# Leak Detection and Quantification of Leak Size along Water Pipe using Optical Fibre Sensors Package

L. Wong[1]*, R. N. Deo[2], S. Rathnayaka[2], B. Shannon[2], C. S. Zhang[2], J. Kodikara[2] & W. K. Chiu[1]

[1]*Department of Mechanical & Aerospace Engineering, Monash University, Clayton Campus, Victoria, 3800, Australia*

[2]*Department of Civil Engineering, Monash University, Clayton Campus, Victoria, 3800, Australia*

H. Widyastuti[3]

[3]*Institut Teknologi Sepuluh Nopember, Jln Arief Rahman Hakim, Surabaya, Indonesia*

**Corresponding author: leslie.wong@monash.edu*

ABSTRACT: Water pipeline condition monitoring is a challenging task that requires in-depth research and investigation. Leakages in pipelines can waste large quantities of water daily and affect the quality of the water supply. Detection, quantification, and accurate localisation of leaks can significantly improve the service delivered. In this context, a 'contact-less' optical fibre sensor package was developed with the ability to measure pressure and detect vibration in pipe. This study provides a description of the developed sensor and presents the findings from a set of experiments with the sensor package deployed inside a pressurised pipe. Results indicate that the proposed sensing strategy for leak detection and quantification is robust and promising.

KEYWORDS: leak detection, leak quantification, optical fibre sensing, distributed acoustic sensor, water pipeline

## 1 INTRODUCTION

Pipelines are economical methods for transporting water over short and long distances to supply the basic needs in both the urban and rural areas. Hence, the water utilities spend a significant amount of money annually to monitor, repair and replace these assets to ensure their continual performance. However, billions of litres of water are still undelivered and wasted every year due to leaky pipes (Lai, 1991). This is still a major issue for the water industries in all countries. There are several Pipeline Leak Detection Systems (PLDS) commercially available (Liu, 2013) that supervise in-service pipelines in order to detect and localise any potential leak development. However, their limitations and costs continue to be an important factor in the non-acceptance of any approach for leak detection and localisation. Therefore, there is a need for new sensors and monitoring techniques to be developed to provide an efficient and cost-effective method for pipeline structural health monitoring.

Over the past decades, Distributed Optical Fibre Sensors (DOFS) have gained attention and successfully demonstrated their potential for pipeline structural health monitoring applications (Rajeev, 2013). The distributed optical sensors can detect ground movement and measure localised deformation by measuring the strain along the pipe (Nikles, 2009). Detecting, locating and monitoring of the bending and buckling effect of a pipe can also be conducted by installing three distributed optical fibre sensors at $120^o$ apart around the pipes. For applications in leak detection, the fibre optic cable, which is buried directly underneath the pipe, can detect a leak by measuring the change in the temperature due to the presence of water leaks (Eisler, 2008). The optical sensors can also be instrumented helically around the pipe to provide circumferential information (Lim, 2016, Inaudi, 2006). Progress has been made recently in improving the dynamic range of the DOFS technology, with Rayleigh-based techniques. Wong et. al. (2016a, 2017a) showed the potential of using DOFS to monitor the dynamic response of a small diameter pipe when subjected to pressure transients. Optical fibre sensors can also be used to detect and monitor the crack growth due to fatigue transient loading (Wong 2017b).

Almost all the fibre optic sensors' deployment methods utilised so far require the fibre optic to be attached or embedded to the structure. These fibre optics monitoring methods restrict the application of fibre optic sensor to be applicable only for new and smart pipelines. A challenge remains for the use of fibre sensors for the assessment of existing buried and old pipelines. In this paper, the optical fibre sensors package is designed with an intention of a 'contact-less' fibre deployment method to continuously monitor the water pressure and detect the presence of leaks via the presence of any anomalous vibrations. The results presented in this paper reports on the investigation conducted on the use of this sensor arrangement for the detection and quantification of leak along a pipeline.

## 2 OPTICAL FIBRE SENSORS PACKAGE

### 2.1 *Design of optical fibre sensors package*

The optical fibre sensors package presented in this paper is a customised optical fibre-based prototype constructed at Monash University. A depiction of the customised sensor is shown in Figure 1(a). Single mode fibre (SMF28e) is used as the sensor of choice for the testing. A cylindrical PVC tube of 100 mm length, 25 mm inner diameter and 1 mm thickness was prepared as the outer casing. Two strands of optical fibre sensor were bonded to the internal surface of a PVC tube with 5 minutes- Araldite as shown in Figure 1(b), namely Fibre Optic 1 and Fibre Optic 2. The total sensing length of the fibre optic is 50 mm. Both ends of the PVC tube were sealed properly with end caps (with optical feedthrough). The remaining loose fibre ends were protected with a rigid rubber tube (4mm diameter). At the final stage of preparation, all the connection points were sealed with water-proof silicone. Figure 1(c) shows the optical fibre sensors package used in the experiment.

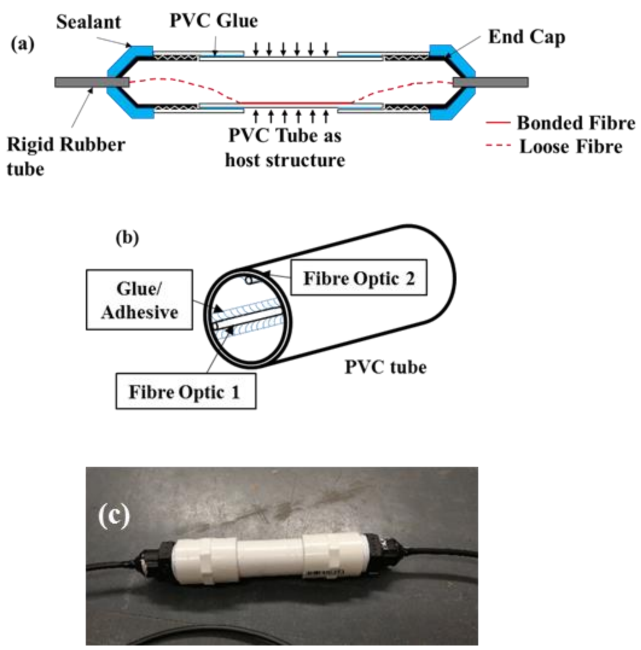


Figure 1(a) Schematic drawing of the prototype submersible optical fibre pressure sensor, (b) depiction of the interior of the PVC tube and (c) depiction of the actual sensor.

### 2.2 *Operating fibre optic systems*

Two different distributed optical fibre sensors systems are employed for the experiment presented in this paper. One of the optical fibre (Fibre Optic 1) from the device shown in Figure 1(b) was connected to the Optical Distributed Sensor Interrogator (ODiSI-B series) from LUNA Technologies. The ODiSI-B functions based on Rayleigh optical frequency domain reflectometry (OFDR) coupled with swept-wavelength interferometry (SWI). The operating principle and the specification of the system were reported in (Sounthararajah, 2017 and Wong 2016b) and has also been successfully demonstrated for monitoring composite and cement structure, thereby substantiating the reliability, accuracy and effectiveness of this sensing technique for both static and dynamic monitoring. The system can measure strain and temperature up to a maximum length of 10 m at 100 Hz.

The second fibre sensors (Fibre Optic 2) from the optical fibre sensor package was connected to FFT Aura-Ai from Future Fibre Technologies. The principal operational of FFT Aura-Ai is based on Coherence Rayleigh Optical Time Domain Reflectometry (C-OTDR) technique. Short light pulses are generated by a highly coherent laser, amplified and sent into the fibre with a repetition rate. An interference pattern can be observed and monitored in the reflected Rayleigh backscattered signal. The presence of any vibrations can cause a temporary change in the interference patterns. The changes of the interference patterns can be digitalised, analysed and post-processed in a computer unit. It is also commonly known as a distributed acoustic sensors (DAS) system. The operating principle and specifications are reported in (FFTsecurity, 2018). According to the specifications provided by its manufacturer, this system can detect vibration to a maximum length of 20km at 20 kHz per channel.

### 2.3 *Pressure calibration*

To perform pressure monitoring, the strain information measured using ODiSI will need to be calibrated against pressure transducer. A testbed is set up in the laboratory as shown in Figure 2(a). Two 1 m u-PVC pipes with an inner diameter of 100 mm and a thickness of 3mm were prepared and jointed with a T-joint (see Figure 2(b)) to make a total pipe length of 2 m for the experiment. Three pipe end caps were prepared and a hole with a diameter of 34 mm was drilled at the centre of all of the pipe end caps. The optical fibre sensors package as described earlier was deployed through one of the pipe end caps and optical feedthrough was properly sealed using water-proof silicone after package deployment. The location placement of the sensors packages the PVC pipe was 1.2 m away from the pipe end-cap (location of insertion). A water inlet and a pressure transducer were connected to another end of the PVC pipe (on the pipe end cap). A ball valve was connected to the last pipe end cap and installed on the T-joint. This ball valve was used to release the pressure in the pipe.

The water pressure will compress the casing of the sensor package and cause a change in strain of the tube. Fibre Optic 1 was first calibrated with the PVC pipe filled with water under a quasi-static pressure condition. The ball valve was left open during the filling process to allow the air within the pipe to be exhausted. After the pipe was filled, the ball valve was closed. Three pressurising and depressurising tests were conducted on the pipe by connecting and disconnecting the inlet of the pipe to the water supply with known operating pressure (500kPa). The optical fibre sensor was calibrated against the pressure transducer. The measurements were conducted with a sampling rate of 100Hz. The relationship between strains measured by the optical fibre sensor against pressures obtained from the pressure transducer for the calibration test is presented in Figure 3. The internal water pressure compressed the optical fibre device and explains the reason of compressive strain measured by the optical fibre sensor. This calibration test shows the linear relationship between the strain of the casing and the water pressure. The calibration factor will be applied to all the following results.

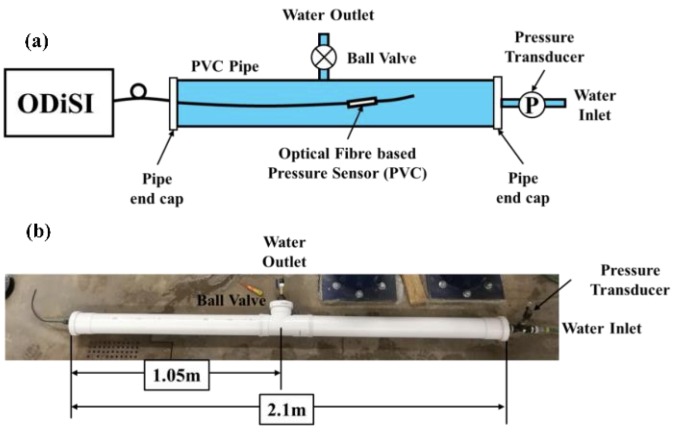


Figure 2(a) Schematic drawing of the experimental set up and (b) the actual experimental set up.

## 3 EXPERIMENTAL SET UP

The optical fibre sensors package was deployed to demonstrate transient-based leak detection using the same experiment set up for calibration test as shown in Figure 2. In this test, another 8 pipe end caps were prepared by drilling a circular hole (damage) at the centre on 7 of the end caps. The diameter of the drilled hole on each end caps was 2.0 mm, 4.5 mm, 7.2 mm, 9.5 mm, 13 mm, 25 mm and 33 mm as shown in Figure 4. The leak size is then defined as the diameter of the hole, which are approximately 3.2 mm$^2$, 16 mm$^2$, 41 mm$^2$, 71 mm$^2$, 132 mm$^2$, 491 mm$^2$ and 855 mm$^2$ respectively. The end cap without any damage (reference) was first installed on the tee-junction (replacing the ball valve) to simulate a no leak situation. A pressure transient event (pressure fluctuation) is induced by quickly turning on the valve that connects the pipe to the water supply with 500 kPa. The transient event was monitored by using Fibre Optic 1 at a data acquisition rate of 100Hz. The experiment was then repeated with the different (damaged) end caps (see Figure 4) one at a time.

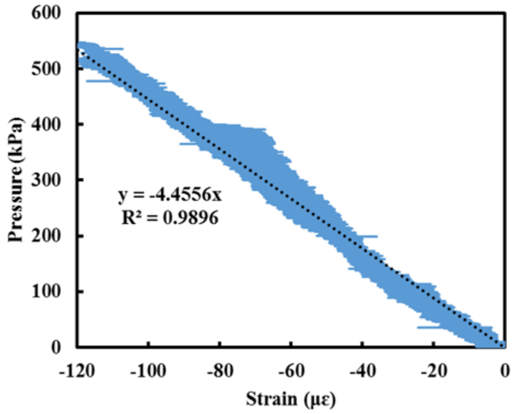


Figure 3. Correlation between the pressure obtained from pressure transducer and strain measured by ODiSI-B.

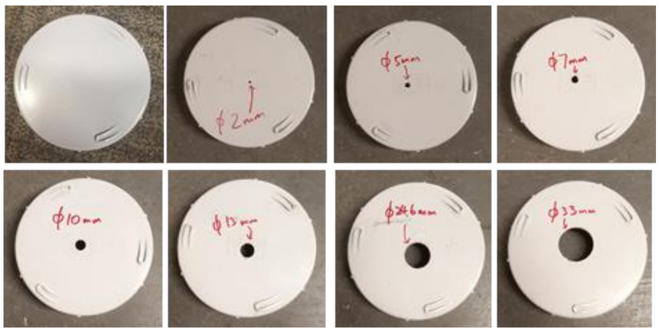

Figure 4. End caps with different drilled diameter at the centre.

## 4 RESULTS AND DISCUSSION

### 4.1 *Fibre Optic 1 – Leak induced damping monitoring*

The strain-pressure calibrated Fibre Optic 1 (as presented in Section 2.3) inside the optical fibre sensors package was used to measure the pressure transient profile within the leaky pipe. It was noted that pressure dropped gradually with leak size. With a large leak size (more than 71 $mm^2$ for this test set up), the water pressure can no longer be held inside the pipe as the rate outflow is more than the inflow. For comparison, the pressure profiles obtained from different leak sizes were normalised against their steady operating pressure for each of these transient cases and the results are reported in Figure 5.

For the pipe without leakage (with undamaged end cap), the pressure transient dampened out in approximately 6 seconds (see Figure 5). The damping coefficient without leakage can be due to several factors (Colombo, 2009 and Wang, 2002) including the geometry of the pipe, friction and the existing fittings within the pipe network. Figure 5 also shows the damping effect increased due to the presence of a leak as the pressure wave took a shorter time (less than 4 seconds) to fully dampened out. The damping ratio was then calculated for each of the transient events presented in Figure 5 through a least-squares non-linear fitting procedure. The damping ratios for different leak size are reported in Figure 6. In Figure 6, the leak size is normalised with the cross-sectional area of the pipe. The result clearly shows that the increment of leak size leads to the increment of damping coefficient. The rapid decaying pressure transient showed in the result obtained from the experiment agrees with the behaviour of the transient signal in the leak system reported by Colombo et. al. (2009). The increment of transient damping, also known as the key premise of transient-based leak detection, can be further studied to achieve better detection and quantification.

The result obtained thus far shows that the proposed pressure monitoring optical fibre-based device can potentially detect and quantify the leak size by monitoring the leak induced damping effect. However, the leak induced damping methods may not be useful for identifying large leak size. Nevertheless, several transient based leak detection techniques have been developed (Shi, 2015, Stephens, 2013 and Gong, 2013) over the last decades. Further research is still needed, especially in the application of the proposed pressure monitoring optical device in conjunction with different transient based leak detection methods to better detect, localise and quantify leakage.

### 4.2 *Fibre Optic 2 - Vibration based leak detection*

FFT Aura-Ai was set to log the vibration data along Fibre Optic 2 (installed in the optical fibre sensor package, refer to Figure 1b) at a rate of 5 kHz over the test. Spectral analysis was performed on the results obtained from Fibre Optic 2. The results are presented in the spectrogram as shown in Figure 7. For better comparison, the pressure measurement obtained from Fibre Optic 1 is plotted directly underneath the spectrogram as shown in Figure 7. The red dashed lines were plotted in Figure 7 to highlight the time region when the pipe was pressurised with different pipe end caps attached (with different leak size). There are some signals detected by Fibre Optic 2 beyond the pressurised periods especially 8.5 - 10 mins. These signals were due to the action of changing the pipe end caps. This result shows the sensitivity of the results obtained from Fibre Optic 2.

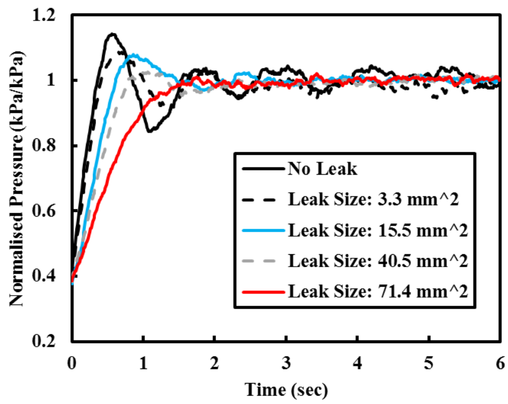


Figure 5. Normalised pressure profile with different leak size.

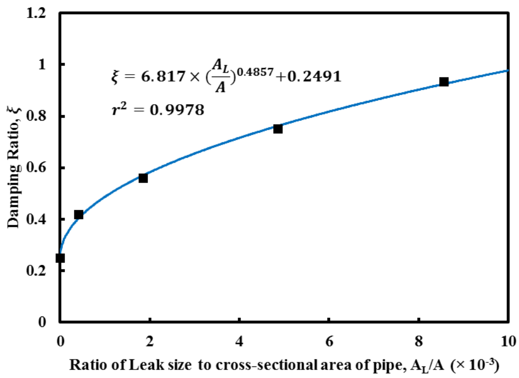


Figure 6. Damping ratios for different leak sizes

From the spectrogram shown in Figure 7, Fibre Optic 2 detected a strong signal with frequencies ranging from 200 Hz to 400 Hz with the presence of a leak. For each test, the pressure cycle lasted for 30 seconds to 1 minute. The leak signal obtained from Fibre Optic 2 is very consistent during each pressure cycle as evident in Figure 7. It is also noted that there is an incremental increase in frequency when the leak size increased (indicated by the line shown in Figure 7). The relationship between the vibration signal and leak size is further analysed and plotted in Figure 8. The leak size is defined in term of percentage over the cross-sectional area of the pipe. There is a non-linear relationship between the leak size and the vibration signal due to the leak rate. However, it is also noted that the vibration frequencies increased linearly when the leak size is less than 2% of the cross-sectional area of the pipe as shown in Figure 9. Further investigation is needed for future testing.

It is also interesting to note that the Fibre Optic 2 can hardly detect high frequency vibration when there is no leak present in a pressurised pipe (from 15 mins – 20 mins) as shown in Figure 7. Moreover, there are some low vibration frequencies (less than 50Hz) detected when the pipe was pressurised. The low vibration frequencies detected could be because of the optical fibre sensors package was floating freely in the pipe. The flowing water is causing the sensors package to knock on the pipe surface and causing those low vibration frequencies. Nevertheless, these hypotheses would need further investigation and testings with different operating conditions (pipe geometry, pipe material, pressures, flow rates and loading condition).

From the results obtained thus far, distributed acoustic sensor (Fibre Optic 2) has the capability to

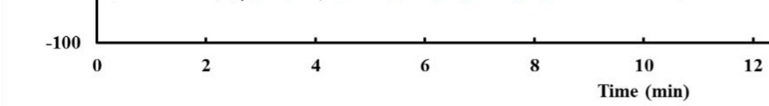


Figure 7. (Top) Spectrogram of the signal obtained from Fibre Optic 2 & (Bottom) pressure measured using calibrated Fibre Optic 1.

detect abnormal vibration in the pipe due to the presence of leakage. The results also showed that the fibre is very sensitive to any vibration (flowing water and knocking) which may not be useful for pipeline monitoring and leak detection. The sensitivity may give off a false positive alarm and therefore, better definition of the signal, signal processing, filtering, data fusion and correlation will need to be further developed and researched for better indication of the abnormal event and quantification. The optical fibre sensors package is also one of the options to prevent false positive alarm as information obtained from multiple detection and sensing methods can be compared and correlated to justify the signal obtained from each sensor technique.

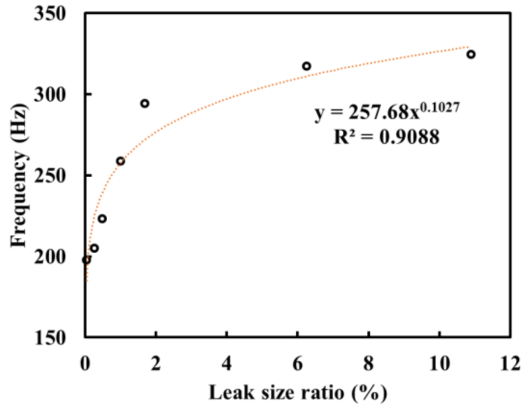


Figure 8. Relationship between the exciting vibration and leak size (in term of % of the cross-sectional area of pipe).

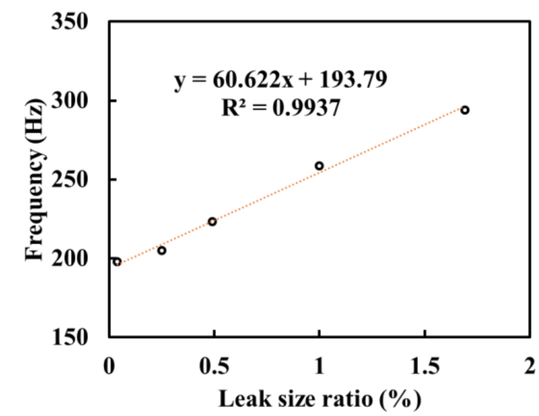


Figure 9. Relationship between the exciting vibration and leak size (less than 2% of the cross-sectional area of pipe).

## 5 CONCLUSION

A concept of 'contact-less' and multiple optical fibre sensors package is introduced in this paper to detect and quantify leak size in a pressurised water pipe. The intention of this concept is to allow deployment of fibre optic based sensor to ageing in-situ pipes without attachment to the pipe's wall surface. This strategy ensures undesired capital works on old pipes are not needed in terms of fibre optic sensor installation

A prototype optical fibre-based device was constructed in the laboratory with the capability of measuring pressure and vibration detection. In this study, we show that the quantification of the leak size with both leak detection methods deployed in the optical fibre sensors package is possible. Moreover, is also possible to correlate the acquired information to minimize a false positive alarm.

Further development of the sensors package and signal processing is ongoing to improve the accuracy and sensitivity of the sensor. Since the optical fibre sensors can be multiplexed easily, it is possible to duplicate the sensors package to perform a distributed and continuous monitoring along the pipe. With more monitoring locations, the sensors package can potentially improve the detection of leaks, quantification of leak size and even localise the leaks accurately. Further investigation on some of the observations presented in this study regarding the 'contact-less' optical fibre sensors package, will be useful in future.

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