Using Novel Fibre Bragg Grating Based Pressure Sensor for Early Detection of Pipeline Leaks

James AA Bremner[1], Matthias Fabian[1], Richard Scott[1], John Carlton[1], Tong Sun[1], Kenneth TV Grattan[1] Heriberto Bustamante[2], James McCulloch[2], Tim Hill[2] Simon Tait[3] Kirill Horoshenkov[3]

1) City, University of London, UK 2) Sydney Water, Sydney Australia 3) Sheffield University

james.bremner.2@city.ac.uk

Abstract: We present a novel FBG-based pressure sensor for detection of pressure waves associated with pipe leaks. It includes the sensor design concept, sensor calibration in a pilot plant scale rig that mimics a water distribution network and the simulated pipeline leakage tests.

1. Introduction

Leakages from pressurized water and sewer mains can cause sudden and serious impacts on both the natural environment and quality of life for affected residents. In order to reduce the impact of these events, it is necessary to detect leaks at their onset so they can be repaired before they become large enough to cause serious harm.

Multiple methods of leak detection have been developed such as acoustic[1] and temperature[2] based sensors. Another detection modality is the use of negative pressure wave (NPW) detection. The onset of a leak will cause a drop in pressure at the leak point, and this pressure drop will travel in both directions down a pipe in the form of an NPW[3]. This NPW can be detected by pressure sensors placed at intervals along the pipeline and the time that the NPW arrives at each sensor will encode information about the location of the leak[4]. In order to detect NPWs, pressure sensors must be placed along the pipeline and are required to be sensitive enough to pick up weak signals that are caused by the onset of leaks.

Therefore, the key technical challenge is to create a novel pressure sensor with a wide sensing range (e.g., 30 bars) yet with very high measurement resolution (e.g., several Pascals). There are no such commercial sensors available due to the demand on both the sensing range and sensitivity required.

In this paper, we discuss the design, construction and calibration of a sensor based on combination of a diaphragm and a fibre Bragg grating (FBG) strain sensor. We then discuss experiments undertaken to measure the capabilities of the sensors to detect leaks of varying sizes in pressurised water pipes.

2. Sensor Design

To measure changes in pressure we designed a sensor in which an FBG-inscribed fibre was placed over a well cut into a metal coupon. The well and the fibre were then covered with a diaphragm to which a small piece of plastic acting as a spacer was attached. This is shown in Figure 1 (a). The inclusion of a spacer here not only creates a better contact between the diaphragm and the pressure grating placed underneath, but also to avoid the breaking of the sensing fibre when the applied pressure exceeds the usual FBG mechanical deformation limit, whereby extending significantly the sensing range.

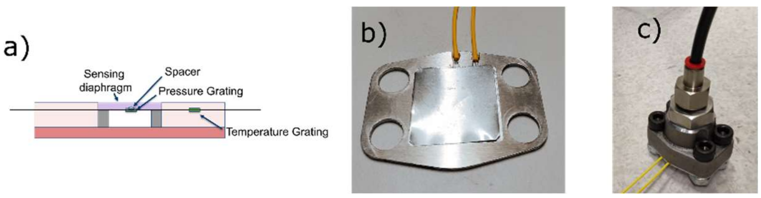

Figure 1Diagram and photos of sensor. (a) A schematic diagram of the parts of the sensing coupon; (b) Photograph of coupon with a stainless-steel diaphragm in place. (c) Photograph of the coupon packaged with a flange and attachments

Pressure applied to the diaphragm causes it to deform and press the spacer down onto the FBG. In turn, this applies a strain to the FBG which causes a change in the reflectance wavelength which can be measured by connecting the fibre to an FBG interrogator. In addition, a second FBG is present that is designed to be isolated from forces associated with the deformation of the diaphragm, allowing for the effect of temperature on the reflectance wavelength to be compensated for.

The deformation of the diaphragm at any given pressure will depend on the properties from which the diaphragm is made. In this experiment, two diaphragm materials were used; 0.3mm thick polyimide and 0.05mm thick stainless-steel as shown in Figure 1 (b). The sensors were made in pairs, two with each diaphragm material.

Figure 1 (c) shows a sensing coupon attached to a stainless-steel flange, which allows the sensor to be connected to sources of pressure for calibration and to water pipes for leak detection testing. An O-ring creates a watertight seal between the diaphragm and the measured pressure source.

3. Calibration

In order to measure the behaviour of the sensors under pressure, they were attached in turn to a water column housed in plastic piping as shown in Figure 2.

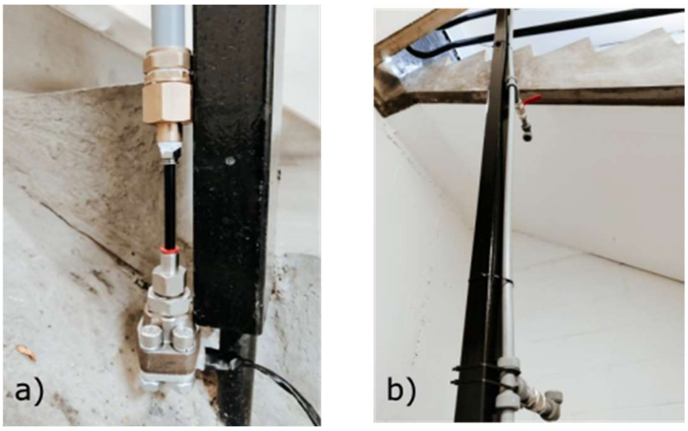

Figure 2 Sensor attached to water column a) connection of sensor b) pipe that contains water column

Taps on the water column allowed the height of the water to be adjusted, changing the static pressure and so changing the strain on the pressure sensing FBG within the sensor and thus its reflectance wavelength. This change in reflectance wavelength of the pressure grating in each sensor was measured using a Micron Optics Hyperion interrogator, assuming the temperature variation during the test period is negligible.

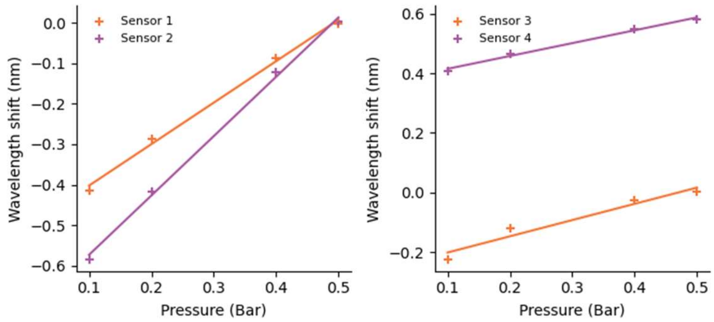

Figure 3 The response of the pressure sensing FBGs in each of the pairs of pressure sensors (a) with polyimide diaphragm; (b) with stainless-steel diaphragm

Figure 3 shows that there is a linear relationship between the reflectance wavelength shift and the applied pressure (R^2>0.95). The sensitivities of the sensors are as follows: Polyimide diaphragm: 1.02 nm/bar & 1.47nm/bar, Stainless-steel diaphragm: 0.55nm/bar & 0.43nm/bar. The sensitivity of each sensor in a pair is not the same. We believe this is due mainly to slight differences in the placement of the spacer on the fibre containing the pressure sensing grating in each sensor

3. Pipeline Testing

In order to test the suitability of the sensors for detecting leaks in pipelines, experiments were undertaken at the Integrated Civil and Infrastructure Research Centre, part of Sheffield University. The schematic drawing of the test pipeline which consisted of 37m of straight MDPE pipe (internal diameter 110mm) connected to a constant head tank providing approximately 5m (0.5 bar) head pressure is shown in Figure 4 (a). At the halfway point of the piping, a T-piece was placed connected to an outlet hose with a valve that could drain into a container. This introduces a simulated leak with leak size being adjustable. Pressure sensors were attached to the pipe at 7.5 from the T-piece, in matching pairs (although their sensitivities are not exactly the same as explained above).

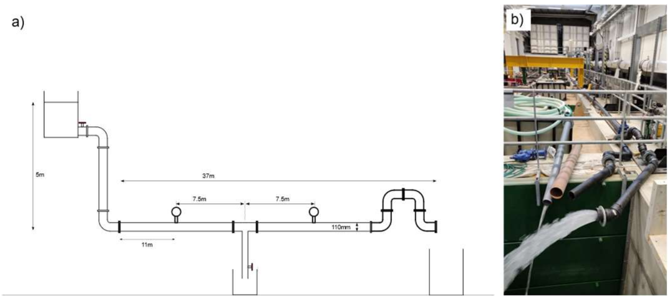

Figure 4 (a) Schematic drawing of a test; (b) Test equipment at Sheffield

Figure 4 (b) shows the test rig at the University of Sheffield and the connection of the FBG-based pressure sensors into the pipeline. Pressure sensors themselves were connected to a Hyperion FBG interrogator and the reflectance wavelengths of each of the FBGs was monitored.

For each test, the valve to the constant header tank was opened causing water to flow through the pipe at a rate of 16ls^{-1}, the pipe was always fully pressurized, and the flow Reynolds Number was around 27,000. After approximately three minutes, the valve on the outlet hose was partially opened to simulate a leak in the pipeline. After 5 minutes the outlet valve was closed and the volume of water that escaped and captured in the measurement tank was measured to allow the calculation of a leak flow rate. An example of the response of the FBGs in each of the two sensors (with polyimide diaphragm) is shown annotated below in Figure 5.

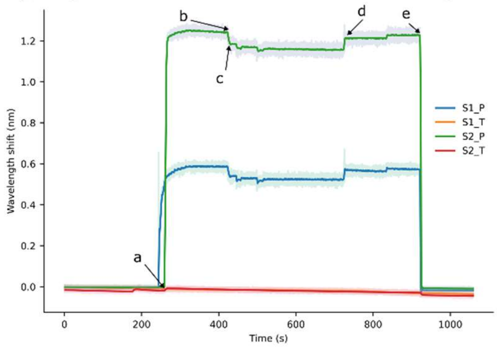

Figure 5 The paired FBG sensor with polyimide diaphragm response to changes in pressure. Sx_T: Temperature sensor grating Sx_P: Pressure sensing grating; a) the time at which water started to flow in the system b) the time at which the leak was opened c) a point just after the leak has been opened d) the point at which the leak was closed and e) the point at which the water flow was stopped

Figure 5 records the wavelength shifts of the pressure gratings in the paired sensors when they are subjected to events from a) to e). Both pressure gratings, S1_P and S2_P, show a rapid increase of the wavelength shift at a), the time at which water started to flow in the system. Both pressure sensors also reveal a sudden step-drop of pressure between b), the time at which the leak was opened and c) a point just after the leak has been opened, indicating the negative pressure change caused by the leak has been picked up by both sensors. When at d) the point at which the leak was closed, the pressure from both sensors is seen to be recovered until e) the point at which the water flow was stopped. It is also noted that the pressure drops from both pressure sensors between b) and c) occurs almost at the same time – this is because they are equally distanced from the leak point. However, if the leak position is changed, the time difference between the two sensors can be used to pinpoint the leak position. Both temperature sensors in Figure 5 show no change – confirming that the temperature variation during this period is negligible.

The experimented was repeated with varying flow rates, and with the two pairs of sensors (polyimide diaphragm and stainless-steel diaphragm) and the results are plotted below.

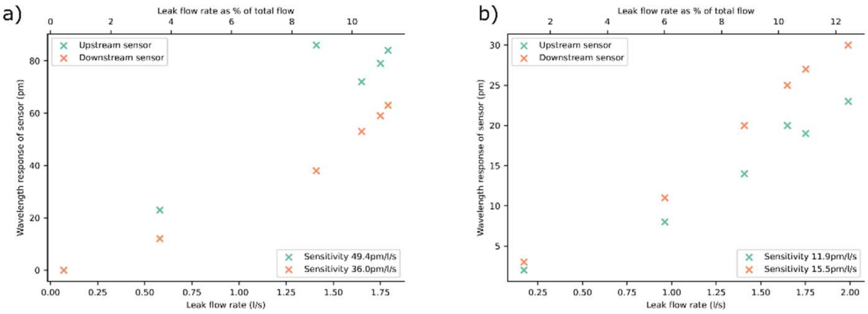

Figure 6 Wavelength response as a function of leak flow rate for the two pairs of sensors (a) polyimide diaphragm; (b) stainless-steel diaphragm

Figure 6 shows that the wavelength shifts of all the pressure sensors downstream or upstream increases with the increase of the leak flow rate. It shows the consistency with the calibration of the corresponding sensors, the pressure sensors with polyimide diaphragm are more sensitive, with a response of 36-49pm per litre per second of leak rate compared to 12-16pm per litre per second. Both sensor types can detect leak flow rates lower than $1ls^{-1}$ and the polyimide sensors were able to detect leak flow rates as low as $0.6ls^{-1}$

4. Conclusions

We have shown the development of an FBG and diaphragm-based pressure sensor which is designed to measure pressure over a wide sensing range with a sensitivity which is high enough to identify the early leak of pipelines. The results obtained are encouraging and further improvement on the sensor design is ongoing. This study has successfully tackled a key technical challenge needed create a pressure sensor with a wide sensing range (e.g., 30 bars) yet with very high measurement resolution (e.g., several Pascals). Future work will be designed to establish if fluctuating pressures induced by pumping or fouling of the sensors affects their performance

This is a new approach to determine the onset of leaks in pressurized pipes that would help take early action and prevent pipe failure

5 Acknowledgments

The authors acknowledge the funding support of Sydney Water and the material assistance provided by Integrated Civil and Infrastructure Research Centre, which was part funded by EPSRC Grant EP/R010420/1. Sydney Water entered into an enforceable undertaking with the EPA after seven discharges of untreated sewage from a Sydney Water rising main in Grasmere in January and February 2020. As part of this undertaking, Sydney Water will contribute funds towards environmental projects.

References

[1] W. Liang, L. Zhang, Q. Xu, and C. Yan, 'Gas pipeline leakage detection based on acoustic technology', *Eng. Fail. Anal.*, vol. 31, pp. 1–7, Jul. 2013, doi: 10.1016/j.engfailanal.2012.10.020.

[2] S. Großwig, A. Graupner, E. Hurtig, K. Kühn, and A. Trostel, 'Distributed Fibre Optical Temperature Sensing Technique - A Variable Tool for Monitoring Tasks', 2001, doi: 10.13140/RG.2.1.4295.3761.

[3] C. X. Hou and E. H. Zhang, 'Pipeline Leak Detection Based on Double Sensor Negative Pressure Wave', *Appl. Mech. Mater.*, vol. 313–314, pp. 1225–1228, Mar. 2013, doi: 10.4028/www.scientific.net/AMM.313-314.1225.

[4] J. Wang, L. Ren, Z. Jia, T. Jiang, and G. Wang, 'A novel pipeline leak detection and localization method based on the FBG pipe-fixture sensor array and compressed sensing theory', *Mech. Syst. Signal Process.*, vol. 169, p. 108669, Apr. 2022, doi: 10.1016/j.ymssp.2021.108669.

[5] S. Kim, B. Choi, and J. Lee, 'Fabrication and experiment of polymeric diaphragm pressure sensors', in *The 6th 2013 Biomedical Engineering International Conference*, Amphur Muang, Krabi, Thailand: IEEE, Oct. 2013, pp. 1–4. doi: 10.1109/BMEiCon.2013.6687663.