REAL-TIME CONTINUOUS PIPELINE INTEGRITY MONITORING UTILISING TELECOMMUNICATIONS OPTICAL FIBRE CABLES

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ABSTRACT
A recent trend in the field of pipeline monitoring has been the utilisation of an optical fibre based distributed acoustic sensing (DAS) technology, for the purpose of security monitoring of buried pipelines [1-3]. The technology comprises an interrogator, connected to an optical fibre cable, which is interrogated to acquire coherent Rayleigh backscatter. Localised environmental vibrations may result in a proportional strain of the fibre. This strain results in a localised optical path length variation, resulting in a phase distortion in the measured signals. Application of signal processing techniques infer the characteristic of the originating stimulus, and thus identify and locate the source activity of interest. Activity may arise as a result of ground excavation, vehicular movement, or similar in the vicinity of the pipeline.

Researchers are now studying the possibility of utilising this technology for the purpose of pipeline leak detection monitoring [4]. This paper provides a review of one such programme of work.

Results are presented for a permanent installation, where signatures relating to leaks were identified, and located in the resulting DAS data. Results are provided relating to liquid leaks, where product was emitted at a flow rate of 20.0l/minute and operational pressure 20.0bar.

Keywords: Distributed Acoustic Sensing, Optical Fibre sensing, Leak Detection.

INTRODUCTION
The vast majority of hydrocarbon product pipelines traverse over extended distances, through both built and natural environments. As such these pipelines require continuous operational monitoring. One aspect of this monitoring relates to the continuous real-time evaluation of the integrity of the pipeline. Specifically, monitoring for the identification of unwarranted environmental product emission, Leak Detection monitoring.

Historically, pipeline leak detection monitoring has been achieved with the aid of a number of technologies, including but not limited to, Mass Balance systems, Acoustic Pressure Wave monitoring systems, and Real-Time Transient Monitoring systems. Recently an emerging technology has been receiving interest, as an alternative for leak detection monitoring provision, one based on the principle of distributed optical fibre sensing. Specifically Distributed Acoustic Sensing (DAS).

DAS technology comprises two components, an optical fibre interrogator (the monitoring instrument) and an optical fibre cable (the sensing element). The interrogators typically work on a principle known as phase sensitive optical time-domain reflectometry (PS-OTDR), where the interrogator is connected to a single-mode optical fibre and measures Rayleigh backscatter resulting from the propagation of intense, short pulses of radiation launched into the fibre. If the instrument laser and optical fibre environment are stable between successive interrogation periods there will be a high level of coherence apparent between successive backscatter traces. However, if the fibre experiences an application of longitudinal strain between to two successive launch pulses a proportional change in the measured backscatter signal will result. Fibre strain may arise as...
a result of one of three physical mechanisms, or a combination thereof, applied strain, applied temperature differential, or vibration of the fibre. The location of any such stimulus can then be identified in the time-domain, and knowing the speed of light within the fibre the associated location may be converted to a physical fibre position.

DAS interrogators are primarily configured to extract the variation in backscatter resulting from strain associated with fibre perturbations due to physical vibrations, arising as a result of either direct dynamic vibration or pressure wave stimulation. Signal processing techniques will then be applied to subsequently infer the physical vibration characteristics of the corresponding stimulus or stimuli.

When this technology is utilised in conjunction with an optical fibre buried below ground level the system will respond positively to ground waves arising from physical activity such as, surface excavation, vehicle and personnel movement on the surface, and other similar environmental activity. If further signal processing techniques are correctly applied to the resulting data many simultaneous vibration events can be both identified and characterised.

This has resulted in successful commercial development of the technology for the application of security monitoring of subterranean assets in recent years. One market sector where the technology is readily applied is that of security monitoring of subterranean pipelines. Rather fortuitously the required single-mode optical fibres are predominantly utilised in optical fibre communications cables. With many global pipelines such cables already traverse parallel to (and in the near vicinity of) an operator’s pipeline, for communication infrastructure requirements. In such cases a DAS interrogator can simply be connected to this cable and consequently commissioned. In the event such a cable is not available a new one may be retrospectively deployed for use. As the core optical fibres exhibit very low optical attenuation characteristics the interrogators can monitor tens of kilometres of cable, typically up to 50km with a single interrogator. When commissioned over this length a DAS system will generally offer a measurement resolution of the order of 1.0m, a spatial resolution of the order of 10.0m, and an acoustic bandwidth of up to 1.0kHz. Certain systems will even operate on fibre lengths of up to 100km.

End users of this technology and researchers in the field of pipeline monitoring are now questioning, and thus researching, whether this technology can equally be applied to the requirement of leak detection [4-5]. Recent experimental apparatus based evaluations have demonstrated a certain level of potential [4], though these studies have been conducted in controlled laboratory-based environments.

This paper presents results of similar testing, but for leak simulations conducted in an actual pipeline environment, where a DAS system is deployed for continuous real-time monitoring requirements. Positive leak detection results are presented from a system commissioned to provide permanent third-party intrusion TPI and leak detection monitoring. During commissioning data was acquired for a series of simulated leaks, which is presented herein, and on completion of commissioning the system was tested and observed to correctly identify the onset of forty five individual leak simulation events over a period of one week, with zero false positive or true negatives in the same period.

PHASE SENSITIVE OPTICAL TIME-DOMAIN REFLECTOMETRY

PS-OTDR based DAS interrogators may identify optical phase changes in monitored Rayleigh backscatter signals arising as a result of localised longitudinal straining of a single-mode optical fibre. This longitudinal strain will arise as a result of either, direct elongation, or elongation resulting from environmentally coupled vibrations and thermal variations.

A detailed discussion regarding the general principles of PS-OTDR operation is beyond the scope of this publication, the principles of one such application may be found in [6], and an excellent reference source for the general science is provided in [7].

More recently DAS researchers have made advances in decoupling the phase variations attributable to temperature variations from those associated with vibration stimulus [8], and are thus additionally starting to leverage this additional measurand in PS-OTDR interrogators. Vendors that achieve this capability term the measurement approach Distributed Temperature Gradient Sensing (DTGS).

As the temperature of an optical fibre changes, thermo-optic effects and local expansion or contraction will create very slow changes in the optical path length differences between interfering waves. In bare silica fibre of length L, a temperature change AT will produce an increment in phase according to:

\[
\frac{\Delta \phi}{\Delta T L} \approx 10^2 \text{ radians per Kelvin metre } \tag{1}
\]

Where:
- \(\Delta \phi\) = Optical Phase Change (radians/second)
- \(\Delta T\) = Temperature Change (Kelvin/second)
- \(L\) = Illuminated Optical Path Experiencing Phase Change (metre)

The continuous phase change produced by a gradual change in temperature produces a cyclic response in the received optical power. A given rate of change of temperature therefore produces a characteristic frequency in the received signal. Then \(\Delta \phi\) in (1) may be represented as:

\[
\Delta \phi = 2\pi f \tag{2}
\]

Where:
- \(f\) = Frequency (Hz)

and for a PS-OTDR type DAS interrogator, from Distance = (velocity x time), variable \(L\) in (1) may be represented as:

\[
L = \frac{C T_{FW}}{2n} \tag{3}
\]
Therefore, the maximum observed frequency in the measured Rayleigh backscatter, attributable to temperature variations may be specified as, inserting (2) and (3) into (1) and rearranging:

\[
f = \frac{100 C T_P \Delta T}{4 \pi n \times 10^{-9}}
\]

Where:
\( C = \) The Speed of Light (metres/second)
\( T_P = \) Launch Pulse Duration (nano second)
\( n = \) The Refractive Index of the Optical Fibre

which simplifies to:

\[
f = 2.386 \frac{T_P \Delta T}{n}
\]

Thus, for a PS-OTDR system of the form of [6], for a given optical fibre refractive index and launch pulse duration one may compute the localised change in temperature exerted on the optical fibre, if one can compute the maximum perturbed frequency in the corresponding Rayleigh scatter signals.

In order to first remove the effects of the acoustic response from the backscatter prior to computing the maximum perturbed frequency one may first adequate temporal averaging to a long time-history length of the data, which results in an additional benefit of readily achieving a very high spectral resolution when subsequently computing the thermal variation induced spectral characteristics.

**DAS SENSITIVITY TO OPTICAL FIBRE STIMULATION ASSOCIATED WITH MONITORED PIPELINE LEAK ACOUSTICS**

As discussed, DAS providers have been successfully commissioning DAS interrogation-based monitoring solutions for the pipeline industry over recent years. However, to date such systems have only truly been successfully commissioned for the application of TPI detection. An application where the hardware and associated software are configured to autonomously identify localised acoustic events in the DAS data which are associated with environmental activity that may pose a threat to the security and integrity of the pipeline. Such events may arise from ground signals associated with the activity of people excavating in the near vicinity of the pipeline, either with the aid of manual or mechanical equipment, either legitimately or maliciously, or as a result of unwarranted personnel movement in unauthorised areas, or unexpected persistent stationary vehicles with idling engines.

However, utilising this technology for the application of leak detection remains a relatively new concept, one with little documented positive proof. As such, if any system is to be commissioned for such a requirement (as is the case in the study presented in this publication) it is first necessary to evaluate system response sensitivity for this new application, to prove applicability. Thereafter, assuming the required response sensitivity is apparent, to ascertain whether the event detection signal processing algorithms could be provided with the correct parameters, which may result in positive event detection.

Such a requirement is only possible with the aid of physical testing, in the actual pipeline environment. To this end it is necessary to first create a leak scenario whilst acquiring the associated DAS data. This data must then be analysed, to confirm adequate response sensitivity, before finally interpreting the data to identify certain signal characteristics, to ascertain whether the system’s signal processing software could be correctly configured for autonomous detection. Finally (assuming all prior stages resulted in a positive outcome) define and implement a parameter set for the system’s software event detection algorithms such that it is possible to demonstrate this autonomous detection capability to the pipeline operator.

This publication presents a case study of one such installation, with a focus on the DAS data acquired during a similar commissioning process for the application of leak detection. The presented results are limited to identifying that the technology does indeed exhibit sufficient response sensitivity, that the corresponding data exhibits response characteristics that can be attributed to leak acoustics, and associated thermal properties, which is validated with the aid of data simultaneously acquired from a number of commissioned accelerometer and thermocouple point sensors. However, it is beyond the scope of this publication to incorporate any further details with respect to the final commissioning of the proprietary event detection software algorithms subsequently correctly commissioned on the final permanent monitoring solution.

**Pipeline Installation**

In 2017 an intensity-based DAS interrogator was commissioned on a 35km long section of fuel distribution pipeline, for the purpose of providing permanent real-time security and integrity monitoring capabilities. The pipeline in question is 300mm diameter steel construction, buried below ground at a varying depth range of between 1.5m and 1.8m. The pipeline route traversed from a fuel refinery to an end-user fuel depot through a combination of built and rural environment, the geospatial route of which is depicted with the aid of a green line in Fig. 1. This pipeline was a new installation and at the time of commissioning the operator additionally installed a standard telecommunications optical fibre cable, which was initially installed for communication requirements but was subsequently used in parallel for this project’s DAS sensing requirements. This cable was deployed in a direct burial manner, buried to the same depth as the pipeline centerline, at perpendicular offset of approximately 0.25m for the entirety of the 35km route, as depicted in Fig. 2. The operator required a robust and economic cable solution, and therefore identified a standard cable design that incorporated steel armouring, which provides a good level of protection when considering potential for environmental damage but may be detrimental for acoustic sensing purposes. This design is depicted in Fig. 3, the specific variant chosen incorporates eight individual optical fibre elements rather than the four depicted in Fig. 3(7), which were encapsulated in a gel(6) filled loose-tube inner element(3), that
is in turn encapsulated in a layer of aramid yarn(2), followed by corrugated steel armour(5), and finally protected with a polymer based outer sheaf(1). Irrespective of this suboptimal design, from a sensing perspective, and as results will identify, such a design is shown to exhibit sufficient acoustic transmission sensitivity to enable positive detection of ground vibrations associated with leak emissions from the pipeline in question.

**Field Apparatus**

On completion of commissioning the pipeline and optical fibre cable the DAS interrogator connected to the cable and the optical signal response was optimised to allow for commencement of system performance evaluation testing.

One difficulty regularly associated with positive testing of leak detection systems, particularly when such systems are commissioned to monitor commercially operating hydrocarbon pipelines is that of simulating a representative leak scenario. Understandably a pipeline operator will neither consider compromising the integrity of the pipeline or the action of an actual release of product to the environment. Thus engineers endeavouring to meet this test objective must design alternate simulation apparatus, apparatus that will adequately mimic an actual product release, but a release utilising an environmentally-safe ‘product’ substitute, which may be released under comparable operating parameters. The pipeline in question was commissioned to convey a liquid based fuel, at an operating pressure in the range of 60-80bar, at flow rates of the order of 10-20litres/minute.

To this end it was decided that water would be utilised as a liquid based substitute product, as this would adequately mimic the liquid-based fluid product but would equally result in minimal environmental issues when product release simulations were initiated. Further, as the monitored pipeline was of steel construction it was decided that simulated leak orifices would be mimicked as pipeline wall pinhole failures, which may arise in steel pipelines, either as a result of substandard welded pipeline joints or initial wall corrosion. This allowed for the construction of a relatively simple apparatus design, where a 50mm diameter, 2.0m long steel pipe structure was fashioned with a conical end cap. The end cap region incorporated two circular pinhole egress orifices near the tip, which were separated by an angle of 60 degrees, as depicted in the schematic of Fig. 4. The other end of this apparatus was threaded to receive a hose connection to valve controlled pressurised water delivery apparatus, as depicted in Fig. 5. The valve arrangement of the pressurised delivery apparatus additionally incorporated pressure and flow rate gauges such that the pressure and rate of the simulated leaks could be adequately controlled.

![Figure 1: Aerial Image Identifying Geographical Route of Monitored Pipeline (Green Line).](image1)

![Figure 2: Image Highlighting Pipeline Trench and Associated Pipeline and Optical Fibre Cable Positions.](image2)

![Figure 3: Cross-Section of Optical Fibre Cable Utilised on Monitored Pipeline for DAS Leak Detection Purposes.](image3)

![Figure 4: Side Elevation & Cross-Section Schematic of Pipeline Leak Simulation Apparatus.](image4)
This pipe based apparatus was then commissioned in the ground such that the egress orifices would be positioned to correctly mimic release of product at a depth coincidental to the centerline of the buried pipeline. Ideally this apparatus would be positioned directly next to the pipeline, such that the distance of separation between stimulus source (leak) and measurement receiver (optical fibre cable) would be truly representative. However, for reasons of safety it was not possible to undertake any excavation/installation activity in the direct vicinity of the pipeline. Therefore, the final commissioned position of the apparatus was such that an identical perpendicular distance of separation was achieved (0.25m), but with the apparatus commissioned on the opposing side of the optical fibre cable, see Fig. 5.

In order that one may be able to correlate any observable DAS response characteristics with actual ground dynamics, be that the vibration waves or temperature variations resulting from leak simulation testing, it was decided that the test area would additionally be instrumented with a number of point sensing measurement devices. That is, in order to correlate any observed DAS acoustic responses with actual resultant ground vibration waves a calibrated accelerometer was coupled to the optical fibre cable. This was clamped directly to the optical fibre cable at a position that was coincidental to the intersect of the major perpendicular axis between the outlet orifices of the leak apparatus and the optical fibre cable. The accelerometer that was utilised was a Dytran 3224A5, with a sensitivity of 10mV/g and a bandwidth of 20kHz. Additionally, five K-Type thermocouples were commissioned, with a linear response range of -75°C to +250°C, which were coupled to a calibrated thermocouple data acquisition system, model: Pico Technology TC-08. These thermocouples were commissioned in a linear fashion, parallel to the direction of the optical fibre cable/pipeline, with an offset of 0.1m from the optical fibre cable, at the same depth as the centerline of the pipeline, and with an incremental separation of 0.25m. The absolute position of the linear array of thermocouples was commissioned in such a way that the location of the central thermocouple (TC3) was positioned to be coincidental with the intersect of the major perpendicular axis between the outlet orifices of the leak apparatus and the optical fibre cable. This configuration is depicted in Fig. 6.

Test Site
In order to diligently evaluate the technology a number of test sites were identified along the entirety of the length of the pipeline, specifically at pipeline distances of: 0.1km, 8.0km, 9.5km, 16.7km, 19.3km, 27.6km, and 34.1km. This ensured the technology was evaluated in a wide variation of local environments and soil types, whilst also enabling system performance evaluation as a function of optical fibre attenuation characteristics, to ensure this equally did not too detrimentally impact sensitivity negatively.

All test sites were chosen to meet a predefined set of requirements. That is, locations that provided easy access on operator’s land, that were not in too densely populated, or owned by private land owners.

However, it was only possible to fully instrument one of these test locations. For a number of reasons (easy access, considerable fibre distance, and conveniently in the near vicinity of the DAS interrogator Control room) the third test site was identified, that located at a fibre distance of 9.5km. This location is identified in Fig. 1 with the aid of a blue rectangle. A higher resolution image of the site is provided in Fig. 7, again with the actual test site annotated with the aid of a blue rectangle, and finally a schematic image identifying the site location relative to the interrogator control room is provided in Fig. 8.

DAS Interrogator Test Configuration
During testing the DAS interrogator was commissioned as follows:

- Laser Pulse Repetition Rate: 2.9kHz
- Temporal Sampling Rate: 150MHz
- Acoustic Sampling Rate: 2.9kHz
- Spatial Sampling Interval: 0.67m
- Spatial Resolution: 5.0m

Which resulted in acquired DAS data with an acoustic bandwidth of 1.45kHz.
4. Commence leak simulation and persist for 120 seconds.
5. Cease leak simulation and continue acquiring all instrumentation data for a further 30 seconds.
6. Cease acquisition of DAS data.
7. Cease acquisition of accelerometer and thermocouple data.

Of these forty-five test repetitions ten were completed at Test sites one (0.1km) and three (9.5km), whilst at all other test sites, two (8.0km), and four through to seven (16.7km – 34.1km) only five repetitions were completed.

RESULTS

The results presented relate to the data acquired for two individual leak simulation test repetitions that were completed at test site three (9.5km along the pipeline route). These tests were identified as test repetition three and test repetition four.

After initial presentation of the corresponding DAS results all remaining presented results relate to the data acquired for test repetition four.

Detailed acoustic results relating to the DAS interrogator response from test four are presented in Fig. 9 to Fig. 13.

Responses that relate to the corresponding data acquired with the subterranean accelerometer are then presented in Fig. 14 to Fig. 17. Before the spectral results for both the DAS and accelerometer responses are presented in an overlaid format from Fig. 18 to Fig. 23.

Figures 24-25 then present the corresponding thermocouple responses for thermocouple 1 to thermocouple 4. These are presented as absolute temperature value measurements in Fig. 24, and as differentials of the absolute measurements in Fig. 25.

Figures 26-28 then present the corresponding DTGS DAS results before the DTGS DTGS response at fibre/pipeline distance 9358.51m is finally presented overlaid with the differential of the absolute measurement from thermocouple four in Fig. 29.

DAS Results

DAS data acquired from a 35km long optical fibre with an acquisition repetition rate of 2.9kHz, sampled at a temporal rate of 150MHz results in an array of data that has a primary dimension of 52,500 spatial loci, and that increases in the second dimension at a rate of 2,900 samples per second.

This results in large volumes of data that require efficient, intelligent processing in a real-time capacity. As localised fibre perturbations will result in proportional localised changes in the intensity of the measured backscatter signals it is possible to simply compute the differential of the time varying backscatter to ascertain a corresponding acoustic representation of the source stimulus. Thereafter possibly applying filtering to ascertain a response with an optimal signal to noise ratio. However, such an approach can be extremely computationally expensive when simultaneously implementing on of the order of 52,500 spatial data points. As such it is desirable to apply some form of temporal decimation to maintain a real-time processing capability with commercially deployed systems. One could therefore simply temporally decimate the raw data, though that
can readily result in an undesirable destructive outcome of aliasing, thus negating an ability to subsequently differentiate unique characteristics that may otherwise be associated with individual source stimuli.

A more appealing approach is to work natively in the frequency-domain, utilising Discrete Fast Fourier Transforms (DFFT), where temporal decimation can be achieved naturally, at a rate commensurate with the chosen DFFT size.

That is, if a single location time varying data point in the backscatter signal, is termed \( x_n \), then the DFFT of \( x_n \) is evaluated as [9]:

\[
X(f) = \sum_{n=0}^{N} x_n e^{j2\pi fn\Delta t} \tag{6}
\]

where

\[ N = \text{the user defined DFFT size, typically specified to be a power of } 2^n \text{ for reasons of computational efficiency.} \]

Then one may further define the corresponding Energy Spectral Density estimate as:

\[
S_{xx}(f) = (\Delta t)^2 \left| \sum_{n=0}^{N} x_n e^{j2\pi fn\Delta t} \right|^2 \tag{7}
\]

and one may finally reduce the computation to a scalar representation for a given DFFT update by computing the associated bandlimited power of the signal in a given frequency band \([f_1, f_2]\) as:

\[
P_{\text{bandlimited}} = 2 \sum_{n=f_1}^{f_2} S_{xx}(f_n) \Delta f \tag{8}
\]

Thus one can readily temporally decimate the raw data rate by a factor of \( N \), to allow for efficient computational update rates, whilst, if required, maintaining a detailed representation of the input data, in the form of \( S_{xx}(f) \).

When such an approach was applied to the DAS data of the case study of this publication, where \( N \) was specified as 4096, with an overlap of 2048, bandlimited Power Estimation waterfalls were computed of the DAS data of the form of that presented in Fig. 9. Applying this DFFT size and overlap resulted in a frequency bin resolution of 0.71Hz whilst maintaining a decimated temporal resolution of 0.7 seconds.

Figure 9 presents the Power Estimation waterfall for the whole of the monitored fibre length, for a five-minute arbitrary time period. Similar Power Estimation waterfalls are presented in Fig. 10 and Fig. 11 for the DAS data relating to time instances when two leak simulation tests were completed at test site three, test repletion three and four. Finally an associated spectrogram, the time varying graphical representation of \( S_{xx}(f) \) is presented in Fig. 13, for a single fibre spatial locus positioned at 9357.8m.
Accelerometer Results

Figures 14-17 present the time-domain response and corresponding frequency-domain representations of corresponding subterranean accelerometer data.

Figures 14 and 16 present the time-histories and associated short-time window spectrograms, whilst Fig. 15 and Fig. 17 present corresponding time averaged power spectral density estimates. In each case spectral representations were computed with a DFFT size of 4096 and an overlap of 2048.
**Figure 17:** Accelerometer Time-Averaged Power Spectral Density Estimate for Response Acquired During Leak Simulation Test Repetition Number Four.

**Figure 20:** Overlay of Accelerometer & DAS Time-Averaged Power Spectral Density Estimates for Response Acquired During Leak Simulation Test Repetition Number Four.

**DAS Vs. Accelerometers**

**Figure 18:** DAS Time-History and Corresponding Short-Time window Spectrogram to Leak Simulation Test Repetition Number Four – Extracted at Sample Point Correlating to a Fibre Distance of 9358.51m.

**Figure 21:** DAS Acoustic Frequency Response Characteristic for Loose Tube Optical Fibre Cable.

**Figure 19:** DAS Time-Averaged Power Spectral Density Estimate for Response Acquired During Leak Simulation Test Repetition Number Four – Extracted at Sample Point Correlating to a Fibre Distance of 9358.51m.

**Figure 22:** Overlay of Original & Cable Sensitivity Adjusted DAS Time-Averaged Power Spectral Density Estimates for Response Acquired During Leak Simulation Test Repetition Number Four.
Thermocouple Results

Unfortunately on commencement of testing it was noted that one of the thermocouples failed to respond, thermocouple number five (TC5 in Fig. 6). As no replacements were available on site, and this particular thermocouple was positioned at an outer extreme of the monitored area it was decided that the test would continue with the absence of this one sensing element.

Figure 24 presents the data of the four remaining thermocouples, acquired during test repetition four. Where the time-history response for the four remaining thermocouples is presented in a time correlated manner with the corresponding DAS data of Fig. 12.

The differential of these individual Thermocouple time-history responses is then presented in Fig. 25.

DTGS Results

The DTGS representation of the DAS data associated with test repetition four is presented in Fig. 26 to Fig. 28, in the form of temperature gradient surfaces, and a single extracted time-history with units of °C/second.

Figure 24: Temperature Time-Histories for Thermocouples TC1 to TC4 Acquired During Leak Simulation Test Repetition Number Four. Time Correlated with Associated DAS Response.

Figure 25: Differential of Temperature Time-Histories for Thermocouples TC1 to TC4 Acquired During Leak Simulation Test Repetition Number Four. Time Correlated with Associated DAS Response.

Figure 26: DTGS Thermal Surface for DAS interrogator Presenting the Response to Leak Simulation Test Repetition Number Four.

Figure 27: Zoom of DTGS Thermal Surface for DAS interrogator Presenting the Response to Leak Simulation Test Repetition Number Four.
DISCUSSION

Figure 9 is provided to aid introduction of the presented form of the DAS response data. Most commercially deployed DAS interrogators have a real-time display of this form, typically referred to as a DAS energy waterfall display. In Fig. 9 the horizontal axis represents distance in metres, and the vertical axis time. Each temporal-spatial locus in this surface represents the bandlimited DAS acoustic power, typically as calculated using equation (8). For Fig. 9 a frequency band of 4Hz to 1450Hz was applied, and the waterfall has a temporal resolution of 0.7seconds. This specific figure presents approximately 5 minutes’ worth of DAS data, for the first 17km from the installed system. The magnitude of the normalised power is represented with the aid of a colourmap, blue for no attributable signal power, through yellow, to red for high signal power. As this is a temporal-spatial surface, stationary responses, for example attributable to energy resulting from leak or excavation acoustics, would appear as a vertical energised power responses.

Whereas, energy resulting from personnel or vehicle movement would appear as a diagonal trajectory, for which the gradient would represent the speed of movement, and the sign of the gradient would indicate direction, examples of which are apparent between 11.5km and 17km in Fig. 9.

Figures 10 and 11 thereafter present similar waterfalls for two of the leak tests at site three, test repetitions three and four respectively. The horizontal axes have been constrained to present greater spatial granularity. Figure 12 then presents a zoomed version of Fig. 11, where the orientation has been rotated 90° to provide a more intuitive representation. Figure 12 has additionally been annotated with the aid of red dashed vertical lines, the leftmost relates to the test engineer’s noted leak emission start time for test repetition four, and the rightmost to the noted end time. Review of the figure clearly identifies a substantial increase in the magnitude of the DAS broadband response power over this time period for a localised region of the DAS data. This region spans from 9352m to 9362m, and is identified with the aid of two horizontal red dashed lines.

The short-time window spectrogram of the response near the centre of this range, specifically at 9358m, is then presented in Fig. 13, where each temporal update of the spectrogram is computed in an analogous manner to that of equation (7). Review of Fig. 13 identifies that the energised frequency response range of the DAS response ranges from 0Hz to approximately 1000Hz, with a bias to the lower frequencies. After the initial onset of the leak, and over the majority of the remaining leak period the primary response energy is seen to exist between 0Hz and 200Hz, with only a much lower magnitude of secondary energy somewhat visibly evident between the frequency band of 600Hz to 900Hz.

When comparing this spectral characteristic to that of the corresponding accelerometer data acquired during test 4, as presented in Figs. 16 and 17, it initially appears the two vibration based responses exhibit drastically differing spectral characteristics. That is, from review of the spectrogram of Fig. 16, it appears that the calibrated accelerometer predominantly exhibits an energised response over the range of 500Hz to 1700Hz, with a much narrower low-frequency component. The lower frequency component is more evident in the two-dimensional Power Spectral Density (PSD) representation of the response, as given in Fig. 17. The PSD was temporally integrated over the time window depicted with the aid of a dashed red line rectangle in Fig. 16, and review of the PSD aids identifying that the response predominantly distributes across two discrete bands, a low frequency band ranging from approximately 10Hz to 80Hz, and the aforementioned higher frequency band ranging from approximately 500Hz to 1700Hz.

A similar characteristic is also apparent in the identical calculated accelerometer response for test number three, which is provided in Figs. 14 and 15. Where the main observable difference is that the low frequency band is narrower in nature, on that occasion only ranging from approximately 10Hz to 20Hz.

Returning to the DAS data, extracting the response from the locus relating to 9385.51m, and identically computing the spectrogram and two-dimensional PSD, it was noted that there is
actually a level of correlation between the two response forms. The DAS result is provided in Figs. 18 and 19. If one reviews the two-dimensional PSD of Fig. 19 it can be seen that the dominant energy ranges from approximately 5Hz to 100Hz, but it is also observable that a lower magnitude of energy also exists in a discrete higher band, from approximately 400Hz to 1000Hz.

When these two PSD’s are overlaid, as presented in Fig. 20 it can be observed that the two noted frequency bands of each instruments response actually coincide relatively well. Although it is acknowledged that the magnitude of the upper frequency band of the DAS spectrum is considerably lower in magnitude that that of the accelerometer.

However, one must at this stage consider the differentials between the two sensor types. With the accelerometer the sensing element, some form of internal mass element, is typically very well coupled to the outer body, and when constructed correctly provides a wide linear frequency response range, the one utilised in this testing ranges from 0.3Hz to 20kHz. If one now considers the sensing cable utilised for DAS sensing in this project (Fig. 3), one may recall the sensing element, the fibre, was suspended in a viscous gel filled loose tube. This, in conjunction with the composite construction of the cable can lead to considerable frequency dampening response characteristics. Indeed, when the authors experimentally verified the frequency response characteristic for this cable it was noted that the cable only allows for a linear response up to 250Hz, see Fig. 21. After which the cable exhibits a relatively linearly increasing attenuation affect, with an approximate gradient of 0.037dB/Hz.

If one then compensates the original DAS spectrum with reference to the cable’s frequency response curve one notes an anticipated amplification of the corresponding upper frequencies of the DAS response, as evident in Fig. 22, where the compensated variant is presented in an overlaid form with the original DAS spectrum. If one then further compares that compensated DAS response spectrum with that of the accelerometer, as presented in an overlaid form in Fig. 23 one notes a relatively good correlation between the two. Inferring that, if frequency response characteristics of the individual sensing elements are considered, and sampling rate differentials are taken into account, then DAS provides a distributed monitoring solution that may be sensitive to ground based vibration waves uniquely associated with leak orifice noise.

The ground temperature profile as measured by the thermocouples during test four is presented in Fig. 24. It can be seen that thermocouples 2-4 identified a temperature change of between 1°C and 6°C during the test. Applying the DTGS processing philosophy of equations (1) through (6) to the DAS data of Fig.12 resulted in the temperature gradient map of Figs. 26 and 27, where the latter is a temporal-spatial zoom of the former. The lower portion of Fig. 28 presents the DTGS time-history, extracted from 9358.51m in the data. When this is overlaid with the differential of the response from thermocouple 4, originally provided in Fig. 25, and presented in an overlaid form in Fig. 29 it is observed that a very high level of correlation is apparent between the two.

CONCLUSIONS

DAS technology, utilising pre-existing communications grade optical fibre cables, deployed for communications purposes has been shown to exhibit sufficient response sensitivity to capture the ground vibration response associated with pressurised product release from a small pipework orifice.

DAS response characteristics are noted to exhibit an acceptable level of correlation with the corresponding response of calibrated linear accelerometer point sensors.

When the frequency response characteristic of the DAS sensing cable is further considered a higher level of correlation can be inferred.

It is possible to deconvolve the thermal strain response from PS-OTDR DAS interrogator data, calibrate this to a linear gradient in terms of scientific units for temperature and time, and confirm a high level of correlation with conventional point sensor temperature measurement instrumentation.

In summary, DAS technology demonstrates considerable potential as a suitable pipeline leak detection monitoring option, with some key benefits when compared to conventional solutions.

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