Sensing accuracy enhancement of long-range distributed fibre-optic temperature sensor using hybrid algorithm

Himansu Shekhar Pradhan

Department of ECE, National Institute of Technology, Warangal, Telangana, India

Abstract

This paper presents a long-range distributed fibre-optic temperature sensor with high sensing accuracy to monitor temperature using Brillouin scattering mechanism. Fourier deconvolution, Fourier wavelet regularised deconvolution, dichotomised singular value decomposition and hybrid algorithms were employed to measure the temperature of proposed sensor. Optical time domain reflectometry technique is used to extract the temperature profile for 70, 60 and 50 km sensing ranges. The improvement of temperature accuracy using hybrid algorithm is achieved for 70 km sensing distance. In order to extract temperature information, the numerical simulation process has been incorporated in the proposed long-range sensing system. Moreover, the temperature accuracy of the proposed system is obtained using Fourier deconvolution, Fourier wavelet regularised deconvolution, dichotomised singular value decomposition and hybrid algorithms for 70, 60 and 50 km sensing ranges. The simulation results show that the temperature accuracy is observed as 4.8°K using hybrid algorithm compared to Fourier deconvolution algorithm that shows temperature accuracy as 14°K at 70 km. In the proposed sensor, a spatial resolution of 20 m is observed for a sensing range of 70 km using hybrid algorithm. In addition, the denoising competence of the proposed hybrid algorithm is validated using 50 km optical time domain reflectometry backscattered trace observed experimentally. Further, a peak dynamic range improvement of optical time domain reflectometry backscattered trace as 3.91 dB is observed using hybrid algorithm.

1 INTRODUCTION

The extensive growth of the fibre-optics technologies and cost reductions in optoelectronic components led to emergence of new application areas. The product outgrowths of fibre-optic telecommunications with optoelectronic devices create fibre-optic sensors. The availability of fibre-optic sensors at a low cost has been made possible in recent years due to the mass production of these systems by industries. Owing to their availability at affordable costs, fibre-optic sensors are able to enter the sensor domain that was previously captured by the traditional electrical sensors. These sensors are used to monitor a wide range of ecological parameters including position, vibration, strain, temperature, humidity, pressure etc. One of the applications, the leakage detection of hydrocarbon pipelines using fibre-optic sensor, was demonstrated by Huang et al. [1]. These sensors can be used in many other applications such as hydrogen leak detection [2], intrusion detection [3], structural health monitoring [4] and in military applications etc. Particularly, monitoring of hydrocarbon supply lines (gas and oil pipeline) is a very critical task. Many of the gas and oil pipelines are deteriorating due to a number of reasons and also need immediate attention for maintenance. These supply lines require repair, maintenance and rehabilitation processes for longevity and safety. Generally, they are buried under the ground or sometimes are laid over the ground. The leaks in underground pipelines create a substantial danger for the human beings and other animals. In addition, oil leakage from pipelines pollutes the earth and also ground water. Moreover, the leakage of gas creates the danger of fire and also explosions. Therefore, it is highly essential to locate and localise the leaks as soon as they occur on a real-time basis. However, the conventional methods of monitoring are only suitable for...
large leaks and also are not able to localise the point of leakage. In recent years, distributed sensing using standard fibre-optic cable is a hot area of research. The distributed fibre sensors have many advantages compared to traditional point sensors. One of the major advantages in distributed fibre sensor over traditional point sensor is that it can be used as a real-time and continuous measurement system for monitoring the measurands. It is a high-tech instrument for real-time measurement of temperature field [5–7]. In the field of public safety and industrial process monitoring, it has become a new detection method. Distributed fibre-optic sensors allow to extract the parameter information such as pressure, corrosion, vibration, temperature, strain etc., with the function of positions along the total length of the sensing fibre. Another advantage of the distributed fibre sensor is that it can extract the parameter information of many points continuously along the fibre under test depending on spatial resolution of the sensor. The distributed fibre-optic sensors are designed based on scattering of light mechanism such as Rayleigh [8], Raman [9] and Brillouin [10–12]. In Raman as well as Brillouin scattering process, a frequency difference between the incident light signal and the backscattered signal is present, whereas no difference in Rayleigh scattering. Raman distributed sensors are becoming popular and commercialised because it is easy to separate the Stokes as well as anti-Stokes signal from Rayleigh signal, high sensitivity and also good temperature accuracy. Therefore, Raman sensing systems have been commercialised and numerous researches are going on to enhance the performances such as sensing range, signal-to-noise ratio, temperature accuracy and the spatial resolution. As the anti-Stokes Raman signal is 30 dB less than the Rayleigh signal, therefore, the detection of Raman backscattered light is more difficult and an accurate detection system is required. Moreover, Raman distributed sensor could not be used for strain sensing because Raman anti-Stokes signal is not at all sensitive to strain variations. In contrast to all the above reasons, Brillouin scattering-based distributed sensing has become increasingly popular, and a substantial attention is being given by the researchers and industry because Brillouin-based distributed sensors are sensitive to both strain and temperature simultaneously [13–17]. Moreover, Brillouin frequency shift measurement does not require calibration of the optical fibre loss and also Brillouin technique has the potential for long sensing range compared to Raman technique because the Brillouin frequency shift is small (about 10 GHz) and it is in the minimum loss wavelength region of 1550 nm. Also, Brillouin backscattered power is about 10 dB higher than the Raman backscattered power with the reference of Rayleigh power.

The author proposes a long-range distributed fibre-optic sensor to monitor temperature using Brillouin scattering mechanism in this paper. Optical time domain reflectometry (OTDR) technique is used for extracting temperature information from the proposed sensor [18]. The temperature profile and accuracy of the designed sensor are obtained using different algorithms such as Fourier deconvolution (FD), dichotomised singular value decomposition (D-SVD), Fourier wavelet regularised deconvolution (FWRD) and hybrid by considering 70 km sensing distance. The performance analysis in terms of sensing accuracy is carried out using different algorithms. A spatial resolution of proposed sensor is also obtained using 70 km fibre under test using numerical simulation technique. The proposed sensor can be used to monitor health condition of long-range oil and gas pipelines with high sensing accuracy.

2 | PROPOSED SENSOR MODEL FOR SIMULATION

A long-range distributed fibre-optic sensor is proposed to measure the temperature of 70 km fibre under test using OTDR technique. The temperature profiles are extracted employing different algorithms using Landau–Placzek ratio (LPR). The schematic of proposed sensor used for simulation process is shown in Figure 1. The temperature accuracy is obtained using hybrid algorithm, and compared with other employed algorithms of proposed sensor. Brillouin backscattered power has a linear relationship with the fibre temperature as well as strain and can be expressed as [19]

$$\frac{\delta \nu_B}{100 \times \delta I_B} = \left[ \frac{C_{\nu e} C_{\nu T}}{C_{\nu e} C_{\nu T}} \right] \left( \begin{array}{c} \delta \varepsilon \\ \delta T \end{array} \right),$$

(1)

where $\delta \nu_B$ is the Brillouin shift, $\delta I_B$ is the intensity variation of the Brillouin signal, $\delta \varepsilon$ is the strain variation of fibre under test, $\delta T$ is the temperature variation of the sensing fibre, $C_{\nu e}$ is the strain coefficient of Brillouin frequency shift, $C_{\nu T}$ is the coefficient of temperature for Brillouin frequency shift, $C_{\nu e}$ is the coefficient of strain for Brillouin intensity variation and $C_{\nu T}$ is the coefficient of temperature for Brillouin intensity variation. On the other hand, the Brillouin gain spectrum as a function of frequency $f$ typically represented by the Lorentzian shape is given by Equation (2) [20]

$$\delta B(f) = \delta B_0 \frac{(0.5 \Delta \nu_B)^2}{(f - \nu_B)^2 + (0.5 \Delta \nu_B)^2},$$

(2)
where $\beta_b$ is the Brillouin frequency shift, $\delta_b$ is the Brillouin gain constant and $\Delta_b$ is the Brillouin linewidth. Typically, the Brillouin linewidth is $\sim$ 35 MHz for a standard silica-based single-mode fibre at 1550 nm [21]. The temperature information can be obtained by taking the ratio of Rayleigh power to the Brillouin power, which is known as the LPR [22]

$$\frac{I_{RS}}{I_{BS}} = \frac{T_u}{T_0} \left( \beta_T \rho_0 V_A^2 - 1 \right), \quad (3)$$

where $I_{RS}$ is the Rayleigh scattering signal intensity, $I_{BS}$ is the Brillouin scattering signal intensity, $T_u$ is the fictive temperature, $T_0$ is the unknown temperature, $\beta_T$ known as isothermal compressibility, $\rho_0$ is the material density and $V_A$ is the acoustic velocity. In the proposed sensor, Brillouin power $P_B(t)$ at the input end of the sensing fibre is calculated by taking the convolution of $p_{in}(t)$ and fibre impulse response $f_b(t)$. The mathematical expression for the same is given below:

$$P_B(t) = p_{in}(t) \otimes f_b(t). \quad (4)$$

In the simulation process, a laser pulse of width $w_0$ and power $P_{in}$ is launched to the 70 km fibre under test. White Gaussian noise is considered for receiving Brillouin backscattered power at the input of fibre under test. The fibre impulse response of the proposed sensor is given as

$$f_b(t) = \frac{1}{2} \alpha R \nu_g S P_{in} \exp \left( -2 \alpha z \right), \quad (5)$$

where $\alpha_R$ is the Brillouin scattering coefficient, $\nu_g$ is the group velocity, $S$ is the backward capture coefficient, $P_{in}$ is the input power of laser pulse and $\alpha$ is the fibre attenuation coefficient. In order to find LPR, the Rayleigh power $P_R$ with the function of fibre length $z$ of the proposed sensor is calculated using the following equation [23]:

$$P_R(z) = \frac{1}{2} P_{in} \gamma_R w_0 \nu_g S \nu_g \exp \left( -2 \gamma_R z \right), \quad (6)$$

where $P_{in}$ is the input power, $\gamma_R$ is Rayleigh backscattering coefficient, $w_0$ is the laser pulse width, $S$ is the backward capture coefficient and $\nu_g$ is the light group velocity of sensing fibre. The Rayleigh power is calculated in the presence of coherent Rayleigh noise (CRN) [24], as this power is fluctuated due to CRN.

The temperature profile of the proposed distributed sensor is calculated using the ratio of LPR at unknown temperature $T_u$ to LPR at a reference temperature $T_R$:

$$T = \frac{1}{K_s} \left( 1 - \frac{LPR(T_u)}{LPR(T_R)} \right) + T_R, \quad (7)$$

where $K_s$ is the temperature sensitivity of the proposed sensing system and $T_R$ is the reference temperature.

### 3 | NUMERICAL SIMULATION AND RESULTS

A short-pulsed laser source of 1550 nm wavelength and pulse width 200 ns with 25 mW power is launched to the sensing fibre. The Brillouin and Rayleigh powers are calculated using Equations (4) and (5), respectively, at the input end of the sensing fibre, as represented in Figure 1. A constant white Gaussian noise of variance $10^{-7}$ W is used in numerical simulation process for 70 km sensing range. In order to extract the temperature information from the proposed sensor, an artificial rectangular pulse variation of temperature at 35 km distance is considered for simulation process. The additional parameters used for numerical simulation process are shown in Table 1. The temperature variation about 5 K at 35 km only of the 70 km fibre under test is used for simulation process. The rest fibre under test is maintained at reference temperature as 300 K.

Using FD, FWRD, D-SVD and hybrid algorithms, the Brillouin backscattered power is obtained in the proposed sensor. Direct deconvolution process is used to calculate the Brillouin backscattered signal in FD algorithm, as mentioned in Equation (4), for 70 km sensing range. The other deconvolution algorithms are used to attenuate the amplified noise, because the direct deconvolution is a highly noise-sensitive process [25]. The steps to denoise the noisy Brillouin signal obtained from FD algorithm using FWRD, D-SVD and hybrid algorithm are discussed as follows.

FWRD is employed to denoise the noisy Brillouin backscattered signal obtained from FD algorithm. In this algorithm, the shrinkage has been done using both Fourier and wavelet domain. The following steps are used in FWRD algorithm to denoise the signal.

### Table 1 | Parameters used for simulation process

| Parameters                | Symbols | Values |
|---------------------------|---------|--------|
| Fibre attenuation coefficient | $\alpha$ | 0.2 dB/km |
| Backward capture coefficient | $\delta$ | $1.6 \times 10^{-3}$ |
| Rayleigh backscattering coefficient | $\gamma_R$ | $4.6 \times 10^{-5}$ 1/m |
| Group velocity | $\nu_g$ | $2 \times 10^5$ m/s |
| Photo-elastic coefficient | $\rho$ | 0.286 |
| Density of silica | $\rho$ | 2330 kg/m$^3$ |
| Fictive temperature | $T_f$ | 1950 K |
| Laser pulse width | $w_0$ | 200 ns |
| Input power | $P$ | 25 mW |
| Isothermal compressibility | $\beta_T$ | $7 \times 10^{-11}$ m$^2$/N |
| Fibre refractive index | $n$ | 1.5 |
1. Fourier shrinkage is done using the observed signal from FD algorithm using the following equation [26]:

\[
X_i = X \ast \frac{|H|^2}{|H|^2 + \alpha N \sigma^2},
\]

where \(X\) is the signal observed from FD algorithm, \(\alpha\) is the regularisation parameter, and \(\sigma^2\) is the noise power.

2. Wavelet shrinkage is done using the observed signal from FD algorithm. The steps involved to improve performance of the proposed sensor. The steps involved to implement the above-mentioned algorithm are as follows:

1. In this step, discrete wavelet transform is applied on observed signal of step 1 \(X_s\), in order to obtain detail and approximate coefficients. Further shrinkage is applied on the approximate coefficients as follows:

\[
\mathcal{A} = \begin{cases} 
0, & |\mathcal{A}| < 1 \\
\mathcal{A}, & \text{otherwise}
\end{cases}
\]

2. Using wavelet shrinkage, the obtained step 2 signal is denoised. In denoised process, Daubechies wavelet is used as optimal wavelet [27], and estimate the output denoised signal by applying inverse discrete wavelet transform.

Another algorithm such as D-SVD algorithm [28] is employed for further attenuation of amplified noise to improve performance of the proposed sensor. The steps involved to implement the above-mentioned algorithm are as follows:

1. Hankel matrix is formed using the Brillouin backscattered signal with noise and decomposition is applied on the matrix given as

\[
H_s = U_s \sum_k V_s^T = \begin{pmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{pmatrix} \begin{pmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \end{pmatrix} \begin{pmatrix} v_{1,1} & \cdots & v_{L-1,1}^T \\ \vdots & \ddots & \vdots \\ v_{L-1,1} & \cdots & v_{L-1,L-1} \end{pmatrix}
\]

2. The singular matrices \(U_s\) and \(V_s\) are used in Equation (10). The matrix \(\sum\) has two significant components such as \(\sigma_1\) and a noisy component \(\sigma_2\); \(\sigma_1\) consists of a prominent part of the signal and hence it is left unaltered [29,30], \(\sigma_2\) represents half of the noise component and very less signal information. Hence, a new matrix \(\sum'\) is obtained by setting the noisy component.

3. A new Hankel matrix, \(H_s'\) is obtained using \(U_s', \sum'\) and \(V_s\).

4. The steps 2 and 3 are iterated for \(k\) number of times and a new Hankel matrix \(H_s^{(k+1)}\) is obtained. The denoised signal is then reconstructed using this new Hankel matrix. In order to get the optimised denoising signal, the \(k\) number of iterations are suitably chosen.

It is observed from above-mentioned denoising algorithms such as FWRD and D-SVD that the noisy Brillouin backscattered signal from direct deconvolution algorithm is denoised up to some extent. Therefore, the sensing accuracy of the proposed sensor is improved. However, a new hybrid algorithm is proposed that is a combination of D-SVD and FWRD in order to further improve the sensing accuracy/resolution without degradation of performance of the proposed sensor as spatial resolution. The further improvement of sensing accuracy/resolution is observed because D-SVD algorithm reduces the maximum deviation (MD) of the temperature measurements and also minimises the root mean square error (RMSE) and FWRD algorithm focuses on the shrinkage of both Fourier as well as wavelet domain, which cannot be obtained in single-transform domain. Therefore, both reduction in maximum deviation and maximum noise shrinkage can be obtained using the hybrid algorithm. The steps of hybrid algorithm used for numerical simulation process are as follows.

1. The Brillouin backscattered signal with noise observed from FD algorithm is used to obtain the Hankel matrix and decomposition is applied on the matrix as

\[
H_s' = U_s' \sum_k V_s' = \begin{pmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{pmatrix} \begin{pmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \end{pmatrix} \begin{pmatrix} f_{1,1} & \cdots & f_{L-1,1}^T \\ \vdots & \ddots & \vdots \\ f_{L-1,1} & \cdots & f_{L-1,L-1} \end{pmatrix}
\]

2. The matrices \(U_s'\) and \(V_s'\) are left unchanged. The matrix \(\sum\), that has a noisy component \(\sigma_2\) is altered by setting \(\sigma_2\) to 0, hence obtaining a new matrix \(\sum'\).

3. A new Hankel matrix, \(H_s^{(k+1)}\) is obtained using \(U_s', \sum'\) and \(V_s\). The steps 2 and 3 are iterated for \(k\) number of times and a new Hankel matrix \(H_s^{(k+1)}\) is obtained. The denoised signal \(X_{D=(S)}\) is then reconstructed using this new Hankel matrix. In order to get the optimised denoising, signal and \(k\) number of iterations are suitably chosen.

4. Fourier shrinkage is done using the observed signal from step 3 using the following equation:

\[
X_s' = X_{D=(S)} \ast \frac{|H|^2}{|H|^2 + \alpha N \sigma^2},
\]

5. In this step, discrete wavelet transform is applied on observed signal of step 4 \(X_s'\) in order to obtain detail and approximate coefficients. Further shrinkage is applied on the approximate coefficients as follows:

\[
\mathcal{A} = \begin{cases} 
0, & |\mathcal{A}| < 1 \\
\mathcal{A}, & \text{otherwise}
\end{cases}
\]
Using wavelet shrinkage, the signal obtained from step 5 is denoised. In denoising process, Daubechies wavelet is used as optimal wavelet, and the output denoised signal is estimated by applying inverse discrete wavelet transform.

As the Brillouin backscattered signal is used for extracting the temperature information from the proposed sensor, therefore, it is required to reduce the noise in order to improve the sensing accuracy. The noisy signal obtained from FD algorithm is regularised using Fourier shrinkage parameter $\alpha = 0.00035$ [17] for FWRD algorithm as mentioned in Equation (8). The room temperature $T = 300$ K and the sensitivity $K_s = 0.33\%/K$ for temperature [31] is used for numerical simulation process. The artificial temperature variation is modelled with rectangular pulse variation of temperature at the point $z = 35$ km. Besides this particular point, the rest of the fibre under test was at room temperature. In order to obtain temperature profile using Equation (7), LPR($T_u$) and LPR($T_R$) are calculated for fibre under test using numerical simulation process. The temperature variation at the point $z = 35$ km is used for simulation process at 305 K, as shown in Figure 1. The combined temperature profiles obtained from proposed distributed sensor of 70, 60, and 50 km sensing range using FD, FWRD, D-SVD and hybrid algorithms are shown in Figures 2, 3 and 4, respectively. It is clearly observed from the above-mentioned results that the noise peaks are more when sensing range increases irrespective of the algorithms used for denoising. This is because of the degradation of Brillouin power as attenuation increased with the increase of sensing distance. Moreover, the temperature accuracy/resolution is calculated by considering exponential fit of the obtained temperature profiles versus fibre length [32]. Figures 5, 6 and 7 show the combined temperature accuracies/resolutions using FD, FWRD, D-SVD and hybrid algorithms for 70, 60 and 50 km sensing range, respectively. These above-mentioned results show that the sensing accuracy/resolution is degraded with increasing sensing range. In addition, the spatial resolution is observed as theoretical and simulated values of the proposed sensor. Spatial resolution is the minimum distance between two consecutive temperature changes on fibre under test. It can be calculated as the distance elapsed between 10% and 90% of the increasing temperature or 90% to 10% response of the decreasing temperature [33]. Theoretical value is calculated using speed of the light in vacuum.
c, fibre refractive index n and laser pulse width \( w_D \) given in the following Equation (14):

\[
\text{Spatial resolution} = \frac{c}{2n} \times w_D. \tag{14}
\]

In numerical simulation process, the spatial resolution is calculated using the distance elapsed between 10\% and 90\% of the increasing temperature, as shown in Figure 8. It is clearly observed that the theoretical value of spatial resolution is same as the simulated value using hybrid algorithm. However, the improvement of temperature accuracy/resolution is observed in hybrid algorithms compared to other algorithms. Therefore, it can be concluded that the significant improvement of sensing accuracy/resolution can be achieved without degrading the other performances using the proposed sensor.

The simulated exact values of the sensing accuracies/resolutions for 70, 60 and 50 km distance using FD, D-SVD, FWRD and hybrid algorithms are tabulated in Table 2. It is observed from the simulation results that a significant
### TABLE 2
Temperature accuracy using different algorithms at 70, 60 and 50 km distance

| Employed algorithms | Temperature resolutions (K) at 70 km | Temperature resolutions (K) at 60 km | Temperature resolutions (K) at 50 km |
|---------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| FD                  | 14                                  | 5.2                                 | 2                                   |
| FWRD                | 9                                   | 3.4                                 | 1.3                                 |
| D-SVD               | 7                                   | 2.2                                 | 0.8                                 |
| Hybrid              | 4.8                                 | 1.7                                 | 0.6                                 |

**FIGURE 9** The basic optical time domain reflectometry (OTDR) setup used for experiment

An improvement in temperature accuracy/resolution is achieved using hybrid algorithm compared to FD algorithm at different sensing ranges. Moreover, sensing accuracy/resolution improvement of 9.2 K was achieved at higher sensing range using hybrid algorithm compared to FD algorithm.

## 4 | EXPERIMENTAL VALIDATION OF HYBRID ALGORITHM

The basic OTDR setup has been done in order to observe the backscattered trace, as shown in Figure 9. In the experimental setup, pulse generator, laser source, circulator, photodetector, signal processing and trace analysis blocks are used. The abovementioned blocks combined in an instrument called OTDR instrument (Yokogawa - AQ7275) have been used for experimental setup. In the experimentation process, a laser pulse was launched into the fibre of 50 km length through circulator. The OTDR backscattered trace is observed at the output of signal processing and trace analysis block and plotted using MATLAB, as shown in Figure 10. The hybrid denoising algorithm is used to attenuate the noise peaks of observed OTDR backscattered trace. Figure 11 shows the OTDR backscattered trace using hybrid denoising algorithm for understanding the denoising capability of proposed algorithm. In addition, the denoising capability of proposed hybrid algorithm is also validated by calculating the peak dynamic range of OTDR backscattered trace.

**FIGURE 10** Optical time domain reflectometry (OTDR) backscattered trace

The dynamic range is calculated using peak noise flooring technique [34] of obtained OTDR backscattered trace and shown in Figure 12. A peak dynamic range of 3.91 dB is observed using hybrid algorithm.

## 5 | CONCLUSION

A long-range fibre-optic distributed temperature sensor using Brillouin scattering is proposed. The performance improvement
in terms of temperature accuracy using hybrid algorithm is presented in this paper. In order to extract the temperature information from proposed sensor, numerical simulation process is used. The temperature accuracy is observed as 4.8 K using hybrid compared to FD algorithm, which shows the temperature accuracy as 14 K at 70 km distance. The temperature accuracy is calculated using FD, FWRD, D-SVD and hybrid algorithms for 60 and 50 km sensing ranges. The simulated spatial resolution of 20 m is observed using 70 km fibre under test in proposed sensor, which is equal to the theoretical value. In addition, the denoising capability of hybrid algorithm is validated using 50 km OTDR backscattered trace observed experimentally. Further, the peak dynamic range of OTDR backscattered trace is obtained with and without hybrid algorithm and an improvement of 3.91 dB is achieved using hybrid algorithm.

The numerical simulation results show that the proposed distributed sensor could be used for real-time monitoring of temperature with high sensing accuracy in long-range sensing applications.

REFERENCES
1. Huang, S.C., et al.: Fibre-optic in-line distributed sensor for detection and localisation of the pipeline leaks. Sens. Actuators, A 155(2), 570–579 (2007)
2. Bevenot, X., et al.: Hydrogen leak detection using an optical fibre sensor for aerospace applications. Sens. Actuators, B 67(1-2), 57–67 (2000)
3. Marchang, N., Datta, R.: Collaborative techniques for intrusion detection in mobile ad-hoc networks. Ad Hoc Networks 6(4), 508–523 (2008)
4. Guo, H.L., et al.: Fibre-optic sensors for structural health monitoring of air platforms. Sensors 11(4), 3687–3705 (2011)
5. Liu, Y., et al.: Distributed temperature detection of transformer windings with externally applied distributed optical fibre. Appl. Optics 58(29), 7962–7969 (2019)
6. Carvalho, R.V., et al.: Distributed temperature sensing in OPGW with multiple optical fibres. IET Sci. Meas. Technol. 13(8), 1219–1223 (2019)
7. Jderu, A., Enacheescu, M., Ziegler, D.: Mass Flow Monitoring by Distributed Fibre Optical Temperature Sensing. Sensors 19(19), 4151 (2019)
8. Gifford, D.K., et al.: Distributed fibre-optic temperature sensing using Rayleigh backscatter, 31st European Conference on Optical Communication, Glasgow, ECOC 2005. pp. 511–512 (2005)
9. Amiru, Z., Mohamed, B., Tahar, E.: Monitoring of temperature in distributed optical sensors: Raman and Brillouin spectrum. Optik 127(8), 4162–4166 (2016)
10. Iezzi, V.L., Loranger, S., Kashyap, R.: High sensitivity distributed temperature fibre sensor using stimulated Brillouin scattering. Opt. Express 25(26), 32591–32601 (2017)
11. Matsumoto, M., Akai, S.: High-spatial-resolution Brillouin optical correlation domain analysis using short-pulse optical sources. J. Lightwave Technol. 37(24), 6007–6014 (2019)
12. Wang, S., et al.: Study on the signal-to-noise ratio of Brillouin optical-time domain analyzers. Opt. Express 28(14), 19864–19876 (2020)
13. Kaur, G., Kalra, R.S.: Nanohybrid optical sensor for simultaneous measurements of strain, temperature, and vibration for civil application. IET Micro Nano Lett. 13(1), 1–3 (2018)
14. Lu, C., Dong, X., Su, J.: Simultaneous measurement of strain and temperature with a few mode fibre. 2017 Conference on Lasers and Electro-Optics Pacific Rim, Singapore. pp. 1–2 (2017)
15. Xie, H., Sun, J., Feng, D.: Simultaneous measurement of strain and temperature based on hybrid EDF/Brillouin laser. Opt. Express 24(11), 11475–11482 (2016)
16. Jiao, Y., Tian, J., Yao, Y.: Simultaneous measurement of temperature and strain based on all-fibre Fabry-Perot sensor. In: Proceedings of the SPIE 10464, Applied Optics and Photonics China (AOPC2017), 2017, Beijing, China, 104641C (2017)
17. Pradhan, H.S., Sahu, P.K.: Measurement of temperature and strain simultaneously with high spatial resolution for long sensing range. IET Optoelectron. 13(6), 288–294 (2019)
18. Wang, F., Zhan, W.: Improvement of spatial resolution for BOTDR by iterative subdivision method. J. Lightwave Technol. 31(23), 3663–3667 (2013)
19. Kim, S., et al.: Performance of a distributed simultaneous strain and temperature sensor based on a Fabry-Perot laser diode and a dual-stage FBG optical demultiplexer. Sensors. 13(11), 15452–15464 (2013)
20. Agrawal, G.P.: Nonlinear Fibre Optics, 2nd ed. Academic Press (1995)
21. Preussler, S., et al.: Brillouin scattering gain bandwidth reduction down to 3.4 MHz. Opt. Express 19(9), 8565–8570 (2011)
22. Soto, M.A., Bolognini, G., Pasquale, F.D.: Analysis of optical pulse coding in spontaneous Brillouin-based distributed temperature sensors. Opt. Express 16(23), 19097–19111 (2008)
23. Brinkmeyer, E.: Analysis of the back-scattering method for single-mode optical fibres. J. Opt. Soc. Am. 70(8), 1010–1012 (1980)
24. Souza, K.D.: Significance of coherent Rayleigh noise in fibre-optic distributed temperature sensing based on spontaneous Brillouin scattering. Meas. Sci. Technol. 17(5), 1065–1069 (2006)
25. Mallat, S.: A Wavelet Tour of Signal Processing, 2nd ed. Academic Press, New York, USA (1999)
26. Neelamani, R., Choi, H., Baramiuk, R.: ForWaRD: Fourier-wavelet regularized deconvolution for ill-conditioned systems. IEEE Trans. Signal Process. 52(2), 418–433 (2004)
27. Bahrampour, A.R., et al.: Spatial resolution enhancement in fibre Raman distributed temperature sensor by employing ForWaRD deconvolution algorithm. Opt. Fiber Technol. 17(2), 128–134 (2011)
28. Pradhan, H.S., Yallabandi, A., Appana, N.: Sensing resolution enhancement of long-range BDTS using D-SVD algorithm, 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT), Kanpur, India, 2019. pp. 1–5 (2019)
29. Wang, H., Wang, X., Cheng, Y.: Research on noise reduction method of RDTs using D-SVD. Opt. Fiber Technol. 48, 151–158 (2019)
30. Yang, W.-X., Tsee, P.W.: Development of an advanced noise reduction method for vibration analysis based on singular value decomposition. NDT & E Int. 36, 419–432 (2003)
31. Chang, T., et al.: Fibre-optic distributed temperature and strain sensing system based on Brillouin light scattering. Appl. Opt. 47(33), 6202–6206 (2008)
32. Soto, M.A., et al.: Distributed temperature sensor system based on Raman scattering using correlation-codes. Electron. Lett. 43(16), 862–864 (2007)

33. Soto, M.A., Bolognini, G., Pasquale, F.D.: Analysis of optical pulse coding in spontaneous Brillouin-based distributed temperature sensors. Opt. Express 16(23), 19097–19111 (2008)

34. Gold, M.P., Hartog, A.H.: Improved-dynamic-range single-mode OTDR at 1.3 µm. Electron. Lett. 20(7), 285–287 (1984)

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