Materials Research Proceedings **18** (2021) 146-153 https://doi.org/10.21741/9781644901311-17

Monitoring of the Operational Conditions in Steel Pipes Using Fiber Optic Sensors

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Keywords: Pipes Condition Monitoring, Structural Health Monitoring, Fiber Optic Sensing

Abstract. Oil and water transport pipeline systems are susceptible to damage due to harsh environmental conditions and operational factors, hence ongoing maintenance and inspection are required. The development of a continuous and reliable monitoring technique will ensure the safety usage of these structures and assist in the extension of their life span. In this study, the monitoring and assessment of pipelines are performed using a network of Fiber Bragg Grating (FBG) sensors mounted along the longitudinal and circumferential directions. The sensitivity of the measurements to assess pressure and flow variation in the pipe, in addition to leakage detection and localization were evaluated. Water at a controlled pressure and flowrate was pumped into the designed six-meter pipe testbed designed for this purpose. Leakage was simulated by opening one of the four designated valves installed on the pipe. The variation in the pressure inside the pipe highly impacted the amplitude of the measured strain increasing it significantly reaching 20%. An increase in flowrate had an inverse effect, it resulted in a 5% decrease in the amplitude of the measured strain drop. The change of hole leakage size greatly influenced the measured signal, resulting in a 55% change in amplitude between a 2 cm^2 and a 5 cm^2 hole leakage. For the location of leakage, only the temporal aspects of the signal were affected resulting in a slight shift in the response time of sensors relative to each other. The results were promising to monitor the structural conditions related to leakage detection and localization, based on the patterns observed.

Introduction

Pipeline systems are remarkable for their practicality, efficiency, and cost-effectiveness in transporting big quantities of dangerous substances [1], in particular, crude oil and petroleum products [2], when compared with other modes of transport. These pipeline systems can be used for short distances (within refineries or between neighboring installations), and over long distances. Oil and gas products from hundreds of thousands of wells, from which, many are located in remote and hostile areas, are transported through pipelines [3].

The large scale and deployment location of pipeline networks make this transportation method susceptible to various types of failures. These failures may not only cause product loss, but also environmental damages and hazards and potential threats to life [4, 5]. Pipeline failures, depending on their location and the nature of the transported substance, can have many negative effects on the economy, the environment, and health. Given the immense scale of the pipeline networks and the severity of possible leakage repercussions, the structural health monitoring (SHM) of pipelines is a challenging yet necessary task. The methods developed over the years

are strictly non-destructive as they must be applied to installed and running pipelines. Several methods have been developed for this purpose [6].

The monitoring of pipeline networks can be performed through externally mounted sensors to detect pipe leakages. These methods are called sensor-based methods. They include the negative pressure wave methods, ultrasonic methods, eddy current, electromagnetic flux, and others [7]. Their main advantages are the quantification of the problem as well as their application without the interruption of the normal pipeline operation. [8-10].

Methods based on intelligent pigging have also been developed for the inspection of pipeline systems [11]. These methods are particularly useful at detecting and localizing change in wall thickness. However, pipeline operation may need to be disturbed to perform the tests, further the monitoring process is not continuous [12].

Other less common pipeline inspection methods are also available. The single measurement analysis method for instance is used for the monitoring of small-scale pipelines (factory-scale). These methods work by monitoring flow conditions at a single point in the pipeline network [13]. Another inspection method is the uncompensated volume balance method in which the sum of flows entering the pipeline and the sum of flows exiting it are compared. If a noticeably large difference is observed, it can indicate a leak in the network [14]. Finally, model-based leakage detection methods [15, 16] in which a model of the pipeline under-study is simulated can be used for inspecting the pipeline. Flow properties at certain locations in the network are then compared to the flow properties in the same locations of the simulated network. This method needs highly accurate inputs and a computer capable of delivering good results in a reasonable amount of time.

Among the above-listed methods, the most effective leakage localization methods in a pipe during normal operation are the ones with externally mounted sensors. Two of these methods are particularly effective, the negative pressure wave method (NPW) and the temperature-based methods.

NPW methods are concerned with the negative pressure wave that is generated when a pipe starts leaking fluid (change in pressure). This negative pressure wave travels through the fluid in the pipe to neighboring pressure sensors that pick up this change in the operational condition [10]. The leakage is then localized using the time difference for the negative pressure wave to reach the two sensors upstream and downstream of the leak location. On the other hand, the temperature-based methods are based on monitoring the temperature of the medium surrounding the pipe. Even though these methods can generally give better outcomes and higher precision than NPW methods, they are subject to noise and errors caused by weather abnormalities or third-party intrusions [17].

In this paper, the operational and structural condition assessment of steel pipes using a sensor network of fiber optic Fiber Bragg Grating (FBG) sensors has been investigated. fiber optic sensors (FOS) was chosen for this application due to its superb capability to provide measurements over long distances. The main aims are to investigate the efficacy of using FBG strain sensors in the structural health and operational condition monitoring of pipelines and develop a good understanding of the effect of flow conditions and leakage on the surface strain in pipelines.

Methodology

This section describes the developed methodology used in this study. The design of the testbed, and the tested scenarios.

Experimental approach

Experiments were conducted by recording the strain data of the FBG sensors mounted on the surface of the pipe in multiple scenarios with different pressures, flow rates, leakage locations, and hole leakage sizes. The main concern was to replicate possible leakage scenarios in actual transportation pipelines. All collected data was gathered from the interrogation of the FBG sensors. By attaching the fibers directly to the pipe's surface, the measured fiber strain and its variation were expected to reflect the properties of the flow inside the pipe. Performing tests under different flow and leakage conditions help determine the effects that these parameters have on the output signals By comparing the signals obtained in various scenarios (by changing one parameter at a time), it was possible to observe the effects that a specific parameter had on the readings.

Experimental Set-Up

A testbed was specifically designed to demonstrate the feasibility of the application of FBG sensors in monitoring the operational and structural conditions of the pipelines. The testbed consists of a 5.95-m-long, black steel pipe with a nominal diameter of 10" (250 mm) and a thickness of 5 mm. The full experimental set-up is shown in Figure 1. Six holes with different purposes were drilled into the pipe in the radial direction on the pipe. Two holes served as the inlet and exhaust of fluid through the pipe, while the others were used to simulate leakage. All necessary connections were established using 1-inch (25 mm) nominal diameter pipes, elbows, and T connections.

As for the instrumentation, two different types of sensors were used in the set-up; these were supplied by Micron Optics. The sensors placed in the longitudinal direction were temperature-compensated FBG strain sensors (os3155) that were spot welded on the pipe. The sensors mounted in the circumferential direction were optical strain gages (os3100) that were epoxied to the pipe. The six mounted sensors were named S1 through S6, starting from the sensor closest to the pipe's inlet. Sensors S1, S3, S4, and S6 were mounted in the longitudinal direction, whereas sensors S2 and S5 were mounted in the circumferential direction.

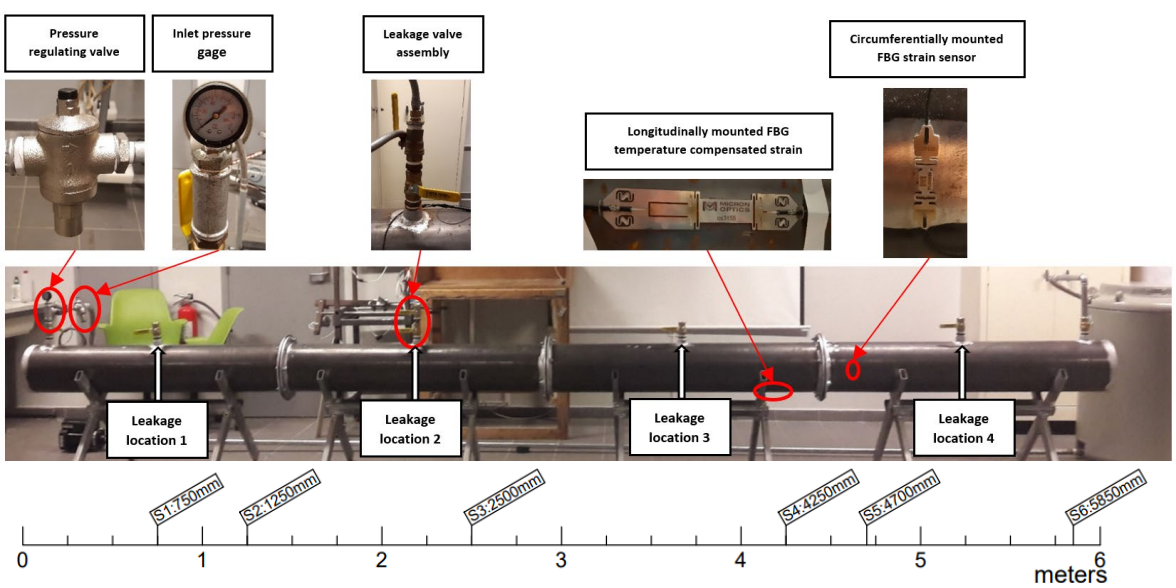

Figure 1: Detailed layout of the testbed and sensor positions.

Experiments were performed using 3 different pressures (60, 80, and 100 kPa), 3 different flow rates (10, 15, and 20 GPM), 4 leakage locations, and 2 leakage hole sizes. A single data point contains 60-second readings of all 6 sensors with a single leakage valve opened at the 30-second mark. Initially collected data contained high noise (signal to noise ratio (SNR) ranged between 1.85 and 10.23) which required filtering. The data was processed and underwent a lowpass filtering with a factor of 10^{-5} and a moving mean filter with a 400 ms range. The signals were then zeroed and trimmed down to 15 seconds to eliminate the redundancy.

Results and Analysis

Signals generated under different flow and leakage conditions can contain traits or patterns that reflect those conditions. To show these patterns, each flow or leakage parameter can be isolated and analyzed separately. This can be done by fixing three parameters, varying the fourth remaining one, and observing changes in the signals. Due to the trimming of the data, leakage in subsequent figures is simulated at t=5 seconds. In this section, data from sensors S1 and S2 are presented. The choice was made to include the sensor with the highest gain for each mounting direction (S1 is mounted in the longitudinal direction and S2 is mounted in the circumferential direction). However, any sensor combination will yield the same results. Figure 2 and Figure 3 show a plot of the strain variations of S1 and S2 in με against time in seconds.

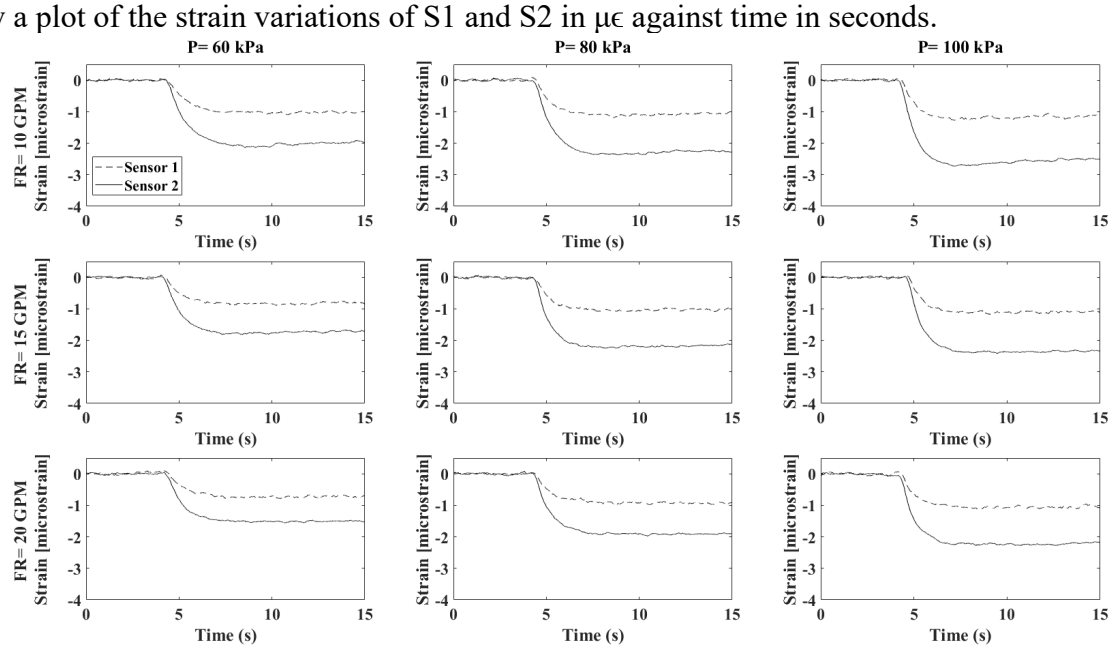

Figure 2:Strain curves with a variation of pressure and flow rate for a small leakage size with leakage simulated at location L1.

Figure 2 shows the surface strain variation measured by sensors S1 and S2 for varying pressures and flow rates. The location of the leakage (L1) and the size of the leakage (small) remain unchanged. Looking at three consecutive plots from top to bottom reveals that increasing the flow rate results in a smaller strain drop at any given pressure. A change in flowrate from 10 to 15 GPM (50% increase) causes on average a 4% decrease in strain drop and a change from 15 to 20 GPM (33% increase) causes a 10% decrease in strain drop. Both circumferential and longitudinal sensors experience the same changes in this scenario. Looking at three consecutive plots from left to right reveals the effect of changing the initial pipe pressure on the signals. An increase in pressure from 60 to 80 kPa (33% increase) causes the amplitude of the strain drop to increase by 31 % for the longitudinally placed sensor and 18% for the circumferentially placed

sensor. Changing the initial pressure from 80 to 100 kPa (25% increase) results in a lass pronounced change in strain drop amplitude of 13.5% for both sensors.

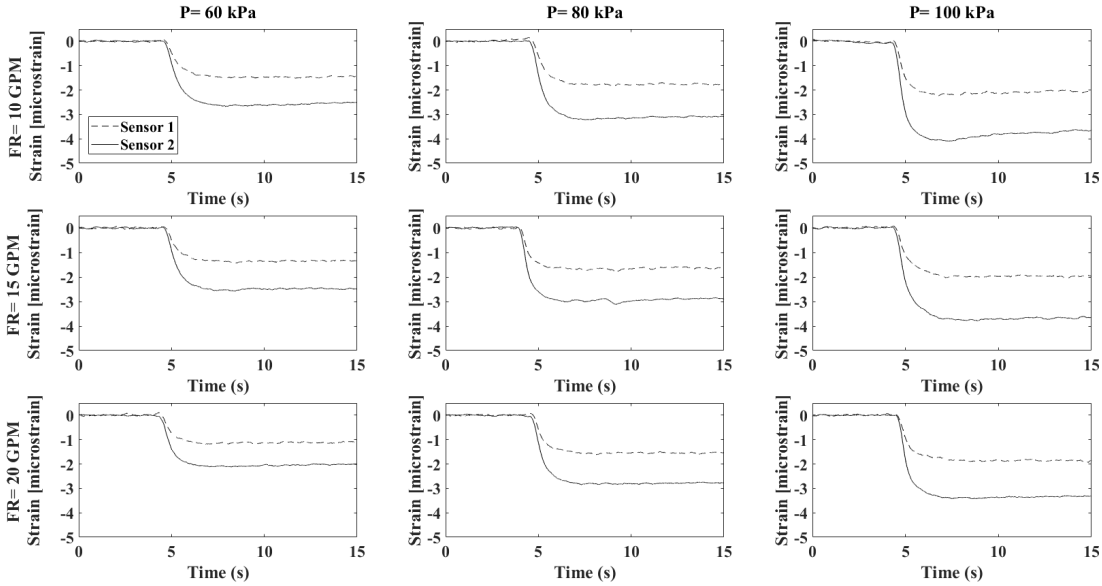

Figure 3: Strain curves with a variation of pressure and flow rate for a large leakage size with leakage simulated at location L1.

When looking at the same variations with a large leakage hole, strain drop amplitude changes vary slightly(Figure 3). A jump in flowrate from 10 to 15 GPM yields a 7 % decrease in strain drop for both sensors and a jump from 15 to 20 GPM yields a 7% decrease in strain drop. Changes in pressure, in this case, are also more noticeable with a 28 % increase in strain drop between a 60 and an 80 kPa pressure, and an 18% drop amplitude increase between 80 and 100 kPa. A larger leakage creates a larger strain drop in all observed cases. A 50 % increase in strain drop on average is observed between data recorded with a small leakage and data recorded with a large leakage. This increase is consistent with an initial flow rate or pressure.

These observed patterns can be used to determine the flow properties and leakage size at the time of leakage which can help determine possible causes of leakage approximate the extent of damages. However, some signal patterns overlap (i.e. the effects that having a high pressure or a low flowrate have on the signals are similar). Circumferentially placed sensors have a higher gain which reduces the amount of information in the data lost to denoising. But longitudinally placed sensors show a higher sensitivity to changes in flow conditions.

The variation in the location of the leakage did not have any effect on the amplitude of the strain drop. However, it does influence the temporal aspect of the strain curve of the sensors. The time it took each sensor to reach the final steady strain state was slightly increased the farther that sensor was located from the leakage location. This delay is visible in the gap between the time it takes S1 and S2 to reach S1's steady-state strain value. This gap is highlighted in Figure 4.

The time difference between the two intercepts appears to increase the more distant the leakage location is relative to the sensor's position. With few exceptions, this pattern holds for different flow rates, pressures, and leakage sizes. The time differences for different flow and leakage scenarios are shown in Table 1.

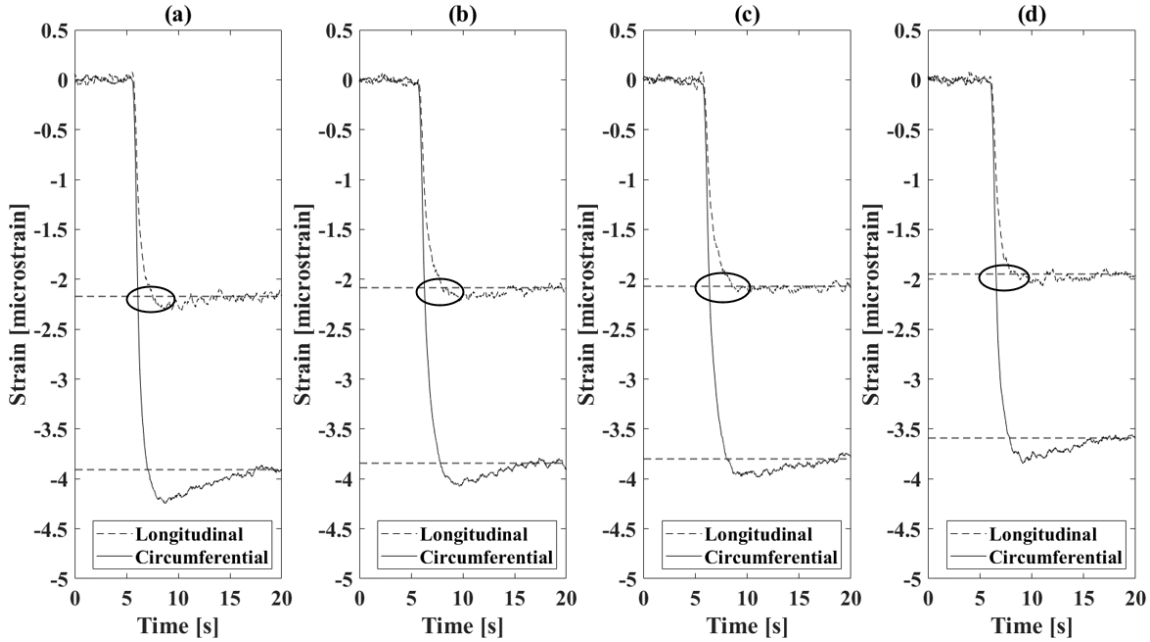

Figure 4: Time gap between the intercepts of S1 and S2 at leakage locations a) L1, b) L2, c) L3, and d) L4 at a pressure of 100 kPa and a flow rate of 10 GPM.

Table 1: Intercept times and time differences for sensors 1 and 2 recorded for different leakage scenarios.

Time intercepts for pressure variations at 15 GPM at leakage location L1 with a small leakage size			
	The intercept of sensor 1 (s)	The intercept of sensor 2 (s)	Time difference (s)
L1	7.525	6.104	1.421
L2	8.029	6.296	1.733
L3	8.552	6.374	2.178
L4	8.544	6.564	1.980
Time intercepts for pressure variations at 15 GPM at leakage location L4 with a small leakage size			
	The intercept of sensor 1 (s)	The intercept of sensor 2 (s)	Time difference (s)
L1	7.626	6.381	1.245
L2	7.547	6.212	1.335
L3	7.939	6.468	1.471
L4	8.152	6.552	1.600
Time intercepts for pressure variations at 15 GPM at leakage location L1 with a large leakage size			
	The intercept of sensor 1 (s)	The intercept of sensor 2 (s)	Time difference (s)
L1	8.147	6.775	1.372
L2	9.133	7.118	2.015
L3	9.118	6.775	2.343
L4	9.327	6.992	2.335
Time intercepts for pressure variations at 15 GPM at leakage location L4 with a large leakage size			
	The intercept of sensor 1 (s)	The intercept of sensor 2 (s)	Time difference (s)
L1	8.091	6.520	1.571
L2	9.284	6.675	2.609
L3	9.843	6.690	3.153
L4	9.081	6.497	2.584

The changes in surface strain measured in this study can be compared to the results reported in previous studies. For instance, tests performed at a pressure of 120 kPa (120 kPa) yielded a change of 5 to 6 με on the surface of the pipe [18]. Other tests performed at a much higher pressure of 1.2 MPa inflicted 90–120 με on the surface of the pipe [19]. These tests were both performed on sections of pipe similar to the one used in this work. Oil transportation pipelines typically operate at much higher pressures than those used in the testbed in this study [20], and hence, at much higher hoop stress. Therefore, in the presence of leakage, these high pressures will increase the observed strain drops due to the higher-pressure amplitude of the NPW, guaranteeing a higher SNR and more easily observable and clear strain drop/ patterns.

Conclusions

In this work, it is clear that pipeline leakages that occur under different operational conditions generate different amounts and variations in the strain patterns on the surface of the pipe. In all the tested scenarios, leakage always resulted in a drop of the strain measured on the surface of the pipe. The amplitude of that drop increased with an increase in pressure, a decrease in flow rate, and an increase in leakage size. The location of the leakage, however, had no effect on the amplitude of that drop but rather on the shape of the signals measured.

Acknowledgments

We acknowledge the financial support of the University Research Board at the American University of Beirut (Award #103604).

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