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Improving Spatial Resolution of Raman DTS Using Total Variation De convolution

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Abstract— Traditional Raman distributed optical sensor (DTS) exhibits a low-pass characteristic that causes sharp temperature changes to be over smoothed. This behavior can be modeled as the convolution of the real temperature profile with the DTS impulse response. This paper presents a deconvolution algorithm developed to improve the spatial resolution of a Raman DTS system. The algorithm is based on a linear DTS model and total variation regularization. The main advantage is the ability to correctly reconstruct hot regions with dimensions down to 15 cm, which represents a resolution gain of up to six times when compared with the DTS spatial resolution of 1 m. We present simulations and experimental results demonstrating the efficacy of the proposed method.

Index ***Terms***— Optical fiber sensor, distributed temperature sensing, DTS system, DTS spatial deconvolution, total resolution, variation.

INTRODUCTION

IN THE recent years, the distributed optical sensor technology (DTS) has shown great potential for application in areas such as electrical power generation and transmission, hydrology and geology, oil and gas production, and in tunnels as fire detection systems [1]–[3]. DTS systems measure temperature through the backscattered light propagating in an optical fiber. Those optoelectronic devices provide a continuous profile of the temperature distribution along the fiber cable. The main DTS technologies are based on Raman and Brillouin scattering theory [1].

Raman DTS systems have become popular for practical applications due to its low cost and great stability when compared to equipment based on Brillouin scattering [1]. Typically, commercial Raman DTS instruments are able to provide a temperature profile along an optical fiber with over 30 km of length, with an accuracy of 0.1 °C and spatial resolution of 1 m [2]. The spatial resolution is defined as the spatial distance

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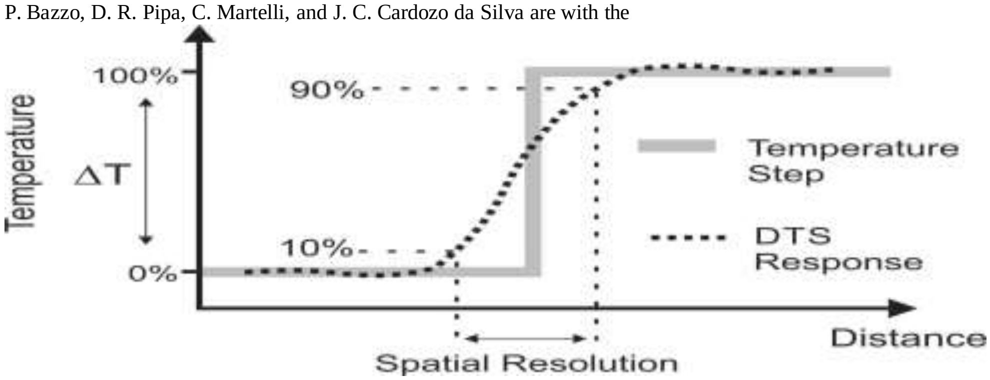


Fig. 1. Example of DTS spatial resolution defined by temperature step.

between the 10% and 90% levels of response to a temperature step, as shown in Fig. 1. In general, for a temperature profile described by a step pulse with length smaller than the spatial resolution, the measured temperature will be smaller than the real temperature by a ratio of the temperature step length and spatial resolution [2]. Thus, this characteristic can be a disadvantage of the DTS systems, and sometimes limits its use in certain applications where thermal variations occur in regions with dimensions less than 1 m [2], [3].

An alternative to the limitations of spatial resolution of Raman DTS are instruments based on Brillouin scattering. Actually, Brillouin DTS systems have shown significant improvement in spatial resolution, with values down to 10 cm. However, some disadvantages such as high cost and cross sensitivity to vibration and mechanical strains, limits its use in applications related to temperature monitoring [1].

Several studies for improvement in spatial resolution of Raman DTS systems have been presented in the litera- ture [4]–[7]. From the hardware view point, one way to improve the spatial resolution is to reduce the duration of the laser pulse. However, this implies further complications to the equipment, especially because of the low intensity of the scattered signal, and the response time of A/D converters. In the experiment presented by Thorncraft et al. [4], they showed a Raman DTS system with spatial resolution of 10 cm using laser pulses on the order of picoseconds. To achieve such spatial resolution, they used an integration time of 5 minutes, which resulted in a temperature resolution of ±5°C. These characteristics can be considered as disadvantages for appli- cations requiring fast and accurate measurements. Recently, Chen et al. [6] presented a technique using dual-channel acquisition system to a fast and accurate Raman DTS, with response time of 1 s and temperature resolution of ±1°C. The

 best results with respect to spatial resolution were approxi- mately 40 cm. One of the smallest spatial resolution achieved in Raman DTS was presented in [7]. In this work, Dyer et al. proposed the use of superconducting nanowire single-photon detectors (SNSPDs). The resulting DTS system presented a spatial resolution of 1 cm, integration time of 1 minute, and the temperature resolution was ±3 °C.

Hence the use of techniques based on more efficient optoelectronic devices have shown significant results regarding the DTS spatial resolution. However, such techniques often have a higher cost, besides other complications that prevent their use on commercial equipment, such the increase in the response time and in the uncertainty of measurement. Therefore, another alternative that is being investigated is the use of signal processing techniques [8]–[10]. These techniques have shown enhancement in DTS performance without increasing equipment costs, as this does not require physical changes in the device. An example is the work presented by Bahrampour et al. [8], which uses a Fourier Wavelet Regularized Deconvolution (ForWaRD) method to improves the signal to noise ratio of DTS system from 1 dB to 25 dB relative to the nondeconvoluted signal. Recently, Wang et al. [9] presented an improved de-noising technique based on wavelet trans-form modulus maxima (WTMM) to decrease the temperature measurement error of a Raman DTS. Similar work was presented by Saxena et al. [10] suggesting the use of discrete wavelet transform (DWT) based technique for the back scattered anti-Stokes and Stokes signals. This technique is simpler in comparison to [8], and allowed dynamic implementation. Although the methods based on wavelet transform show improvements in temperature uncertainty (about ±1 °C), they do not show significant gains with respect to spatial resolution, when compared to the use of more efficient optoelectronic devices [4]–[7]. This motivates the analysis of other signal processing methods to achieve a spatial resolution on the order of centimeters.

This paper proposes the use of a deconvolution algorithm for improving the spatial resolution of a commercial Raman DTS system. The algorithm uses a linear model for the DTS system,

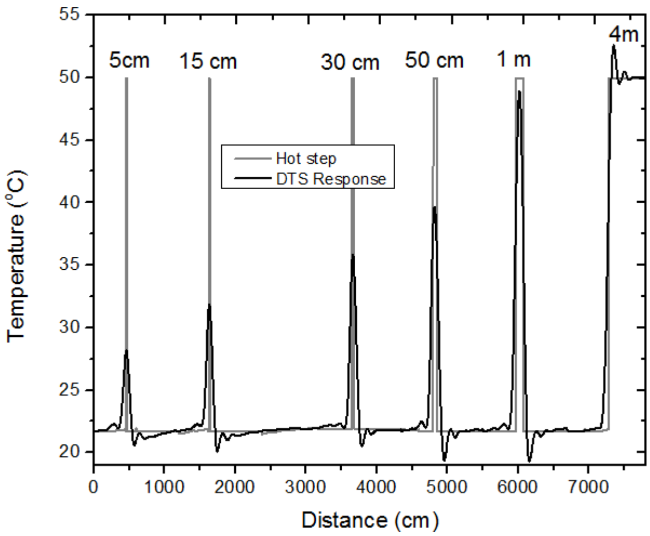


Fig. 2. Experimental results used to identify the DTS system model.

I. DTS System Model Identification

The modeling of the DTS system was based on linear system identification techniques [11]. The input $f(z)$ is the real temperature profile and the output $g(z)$ is the DTS temperature readings. As we are considering the steady-state,

i.e. no time variations, the only independent variable is z which represents the distance (cm) along the optical fiber sensor. Considering the DTS as a LTI (Linear Time-Invariant) system, the response $g(z)$ is obtained by the convolution of the DTS impulse response $h(z)$ with input $f(z)$, as shown in Eq. 1 [11]:

$$g(z) = h(z) * f(z) \quad (1)$$

By applying the Laplace transform we obtain Eq. 2:

$$G(s) = H(s)F(s) \quad (2)$$

The system identification consists in estimating the poles and zeros of a transfer function $H(s)$, as shown in Eq. 3 [11]:

which was empirically determined, and a Total Variation reconstruction approach to estimate hot regions with lengths smaller than 1 m. Unlike other methods presented in [8]–[10],

which focus on improvements in the temperature resolution, this method aims to achieve a spatial resolution on the order of centimeters, with similar results to those obtained by techniques based in optoelectronic devices. Another advantage is that the method can be applied to any commercial equip- ment, without the need to change the optoelectronic circuit. This technique can contribute to a more accurate monitoring using traditional Raman DTS systems, broadening the use of distributed sensors to other application areas without the need to replace equipment with higher-cost alternatives.

The remaining of the paper is organized in 5 sections: Section II presents the methodology used for the DTS model identification. The details of the algorithm are presented in Section III, and the results are shown in Section IV. Finally, Section V presents the main conclusions on the results obtained.

where β_i are the poles and α_i are the zeros.

The DTS system used in this works was an AP Sensing N4385B model. This model features a spatial resolution of 1 m, acquisition time of 30 s, sample interval down to 15 cm, and temperature resolution of 0.04 °C for fibers of up to 2 km. To evaluate the equipment response, an experimental test was carried out in a thermal bath LAUDA ECO RE415G model, with stabilized temperature at 50 °C, providing hot steps of different lengths. The ambient temperature was 21.7 °C. The input $f(z)$ and output $g(z)$ were obtained for hot steps at 50 °C with lengths of 5 cm, 15 cm, 30 cm, 50 cm, 1 m, and 4 m, as shown in Fig. 2.

To facilitate the estimation of $H(s)$, was employed the Matlab script *tfest*, which uses the prediction error mini- mization (PEM) approach to estimate the transfer function coefficients. In this case, from initial estimates, the parameters

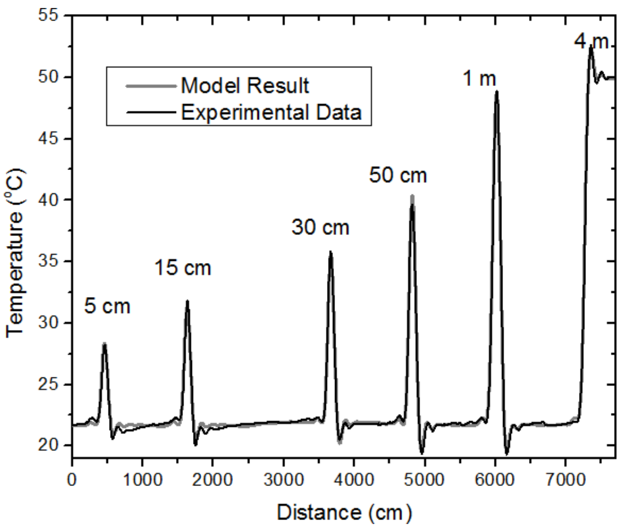


Fig. 3. Experimental results vs. estimated DTS model.

are updated using a nonlinear least-squares search method, where the objective is to minimize the weighted prediction error norm [11]. As a result, a transfer function with 9 poles and 4 zeros with 98% accuracy was obtained. The comparison between experimental data and model simulation is shown in Fig. 3. As it can be seen, there is a good match between the DTS equipment response and the model results.

Taking the inverse Laplace transform of the transfer function, the impulse response of the system $h(z)$ was found, presented in Fig. 4. The DTS impulse response $h(z)$ is used in the deconvolution algorithm, which is based on inverse problem techniques. The algorithm aims to reconstruct the original DTS response, including hot steps with lengths smaller the equipment spatial resolution. Section III presents the details of the developed algorithm.

As it can be seen in Fig. 4, the DTS "spreads" the impulse, which is a characteristic of low-pass systems. This is translated into an ill-conditioning of matrix **H**. Thus, the recovering of the temperature profile by simple inversion of Eq. 4 yields high

where $\hat{\mathbf{f}}$ is the reconstructed signal, p is the norm used in

where **g** is a vector formed by the sensor data (DTS readings), **H** is the sensitivity matrix, assembled from the DTS impulse response, **f** is a vector representing the temperature profile, and **n** is a vector representing all sources of additive white gaussian noise.

the data-fidelity term, λ is the regularization parameter which

controls the sensitivity of the solution to the noise, and **D** is a finite difference matrix.

is itself a source of noise, a statistical analysis of the residuals (histogram of $\mathbf{g}-\mathbf{Hf}$) was performed, as shown in Fig. 5 [13]. The residuals have Laplacian behavior which indicates that the L_2 norm should be replaced by an L_1 norm, i.e. we set

$p = 1$ [12], [13].

To solve Eq. 6 with $p = 1$, was used the Interactive Reweighted Least Squares (IRLS) approach. This method consists of approximating the data term $\|\mathbf{g} - \mathbf{Hf}\|_1$ and

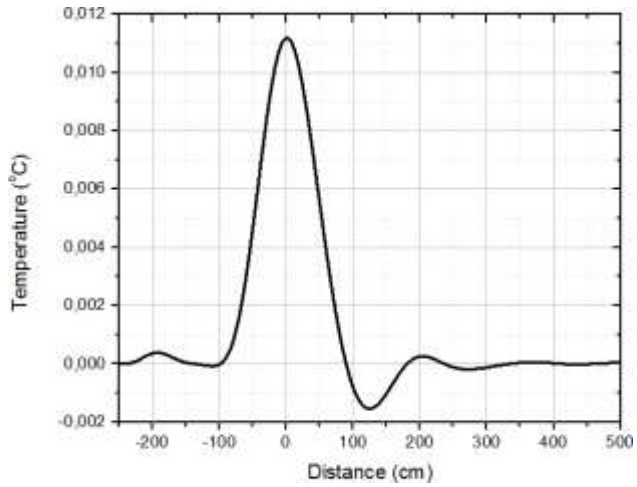
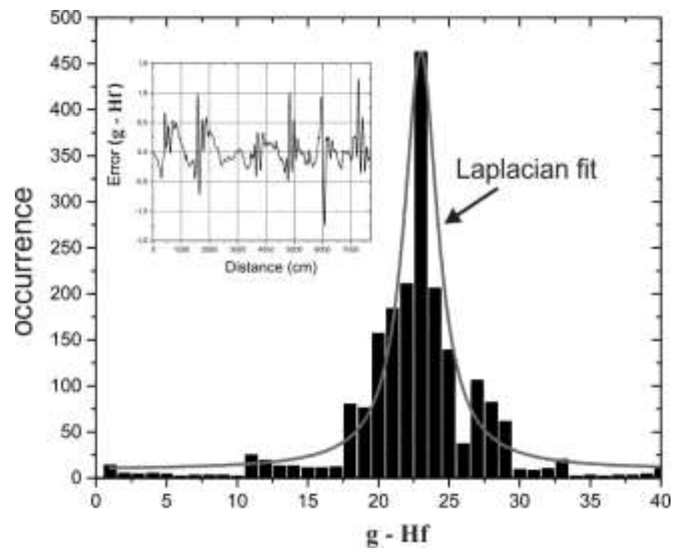


Fig. 4. Estimated DTS system impulse response $\boldsymbol{h}(\boldsymbol{z})$.



the cost function $\|\mathbf{Df}\|_1$ by weighted quadratic L_2 norms, updating

the solution by solving a least squares problem and reiterating those two steps until some stop criterion is attained, usually defined by a minimum update rate [14]. The implementation details in Matlab are shown in the Algorithm 1.

II. Results

To evaluate the performance of the iterative algorithm presented in Section III, deconvolution reconstructions using the proposed approach for real-world DTS signals acquired for different hot steps lengths was carried. For all cases, the temperature of the hot steps was 50 °C, and the environment temperature was stabilized at 22 °C. The purpose of the tests was to verify the algorithm ability to reconstruct hot steps with lengths smaller the DTS spatial resolution (1 m).

Fig. 6 shows the obtained results for a hot step with length of 1 m. It is possible to observe that even for lengths compat- ible to the spatial resolution, significant improvements in the reconstructed response was obtained. First, the reconstruction corrected a temperature error of approximately 2 °C between the real hot step and the DTS response. In addition, the reconstruction improved the estimation of the step width. This shows that the proposed algorithm can also be used to enhance measurements in hot regions above the DTS spatial resolution.

The reconstructed signal for a hot step of 30 cm is shown in Fig. 7. This result defines a minimum length to which reconstruction is possible. Temperature was correctly esti- mated (50 °C) as well as the length measured on top of the step (30 cm). Although it may be noticed a difference of approximately 15 cm in the width if measuring on the bottom of the step, this is a considerable improvement when compared to the raw response that was approximately 150 cm.

Fig. 6. Result of hot step reconstruction with 1 m length and 50 °C.

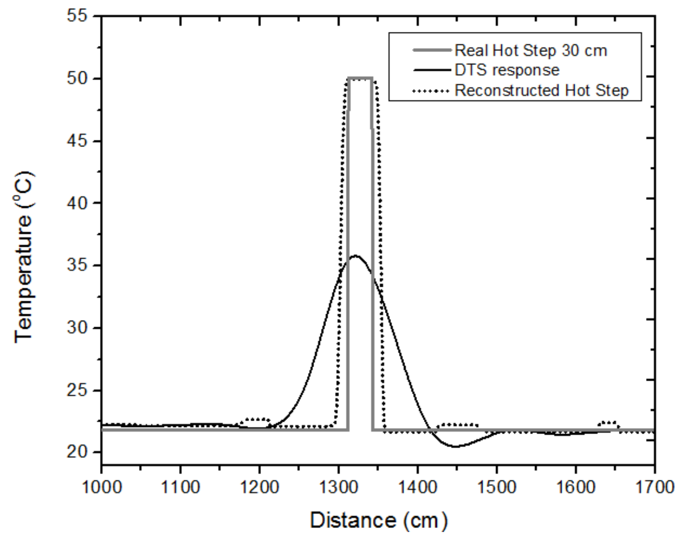
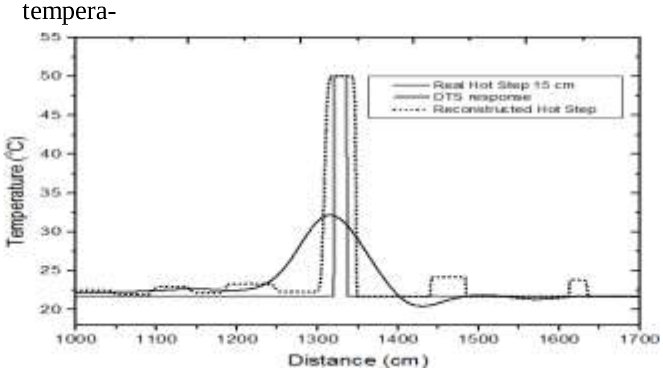


Fig. 7. Result of hot step reconstruction with 30 cm length and 50 °C.

The deconvolution of a hot step of 15 cm is shown in Fig. 8. This result shows a great improvement in the DTS response, where the temperature was estimated correctly,
i.e. 50 °C. Furthermore, the estimated length was 20 cm, which can be considered a small difference when compared to the DTS raw data that was 150 cm. Thus, the proposed algorithm corrects temperature measurements for hot regions up to 6 times smaller than the DTS spatial resolution.
Finally, Fig. 9 shows an extreme case, when trying to reconstruct a hot step of 5 cm. As it can be seen, the algorithm was able to recover only half of the temperature variation, and also failed to correctly estimate the length of the hot step. The estimated temperature was 36 °C (real temperature 50 °C) and the estimated length was 40 cm for a reference of 5 cm. Again, if compared to DTS unprocessed data (28 °C and approximately 150 cm in length), there is a significant improvement.
The results show that the proposed method based on Total Variation deconvolution can be applied to reduce the tempera-



III. CONCLUSION

This paper proposed a deconvolution algorithm to improve the spatial resolution of commercial Raman DTS systems. A linear model for the DTS system and a Total Variation reconstruction strategy to recover step-like temperature signals from raw DTS data was used.
The results show that it is possible to correctly measure temperature variations in lengths as short as 15 cm and to have significant improvements for lengths down to 5 cm. Thus, the proposed method showed similar results to those obtained by techniques that require changes in the optoelectronic circuit. The same cannot be observed in other signal processing technique based on wavelet transform. For hot steps with lengths compatible to the DTS spatial resolution (1 m), the proposed method also enhances the temperature and width measurements of the hot steps, which indicates that the algorithm may be advantageous even for those situations.
When compared to more expensive equipment, such as Brillouin system with spatial resolution on the order of 10 cm, the Total Variation deconvolution method allows similar spatial resolution performance. The proposed method can be applied to any commercial Raman DTS system, allowing the use of equipment in other application areas that require spatial resolution about 15 cm.

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