Early Leak Detection in Wastewater Pipelines Using Fibre Bragg Grating Sensors

Matthias Fabian[*a,b], *Joanna M Coote*[b], *Richard Scott*[a], *Tong Sun*[a,b], *Kenneth T V Grattan*[a,b], *Heriberto Bustamante*[c], *Timothy Hill*[c], *James McCulloch*[c], *Simon Tait*[d], *Kirill Horoshenkov*[d]
[a] City St George's, University of London, London, EC1V 0HB, UK; [b] City Optotech Ltd., London, EC1V 0HB, UK; [c] Sydney Water Corporation, Parramatta, NSW 2124, Australia; [d] The University of Sheffield, S10 2TN, UK
*matthias.fabian.1@city.ac.uk

ABSTRACT

We report on improvements in the design and data processing of a ruggedised, highly sensitive fibre-optic pressure sensor for use in pumped sewer mains. Leak detection and localisation tests were carried out on a plant scale test rig using mains water for a range of leak sizes. The leak-induced pressure drop resolution achieved is better than 100Pa (1mbar) which corresponds to a leak size of approximately 2mm (in a pipe of 100mm in diameter and a flow rate of 16 litres per second).

Keywords: optical fibre sensors, high sensitivity pressure sensor, leak detection, pressurised (non-gravity) pipeline, water industry

1. INTRODUCTION

Across the world, ageing water infrastructure is still in operation, often decades beyond their intended service life. This gives rise to an increasing demand for sensing technology that does not require expensive excavation as pipelines are generally buried underground with few access points. For that reason, leaks can often go undetected for months in isolated areas and cause serious impacts on the surrounding environment.

Various sensing solutions have been used to detect the onset of leaks, including acoustic [1] and temperature-based [2] sensors. The most promising approach, however, appears to be the monitoring of tiny negative pressure waves caused by leak-induced drops in pressure [3]. If the propagation speed of a pressure wave in a medium is known, then the leak location can be estimated based on a series of distributed pressure sensors along a pipeline [4].

The limiting factor is the sensitivity of commercially available pressure sensors, which is directly linked to how small a leak they are capable of detecting. The earlier a leak can be detected and located, the smaller is its environmental impact as well as the financial implications of resolving it prior to catastrophic failure. This report builds on the original proposed FBG based sensor design (section 2) previously reported by the authors [5] with improvements in leak detection analysis as well as leak localisation.

2. SENSOR DESIGN AND TEST SETUP

The sensor comprises of a stainless-steel diaphragm that deforms under pressure and induces strain to a fibre Bragg grating (FBG) [6] located underneath it (Figure 1(left)). To ensure reliable contact between the diaphragm and the FBG at zero pressure a small cylindrical spacer is attached to the underside of the diaphragm. Since FBGs are sensitive to both strain and temperature a second FBG is embedded in the sensor's aluminium body, monitoring temperature only for compensation purposes. Additional components are used to enhance the robustness of the sensors as well as to encapsulate the optical fibres in the sensors housing for protection during their installation (Figure 1(right)).

Large scale tests were carried out at the National Distributed Water Infrastructure Facility based within the Integrated Civil and Infrastructure Research Centre (ICAIR) at the University of Sheffield, UK. Figure 1(right) schematically shows the 37m long high-density polyethylene pipeline (HDPE, 100mm dia.) used in this investigation. Water is supplied by a 5m constant head tank at a flow rate of 16 litres per second. At approximately the half-way point, an access point allowed for simulating leaks by inserting disks of varying holes sizes. Four pressure sensors (S1-S4) were connected to additional access points, two on either side of the leak position and approximately 5.6m apart.

Calibration was carried out against temperature as well as pressure. The former was done using a climate chamber and the latter using an air compressor and an electronically adjustable valve. Throughout this investigation, the FBG sensor data was acquired using a Luna optical sensing instrument (si155, Hyperion) at a sampling rate of 5kHz.

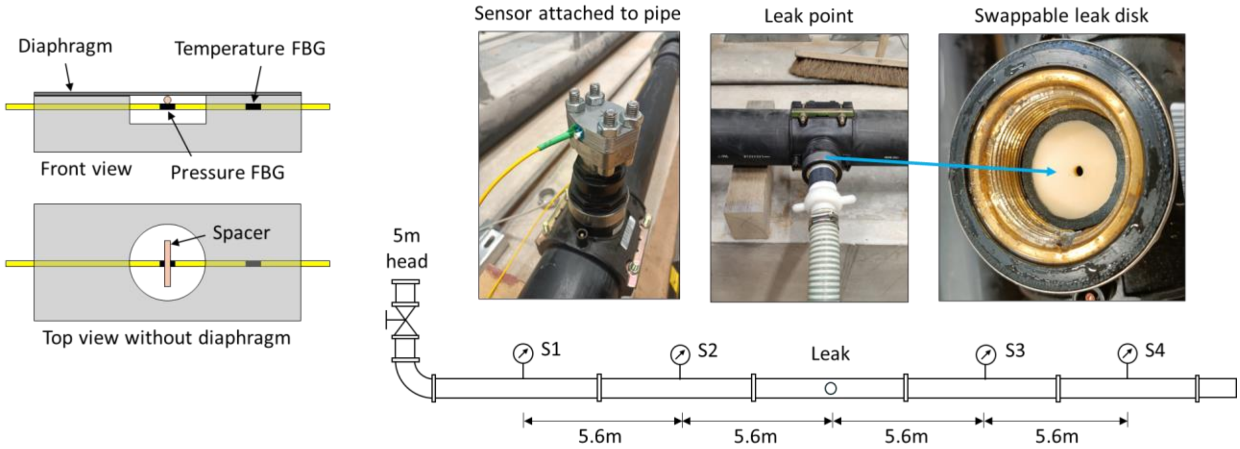

Figure 1. (left) Schematic diagram of the pressure transducer design. A diaphragm deflects under pressure inducing strain in the optical fibre located beneath it. (right) Test setup comprising of 37m HDPE pipe connected to a constant head tank. Four pressure sensors are distributed along the pipe, two on either side of the simulated leak point.

3. RESULTS AND DISCUSSION

The sensor responses to temperature (5-50°C) are shown in Figure 2(left) highlighting the linear relationship of the temperature FBGs and a small quadratic component in the pressure FBG response coming from the diaphragm deflecting with increasing temperature in addition to the sensor body expanding. The sensor responses to pressure are shown in Figure 2(right) with S1 and S2 exhibiting a greater sensitivity than S3 and S4 due to the difference in their diaphragm thickness, 50µm and 100µm respectively. The pressure range used for the calibration of up to 5 meters (0.5 bar) corresponds to the maximum pressure of the head tank system.

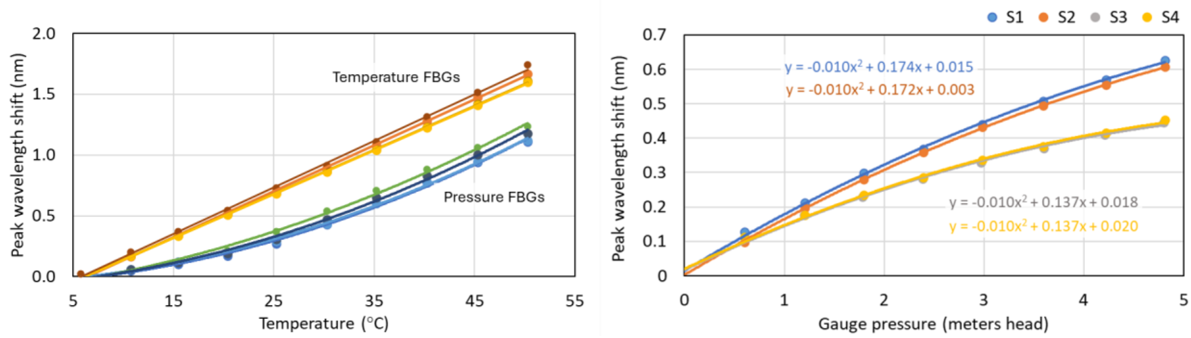

Figure 2. (left) Response of both FBGs of Sensor 1 vs temperature. (right) Response of the pressure sensitive FBGs of all four sensors versus pressure (50µm diaphragm (S1, S2) and 100µm diaphragm (S3, S4)).

Tests were carried out for leak sizes from 12mm down to 1mm following the schedule depicted in Figure 3: (i) Empty pipe – baseline recording for one minute; (ii) Main valve open – water flow allowed to stabilise for two minutes; (iii) Leak open for one minute; (iv) Leak closed for two minutes; (v) Main valve closed – continued recording for one minute to capture the water hammer caused by the valve being closed.

Figure 3(left) shows the individual calibrated sensor responses to the above test schedule for a leak size of 12mm with Figure 3(right) highlighting the “Leak open” to “Leak closed” section of S1. It is clear from Figure 3 that the static pipe pressure drops along its length verifying the calibration of the sensors. It is also clear that the simulated leak causes a sudden drop in pressure, as well as certain transient signatures when the leak is opened and closed – a negative pressure wave and a mini water hammer respectively. Detecting the pressure drop in turbulent flow data becomes increasingly challenging as the leak size decreases. However, the spectral features contained in transients may reveal characteristic signatures suitable for detecting smaller leaks. For that purpose, the raw data of sensor 1 was high-pass filtered (2nd order Butterworth, 0.125Hz) to remove the static pressure before being converted into the frequency domain. The resulting spectral signatures are plotted against time in Figure 4.

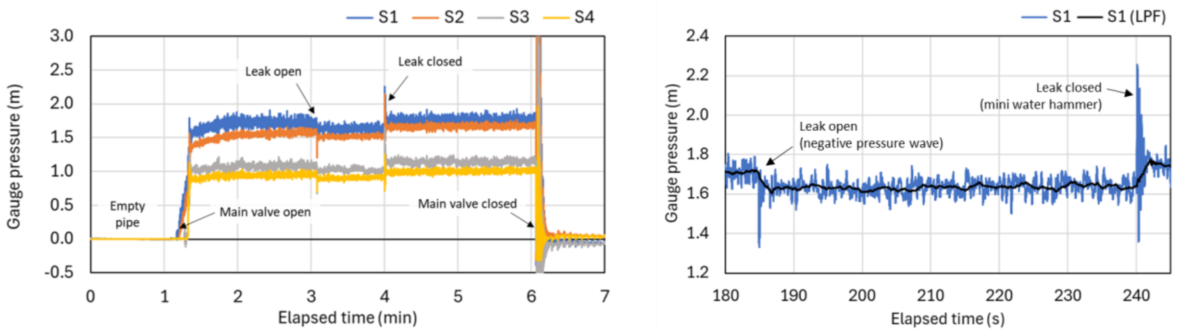

Figure 3. (left) Pipe pressure at the different sensing locations for an exemplary test cycle. (right) Pressure drop and transient signatures caused by a leak of 12mm in diameter. Blue line (raw data); Black line (low-pass filtered, 2nd order Butterworth, 0.1Hz).

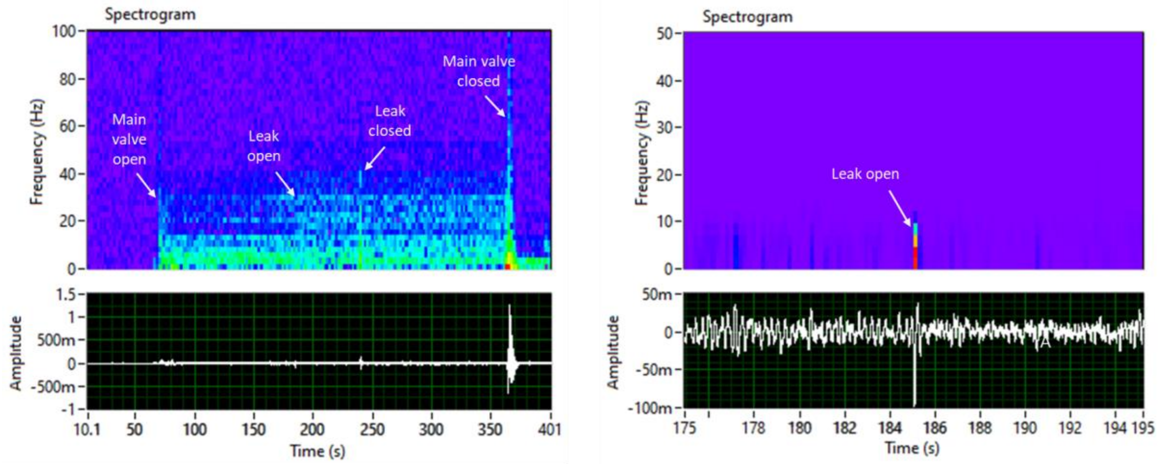

Figure 4. (left) Spectral features extracted from the data of sensor 1 over an entire test cycle. Bottom graph: High-pass filtered trace. Top graph: Spectrogram of the high-pass filtered signal revealing the spectral components contained in the real-time signal. (right) Same as left image but focused around the 'leak open' event with optimised filtering, revealing the event as a distinct feature.

It is apparent in Figure 4(left) that the turbulent flow of water in the pipe results in persistent low-frequency features (<30Hz) captured by the sensor. They are, however, overshadowed in magnitude by the water hammer signature (main valve closed) near the end of the cycle which makes the leak events themselves hardly detectable. Knowing the frequency bands of those unwanted events, it is possible to disregard them by adjusting the filter parameters, eventually revealing the leak as a distinct event in the spectrogram of Figure 4(right).

Using this approach of detecting leaks by their spectral signatures allowed for the identification of leaks down to 2mm in diameter (pressure drop <100Pa, 1mbar) as depicted in Figure 5(left). The results shown in the figure also confirm the expected relative pressure drops to be greater in magnitude closer to the leak than further away from it, i.e. sensor 2 registering a larger drop than sensor 1 and sensor 3 a larger drop than sensor 4.

Leak localisation can be achieved by looking at the time delay between the sensor responses to a negative pressure wave if its propagation speed in the pipe is known through [7]

$$C = \frac{1}{\sqrt{\rho\left(\frac{1}{\kappa} + \frac{D}{eE}\right)}}$$

where C is the sonic speed in a pipe (m/s), ρ is the fluid density (997kg/m^3), κ is the bulk modulus of the fluid (2.1E+09N/m^2), D is the diameter of the pipe (0.095m), e is the wall thickness of the pipe (0.0075m), and E is the Young's modulus of the pipe material (1.0E+09N/m^2). For the given values, the sonic speed of water in the pipe used is 276m/s. Knowing this and the time delay in the sensor responses of 19ms (Figure 5(right)), the distance between the sensor pairs is estimated to be 5.52m which is in close agreement with the actual value of 5.6m.

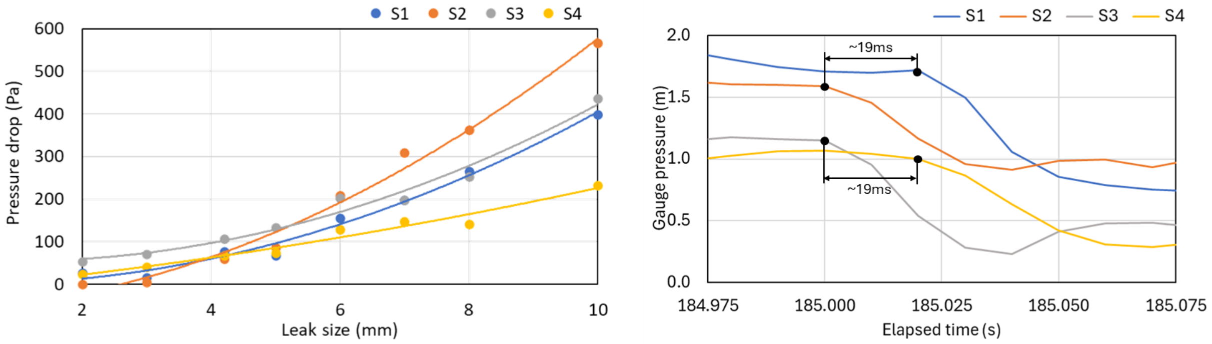

Figure 5. (left) Pressure drop vs leak size. Leaks down to 2mm in diameter were successfully identified. (right) Time delay in the response of the sensors further away from the leak (S1 and S4) to those closer to the leak (S2 and S3).

4. CONCLUSIONS AND FUTURE WORK

It has been shown that the proposed FBG-based fibre-optic sensor design can detect minute pressure drops (100Pa, 1mbar) in pressurized water pipes. The combined use of spectral analysis and adaptive filtering allowed for the detection of the 'onset' of leaks as small as 2mm in diameter under the described test conditions. It has also been shown that the time delay between the sensor responses can be used to localise leaks if the highlighted parameters of the pipe and the medium are known. Future work involves the deployment of the sensors in a live pressurised pipeline in Australia.

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