FEASIBILITY STUDY: CONTINUOUS MONITORING OF PIPES USING DISTRIBUTED ACOUSTIC AND FIBRE OPTIC SENSORS

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ABSTRACT

The feasibility study „AGIFAMOR. Ageing infrastructures – distributed acoustic monitoring of pipes” is an interdisciplinary research project at BAM internally financed from 2015 to 2018. Therefore, the quite young fibre optic sensing technology of distributed acoustic sensing (DAS) was investigated to possibly be extended towards a global condition monitoring system for pipelines operating in real time.

DAS is a highly dynamic fibre optic sensing technology based on the method of coherent optical time domain reflectometry (C-OTDR). DAS allows capturing strain changes in the range of kHz. For the experimental work, the most suitable application yielding an optimum sensitivity was proven by wrapping a standard single-mode silica fibre around the pipe.

The DAS sensitivity was investigated regarding the detection of 1) incidents that initiate propagation of acoustic waves in the pipe wall, 2) changes inside the pipeline causing altered flow and 3) damage development in the pipe wall. Therefore, several testing setups in laboratory as well as in real scale were realized. For comparison purposes, experiments were accompanied by acoustic emission analyses and by measurements with accelerometers.

DAS was found to be very sensitive to gas ignition and its propagation across the pipe. Furthermore, the ability of DAS to detect and localize acoustic signals associated with pipeline leakage was demonstrated. The detection of crack formation and propagation within the pipe wall by means of DAS was studied during bending tests on several pipe segments, but was not proven so far with certainty. As expected, these studies turned out as the most difficult challenge due to the random occurrence and transient nature of microscopic damage phenomena.

KEYWORDS: Fibre optic distributed acoustic sensing, Continuous monitoring, Acoustic emission, Accelerometers, Bending tests on pipe segments, Leak detection

1. INTRODUCTION

Small leaks in a pipeline transporting hazardous substances are a very high risk for humans and nature and have high and irreversible environmental impact. Thus, the early detection of damage and potentially critical degradation of pipeline is of crucial importance. Nevertheless, the large dimensions of oil and gas pipelines and the wide branches of pipework systems pose an immense challenge to the monitoring technology. Therefore, the technology of distributed sensing methods would be highly suitable, since, instead of numerous discrete sensors, only one single optical fibre would have to be installed serving as a spatially continuous sensor as well as signal transmitter. By doing so, hundreds of kilometers of already existing pipelines can be upgraded, and the installation effort could be kept at a minimum.

To this end, the feasibility study “AGIFAMOR. Ageing infrastructures – distributed acoustic monitoring of pipes” aims to identify potentials and limitations of the distributed acoustic sensing (DAS) based on fibre optic sensors for various pipeline monitoring tasks. Since DAS is a very young technology, preliminary studies focused on an optimized application of the fibre optic sensor to the pipe [1] as well as on adequate acquisition setups and data processing procedures. The studies also addressed the technological demands on the condition monitoring system regarding measurement sensitivity, localization and unambiguous identification of damage [2], [3]. Potentially critical pipe degradation scenarios that might generate characteristic acoustic signals had been identified. For each of these scenarios, experimental setups were designed in laboratory and/or in real scale:

1. Incidents causing dynamic changes of the pipe material, e.g. pressure shocks and cavitation, external induced vibrations.
2. Alterations of the pipe inner profile accompanied by changing internal medium flow in the pipeline, e.g. corrosion or sedimentation, also noise caused by leakage.
(3) Critical material degradation, e.g. crack propagation in the pipe wall.

2. **EXPERIMENTAL SETUPS AND TEST RESULTS**

2.1 DISTRIBUTED ACOUSTIC SENSING (DAS)

For DAS measurements, a standard single mode glass fiber SMF28e+ (Corning), with an Acrylate coating (core/cladding/coating: 9/125/250 µm) was used. Acquisition was performed with the Helios DAS system (Fotech Solutions). The measuring principle is based on coherent optical time domain reflectometry (C-OTDR) with a maximum pulse repetition rate of up to 80 kHz (bandwidth of 40 kHz) and optical pulse lengths of 10 ns up to 1000 ns (spatial resolution of 1 m up to 100 m). Raw data were processed by Fast Fourier Transform (FFT) in defined time intervals.

For reference, additional monitoring with accelerometers and acoustic emission sensors were employed, since these non-destructive testing methods are commonly used for periodic pipeline monitoring procedures.

2.2 GAS IGNITION TESTS

Gas ignition tests were carried out to monitor the propagation of pressure waves through the pipe after ignition using DAS. The tests were performed on a seamless DN30 pipe of 6 m length with a wall thickness of 4 mm. By using a winding machine, the fibre was wrapped around the pipe with 1 cm distance between the windings. To realize a good transmission of the circumferential changes of the pipe to the fibre, the fibre was pretensioned. Due to the windings, in total, 4 m of pipe length was monitored by approximately 47 m of optical fibre. Two different gas mixtures (propane/air, methane/air) and different pressure levels above ambient pressure (2-6 bar) inside the pipe were used for ignition tests. Ignition was carried out from one end of the sealed pipe and the pressure wave was monitored by DAS and additional pressure sensors for comparison.

First analysis of DAS data shows the expansion of this pressure wave spatially resolved along the pipe. Velocities could be determined and were found in accordance with the values derived from the pressure sensors. Therefore, DAS may provide a useful tool to detect shock waves in pipes and to monitor different evolutions of explosions (deflagrations, detonations). Additionally, acoustic waves, which were stimulated by the sudden pressure change in the gas mixture within the pipe, could be observed with velocities matching the expected value for solid-borne sound in steel.

Further analysis of the data is currently under way and will be presented in a forthcoming paper.

2.3 BLOCKAGE TESTS ON A PIPELINE

To investigate the changes of acoustic signature of medium flow through the pipeline with altered cross-section, blockage tests were performed on a DN 100 pipeline setup of 38 m length (Fig. 1). At the open end of pipe segment No. 1, an industrial fan was installed to produce the air flow through the pipeline. The other end of the pipeline (segment No.13) was left open; i.e. the internal pipeline pressure was equivalent to the ambient pressure.

The pipeline is partly located inside a building, where the pipe segment No. 2 of 3 m length was instrumented with optic fibre and AE sensors for reference purposes (Fig. 1, zone 0). For the main measurements, three adjacent pipe segments No. 9-11 (Fig. 1, zones 1-3) of the pipeline’s outside part were instrumented with the optical fibre, accelerometers and AE sensors. Optical fibre was wrapped helically around the individual pipe segment with 2.5 cm pitch. Pipeline blockage was simulated by orifices with different outlet opening diameters that were mounted between pipe segments No. 9 and 10 (Fig. 1, 1) orifice). Measurements were carried out using different sizes of circular orifices at different fan speed settings.
Fig. 1  Setup of the blockage and leakage tests on the 38 m long model pipeline. Reference and monitored region were instrumented with optical fibres, accelerometers and AE sensors. 1) For blockage experiments, orifices were mounted between pipe segment No. 9 and 10. 2) For leakage tests, holey adapter caps simulating the pipeline leak were assembled in the middle of the segment No. 10.

For data acquisition, pulses of 100 ns length, 40 kHz sampling rate and 400 mV amplification were applied. Spectral signals were determined based on 30 s recording of the continuous acoustic signal. Generally, the majority of relevant spectral signals that were observed throughout the experiments by means of DAS appeared in the frequency range up to 5 kHz. Figure 2 compares the recorded DAS signals in low-frequency range (up to 2 kHz) for the flow measurements at the maximal fan speed setting (3000 rpm) for the free pipe without blockage and for the pipe blocked with orifices of different sizes. Already for the measurement of the free pipeline, relatively strong low-frequency signals containing several distinctive spectral features are present in all four monitored pipe segments. These signals can be considered as a reference pipeline vibration background. Comparing reference measurements of the free pipe with the blocked pipes, for the blockages, a “bulge” in the low-frequency signal at the beginning of the zone 2 appears, visible as a short region where detected signals extend from low frequency also up to higher frequencies. This signal feature is most probably associated with local orifice-induced vibrations and could be potentially used as indication of pipeline blockage. However, the feature’s spectral extent towards higher frequencies diminishes as the size of the blockage decreases, which makes it hard to detect the feature for smaller size blockages, e.g. 90 mm orifice. In addition, with decreasing fan speed (i.e. flow rate), the amplitude of the spectral signals decreases and became virtually undetectable for the fan speeds below 1500 rpm. For the used DN100 pipeline, this corresponds to a volume flow of approximately 1930 Nm⁻¹h⁻¹ and an air flow speed of roughly 70 ms⁻¹.

Fig. 2 Pipeline blockage experiments using circular orifices of different sizes at fan speed of 3000 rpm: Time-averaged pipeline spectra (0-2 kHz) measured with the DAS system using 100 ns pulse length, 40 kHz sampling rate (20 kHz maximal spectral extend) and 400 mV amplification.
2.4 LEAKAGE TESTS ON A PIPELINE

For the pipeline leakage experiments, a sealed pipeline configuration was used, and auxiliary pressure buffer was connected to the pipeline through a 1-inch flexible tube with remotely-controllable valve connected to pipe segment No.1. Leak in the pipeline was simulated using holey adapter caps assembled at the middle of pipe segment No. 10, i.e. in the middle of the DAS monitored region (Fig. 2, 2). Side adapter caps with circular holes of different opening diameters in 1-8 mm range were tested. Pressure buffer was pumped using compressed air up to 30 bars. The valve between the buffer and the pipeline was opened leading to pressurization of the pipeline and leaking through the holey adapter located in zone 2. Pipeline and buffer internal pressure was monitored using electronic pressure gauges. Measurements were performed for various combinations of leak sizes, internal pressures and DAS settings. For comparison purposes, zones 1-3 were additionally instrumented with accelerometers and AE sensors. Presented data were acquired using pulses of 200 ns length, 80 kHz sampling rate and 800 mV amplification. Spectral signals were determined based on 30 s recording of the continuous acoustic signal.

![Diagram of pipeline leakage experiments](image)

**Fig. 3** Pipeline leakage experiments with leak of different sizes at 10 bar pressure level: time-averaged DAS spectra along the fibre.

![Spectra comparison](image)

**Fig. 4** Pipeline leakage experiments with leak of different sizes at 10 bar pressure level: Time-averaged spectra measured by two accelerometers located in zone 2, approx. 30 cm distance to the leak.

The DAS system is able to detect and localize pinhole size leaks with diameters down to 1 mm at pressures down to 10 bars (Fig. 3). The leak-generated spectrally distinct signal components predominantly present in the zone 2 (with leak) were shown to correspond to pipeline natural vibrational modes [4]. The signals of interest are broadly located in the spectral range between 500 Hz and 5 kHz and might be used as pointers for detection and localization of the pipeline leaks. For 1 mm leak, the spectrum recorded by the DAS system is dominated by spectral features between 1.5 kHz and 2.5 kHz. Increasing leak size at constant pressure level seems to lead to excitation of pipe vibrations at higher frequencies. This trend also is confirmed by the measurements with accelerometers (Fig. 4). However, in case of high leak rates (large leak sizes and/or high pressures), parasitic signals occurred in the reference zone 0 and propagated along the entire pipeline as shown for the leak with 6 mm opening diameter (Fig. 3). These parasitic frequency peaks at 1.2 kHz and 1.3 kHz were measured by the DAS system (Fig. 3) as well as by the accelerometer sensors (Fig. 4). The majority of dominant peaks in the spectra measured by DAS are in good agreement
with those detected by the accelerometers. The study showed that the DAS system is capable of detecting weak leak-induced pipeline vibrations for leak rates well below 1% of the pipeline nominal medium flow. Rather than spectral filtering and tracking of a single frequency feature (vibration mode), considering integral intensity/energy in the entire spectral band (0.5 – 5 kHz) was shown to be more appropriate way for leak detection and localization tasks [4].

2.5 BENDING TEST ON PIPE SEGMENTS

A four-point bending test was carried out on a pipe segment made of steel grade S355J2H. The pipe segment was 2.5 m long, had a wall thickness of 16 mm and an outer diameter of 168 mm. Centered at 1.25 m length, a 90°circumferential notch was shaped into the outer pipe wall with an opening angle of 90°, a notch root radius of 0.2 mm and a ratio of depth to wall thicknesses of 0.5. The bending test was performed with a 4 MN universal testing machine that operates hydraulically. The test was performed displacement controlled with a test speed of 0.25 mm min⁻¹.

Fig. 5 Experimental setup of the four-point bending test of a pipe segment monitored by DAS (wrapped around optic fibre and spooled optical fibre used as point sensor), accelerometers, AE (four VS9000-M sensors) and by DCPD.

At 20 mm distance to the notch, roughly 40 m of the optical fibre were densely wrapped around the pipe and glued to it (Uvirapid 701, Best Klebstoffe). Additionally, a DAS point sensor was mounted to the pipe at a distance of 100 mm to the notch (Fig. 5). The DAS point sensor is an in-house-made sensor consisting of roughly 20 m fibre coiled around a small plastic cylinder imbedded in silicone rubber. For reference measurements, four accelerometers with 10 mV/g and four accelerometers with 100 mV/g output sensitivity as well as four broadband AE sensors of type VS-900-M were mounted to the pipe at distances less or equal to 100 mm to the notch. Furthermore, the method of the Direct Current Potential Drop (DCPD) was employed to determine the time of crack initiation at the notch.
The results of the AE measurement and the DCPD method agree well, since the time of crack initiation determined by the DCPD method correlates with the onset of AE accumulation located at the notch (Fig. 6). The peak amplitudes of the AE events during crack growth through the pipe wall range between 40-70 dB\text{AE}. The macroscopic crack leading to pipe wall penetration (leakage) generated a single AE event with a peak amplitude above 80 dB\text{AE}. Additionally, a test procedure was performed to evaluate the sensitivity of the DAS system to acoustic events. Therefore, ten pencil lead breaks (Hsu-Nielsen source) were carried out located at the notch of the pipe segment. In AE measurement, these pencil lead breaks generated signals with larger peak amplitudes than those produced during the bending test. These pencil lead breaks are already hard to detect by the DAS sensor wrapped around the pipe (Fig. 7). Hence, the employed DAS system seems to be incapable to detect the comparatively smaller acoustic signals generated by crack growth in the pipe wall, particularly, when taking into account the acoustic noise level increasing with progressive load application.
3. CONCLUSION

(1) The ability of the DAS to detect dynamic changes of the pipe material was proven by gas ignition tests. The typical sound velocity of the pipe material stimulated by the sudden pressure change in the gas mixture as well as the velocity of the pressure wave in the gas phase were determined from DAS signals and found in good agreement with the values determined by the reference methods.

(2) The acoustic characterization of changing medium flow caused by alteration of the inner pipeline profile, e.g. by sedimentation or corrosion, was studied by means of the blockage and leakage tests on a model pipeline. For simulation of a blockage, orifices of different size were installed into the pipeline. For leakage, adapter caps with circular holes of different opening diameters in 1-8 mm range were installed to the model pipeline. Generally, the DAS detected acoustic signatures assigned to a changing inner pipe profile, but with limitation. The DAS system detected simulated sedimentation of more than 20 mm depth (80 mm orifice opening diameter), at flow rates above 70 ms⁻¹. It is also worth noting that these pipeline blockage experiments were performed only at atmospheric pressure, not representing the realistic situation where gaseous medium is transported through the pipeline under high pressures. Pipeline leaks with diameters down to 1 mm (minimal tested size) were successfully detected by the DAS system at pressure of at least 10 bar.

(3) To detect the accumulation of microscopic material degeneration poses the highest demand on the sensitivity of the DAS system. Beside the high technical effort to investigate the detection of crack growth in a pipe wall under bending load, also the comparison of all measured data from the various NDT methods is very challenging, especially, since cracking processes are spontaneous, local and transient events. Further studies simulating cracks by pencil lead breaks performed at the pipe wall showed that the signal-to-noise ratio of the DAS is insufficient to monitor microscopic crack growth for this designed experimental setup. The ability of the DAS system to detect acoustic events generated by crack growth were neither verified nor disproved.

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REFERENCES


