Monitoring of Buried Pipeline using Distributed Fiber Optic Technologies: Combined Acoustic-Temperature-Strain Sensing

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ABSTRACT: This paper presents the development of distributed optical fiber sensing system, which combined acoustic-temperature-strain sensing to enhance the condition monitoring of buried pipeline. The developed optical fiber system was tested using the 140 m long pipe-soil test facility built in the Hawk testing yard. Cement lined steel pipes with the diameter of 100 mm and 500 mm were buried at the depth of 800 mm and optical fiber cables were attached at four different locations around the pipe section. The pipe section was also instrumented with contact microphones to detect the acoustic signal. Various size of leaks were made along the pipe section and monitored using the acoustic signal and temperature sensing. Both acoustic and temperature sensing detected the leak reliably with required accuracy up to distance of 40 km. Using the combination of acoustic and temperature helped confirm the leak and reduce the false positives.

KEYWORDS: Brillouin scattering, Rayleigh scattering, Raman scattering, Distributed sensor, COTDR, Buried pipe

1. INTRODUCTION

Pipeline is a vital infrastructure, which transport water, gas and oil. Due to ageing of pipeline, leaking, which result from various causes such as corrosion, joint failure and third-party damages, is a common observed failure in buried pipes (Rajeev et al. 2014). This not only causes great economic loss to the asset owners, but also has social and environmental impacts such as pollution and contamination (Hang et al, 2008). Therefore, the continuous monitoring of pipeline is essential over time. The conventional condition monitoring techniques provide information in discrete locations and have difficulties in get reliable data over time.

Fiber optic sensors offer a relatively new technology to monitor the condition of spatially distributed structures such as pipeline, bridge and tunnels. Distributed fiber optic sensing has the ability to measure strain, temperature and acoustic signatures at thousands of points along a single mode fiber (e.g., Inaudi and Glisic, 2010; Rajeev et al., 2013).

This paper presents the development a of distributed optical fiber sensing system, with combined acoustic-temperature-strain sensing to enhance the condition monitoring of buried pipeline. The performance of this system was tested using the 140 m long pipe-soil test facility built in the Hawk testing yard. Mild Steel Cement Lined (MSCL) pipes with nominal diameters of 100 mm and 500 mm were buried at the depth of 800 mm. Optical fiber cables were attached at four different locations around the 500 mm pipe section, which was also instrumented with contact microphones to detect the acoustic signal, and then used to validate the optical fiber measurements.

Various size of leaks were made along the pipe section and monitored using the acoustic signal and temperature sensing. Both acoustic and temperature sensing detected the leak reliably with required accuracy up to distance of 40 km. The system could detect the leak down to 2 mm size with distance resolution of 0.5 m. Using the combination of acoustic and temperature helped confirm the leak and reduce the false positives.

The strain sensing also provided reliable results for a pipe bending test with the resolution of 20 uε. The advantage of having the combined monitoring of strain helped to evaluate the stress increment in pipe section due to leak induced soil erosion.

Hence, the distributed optical fiber sensing of acoustic-strain-temperature enhanced the condition monitoring of buried pipes together with third-party damage and intrusion monitoring.

2. FIBER-OPTIC CABLE AS A DISTRIBUTED SENSOR

Physical parameters such as vibration, strain and temperature can affect the light propagating properties of fiber-optic cable. These effects are able to be measured and localized over long distances by interrogating the various backscatter signals which occur as a result of light stimulation applied to one or both ends of the fiber.

The major backscatter signals are known as Rayleigh, Brillouin and Raman. Rayleigh backscattering is caused by time-varying strain as a result of acoustic energy on the fiber. Brillouin backscattering results from application of static temperature or strain on the fiber. Raman backscattering is present at different static temperatures. As Brillouin backscattering can be influenced by both temperature and strain effects, there are methods to isolate the strain component.

Some methods rely on careful design of the fiber optic cable, such that either temperature or strain components are exclusively sensed. The method deployed in the system used in this study relies upon the mathematical resultant of independent measurement of temperatures using both Raman backscattering and Brillouin backscattering, which then leaves just the strain component. For best accuracy, either the same physical fiber must be switched, or a companion fiber within the same cable, subjected to the same temperature, must be used.

Figure 1 shows a typical wavelength spectrum as it might occur at a particular position along a fiber optic cable due to propagation of a short pulse of light applied to the left hand end. The backscattering light returns to the left hand end. Energy of the forward-moving pulse is dissipated at the far end to avoid direct reflections.

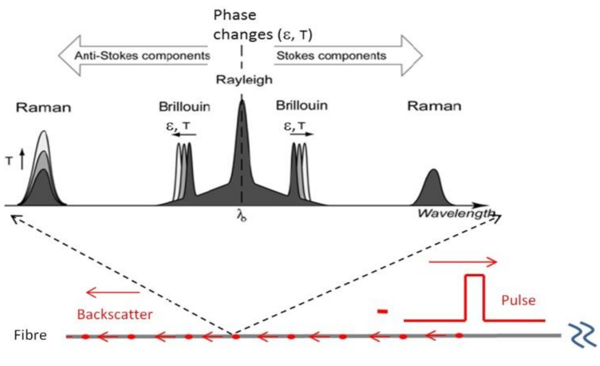

Figure 1 Backscatter light from an optical fiber

3. OVERVIEW OF OPTICAL FIBER SYSTEM USED IN THIS STUDY

The FOS Data Collection System under discussion is shown in Figure 2. It is constructed using each of these three types of measurement, using relatively inexpensive Single Mode Fiber-Optic cable as the distributed sensor.

Figure 2 FOS Data Collection System

All of these sensing methods rely on the principle of measuring some aspect of the scattered light which reflects backwards along the fiber. Some methods require a succession of scans to create a multidimensional 'picture' with respect to time. Fine resolution of distance requires many rapidly sampled points.

A brief description of each interrogation block follows.

The prototype system utilized dual laser sources. Common hardware functions such as DAQ sampling ports were switched between interrogation blocks to reduce system complexity.

In Figure 3, the purple block detected acoustic signals by interrogating Rayleigh backscattering using one form of Coherent Optical Time Domain Reflectometry (COTDR).

The green block detected temperature and strain signals by interrogating Brillouin backscattering using Brillouin Optical Time Domain Analysis (BOTDA).

The yellow block was to detect temperature signals by interrogating Raman Optical Time Domain Reflectometry (ROTDR).

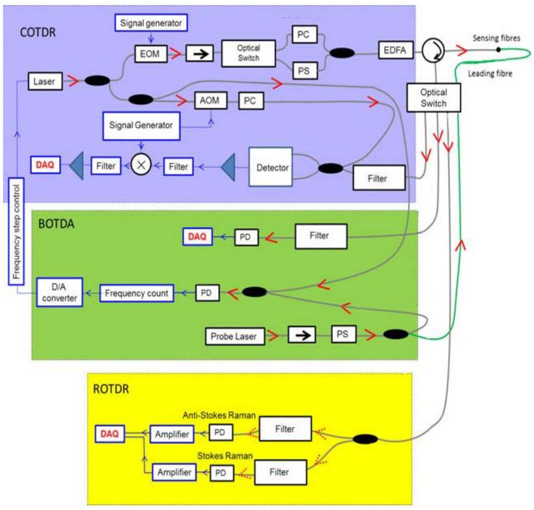

Figure 3 Basic block diagram of prototype system

3.1. DISTRIBUTED ACOUSTIC SENSING (DAS)

Method for Acoustic sensing was Coherent Optical Time Domain Reflectometry (COTDR). The purple block contains the optical pulse generation components which are common to the other blocks.

A succession of light pulses was sent along the fiber. The Rayleigh backscatter, affected by phase change of light induced by time variation of strain, is processed after each pulse. A number of pre-existing ripples will be present, and any changes to these on successive scans (related to time) is interpreted as an acoustic signal which occurs at a particular location along the fiber. 100,000 samples are required to achieve 0.5 m distance resolution, which calls for an acoustic amplitude sample rate of 2.5 nanoseconds. The low fidelity audio stream from any defined distance location can be monitored. The audio spectrum was processed and logged in the data collection system.

Bit depth needs to be sufficient to cover the required acoustic dynamic range, and this is definitely a compromise. 8-, 10-, and 12-bits give 48, 60 and 72 db range respectively. Although this system could measure 'loud' sounds adequately, the acoustic sound of a small water leak is very weak by comparison.

Figure 4(a) shows the interferometric signal. These ripples, because they are related to the fixed Rayleigh scatter sites within a fiber, are static as long as the fiber is static. If an acoustic wave impacts on the sensing fiber (as shown by a red arrow), the ripple at the position where the acoustic wave affects the sensing fiber starts to change due to the phase change of light induced by the variation of strain.

The interferometric signal intensity variation is processed and maximum intensity change along the position of optical fiber is calculated (Figure 4b). Acoustic signal waveform at the red arrow (Figure 4c) and spectrum (Figure 4d) at that position could be obtained by tracing the interferometric signal intensity variation.

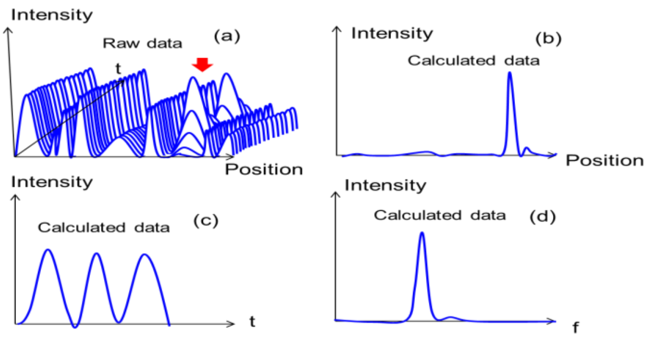

Figure 4 Data collection of COTDR. (a) Detected interferometric signal (b) Interferometric ripple variation peak vs position (c) Acoustic signal waveform. (d) Acoustic signal spectrum

3.2. BOTDA TEMPERATURE & STRAIN SENSING

A description of the BOTDA (green) block follows. The BOTDA method requires both a pulsed light source, generated within the purple block, plus a CW light source applied to the far end of the fiber. A succession of light pulses from the first laser source was thus sent along the fiber from one end. The (second) tunable laser wavelength is incremented by one small step for every scan.

Wavelength difference between the two lasers could be set to a particular value corresponding to the Brillouin frequency of the optical fibers, and the CW probe light experienced gain variation along the fiber. This gain as a function of position along the fiber could thus be determined by the time dependence of the detected CW light. The interaction between these opposing light sources generated the Brillouin backscattering signals. As the sidebands are equal, only one was used.

200,000 scans were required to measure up to 20,000 με maximum strain level, and this took 100 seconds with repetition rate of 0.5 ms. Same as for acoustic sensing, 0.5 m distance resolution required a sample rate of 2.5 nanoseconds.

The combined value of stress/strain/temperature at a particular distance corresponded to the frequency of the Brillouin peak. There was only one peak at any distance position. By measuring the time dependent CW signal over a wide range of frequency differences between the pump and probe by sweeping the frequency of the pump laser, the Brillouin frequency for each fiber location could be determined via pre-calibration as shown in Figure 5(a). This allowed us to establish the temperature (or strain) distribution along the entire fiber length in the form of the three dimensional graph as shown in Figure 5(b):

$$\Delta f = C_{\varepsilon}\Delta\varepsilon + C_t\Delta T \tag{1}$$

where, C_{ε} is the strain coefficient, C_t is the temperature coefficient, $\Delta\varepsilon$ is the change in strain and ΔT is change in temperature.

Polarization scramblers were included to ensure data consistency, and moving averaging was used to further reduce the noise floor.

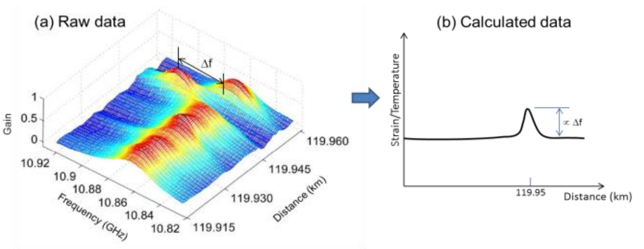

Figure 5(a) Optical intensity distribution of probe laser along different positions of optical fiber for different frequency separation between counter-propagating probe light and pump light.
Figure 5(b) Calculated strain using the data in (a)

3.3. ROTDR TEMPERATURE SENSING

A description of the ROTDR (yellow) block follows, as implemented. The same tunable laser and EOM could be utilized from the purple block. Raman back-reflection sidebands, called Stokes (S) and Anti-Stokes (AS) channels with independent filters, both behave differently to each other and are therefore required to be sampled concurrently. The Stokes channel remains virtually constant, whereas the weaker Anti-Stokes channel varies with temperature.

After sampling, this data set was processed by calculating the ratio of Stokes to Anti-Stokes intensity to determine the distributed temperature profile.

The ROTDR method requires a similar series of light pulses as generated within the purple block. Low level Raman backscattering signals were produced from each pulse. Any Rayleigh backscatter and Brillouin backscattering signals were removed using custom band reject filters.

Despite this filtering, the remnant Raman signals were buried deeply in noise, and a significant amount of averaging was necessary to achieve the clean looking graphical result shown in Figure 6(b). Best temperature accuracy can take several minutes of data accumulation time.

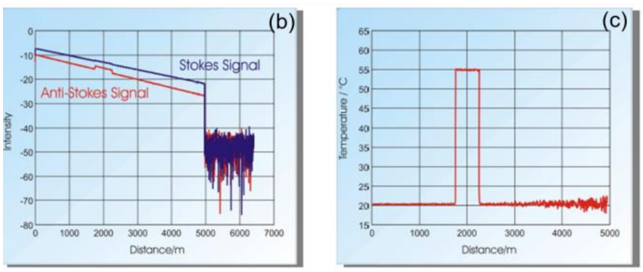

Figure 6 Raman Signals. (b) Relative intensity of Raman AS and S, (c) Normalized temperature derivation

3.4. DISTRIBUTED STRAIN SENSING (DSS)

The method used for Stress and Strain sensing was BOTDA and RODTR in combination, since the BOTDA method cannot exclusively measure distributed Stress/Strain values.

The resultant was effectively derived by subtracting the ROTDR and BOTDA data sets, thereby cancelling out the distributed temperature information. The advantage of this method was that there was no requirement for special fiber optic sensing cable to eliminate the temperature component.

4. FIELD MONITORING OF BURIED PIPE

Water pipeline integrity and potential threats of failure are generally difficult to monitor continuously. A major issue of monitoring existing pipelines is that most pipelines are buried and it is not easy to get access to retrofit monitoring sensors. However, when new pipelines are installed, it is relatively easy to install monitoring systems (Rajeev et al, 2013).

However it is possible to install fiber optic cable along the inside of an existing pipeline for acoustic and limited temperature/strain sensing. The pipe testing facility developed at Hawk has the provision for such installation.

5.1. DESCRIPTION OF HAWK PIPE TEST FACILITY

The pipeline testing facility (Figure 7) has 140 m long MSCL pipe of 114 mm diameter buried at 0.8 m depth. The pipeline has custom designed flanged connections every 6 m. Fiber optic cable was run along the complete pipeline length through a 32 mm diameter polyethylene conduit strapped to the outside of the pipeline, and the special flanges allowed the conduit to make optimum contact with the pipe surface.

Figure 7 Elevated test area. Large diameter water pipe inside the test area from South end (bottom left) and buried with 0.8m crushed rock (bottom right)

The elevated test area was designed to enable selective burying with easy access. Conduit containing the fiber optic cable was able to be positioned along either the DN100 or DN500 pipe.

Arrangement of the additional conduit sections was in such a way to allow a single fiber cable to pass along each in sequence, as shown in Figure 8, which eliminated a number of optical connectors.

Several conduits with fiber optic cable were bonded at various positions around the pipe to confirm if water leaks can be detected at any location on the pipe, rather than by the sensing fiber in the conduit closest to the leak. The leaks were created at the predefined locations.

A 1.5 m waterproof membrane, filled with a 50-75mm layer of fine crushed rock and scoria, was fitted around the large diameter pipe. An outlet tube with filter at the bottom allowed the leaked water to selectively collect and pool or drain away, capacity 50 liters (See Figure 9).

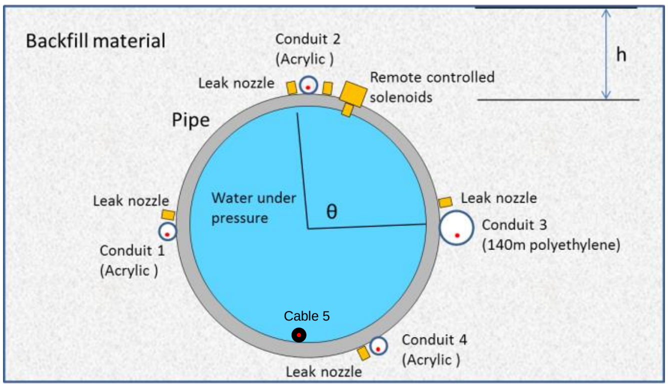

Figure 8 Large diameter pipe with multiple conduit and nozzle positions. Red dots = fiber

Figure 9 Multi-conduit installation of conventional sensors at centre of test area. Fiber optic conduits 1, 2 and 3 can be seen at left, centre and right respectively. Conduit 4 is located underneath the pipe, approximately below conduit 2

Conventional strain gauges were installed to monitor the longitudinal and circumferential strain variations. RTD temperature sensors and hydrophones were also installed to monitor the temperature variation and acoustic signals.

5.2. EXPERIMENTAL PROCEDURE

Tests were conducted to study the leak detection in buried pipe. The leak were induced at designated locations along the pipeline and pressurized water was supplied at 300, 500 or 700 kPa depending on test requirement. Various level of leak was created with 2 mm and 4 mm nozzles.

The variation of temperature and acoustic signature due to leak was recorded from the optical fiber and conventional sensors. The nozzle was opened for 5 sec and closed for 5 sec to simulate the leak (i.e., 6 bursts in 60 s). The temperature change was picked up by optical fiber after 60 sec. Figure (10) shows the temperature variation recorded by the optical fiber cable and conventional temperature sensor. At location 2 (~ 7.5 km), the significant change in intensity change was observed. See also Figure 11 which shows a 3D representation of the raw data. These readings are in line with the conventional sensor temperature readings at the leak location. Therefore, the system is able to monitor temperature variations for long distance with single mode fiber.

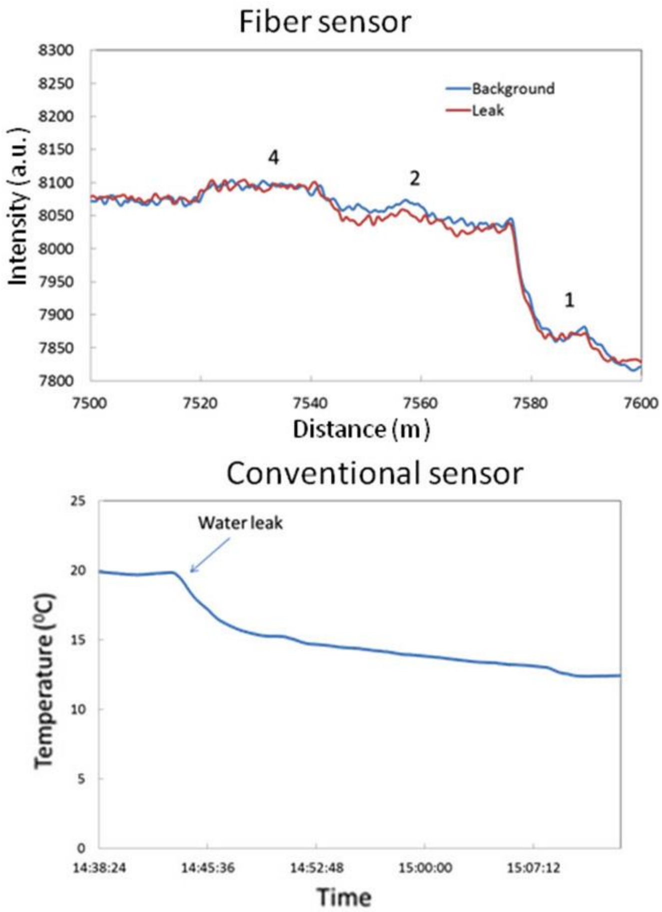

Figure 10 Temperature change due to a water leak

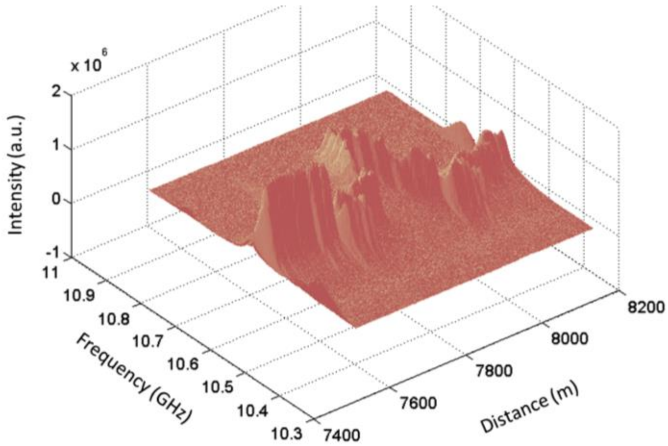

Figure 11 Representation of three dimensional data from BOTDA scan – looking like a mountainous landscape. Temperature/Strain value vs distance corresponds to the peak Brillouin frequency. Fiber position 2 shows a change in temperature and strain (8000 m)

The developed system was also capable of measuring the acoustic signals. The leak size was only 2mm and the test was carried out at pressures within the normal water supply range 300 kPa up to 700 kPa.

Figure 12 shows the acoustic signals with distance and time at different cable locations (in Figure 8).

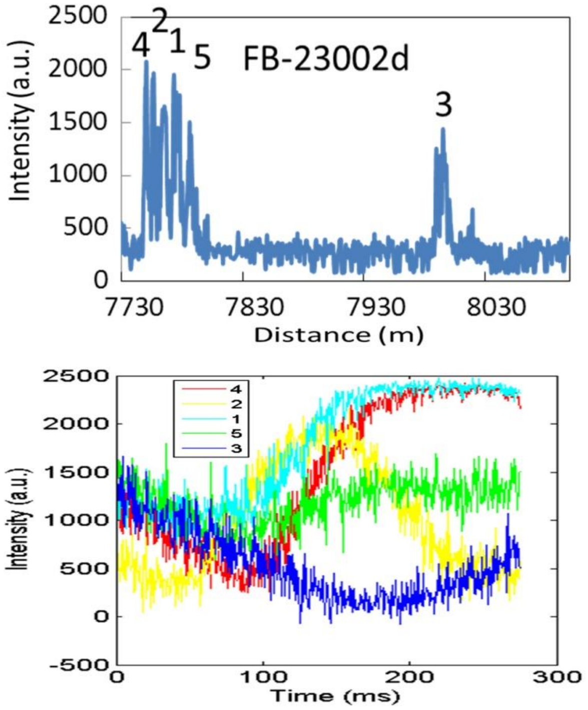

Figure 12 Water pressure 300 kPa, Leak at Nozzle #2 (2 mm hole). Raw acoustic signals shown in real time (colored)

Fiber sensors in all positions around the 500 mm pipe were able to detect water leakage at low pressure. Figure 13 shows the acoustic signature of a higher pressure leak.

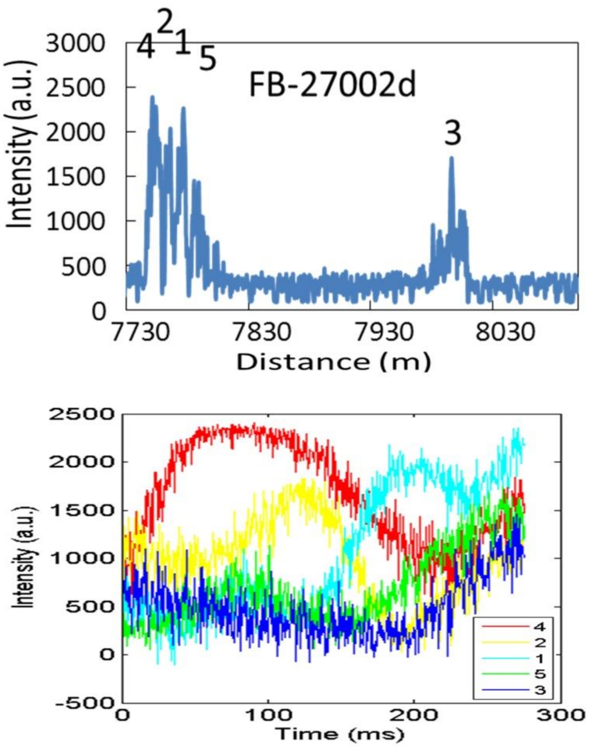

Figure 13 Water pressure 700 kPa, Nozzle #2 (2 mm hole)

High intensity signals were detected at higher water pressure.

6. CONCLUSION

Optical fiber sensing system which combined the acoustic-temperature-strain measurements with a single mode fiber was tested. The capability of this system was demonstrated via pipeline leak detection application in the field. The following observations were made from the test;

- Pipeline water leak was able to be detected over many kilometers using a combination of interrogation methods to determine the presence of acoustic, temperature and strain signals at the leak location using a fiber optic cable which was attached to the pipeline as a sensing element.
- System was able to detect the leak at low pressure with high accuracy and special resolution. Small leak (2 mm hole) at low pressure down to 300kPa can be detected by both acoustic signal and temperature variation within short period of time (i.e., < 60 s)
- Combined sensing enhanced the detection accuracy and increase the certainty of detection - free from false positives which can occur in systems which offer only a single method of interrogation.
- Third party disturbance events and strain due to ground subsidence were able to be detected.

Technology discussed in this paper has applications far beyond the monitoring of water pipe infrastructure. By developing and deploying the appropriate fiber optic sensors, the same FOS Data Collection System could readily be used to monitor the structural health of critical assets such as bridges, reservoir retaining walls, high rise building cores, ship hulls, earthquake fault regions and other applications.

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