An introduction to fibre optic Intelligent Distributed Acoustic Sensing (iDAS) technology for power industry applications

Chris **CONWAY**; Bandweaver, UK, chrisconway@bandweaver.co.uk
Michael **MONDANOS**, Silixa, UK, michael.mondanos@silixa.com

ABSTRACT

This paper provides an explanation of the general principles of operation of the Intelligent Distributed Acoustic Sensing technology and focuses on the current areas of interest and applications of this technology within the industry. Currently the technology is mainly used for perimeter monitoring of utility assets and third party intervention monitoring on buried pipelines. In the oil & gas sector distributed acoustic measurements are used in vertical seismic profiling and flow allocation measurements. The paper explores some of current applications of this technology. This paper also explores and provides information that will enable the potential for future applications.

KEYWORDS

DAS, DVS, DTS, Smart Grid.

AUTHOR NAMES & AFFILIATIONS

Chris **CONWAY**; BEng (Hons) Electronic Systems, University of Ulster, MIEEE PES ICC, London, UK.

Michael **MONDANOS**; PhD, Optical Fibre Sensing, Imperial College, University of London, MIEEE, London UK

INTRODUCTION

The application of new technologies to the existing and future electric transmission and distribution network, with real-time knowledge of current and possible future demand, status of present infrastructure is coined by the term Smart Grid. Running in parallel to this complex changing network demand structure we see that technology is changing at a rapid pace. Increasing computing processing power and ability to communicate with a variety of network infrastructures has enabled new possibilities and applications to enhance the electric industry's demand for real-time monitoring.

Changes in the distributed optical sensing area are happening fast with ever improving capabilities in terms of distributed temperature measurement and interpretation of the immense amount of data such systems produce into meaningful user friendly data. We see this through the active deployment and integration of DTS and DCR technologies. The introduction of tried and proven distributed fibre optic acoustic sensing technology may help to provide further capabilities in terms of real-time monitoring and could have potential to be retrofitted into existing network infrastructure.

POINT AND DISTRIBUTED SENSORS

Firstly however let us define what we mean by distributed and point sensors in terms of optical fibre based sensing technologies. Fibre optic point sensors are generally passive point based transducers that are designed to provide the quantification of a measurand (temperature, strain, displacement, sound, gas concentration etc.), and through interconnecting fibre optic cables, communicate that quantity to a remote sensor control unit. Generally the sensor control unit will convert that optical signal to a digital or analog value, to be further processed within the control system. Such systems have been successfully deployed with the electric industry for monitoring applications related to transformers, busbars, generators, switchgear etc.

With distributed sensors on the other hand, an optical fibre core with a fibre optic communication cable, is the distributed transducer. There are no additional transducers within the optical path. The sensor control unit in this case will tend to interrogate the fibre optic cable using laser pulse sequences, and records the response due to naturally occurring light scattering phenomena within the fibre. Responses can be taken continually along the entire length of the optical path. Such fibres tend to utilise standard multimode and singlemode fibre optics used in data communications applications and are currently deployed to quantify a number of measurands e.g. sound, vibration, temperature, strain etc. As such, there is the potential to utilise existing fibre optic network infrastructure and so may provide the opportunity for retrofit type applications.

Classically, point sensors, which typically have a higher signal to noise ratio than distributed sensors, have been used where high precision, fast measurements are needed; with distributed sensors favoured where extensive coverage is needed, with a compromise made on either measurement time or resolution/accuracy. Here we report on a new type of intelligent Distributed Acoustic Sensor [1], which achieves both the precision of a point sensor with the wide coverage of a distributed sensor. This system measures the true acoustic signal at every point along an optical fibre. By using digital signal processing, the acoustic response along the fibre can be combined to enhance the detection sensitivity, thereby exceeding the sensitivity of point sensors, as well as achieving highly directional information, facilitating super resolution imaging. Here we report on different array processing techniques which can be effectively used for seismic applications using the new sensor.

Raman and Brillouin Systems

At the core of each of these technologies is the technology known as Optical Time Domain Reflectometry (OTDR) technology. This technology was originally developed for the telecommunications industry as an effective means to determine the optical losses within a fibre optic circuit and produce a loss profile for that circuit. With OTDR technology a light signal is launched into the fibre and transmitted along its entire length. The OTDR essentially uses precise timing to measure the quantity of scattered reflected light in the fibre over time. The timing of received light signal is used to determine the actual position along the fibre length. The intensity of the received light signal is used to determine the actual loss profile within the fibre circuit. The major part of the scattering occurs at the transmitted Rayleigh wavelength and these losses are used to calculate the actual loss profile within the fibre circuit.

The scattered light radiation also comprises Raman and Brillouin reflections which each consist of two components, namely Stokes and Anti-stokes light. Stokes light is at a longer wavelength to the incident Rayleigh wavelength and Anti-Stokes is at a shorter wavelength to the same Rayleigh wavelength. Sensor control units for Raman and Brillouin systems measure the intensity of the light in their respective Stokes and Anti-stokes wavelength bands and use this data, combined with the OTDR technique, to determine a measurand profile.

The Raman scattering comes for the molecular vibrations within the fibre optic core occurring along its entire length. The measure of the molecular vibrations, a result of the fibre's natural kinetic energy, is directly related to temperature. By being able to quantify the measure of Anti-Stokes and Stokes energy received, in combination with the OTDR principle, enables a complete temperature profile across the entire optical path to be determined on a continuous basis. This is the core principle at the centre of Raman based DTS technology.

In contrast, the wavelength and frequency of the Brillouin wave reflections are affected by both strain and temperature events. The Brillouin wavebands are much closer to the incident Rayleigh wavelength and, although their intensity is relatively greater than that of Raman, it is more difficult to filter the Brillouin bands from the incident Rayleigh signal due to their close proximity. Coupled with the combined effects of both temperature and strain events on the signal strength, this leads to further challenges in being able to determine temperature events from strain events at any location along the fibre optic path. It may be relatively easy to demonstrate a Brillouin systems ability in a controlled laboratory or Factory Acceptance Test (FAT) environment, however we should review what may happen in an actual installation when completing a Site Acceptance Test (SAT). As a relevant example, a fibre optic cable may be either attached to the outer surface or possibly with the fibre embedded within the power cable structure. There is no guarantee that the particular fibre optic cable will exhibit the same loss profile as that provided in the FAT, simply on the grounds that it is commonly a different fibre optic cable, although may have the same cable standard. On site the fibre optic splices will normally be of varying loss along the fibre length and not as per FAT conditions. The ability of a system to calibrate for these differences between FAT and SAT conditions is fundamentally important.

Some have concluded that their preferred option is to use Raman based DTS measurements in parallel with Brillouin temperature and strain monitoring, and use the independent Raman distributed temperature measurement to further qualify the distributed strain or temperature measurement.

DVS and iDAS

DVS

Distributed Vibration Sensors (DVS),[2] have been used for intrusion detection as they provide vibrational sensitivity together with electromagnetic interference immunity. The idea is based on the interferometric demodulation of back scattered Rayleigh signals from the optical fibre. The sensor can identify optical path changes due to disturbances in the environment that strain the fibre. Sensitivity in DVS is limited by phase fading and a highly non-linear amplitude response.

A major limitation of such disturbance sensors is that they are incapable of determining the full acoustic field – namely the amplitude, frequency and phase – of the incident signal. Commonly, however, these disturbance sensors are described as Distributed Acoustic Sensors (DAS), although the acoustic field cannot be reassembled fully.

The techniques described here can only be achieved using a sensor capable of full acoustic measurements with a high dynamic measurement range (which we differentiate here by referring to as iDAS). The difference between various sensing systems is based on fundamental variations of the hardware architecture of the interrogator and the processing of the backscatter light. We will show here that using the new measurement technique embodied in the iDAS, we can use this full acoustic field to accurately detect and identify events in intrusion detection applications and produce both surface and downhole seismic profiles.

iDAS offers a true acoustic response with a fully-representative detection of the acoustic field at typically every metre along a length of fibre. The iDAS system is the true analogue to a synchronised microphonic array, and so can be used for beamforming (the phase-shifted addition of acoustic fields measured at different sensing points).

iDAS

The iDAS is using the same underlying principle as that of the DTS and OTDR. The acoustic field exerts tiny pressure/ strain changes onto the fibre. The iDAS utilizes novel optoelectronics modules that uniquely measure local axial strain changes along the fibre. As backscattered light is generated, the system builds a dynamic profile of the strain along the entire fibre length. The iDAS measures these pressure changes at a rate of up to several tens of kilohertz and so can be used to measure the acoustic field. The system digitally records both the amplitude and phase of the acoustic fields at every location and hence can "listen" to every point. The fibre acts as an acoustic antenna which can be deployed in multi-dimensional configurations to enhance its sensitivity, directionality and frequency response.

When a pulse of light is launched into an optical fibre, a small amount of the light is naturally scattered. The scattered light is carried back to the sensor unit. By analysing these reflections, and measuring the time between the laser pulse being launched and the signal being received, the IDAS can measure the seismic signal at all points along the fibre, tens of kilometres long. Typically the spatial resolution obtained with such a distributed fibre sensor is about one metre. The principle of distributed sensing is well known from the distributed temperature sensor (DTS) which uses the interaction of the source light with thermal vibrations (Raman scattering) to determine the temperature at all points along the fibre. Because the returning light level is very weak this measurement typically requires a few minutes averaging to get a reasonable signal-to-noise ratio.

Light in an optical fibre travels at about 0.2 m/nsec. That means that a 10-nanosecond pulse of light occupies about 2 metres in the fibre as it propagates and that each 10 nanoseconds of time in the optical echo-response can be associated with reflections coming from a 1-meter portion of the fibre.By generating a fresh pulse every 100 µsec and continuously processing the returned optical signal, one can, in principle, interrogate each meter of a 10 km fibre at a 10 kHz sample rate. Local changes in the optical backscatter due to changes in the environment of the fibre can thus become the basis for using the fibre as a continuous array of sensors. In particular, when components of the local acoustic field are coupled by friction or pressure to local strain on the fibre, the fibre can become a distributed acoustic array with thousands of channels and nearly continuous sampling in both space and time. Recent advances in opto-electronics and associated signal processing have enabled the development of a commercial distributed acoustic sensor (DAS) that actualizes much of this potential. Unlike disturbance sensors [3], the iDAS measures the strain on the fibre to characterise the full acoustic signal.

With the iDAS system, measurements can be done at a rate of up to 100kHz, (with a bandwidth from 8mHz to 50kHz), opening up possibilities for seismic measurements. The iDAS measures from one end of a single mode, standard telecoms fibre, without any special components, such as fibre gratings, in the optical path. It can even be used on existing cables, although custom cables will give a better response.

The technically most challenging aspect of the iDAS design specification is the ability to faithfully record the acoustic signal, rather than merely record an approximation of the signal. The signal fidelity can be determined by subjecting a section of the fibre to a known signal, the most convenient being a sine wave. The iDAS acoustic signal and the FFT of this signal can then be used to calculate the degree of any harmonic distortion (Figure 1). Additionally, the intermodulation distortion response can be tested by subjecting the sensing fibre to two tones simultaneously (Figure 2).

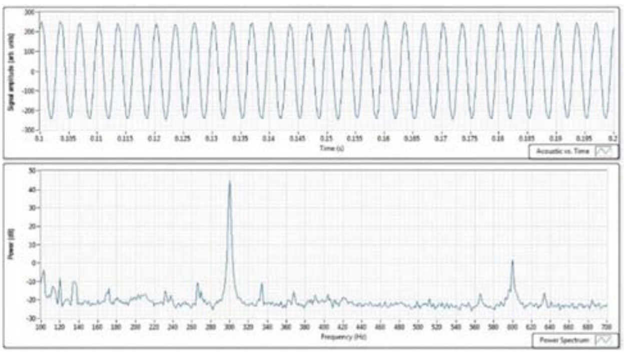

Figure 1: iDAS time-amplitude and power spectrum from a single measurement point with 50kHz sampling, for a 300Hz sine wave excitation. The -45dB level harmonic distortion is expected to be dominated by the source response rather than the sensor response.

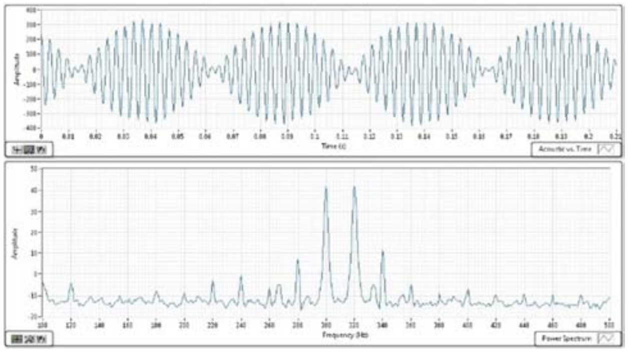

Figure 2: iDAS time-amplitude and power spectrum from a single measurement point excited simultaneously by tones at 300Hz and 320Hz. The -30dB side bands are expected to be mostly attributed to the performance of the audio amplifier/speaker used to excite the fibre.

The system can be calibrated to absolute strain rate. The response of the iDAS to a fibre stretcher at 1 kHz is shown in fig3.

Present systems can process up to 40,960 sensing points simultaneously, typically with a 1m to 2m spatial resolution and a sampling resolution down to 25 cm. The fine spatial resolution achieved is significant in that it is both technically challenging to achieve a spatial resolution below 10m, and because a fine resolution is required for advanced imaging applications. Silixa has demonstrated signal-to-noise ratios sufficient for beam forming applications for fibre lengths up to 82 km using a bidirectional erbium doped fibre amplifier (EDFA) chain. In principle, it may well be the EDFA chain can be increased to extend the range up to the 320km achieved in ODTR systems, and so form a massive sensing system.

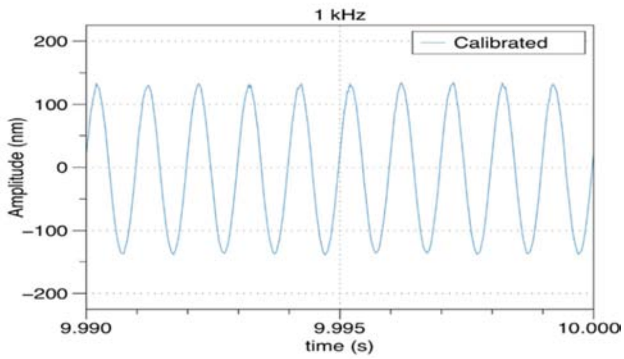

Figure 1:Calibrated response of iDAS at a fixed modulation of a 1 kHz sine wave excitation.

CURRENT AND POTENTIAL APPLICATIONS FOR iDAS

Pipeline Monitoring

Integrity monitoring of oil and gas pipeline pipelines requires that a system be able to quickly identify a leak or third party intrusion event. An effective and appropriately implemented monitoring system can easily pay for itself through reduced product loss, potential consequential losses and an increase in public confidence.

Integrity monitoring is offered using both DTS and iDAS technology. Additional features are also possible to monitor flow at discrete locations and to track other maintenance services such as pigging.

Distributed optical fibre sensing offers a pipeline monitoring system that is not available with any other technology. Distributed optical fibre sensing is the only method to monitor for leaks continuously in both distance and time. Early detection of a leak or intrusion together with the accurate identification of the location allows time for either safe shutdown or rapid dispatch of assessment and clean-up crews.

Intrusion detection operates by using the fibre as a microphone array and by listening to the activity in the proximity of the cable. By employing acoustic recognition it can classify the activity taking place and hence warn the operator of threats, both deliberate and accidental, before they interrupt the operation of the pipeline. The same techniques used to identify external threats to pipeline integrity can also be used to provide acoustic based leak detection. For intrusion detection threats such as digging and vehicular activity, events can be detected many metres away from the pipeline and can be positioned to within 10m along the full pipeline route. Many simultaneous threats can be identified, classified and alarms raised.

Detection works by energy comparison; put simply, it compares energy of current sample with energy of the noise floor. If the energy increases certain threshold, detection is triggered.

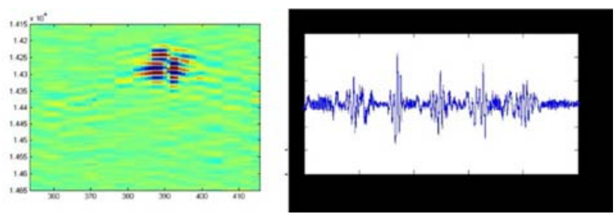

Figure 4. Waterfall showing a digging event. The waveform for a single sampling point is also shown.

Classification extracts features of interest from the acoustical data and then a classifier (e.g. neural network) makes a decision based on these features. The differentiation will be done in classification: all the events will be detected and tracked and classification will tell which is which. Depending on the traffic and coupling of vibration waves to the pipeline we would expect saturation of the system. It is possible to raise the detection threshold for that region of the pipeline since usually car signal power is lower than that of digging or walking (with some reservation on the amount of power coupled to the cable, etc.) Beamforming allows us to find the position of acoustic sources relative to the cable, and selectively listen to different points in the acoustic field. The iDAS system has a wide dynamic range and we can accurately measure the waveform amplitude and phase for small acoustic as well as for large vibration signals. A cost function is computed over possible distances and speeds to estimate the distance of the source simultaneously with the speed of sound through the medium between the source and the fibre.

Production Monitoring and well Integrity

A significant number of wells have been instrumented with optical fibres to allow for the tracking of steam flood where enhanced recovery of heavy oil is required. The high temperatures experienced as a result of steam injection have led to a combination of high temperature cable construction as well as methods of injecting high temperature fibres into capillary tubes in a repeatable way such that fibres can be retrieved and replaced without the need for well work-over.

With optical fibres in place it is possible to use the temperature and acoustic attributes of the well to determine where fluid inflows and outflows are occurring as well as tracking the fluid movements that are indicative of well integrity failures such as leaking packers or poor cemented isolation.

Where is it practical to place optical fibres across a producing interval, such as a series of perforations or slotted production liner, it becomes possible to characterize the inflows/outflows at given intervals by means of relationships linking the temperature and/or acoustic response to flow rates and fluid types. This method is further enhanced by the application of unique array processing methods capable of quantifying fluid speed of sound and flow speed from the true acoustic field achievable from the iDAS. With sound speed and flow speed parameters the production engineer can define fluid types and zone-by-zone production rates as well as establishing fluid fractions in two-phase flow scenarios. The information achievable from an optical fibre across the production interval can be likened to the answers taken from a conventional production log and allow the user to manage the well performance for optimum recovery by making informed decisions about remediation such as produced water control.

The applicability of optical fibres to the harsh conditions encountered in the oil and gas borehole have also led to growing use of distributed sensing as a monitoring solution for hydraulic fracturing of hydrocarbon bearing shales. Placement of the optical fibre cable across the region to be fractured allows the operator, through the gathering of temperature and acoustic data, to monitor the placement of frack water and proppant so that they can understand the effectiveness of the fracturing process and adjust practices are necessary. The immediate benefits of the technology in this application can be to limit the quantities of frack water required to effectively stimulate the shale and ultimately to improve the per-well-recovery of shale exploitation. Interest in the micro-seismic application of distributed acoustic sensing aims to target the characterization of fracture growth as a method to assure against damage to aquifers or otherwise to the environment.

The iDAS has been used in many seismic acquisitions, encompassing vertical seismic profiling, in both flowing and non-flowing wells, CO2 storage wells and surface seismic. The use of iDAS was facilitated by the deployment of a modular borehole monitoring (MBM) package on production tubing under the Citronelle carbon sequestration and storage project. The chosen monitoring well included multiple fibre-optic cables and an 18-level clamping geophone string (information available at http://www.co2captureproject.org/reports.html). The fibre was included in metal tube which was itself part of a multiconductor cable clamped to the production tubing, in the fluid–filled annulus between tubing and casing to a depth of almost 3 km. Data acquisition was sufficiently successful to move forward with work on improving acquisition and planning.

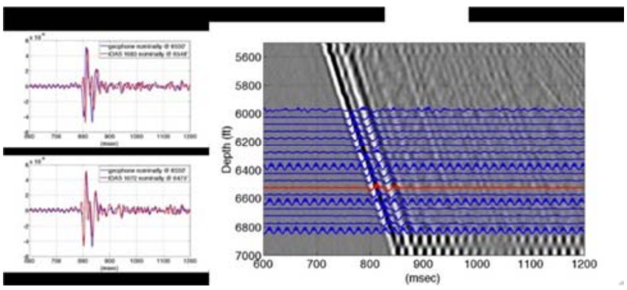

Figure 5. Comparison between the iDAS response and geophones.

The iDAS response is a local average of strain rate of fibre core, continuously sampled in space and time. The relationship between iDAS signal and the seismic vibration field depends on coupling between fibre core and environment. More stacking is required than for standard geophones; however, the vast increase in channel count more than compensates in terms of efficiency.

iDAS Power Industry Applications

Transmission and distribution assets are viewed globally as asset of critical national security in much the same way as any other energy transfer infrastructure. Here we shall explore some current applications and also take a view to some further potential applications for iDAS technology with a view to providing utilities with additional capability in terms of reliability and security. It is not intended to be a comprehensive and exhaustive list but we hope it may provide some food for thought and indeed, there may be many other applications for such technology in the future that are yet realised.

The inherent long term reliability and passive nature of fibre optic based acoustic sensing makes iDAS a worthy technology for many power industry applications. The most advanced DAS technologies may be deployed through existing fibre optic infrastructure making the technology ideal for retrofit applications. However it is important to note the physical location and medium in proximity of the fibre optic cable with respect to the cable asset and the particular desired design achievement on of applying such technology.

By utilising existing fibres within buried and subsea power cable iDAS potentially offers operators additional data which could be utilised to manage buried cable intervention events. Such events may be due to local ground excavation works and as such assist in cable reliability and reduce the need for spontaneous repair works. The cable to a mapped cable route as illustrated below may assist with pinpointing the event with an operator's network.

Figure 6. Example user interface for iDAS system

For subsea cables involving free spans and towed cables, it may be possible to utilise such technology for solutions related to vortex induced vibrations (VIV) [4]. These vibrations are important because a cable can develop an increased drag coefficient and therefore increases the static loading [5], [6]. In addition these excitations can produce large dynamic loads at the forcing frequency, reducing the cable's fatigue life. Full-scale studies reveal that the vibrations are characterized by a spectrum containing several frequencies, often dominated by strong beating oscillations [7]. At the present time such applications for VIV monitoring in subsea cables are largely theoretical, and further full scale analysis and testing are required in order to the determine practical solutions regarding the application of iDAS technology for this particular application.

Other potential applications for iDAS technology may imply its application to OPGW and OPPC infrastructure. Utilising this technology may help determine the location of lightning strikes, corona events and possible contact with ground vegetation by analysing differences between the normal audio and vibration spectra. One significant inherent limiting attribute of the technology is the systems response to the audio and vibration bandwidth with respect to distance. The bandwidth of the received response is inversely proportion to the distance along the fibre path. The audio bandwidth maybe capable of detecting an audio band up to 50kHz at short distances (<1km), but this bandwidth is significantly reduced (< 1kHz) at distances beyond 20km.

CONCLUSIONS

iDAs technology is capable of determining the full acoustic field – namely the amplitude, frequency and phase – of the incident signal. iDAS technology is currently being utilised within the power industry for effective intervention and intrusion monitoring. The system structure enables its integration within utility SCADA network and can also capitalise on the existing fibre optic infrastructure within the network. However there are limitations with regard to its audio bandwidth versus distance. With further application experience, and development of processing hardware and software, iDAS technology has a promising future for the electric power industry.

REFERENCES

For a Conference citation:

[1] Farhadiroushan, M., Parker, T.R. and Shatalin, S., 2009, " Method and Apparatus for Optical Sensing", WO2010136810A2

[2] Shatalin, S.V, Treschikov, V.N. and Rogers, A.J. 1997 “Interferometric optical time-domain reflectometry for distributed optical-fiber sensing”, Applied Optics, 37, 5600-5604

[3] Shatalin, Sergey et al., “Interferometric optical time-domain reflectometry for distributed optical-fiber sensing”, Applied Optics, Vol. 37, No. 24, pp. 5600 - 5604, 20 August 1998

[4] R. Svoma, R. Kluth, K. Singh, “Application of Temperature sensing and dynamic strain monitoring to subsea cable technology”, 2007, Jicable proceedings

[5] Every,M.J, King,R.& G. Riffen, 1981, “Hydrodynamic loads on flexible marine structures due to vortex shedding. In Proceedings ASME Winter Annual Meeting ,Washington DC, USA

[6] Sarpkaya,T. 1978 Fluid forces on oscillating cylinders . ASCE Journal of Waterway Port, Coastal and Ocean Division , 104 , 275 – 290

[7] Yoerger,D.R., Grosenbaugh,M.A Triantafyllou, M.S .& Burgess, J.J . 1991 Drag forces and flow-induced vibrations of a long vertical tow cable—Part I : Steady-state towing conditions . ASME Journal of Offshore Mechanics and Arctic Engineering 113 , 30 – 36

GLOSSARY

DVS: Distributed Vibration Sensing
DTS: Distributed Temperature Sensing
DCR: Dynamic Cable Rating
OTDR: Optical Time Domain Reflectometer
DAS: Distributed Acoustic Sensing
iDAS: Intelligent Distributed Acoustic Sensing
FAT: Factory Acceptance Test
SAT: Site Acceptance test
FFT: Fast Fourier Transform
MBM: Modular Borehole Monitoring
OPGW: Optical Path Ground Wire
OPPC: Optical Path Phase conductor