

Fibre Optic Distributed Scattering Sensing System: Perspectives and Challenges for High Performance Applications

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ABSTRACT

As fiber optic distributed scattering sensing systems are providing innovative solutions for the monitoring of large structures, the comparison of the different techniques and solutions is difficult because of the lack of standardized specifications and the difficulty associated to the characterization of such systems. The article presents a tentative definition of performance specifications and qualification procedures applicable to fiber optic distributed sensing systems aiming at providing clear guidelines for their design, specifications, qualification, application and selection.

Keywords: fibre optic sensor, distributed sensor, Brillouin scattering, temperature, strain, spatial resolution.

1. INTRODUCTION

The unique feature of fibre optic distributed sensing systems is the ability to perform measurements at thousands of locations along an optical fibre. If only fully distributed systems (as opposed to the multiplexing of point sensors) are only considered, the measurement techniques are all based on optical time (or frequency) domain reflectometry and they offer solutions for the monitoring of distributed temperature, strain or pressure. Since the early 90's commercially available instruments have been successfully used for monitoring large structures such as dams, tunnels, pipelines, oil wells, power cables, land slides, etc. Despite the success and the growing demand for such systems, there are neither guidelines nor standards available for the specification and the characterisation of such sensing systems [1]. From the user's point of view, the actual comparison of the different monitoring solutions is difficult or nearly impossible. Furthermore the definition of performance specifications is more difficult for distributed sensors than for traditional point sensors in the sense that the performance depends on a combination of related measurement parameters. For instance, the temperature accuracy depends on the spatial resolution, acquisition time, distance range and even on the distance location and effects/interaction prior to the location. Nowadays, one can find listed technical specifications such as 0.1 K resolution, 1m spatial resolution, 10 second acquisition time, 50 km distance range. Beyond the definition issues of each individual specified parameter, the interdependence of the different parameters affects the others is often neglected leading to misleading performance specifications since the advertised performance cannot be achieved simultaneously. As a result for wider product acceptance, standardized specifications are needed with well understood properties and validated performance characteristics.

This article presents an attempt to define qualification procedures associated to the different parameters of distributed sensors based on application requirements and providing a more accurate picture of the complete system performance. For demanding applications, it is of utmost importance to be able to validate system performance according to established specification rules. The presented study is based on a commercially available Brillouin-based distributed temperature and strain sensing system referred to as the DiTeSt measuring system.

2. DISTRIBUTED SENSING TECHNIQUES AND SYSTEMS

Developed for telecommunication applications, OTDRs have been the starting point of distributed sensing techniques. They use the Rayleigh scattered light to measure the attenuation profiles of long-haul fibre optic links. In the optical time-domain-coded technique, an optical pulse is launched into the fibre and a photodetector measures the amount of light which is backscattered as the pulse propagates along the fibre. The detected signal, the so-called Rayleigh signature, presents an exponential decay with time which is directly related to the linear attenuation of the fibre. The time information is converted to distance information provided that the speed of light is known, similar to radar or lidar detection techniques.

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In addition to the information on fibre losses, the OTDR profiles are very useful to localize breaks, to evaluate splices and connectors, and in general to assess the overall quality of a fibre link.

Raman and Brillouin scattering phenomena have been used for distributed sensing applications over the past few years. Raman was first proposed for sensing applications in the 80's [2], whereas Brillouin was introduced later as a way to enhance the range of OTDR [3] and then for strain and/or temperature monitoring applications [4]. Fig. 1 schematically shows the spectrum of the scattered light from a single wavelength λ_0 in optical fibres. Both Raman and Brillouin scattering effects are associated with different dynamic non-homogeneities in the silica and therefore have completely different spectral characteristics.

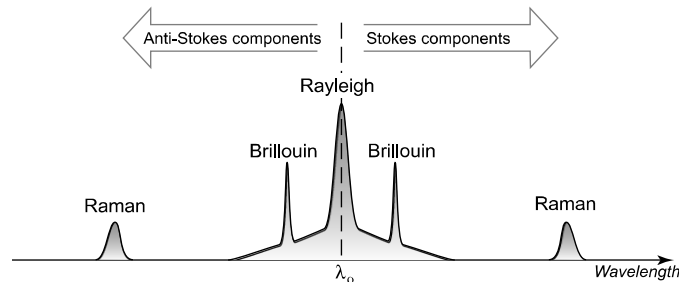


Fig. 1: Schematic representation of the scattered light spectrum from a single wavelength signal propagating in optical fibres. An increase of the fibre temperature has an effect on the Raman and Brillouin components, whereas strain has an effect on Brillouin components only.

The Raman light scattering is caused by thermally influenced molecular vibrations. Consequently the backscattered light carries the local temperature information at the point where the scattering occurred. The amplitude of the Anti-Stokes component is strongly temperature dependent whereas the amplitude of the Stokes component is not. Raman sensing requires some filtering to isolate the relevant frequency components and is based on the recording and computation of the ratio between Anti-Stokes amplitude and Stokes amplitude, which contains the temperature information. Since the magnitude of the spontaneous Raman backscattered light is quite low (10 dB below spontaneous Brillouin scattering), high numerical aperture multimode fibres are used in order to maximize the guided intensity of the backscattered light. However, the relatively high attenuation characteristics of multimode fibres limit the distance range of Raman-based systems to approximately 10 km, beyond which their decline in usefulness in most practical cases.

Brillouin scattering occurs as a result of an interaction between the propagating optical signal and thermally excited acoustic waves in the GHz range present in the silica fibre giving rise to frequency shifted components. It can be seen as the diffraction of light on a dynamic grating generated by an acoustic wave (an acoustic wave is actually a pressure wave which introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift since the grating propagates at the acoustic velocity in the fibre. The acoustic velocity is directly related to the medium density which is temperature and strain dependent. As a result the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fibre as shown in Fig. 2 [5].

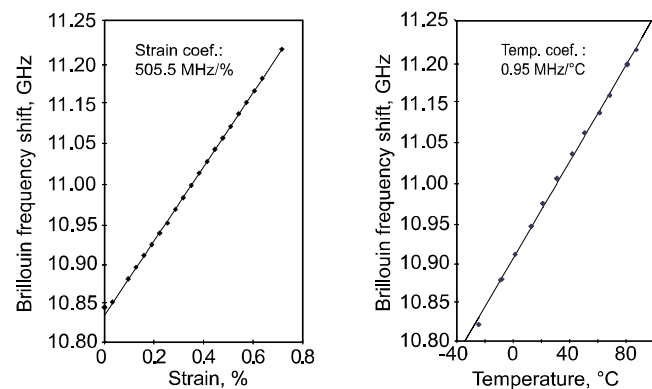


Fig. 2: Strain and temperature dependence of the Brillouin frequency shift of standard telecommunication optical fibres.

Brillouin-based techniques bring the following advantages over other distributed techniques:

1. The technique makes use of standard low-loss single-mode optical fibre offering several tens of kilometres of distance range and a compatibility with telecommunication components.

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2. It is a **frequency-based technique** as opposed to Raman-based techniques which are intensity based. Brillouin based techniques are consequently inherently more accurate and more stable in the long term, since intensity-based techniques suffer from a higher sensitivity to drifts.
3. Brillouin scattering can be optically **stimulated** leading to a much greater intensity of the scattering mechanism and consequently an improved signal-to-noise ratio.
4. The stimulation mechanism involves two counter-propagating lightwaves which can be controlled individually providing a very valuable way to adjust the measurement parameters with respect to the application requirements in terms of resolution, distance range and acquisition time.

The active stimulation of Brillouin scattering can be achieved by using two optical lightwaves. In addition to the optical pulse usually called the pump, a continuous wave (CW) optical signal, the so-called probe signal is used to probe the Brillouin frequency profile of the fibre. A stimulation of the Brillouin scattering process occurs when the frequency difference (or wavelength separation) of the pulse and the CW signal corresponds to the Brillouin shift (resonance condition) and provided that both optical signals are counter-propagating in the fibre. The interaction leads to a larger scattering efficiency resulting in an energy transfer from the pulse to the probe signal, and an amplification of the probe signal, as can be seen on Fig.3a. The frequency difference between pulse and probe can be scanned for precise and global mapping of the Brillouin shift along the sensing fibre (Fig. 3b). Lastly at every location, the maximum of the Brillouin gain is computed (Fig. 3c) and the information translated to temperature or strain using the calibration coefficients in Fig.2. The probe signal intensity can be adjusted to acceptable levels for low-noise fast acquisition whatever the measurement conditions and fibre layout, thus solving the small signal-to-noise ratio issues which are generally associated with distributed sensing based on spontaneous light scattering.

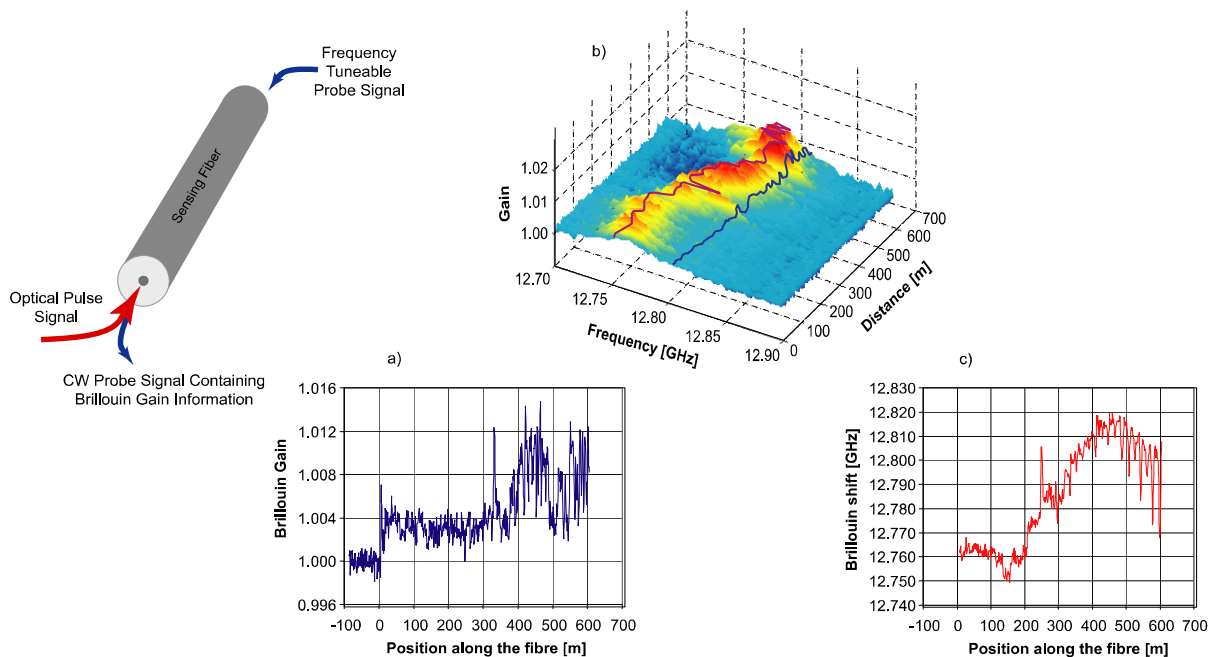


Fig. 3: Schematic representation of the optical signals used to stimulate the Brillouin interaction in optical fibres. a) Amplification profile as function of distance along the test fibre, b) Frequency mapping of the Brillouin gain along the fibre, c) Brillouin shift profile extracted from Fig. 3b).

The localization of the temperature or strain information along the fibre is possible using a pulsed pump signal. The interaction of the probe with the pump is recorded as a function of time and the time information can be converted into distance. An actual temperature profile of the fibre can be computed using calibration curves (Fig. 2). Thanks to the high

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speed of light, fibre lengths of several kilometres can be scanned within a fraction of second, yielding several thousands of measurement points.

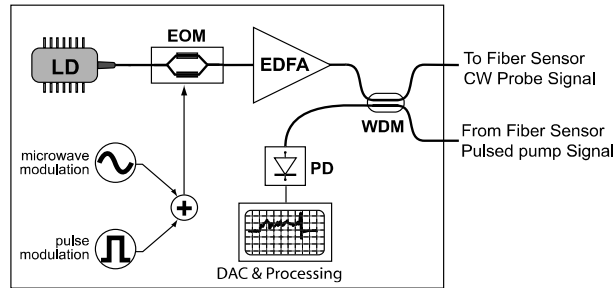


Fig. 4: Schematic setup of the DiTeSt instrument developed for the measurement of Brillouin frequency shift in optical fibres. The monitoring configuration requires a so-called double-ended configuration where both fibre ends are connected to the instrument.

3. DEFINITIONS OF THE SPECIFICATION AND PERFORMANCE OF DISTRIBUTED SENSING SYSTEMS

The challenge to accurately specify a distributed monitoring system lies in the fact that the parameters defining the performance of the system are inter-related. Moreover, such systems use optical fibres (standard or speciality fibres) whose characteristics may directly affect the monitoring performance. The sensing fibre integration/deployment needs to be taken into account since the actual fibre characteristics may be far from those of the bare fibre as soon as the fibre is embedded in the structure. Based on the above statements it appears that it will be impossible to specify system measurement performance without including fibre losses, distance range and acquisition time information.

From the user's perspective the important parameters are: measurement resolution and accuracy, spatial resolution, distance range, acquisition time and dynamic range. Here is a tentative way to define for a distributed temperature and strain monitoring system each of the listed parameters and their impact on the others:

Spatial resolution:

The spatial resolution is the ability to discriminate between two adjacent locations submitted to different temperature/strain conditions. For optical time-domain-coding-based systems, the spatial resolution is directly related to the optical pulse width or the distance L illuminated by the pulse at a given time $L = \tau v_g / 2$, where τ is the pulse width and v_g is the group velocity of the pump pulse. Since in silica fibre the group velocity is $v_g \approx 2 \times 10^8$ m/s the rule of thumb that 10 ns corresponds to 1 m spatial resolution can be used. Based on this definition, a given temperature/strain that spreads uniformly over a distance greater than the spatial resolution is measured with 100% of instrument accuracy. If a local temperature/strain change occurs in a distance scale smaller than the preset spatial resolution, it might still be detected but the change will not be measured with the full accuracy.

Distance resolution and distance precision

In optical time-domain-coding-based systems, the distance resolution is completely de-coupled from the spatial resolution in the sense that it depends on the acquisition scheme, i.e. the sampling rate of the detection system. It sets the number of points along the distance (sampling interval) and is independent from the spatial resolution.

The distance precision corresponds to the localization precision of a measured point with respect to its geographical position. It depends on the performance of the time acquisition, on how accurately the index of refraction of the fibre and how well the fibre lay-loss are known and can be controlled. In the case of very long distance measurements, the temperature effects on the index of refraction might have to be taken into account in order to maintain the distance precision and to re-adjust the exact physical location of the measured points.

Temperature/strain resolution and accuracy

The measurement accuracy is defined as the overall agreement of a measurement to a known value. It includes a combination of random error (precision) and systematic error (bias) components and is directly related to the noise. The noise includes spontaneous, short duration deviations in output (reading) about the mean output (reading), which are not

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caused by measurand changes. Noise is determined as the standard deviation about the mean and is expressed in measurand units. The measurement precision is a measure of the agreement between repeated measurements of the same property under identical, or substantially similar, conditions; the precision is defined as twice the standard deviation of the noise (+/- twice the standard deviation includes 95.4% of the measurements). The measurement resolution can in turn be defined as +/- the standard deviation of the noise. The precision is well quantified by the repeatability, whereas the bias requires measurement(s) performed with a reference measuring system.

Distance range

The distance range corresponds to the maximum distance over which the measurements can be performed while maintaining the rated spatial resolution and measurement precision.

Dynamic range

The dynamic range is the maximum cumulated optical loss until the rated spatial resolution and measurement precision can no longer be met. This characteristic, often neglected, needs to be fully characterized since in practical applications high fibre loss can be expected, especially in the case of embedded fibres for structural monitoring or when speciality fibre cables need to be used.

Specifications interdependence

The performance of distributed sensing systems depends on the combination of the above parameters and it may not be constant over the distance range. It may also depend on the distance location and the effects/interaction prior to the location [6]. The measurement accuracy depends on the signal-to-noise ratio (SNR) of the detected optical signals and/or on the measurement contrast in the case of stimulated scattering systems. Both SNR and contrast are related to the spatial resolution, pulse intensity, distance and fibre attenuation. As a result, for a given spatial resolution the accuracy is not constant over the fibre length since the intensity is affected by the fibre attenuation and the noise increases with distance. A proper qualification of a distributed scattering system shall therefore include the quantification of the accuracy vs. distance for the rated fibre attenuation.

The spatial resolution may also be affected by dispersion, which introduces pulse broadening with distance, especially when multimode fibres are to be used (Raman-based systems). Moreover the acquisition time should also be taken into account since the SNR is affected by the acquisition (integration, averaging) time. Attempts to increase the SNR by increasing the optical pulse intensity are limited by non-linear effects (both Raman and Modulation Instabilities in single-mode fibre based systems), which affect the distance range [7] and the accuracy [8]. As a result, both dynamic range and distance range are acquisition time dependent. Moreover for a given spatial resolution the distance range is limited, which means that the measurements cannot be performed with the specified accuracy beyond a certain distance. One has to accept either a lower measurand accuracy to reach farther distances or use a lower spatial resolution.

The ultimate answer to the specifications of the performance of a distributed sensing system lies in the clear description of how the specification parameters are inter-related, i.e. information about the measurement accuracy shall always be given for given distance (including fibre losses) in conjunction with a given spatial resolution and a specified acquisition time.

4. QUALIFICATIONS OF DISTRIBUTED SENSING SYSTEMS

This paragraph provides information about a tentative qualification of a stimulated Brillouin scattering distributed sensing system aiming at validating its performance.

Spatial resolution:

A simple method to verify the spatial resolution of Brillouin-based system is to use fibre segments of different lengths (0.5, 1.0, 1.5 and 2 m in Fig. 5) spliced to fixed length of a different type of fibre. This creates abrupt Brillouin frequency shift steps as shown in Fig. 5 because of the difference in core composition [4], from roughly 10.85 GHz (standard ITU-T-G652 fibre) to 11GHz (pure silica core fibre) (equivalent to 3000 microstrains). Although the above test efficiently confirms the system's spatial resolution (sections of at least equal or longer distance than the spatial resolution should be resolved), it provides little information about the ability to meet the measurement accuracy on the given spatial resolution. It can also be seen from Fig.5 that the transition depends on the distance resolution (sampling interval) and it occurs over 0.1 m whatever the spatial resolution was. As a result the spatial resolution definition based on the distance over which a 10% to 90% step change occurs is not applicable.

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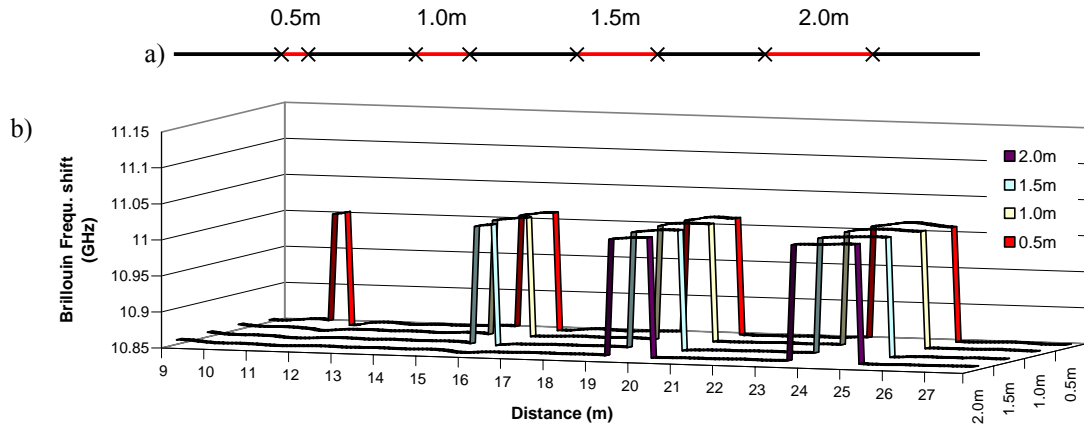


Fig.5: (a) Test setup of the spatial resolution using sections of two different fibre types; (b) test results for different spatial resolution settings ranging from 0.5 m to 2 m..

Actual temperature and/or strain steps should be used to fully qualify the system performance. Fig.6 shows the result obtained using a temperature controlled bath and sections of different fibre lengths (10 m, 5 m, 2 m, 1 m and 0.5 m) exposed to the water temperature whereas 5m sections remain at room temperature in between the sections placed in the bath. The measurement performed with a 1 meter spatial resolution shows that the 10 m, 5 m, 2 m and 1 m sections are measured with the full accuracy whereas the 0.5 m section is not measured with the full accuracy although the section is clearly detected. The test confirms the 1m spatial resolution characteristic of the system.

A similar test could be performed using an elongated fibre section of known length using a micro-positioning unit. The temperature test of Fig. 6 is easier to perform since strain tests require reliable and good fixing points. Fig. 7 shows the results obtained with a 2 m fibre section gradually stretched by 0.2 mm steps (corresponding to 100 microstrains additional strain per step). The measurement was performed with a 1 m spatial resolution.

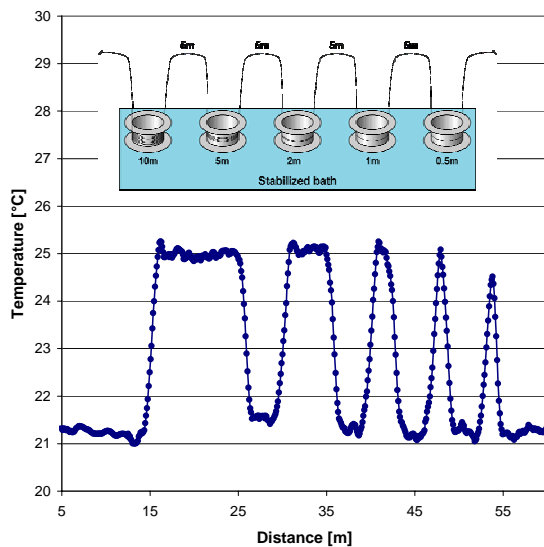


Fig.6: Sections of different lengths placed in a temperature controlled bath set to 25°C. Measurement performed with a 1m spatial resolution.

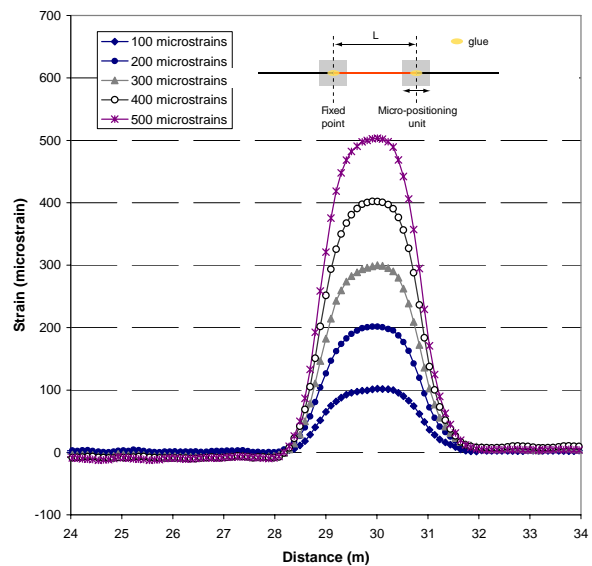


Fig.7: Strain test results performed on a fibre section L=2m submitted to given strain by means of a micro-positioning unit.

Measurement precision and resolution

The measurement precision can be quantified by the repeatability, i.e. the difference between measurements performed in identical conditions. It can be measured locally and evaluated as a function of the distance for a given spatial resolution and acquisition time, as well as specified fibre attenuation. Fig. 8 shows typical repeatability measurement

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results obtained in a 20 km fibre (ITU-T-G652 fiber 0.2 dB/km) with a 1 m spatial resolution and a 2 minute acquisition time. Twice the standard deviation of the repeatability calculated over 100 m sections in the same fibre is also shown.

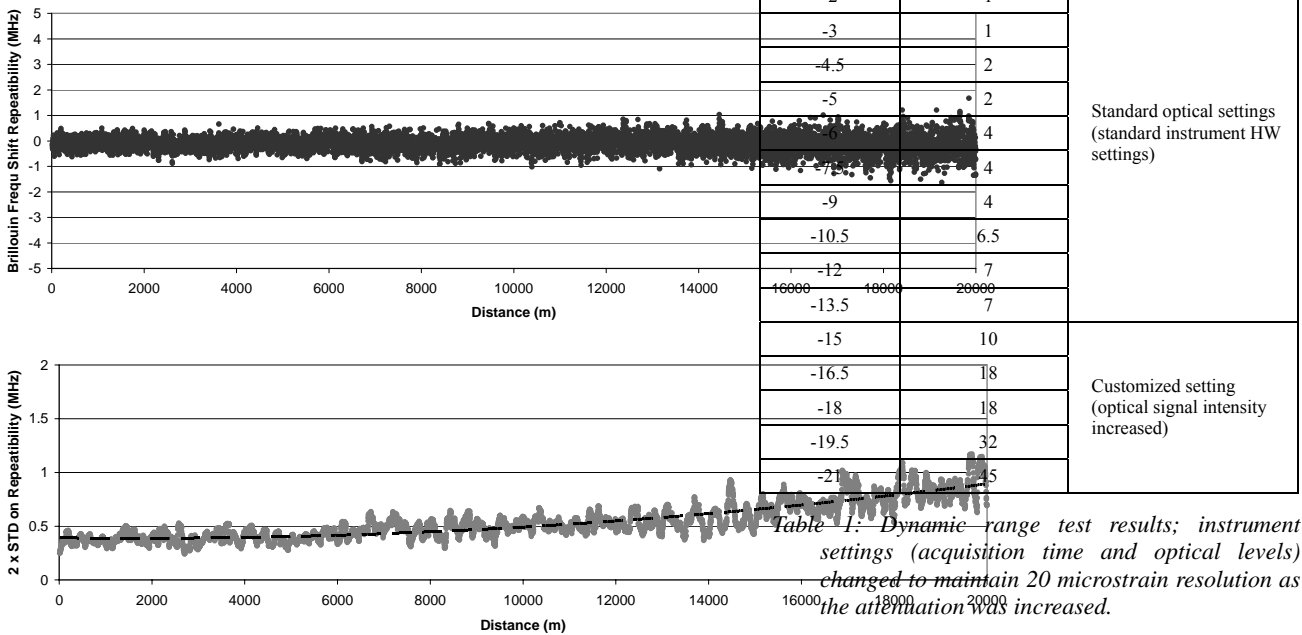


Table 1: Dynamic range test results; instrument settings (acquisition time and optical levels) changed to maintain 20 microstrain resolution as the attenuation was increased.

Fig. 8: Difference between the measurements of the Brillouin frequency shift repeated in identical conditions over 20 km, using a 1 m spatial resolution and 2 minute acquisition time. Evolution of the precision (twice the standard deviation of the noise computed over 100m section) as a function of distance and quadratic fit.

In order to fully assess the measurement precision for a given spatial resolution and fiber losses but taking into account different acquisition times the procedure described in Fig. 8 needs to be repeated for different acquisition times. The overall measurement precision figures in terms of temperature and strain accuracies is then fully characterized as in Fig. 9, which shows typical repeatability features which can be obtained in a 30 km fibre (ITU-T-G652, 0.2 db/km) obtained with a 1.5 m spatial resolution and different acquisition times. The representation in Fig. 9 is the most appropriate way to fully and accurately describe the performance of a distributed scattering sensing system. The calculated precision is given in temperature and strain units using the calibration shown in Fig. 2.

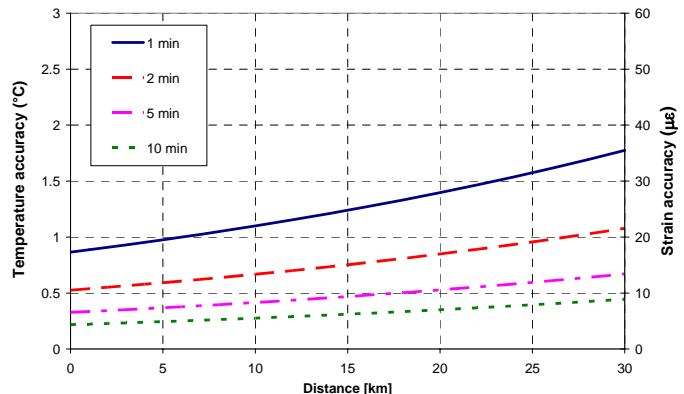


Fig. 9: Measurement precision in terms of temperature and strain as a function of distance for a 1.5m spatial resolution and different acquisition times; measurements performed on a 30 km fibre spool (ITU-T G652 0.2 dB/km attenuation).

Dynamic range

The dynamic range can be tested using a manual optical attenuator inserted before a fibre test sample. In Table 1, a 10 km fibre (ITU-T-G652) was measured with the DiTeSt stimulated Brillouin scattering sensing system while a manual

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attenuator was used to simulate high fibre loss. The attenuator affects both pump and probe signal only once, in the sense that the attenuation is located in one branch of the loop near the zero meter position and before the 10 km fibre. The measurement parameters were changed in order to maintain a 20 microstrain resolution (i.e. repeatability between measurements better than 20 microstrains). From 0 dB to 15 dB attenuations, the acquisition time had to be increased to maintain the specified 20 microstrain resolution.

Beyond 15 dB of attenuation, the optical intensity settings had to be changed and the acquisition time further increased in order to compensate for the high attenuation of the sensing fibre. Beyond 21 dB, the measurements performance could not be maintained anymore and hardware modification would be required to further increase the measurement dynamic range. The measurement time is increased is due to the fact that longer averaging times and smaller frequency steps were required to maintain the 20 microstrain resolution.

A clear advantage of stimulated Brillouin-based systems can be seen giving the flexibility to adjust pump and probe intensities can be used to compensate for high fibre losses.

5. CONCLUSIONS

The ability to meet the requirements of demanding applications such as structural monitoring (high dynamic range, high spatial resolution, high sensitivity), pipeline monitoring (high sensitivity, medium to high spatial resolution, long distance), oil wells monitoring (high dynamic range, high precision) or else fire detection (short acquisition time) with a Brillouin-based distributed fibre optic sensing system has been demonstrated.

The need to qualify the system performance according to established extensive standards was emphasized and some guidelines for test procedures were described. It is of prime importance to have agreed standardized definitions about how to describe system performance under given operational conditions in order to deliver a clear message to the users and to provide possibilities to enable comparison of various systems. The future success of fibre optic distributed sensing techniques depends on the customer's satisfaction with their purchase and on the community's ability to come up with guidelines and standardized definitions for their qualifications and eventually to help the customers in the selection of the appropriate solution with respect to the application requirements.

REFERENCES

1. W.R. Habel, "Guidelines and standards for fiber optic sensors – Quo Vadis", Proc. of SPIE, SSSM'06, Vol 6167, pp. 61671A-1-9 (2006)
2. J.P. Dakin, D.J. Pratt, G.W. Bibby, J.N. Ross, "Distributed optical fiber Raman temperature sensor using a semiconductor light source and detectors", Electronics Lett., 21, pp. 569-570 (1988).
3. T. Horiguchi, M. Tateda, "Optical-fiber-attenuation investigation using Brillouin scattering between a pulse and a continuous wave", Optics Lett., Vol. 14, p. 408 (1989)
4. T. Horiguchi, T. Kurashima, M. Tateda, "Distributed-temperature sensing using stimulated Brillouin scattering in optical silica fibers", Opt. Lett., 15, N°8, pp.1038-10-140 (1990)
5. M. Niklès, L. Thévenaz, Ph. Robert, "Brillouin gain spectrum characterization in single-mode optical fibers", J. Lightwave Technol., LT-15, pp. 1842-1851 (1997)
6. A. Minardo, R. Bernini, L. Zeni, L. Thevenaz, F. Briffod A reconstruction technique for long-range Stimulated Brillouin Scattering distributed fiber-optic sensors: experimental results, Measurement Science and Technology, vol .16, pp. 900-908 (2005)
7. A. Fellay, L. Thevenaz, M. Facchini, M. Nikles, P. Robot, "Distributed sensing using Stimulated Brillouin scattering: towards ultimate resolution," Proceedings of OFS'97 16, pp. 324-327 (1997)
8. D. Alasia, M.H. Gonzalez, L. Abrardi, S. Martin-Lopez, L. Thevenaz, "Detrimental effect of modulation instability on distributed optical fiber sensors using stimulated Brillouin scattering" Proceedings of the SPIE, OFS'05 Volume 5855, pp. 587-590 (2005)

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