching the maximum load. For a more quantitative comparison and evaluation of the sensitivity of DAS further bending tests under refined conditions are currently under way.

Additionally, real-scale tests on pipelines of 30 m length and diameters up to 300 mm, which may be flooded with gases or liquids, are planned in the course of the project AGIFAMOR. They will be carried out on the BAM test site for technical safety (BAM-TTS), where realistic conditions as encountered on industrial sites (e.g. background noise, aged pipe segments, changing environmental temperatures) may be simulated.

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