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Water Pipe Condition Assessment Using Submersible Quasi-distributed Optical Fibre based Pressure Transducers

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ABSTRACT: Transient based technique is known as one of the most economical ways for pipeline condition assessment. This technique involves monitoring and analysing pressure transient profiles at multiple points in a distributed system. Its application is restricted due to its low spatial resolution (10 m). It is hypothesised that by increasing the number of pressure transducers and reducing the gauge length (distance between the transducers), the spatial resolution of the measurements would highly be improved. However, the deployment of pressure transducers is restricted to the location of the hydrants. In this paper, a submersible quasi-distributed optical fibre based pressure sensors were proposed, constructed and tested in laboratory to verify this concept. For this context, this paper describes the proposed optical device and presents some preliminary analysis and results obtained from a set of experiments. The experimental results show that using the quasi-distributed optical fibre based pressure transducers for pressure transient analysis can potentially detect small anomalies (200 mm) and measure the growth of the anomalies along a water pipe.

KEYWORDS: Condition Assessment, Quasi-distributed Optical Fibre, Pipeline, Sensor, Anomaly Detection

1 INTRODUCTION

Condition assessment for water pipeline is a challenging task that still requires in-depth research and investigation. Pipelines fail after a period of service time due to structural deterioration and ageing. Failure of these assets can lead to economical loss, reduction in hydraulic capacity in the distributed systems and affecting the water quality. Pipeline failures are usually due to a combination of factors, predominantly occur when severely deteriorated or corroded pipes are subjected to excessive internal and external loadings (CSA 2007 and Zhou 2011). The dominant factors which lead to failure in a specific pipeline are often difficult to identify and has not yet been resolved satisfactorily. According to previous data analysis and prediction, the annual replacement costs would decrease by 50% if the repairs were done proactively instead of reactively (Vitanage 2014). This is forcing the water utilities to search for new sensing technology to perform real-time and permanent pipeline integrity monitoring strategies.

There are many fluid transient based condition assessment techniques that have been developed (Shi 2015, Stephens 2013, Colombo 2009, and Gong 2013) over the last decades. These techniques are known to be one of the most economical strategies to quantify the health of the pipeline. The transient based technique involves measuring the pressure transient profiles at a high data acquisition rate and at multiple points (installed on hydrant) along the distributed pipeline networks. An advanced signal processing and filtering can be applied on the measured pressure profile to detect and localise leakages, blockage and even report the remaining pipe wall thickness with a certain spatial resolution. One of these commercialised services is known as p-CAT™ (Services 2016). However, the locations of the pressure transducers installed are restricted to the location of the hydrant and the spatial resolution is still relatively low (signal averaged over 10m). In many pipe burst case studies and reports provided in critical pipes (Criticalpipes 2015), it was found that pipe burst can even occur on a pipe without high amounts of uniform corrosion but with a localised corroded patch as small as 200 mm in diameter. The low spatial resolution of the pressure transient based technique has restricted its application for detecting small anomalies or corroded patches along pipe.

It is hypothesised that with an increased amount of pressure transducers and closer proximity to each transducer, the spatial resolution can be improved. Thus, the aim of this paper is to demonstrate the applications of quasi-distributed optical fibre based pressure sensors for transient based pipeline condition assessment. Two customised optical fibre based pressure sensors were built in the laboratory and the sensors are arranged in series. This paper reports on preliminary investigation conducted on the application of this optical fibre sensor deployment methods.

2 OPTICAL FIBRE BASED PRESSURE SENSOR

2.1 *Applications of DOFS for pipeline monitoring*

Distributed Optical Fibre Sensors (DOFS) have gained attention and successfully demonstrated their potential for pipeline structural health monitoring applications (Rajeev 2013) over years. 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 along pipes (Cauchi 2007). For water leak detection, the fibre optic cable, which is buried directly underneath the pipe, can detect leak by measuring the change in temperature due to the presence of leak (Eisler 2008). The optical sensors can also be instrumented helically to provide circumferential information (Lim 2015 and Inaudi 2006). Some progress has been made recently in improving the dynamic range of DOFS technology, in particular with Rayleigh-based techniques. Wong et. al. (2016a and 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).

2.2 *Design of optical fibre based sensors*

Almost all of the fibre optic sensors' deployment methods would require the fibre optic to be attached or embedded to the structure. However, these fibre optic sensor deployment methods still remain challenging for the assessment of existing buried and old pipelines. In this paper, the optical fibre sensors package is designed with an intention of an "attachment-free" fibre deployment method to continuously monitor the water pressure and detect anomaly vibration due to the presence of leak.

The optical fibre based pressure transducer presented in this paper is a customised optical fibre-based prototype constructed in Monash University. A schematic and 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. Two cylindrical PVC tubes of 100 mm length, 25 mm inner diameter and 1 mm thickness were prepared. A single strand of optical fibre sensor was bonded to the internal surface of the PVC tube with araldite as shown in Figure 1(b). 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). All of the connection points were sealed with waterproof silicone. Figure 1(c) shows the optical fibre sensors package used in the experiment. The same preparation process was repeated for the second PVC tube. After the second sensor was constructed, it was then spliced and connected to first sensor in series with a distance of 1 m in between as shown in Figure 1(d). The first sensor is defined as 'S1' whereas the second is defined 'S2' in the following sections.

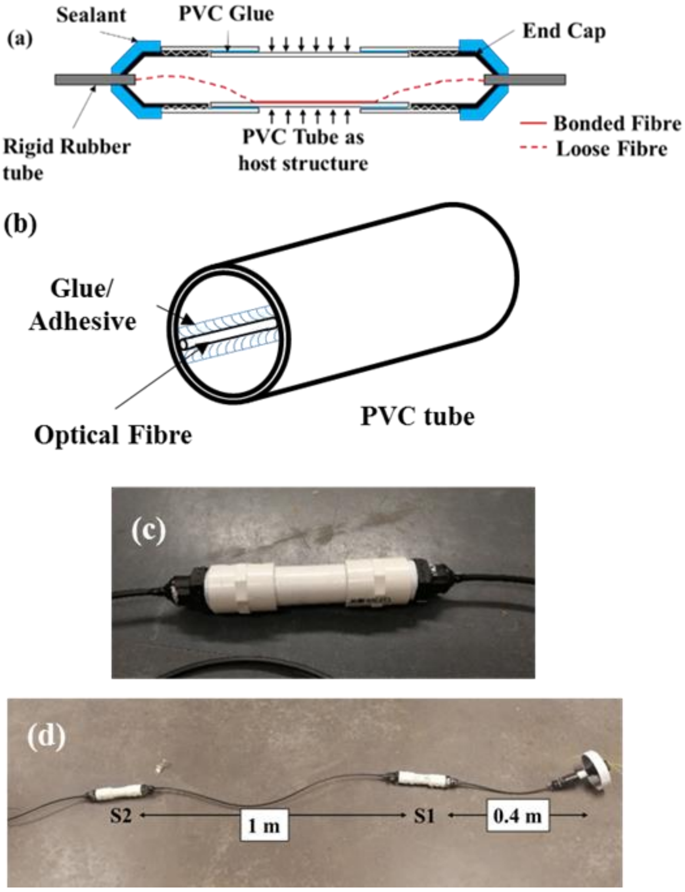

Figure 1(a) Schematic drawing of the prototype submersible optical fibre pressure sensor, (b) depiction of interior of the PVC tube, (c) depiction of the actual sensor and (d) final arrangement of sensors.

2.3 *Operating fibre optic systems*

The fibre optical cable 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 coupled with swept-wavelength interferometry (SWI). The system can measure strain and temperature up to a maximum length of 10 m at 100 Hz. The system reported in this paper has also been successfully demonstrated for monitoring composite (Wong 2016b) and cement structure (Sounthararajah 2017), thereby substantiating the reliability, accuracy and effectiveness of this sensing technique for both static and dynamic monitoring.

2.4 *Pressure calibration*

In order to perform pressure monitoring, the strain information using ODiSI was calibrated against a pressure transducer. A test bed was set up in the laboratory as shown in Figure 2(a). Two 1m u-PVC pipes with an inner diameter of 100mm 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 end caps were prepared and a hole with diameter of 34mm 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 end caps and properly sealed using water-proof silicone. When the two optical devices were placed in the PVC pipe, the S1 sensor was located 0.4m away from the end-cap (location of insertion), whereas S2 was located 1.4m away from the point of insertion. The locations of both sensors were marked on the surface of the pipe for better indication of the location of these sensors. A water inlet and a pressure transducer were connected to another end of the PVC pipe (on the end cap). A ball valve was connected to the last end cap and installed on the T-joint. This ball valve was used to release the pressure in the pipe.

The two sensors were then calibrated against the pressure transducer with the PVC pipe subjected to a known pressure loading (500kPa). The strain measured in both S1 and S2 were recorded. The relationship between the water pressure and strain of the casing was found to be linear and the calibration factors were -4.43 kPa/με and -3.47 kPa/με for S1 and S2 respectively. The information obtained from the ODiSI will be described in term of water pressure in the following sections.

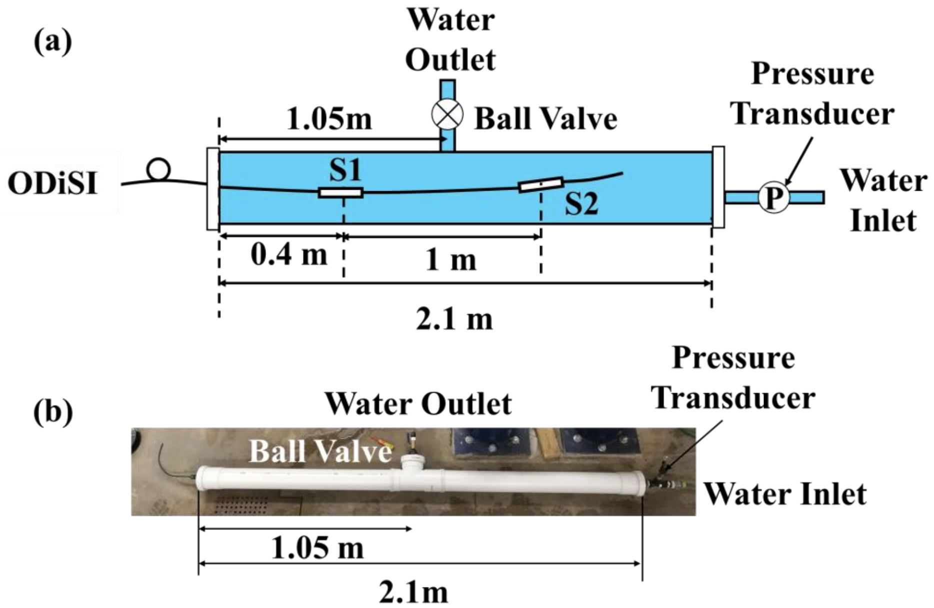

Figure 2(a) Schematic drawing of the experimental set up and (b) the actual experimental set up.

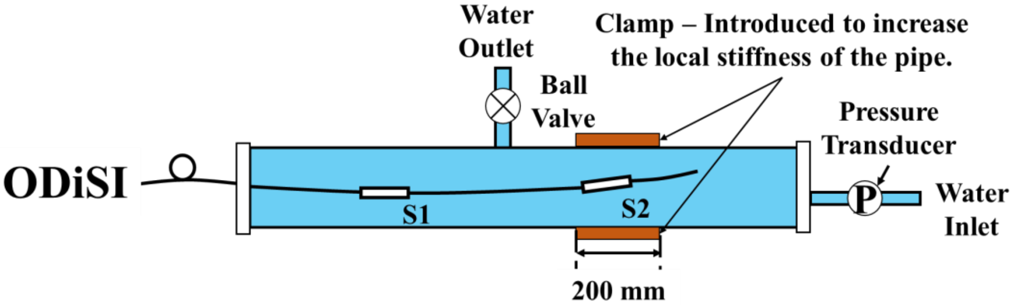

Figure 3. Experimental set up for Test 1.

3 EXPERIMENTAL PROCEDURES

The aim for the following experiments was to investigate the changes in pressure transient events to detect the presence of an anomaly along a pipe. The same experiment set up for the calibration test as shown in Figure 2 was used for this purpose. Two different tests were conducted using the optical fibre based pressure transducers.

The purpose of the first test was to investigate the pressure transient at the location around the region of the anomaly along the pipe. In this test, the pipe section closer to the location of S2 was examined. A pressure transient event (pressure fluctuation) was induced by quickly turning on the valve that connected the pipe to the water supply with a known pressure head of 500 kPa. The transient event was monitored on S2 at a data acquisition rate of 100Hz. The experiment was then repeated with that section clamped with (1) steel clamps and (2) rubber clamps (one scenario at a time). The clamps covered a 200 mm section of the pipe at the region closer to S2 as shown in Figure 3. The clamp was introduced to change the local stiffness of the pipe. This method has also been used in (Wong 2016a and 2017a) to simulate a change in local stiffness (anomaly) along the pipeline in laboratory. The steel clamps and rubber clamps section are shown in Figure 4(a) and (b) respectively.

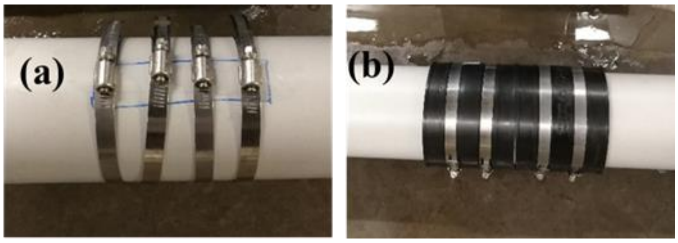

Figure 4 (a) Steel clamps and (b) rubber clamps at the region closer to S2.

The second test was planned with an intention of simulating the growth of the anomaly along the pipe section. Therefore, in the second test, the entire pipe was first clamped with rubber clamps as shown in Figure 5. The valve at the water inlet was turned on quickly to stimulate a pressure wave to propagate along the pipe (same method as mentioned in the first test). The pressure wave was monitored using both sensors (S1 and S2) at 100Hz. The test was then repeated with the rubber clamps unclamped from R1 to R4 (one at a time). Each unclamped region was approximately 200mm. S1 was located in between R2 and R3 region. In this test, S1 acted as a sensor in the near field to the anomaly section along the pipe whereas S2 represented the sensors installed in far field.

Arrow indicates the direction of unclamping the pipe

Figure 5. Pipe is fully clamped with rubber clamps

4 RESULTS AND DISCUSSION

4.1 *Test 1 – Detection of localised stiffness change*

The signals measured at S2 during the transient event in Test 1 include both dynamic response (pressure wave) and static function (operating pressure). For comparison, the pressure transient event monitored using S2 for Test 1 was first normalised with the static operating pressure (500kPa) and the static operating pressure was then removed. The results for Test 1 were plotted in Figure 6 over a period of 8.5 seconds. A spectral analysis was also performed on these results and presented in Figure 7.

For the pipe without any clamps or reinforcements, the pressure wave had a period of 1.3 seconds and it dissipated over 4 seconds (see black solid line in Figure 6). The pressure wave has the fundamental oscillating frequency of 0.76Hz as shown in Figure 7(a). This domain frequency will be the baseline of the pressure wave when the pressure wave was propagating in the pipe without any inhomogeneity. In this test, the pressure transient acted as a naturally occurring stimulus to assess the condition of the pipeline.

The pressure profile measured by S2 when the rubber clamp was clamped at the pipe section (exactly on top of location of S2) is plotted as the grey solid line shown in Figure 6. As the rubber material absorbs the energy due to the pressure transient, the pressure wave dampened out faster as indicated in Figure 7(b). When the pipe section at S2 was reinforced with the steel clamps, a higher frequency was determined by S2 (see red solid line in Figure 6). As circled in Figure 7(c), a frequency of 2.1 Hz was determined in the measurement obtained from S2. It is because the steel clamp increases the local stiffness of the pipe and it caused a reflection of a higher frequency wave within the pipe. There is also a subtle phase shift as shown in the red line in Figure 6, which indicated an increase of wavespeed. It is also noted that the pressure wave took a slightly longer time (approximately 6 seconds) to dissipate as indicated in Figure 7(c). As the expansion of that pipe section was restricted, the energy was preserved and the energy loss was also reduced. The results obtained in this test can be very subjective and may not be useful for the field application as there is a very large change in stiffness (steel vs PVC). Further investigation is still needed for future testing.

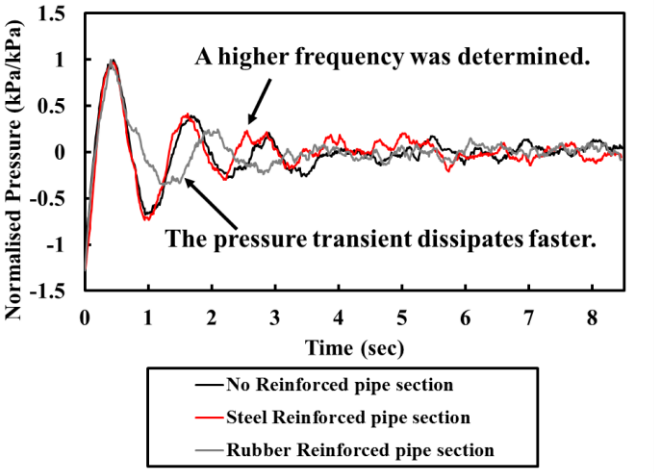

Figure 6. Normalised pressure profiles measured at S2 with different local stiffness along the pipe.

4.2 *Test 2 – Determine the growth of the anomaly*

The pressure profile measured at S1 and S2, when different pipe conditions were subjected to pressure transient, are reported in Figure 8 and 9 respectively. In Figure 8, S1 measured some higher frequencies when the pipe was fully clamped and the pressure wave dissipated over 10 seconds. The black solid line is the baseline for this analysis. When the region of the pipe closer to S1 was unclamped, the higher frequencies dampened faster. There is also a clear change in its damping as circled in Figure 8 when the unclamped (less stiff) regions grew closer to the location of S1. The results presented in Figure 8 shows the response of the pressure wave at the region of the anomaly which simulate a near field scenario.

The pressure profile measured at S2 was simulating the response of pressure wave away from the region of interest (anomaly). In Figure 9, there are subtle changes in the period and damping measured at far field. However, several large reflections were detected when the unclamped region became larger (unclamped up to R3) as circled in Figure 9. It could be due to the amplification of the reflection from the anomaly after certain period of time.

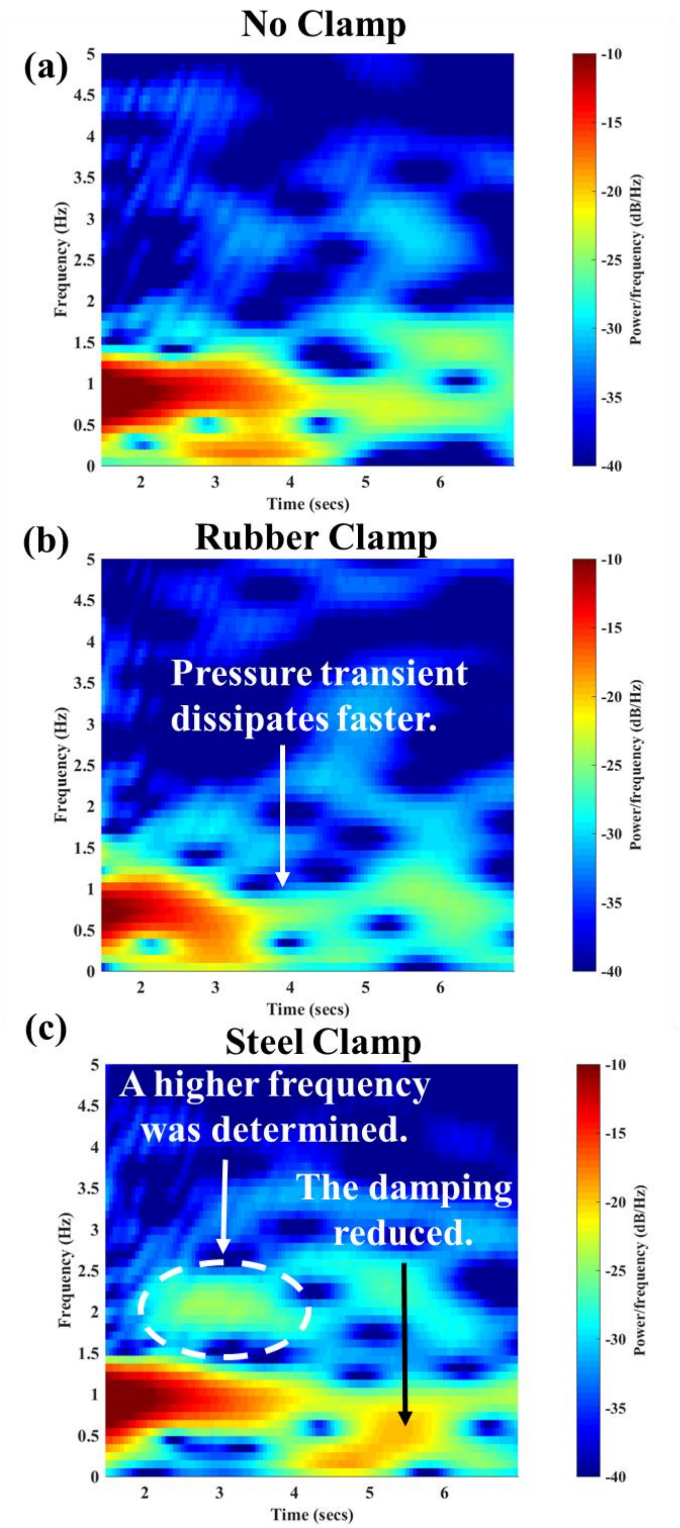

Figure 7. Spectrogram of the pressure profile obtained at S2 when the pipe section at S2 were (a) unclamped, (b) reinforced with rubber clamp and (c) reinforced with steel clamp.

The results thus far have showed the preliminary investigation on the pipeline condition assessment based on the measurement obtained from the quasi-distributed optical fibre based pressure transducers. The presented results showed that the pressure transient can act as a naturally occurred stimulus to assess the condition of the pipeline. With the pressure transducer placed closer to the anomaly along the pipeline, the transducer manages to determine the changes in pressure wave which indicate the presence and growth of inhomogeneity on the pipe. To improve the accuracy and sensitivity of the signal, the natural frequencies for the casing of the optical fibre based pressure sensors can be further tuned accordingly to the frequency that is causing changes due to the presence of an inhomogeneity.

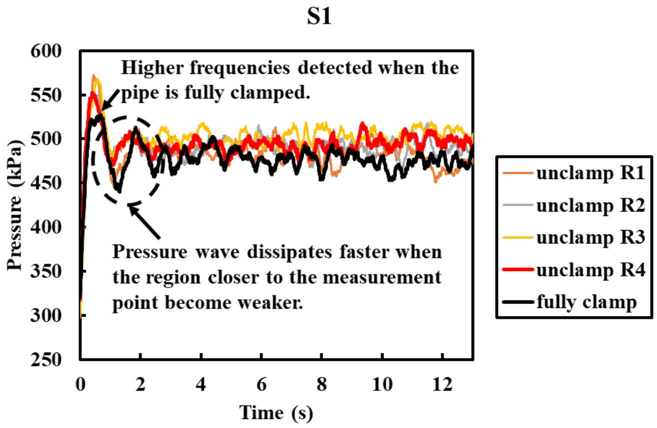

Figure 8. Pressure profiles measured at S1 with different region of the pipe unclamped to simulate growth of anomaly along pipe.

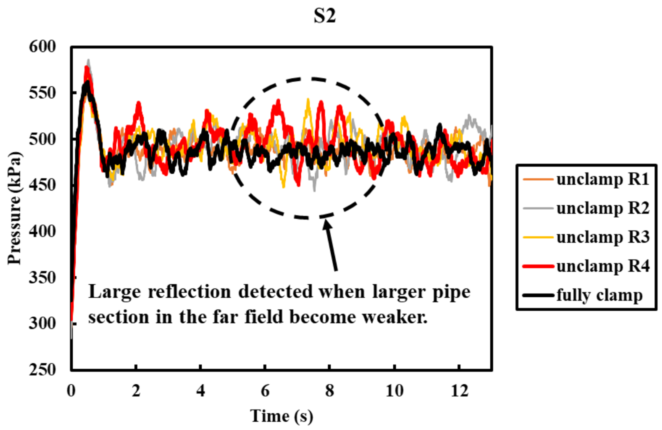

Figure 9. Pressure profiles measured at S2 with different region of the pipe unclamped to simulate growth of an anomaly along pipe.

5 CONCLUSION

A quasi-distributed and ‘attachment-free’ multiple optical fibre sensors package is introduced in this paper to monitor pressure transient profile for condition assessment of pressurised pipe. The transient based condition assessment technique was conducted on a pipe with localised anomaly. This paper reported the results obtained using the optical fibre device to detect the presence of anomaly. The results also show that it is possible to monitor the growth of the anomaly.

Further development of the quasi-distributed optical fibre based pressure sensors and signal processing are still ongoing to improve the accuracy and sensitivity of the sensor. In conclusion, more research is still needed to improve the transient based pipeline condition assessment using the submersible quasi-distributed optical fibre based pressure sensors.

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