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Source Separation and Distributed Sensing: the Key for an Efficient Monitoring

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Abstract— As a complement to classical sensors, Distributed Optical Fiber Sensors now play a prominent role in several engineering fields and act as an antenna array. Depending of the devices used (Raman, Rayleigh, or Brillouin scattering), measurement record depend on temperature, strain, or pressure profile. As the wanted signal is often hidden by noise and other undesired sources, we can express the problem as a source separation problem. In this paper, we show that with the help of recent techniques based on data decomposition and source separation (PCA, ICA NMF techniques) from the virtual antenna, we can accurately identify water leakages from a noisy Raman spectra or a strain profile from Brillouin spectra with a spatial resolution of 1cm instead of 1 meter for classical devices.

I. INTRODUCTION

Distributed Optical Fiber sensors (DOFS) have been employed in diverse domains like: oil and gas industry [1] for parameter monitoring in extreme environments (temperature, pressure, viscosity, flow, etc.[2]); civil engineering for strain measurement and structural health measurement [3], fire detection (underground structures and tunnels [4]), electrical fault detection and metering [5], pollution control through chemical detectors (H₂, CO₂, explosive detectors), pipeline leakage control, etc [6], [7], [8]. The optical fiber acting as an intrinsic distributed sensor, DOFS offers numerous advantages over the conventional sensors. The possibility of multiplexing a large number of sensors on a single optical fiber and the flexibility of sensor placement are some of the unrivaled advantages. Now, fiber sensing technology can replace the legacy electronic temperature, pressure and strain gauges [9]. Given that this technology has been field-proven, new applications and services are emerging in harsh environment [10]. These new sensing applications are driven by the quest of the smallest possible changes in temperature, pressure, strain (geomechanics parameters) and the capability to monitor large sites and areas as oil reservoirs, wells, dams, industrial structures with the smallest possible spatial resolution. For instance, the durability of civil infrastructures [11], [12], or the monitoring of specific areas as oil reservoir is a crucial issue that can have major economic, social and environmental impacts. In civil engineering, many aging structures may become vulnerable due to internal erosion, climatic conditions and other natural phenomena.

Optimization of maintenance and extension of service life are difficult challenges, real-time diagnosis of the state of wear/damage of a structure representing a key procedure for monitoring. Different techniques (interferometric, polarimetric, Brillouin, Rayleigh and Raman scattering) are in development to create optoelectronic devices able to measure temperature, strain, pressure strain etc.

Using a combination of the measurement of backscattered light and advanced signal processing, an optoelectronic device called interrogator sees the optical fiber as an array of individual sensors. This array allows the detection, discrimination, and location of events over several kilometres. Using signal processing techniques, it is possible to detect and identify a specific signature (leak, strain etc) and eliminate unwanted events. In this paper, we show that advanced signal processing algorithms (subspace decomposition, source separation and non-negative matrix factorization) are necessary to extract the wanted events with high resolution over noisy data. We present two cases, the distributed temperature sensing systems for water leakage detection and the distributed Brillouin sensing systems for strain estimation.

II. ACQUISITION PRINCIPLE

The main important part of the DOFS is the sensing cable composed of several optical fibers, made in silica, wrapped into a protective coating. The interrogator launches a light pulse at a frequency ν_0 , into an optical fiber and records the backscattered light. In frequency domain, three distinct phenomena can be highlighted (Fig. 1.)

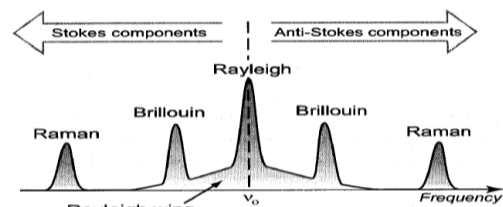


Fig. 1. Backscattering spectrum of a monochromatic wave into an optical fiber exhibiting three scattering phenomena (Rayleigh, Brillouin and Raman) depending on the temperature and/or strain into the silica.

The first one is the Rayleigh scattering: it is due to fluctuations of silica density and composition. The light

returns with the same frequency ν_0 but parts of the power, called the Rayleigh wing, have been frequency shifted. The second one, the Brillouin scattering due to photon-phonon interaction, is based on the conversion of hydrostatic pressure into distributed mechanical strain acting along a specially coated optical fiber. Measurements of distributed pressure can be thus inferred by converting the applied hydrostatic pressure into distributed mechanical strain. The Brillouin scattering is characterized by a shifted frequency spectrum in the Stokes and Anti-stokes components (see Fig. 1). Those two phenomena are both sensitive to both temperature and strain changes in the optical fiber. The third one, the Raman scattering, is also a shifted frequency spectrum caused by thermal molecular vibration and is only temperature sensitive.

III. THE DISTRIBUTED TEMPERATURE SENSING SYSTEMS CASE

The Distributed Temperature Sensing Systems (DTS) are fiber optic cables coupled with Raman scattering. Measuring the travel time and knowing the speed of light inside the fiber, the Optical Time Domain Reflectometry (OTDR) principle allows formulating the temperature as a function of distance along the fiber. Moreover, the long-range measurement capability of up to 20 km with typical spatial resolution of 1 m and temperature resolution of 0.05°C , gives a distinct edge acting as an antenna array. For dike and dam monitoring, several sites along hydraulic power stations have been equipped with DTS to check possible water leakages for French Power Company (EDF). The goal is to extract the information pertaining to leakages (both natural and controlled in our case) in the dike of canal as water leakage across the dike generates a thermal anomaly recordable by the fiber optic cable.

A. Data acquisition

In the presented study, the optical cable is buried at 1m in the dike toe. This cable lays 30 m from the canal toe and cover two kilometers (Fig. 2). This choice made owing to previous studies and suspicion of water leakages in this area [13]. The configuration presents two distinct elevation levels (Zone 1, from 0.1 km to 1.25 km and Zone 2, from 1.25 km to 2.2 km) which are differently exposed to the sunlight (i.e. they will exhibit two different thermal behaviors).

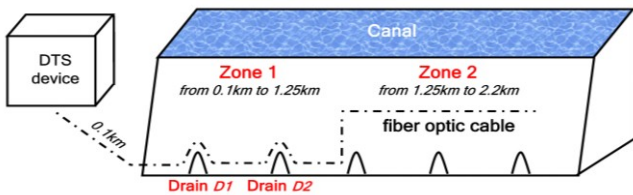


Fig. 2. Site experiment.

In its path, the optical fiber cable longitudinally circumvents two drains labeled hereafter as D1 and D2, provoke a peculiar thermal response and constitute a distinguishable type of anomaly. Along zones 1 and 2, the soil is not homogeneous. During 6 months in 2005, we recorded 12 times a day the temperature along the fiber with 1m resolution. In order to validate the acquisition system and leakage detection analysis method, on May 10th and 12th, three artificial leakages marked

L1, L2 and L3 (fig. 5), were introduced with different flow rates of 5, 1 and 1 lit/min at the positions: 1.562, 1.547 and 1.569 km, respectively (Red circle on Fig. 3). A hot point (HP) was also introduced on day 10th at 0.674 km. On Fig. 3, spring and summer seasons can be seen (blue showing lowest temperature and red the highest). We also note the behavior of rainfall expressed as line in horizontal striations.

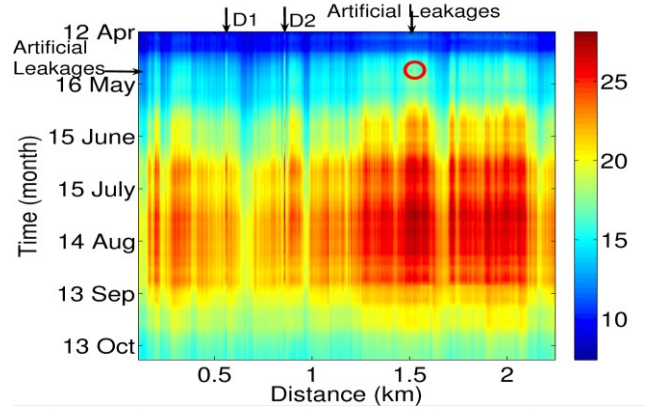


Fig. 3. Real DTS temperature dataset recorded on 6 months (2005).

The identification of the water leakages on the raw data is not straight forward, thus requiring source separation processing to extract information concerning the leakages.

B. Source separation

To go directly to the wanted signal (leakages), we remove, first, daily (24h) and seasonal effect (month) by a low pass filter and secondly, rainfall periods (hours) by a Kurtosis criteria based filter [14]. After dataset $\mathbf{D}$ can be considered as a linear mixture of independent sources expressed as: $\mathbf{D}^T = \mathbf{M}\mathbf{F}^T$, (a source separation problem) with $\mathbf{D} \in \mathbb{R}^{N_x \times N_t}$ the acquired data, $\mathbf{M} \in \mathbb{R}^{N_t \times p}$, the mixing matrix and $\mathbf{F} \in \mathbb{R}^{N_x \times p}$, the p independent sources matrix. The source separation processes used are based on Singular Value Decomposition (SVD) and Independent Component Analysis (ICA) [15-16].

The singular value decomposition of the $\mathbf{D}$ can be expressed

$$\text{as: } \mathbf{D} = \mathbf{U}_N \mathbf{\Lambda}_N \mathbf{V}_N^T = \sum_{j=1}^m \lambda_j \mathbf{u}_j \mathbf{v}_j^T + \sum_{j=m+1}^N \lambda_j \mathbf{u}_j \mathbf{v}_j^T \quad (1)$$

where $N = \min(N_t, N_x)$, $\mathbf{\Lambda}_N$ is a diagonal matrix containing the singular values $\lambda_j \geq 0$, arranged in a descending order. $\mathbf{U}_N$ and $\mathbf{V}_N$ are orthogonal matrices, containing N left and right singular vectors $\mathbf{u}_j$ and $\mathbf{v}_j$ respectively. Eq. 1 allows decomposition of data into two subspaces: $\mathbf{D}_{\text{ground}}$ (first m matrices) and $\mathbf{D}_{\text{useful}}$, containing leakages. The orthogonality condition imposed by SVD is not sufficient for separation of leakages modeled by sparse and non-Gaussian sources. A more realistic approach based on a blind decomposition (ICA), requiring no a priori information about the sources, is applied on the $\mathbf{D}_{\text{useful}}$ subspace. As sources in this context are mutually independent, we estimate them and their weights by maximizing a statistical independence criterion. Details do not fit into the scope of this paper so the interested readers can

refer to [17]. Taking $\mathbf{D}_{\text{useful}}$, ICA allows separation of leakage related subspace $\mathbf{D}_{\text{leakage}}$, from the rest of the signal, $\mathbf{D}_{\text{rest}}$, as:

$$\mathbf{D}_{\text{useful}} = \sum_{j=m+1}^{m+q} \lambda_j \mathbf{a}_j \mathbf{b}_j^T + \sum_{j=m+q+1}^{m+p} \lambda_j \mathbf{a}_j \mathbf{b}_j^T \quad (2)$$

$$= \mathbf{D}_{\text{useful}} = \mathbf{D}_{\text{leakage}} + \mathbf{D}_{\text{rest}} \quad (3)$$

where $\mathbf{b}_j$ the independent sources obtained from decorrelated ones $\mathbf{v}_j$. The important parameters are: “ m ”, the number of singular values for building ground subspace, “ q ”, the number of ICA sources to be estimated (m and q are chosen by eigenvalue decreasing studies). Signal subspace built by the first singular vector is identified as ground response (Fig. 4a) where zone1 and zone2 can be seen. A ground singularity has been also detected (specific soil on site). The first ICA source identifies clearly drains D1 and D2 (Fig. 4b) and the second ICA source gives information on leakage (Fig. 4c).

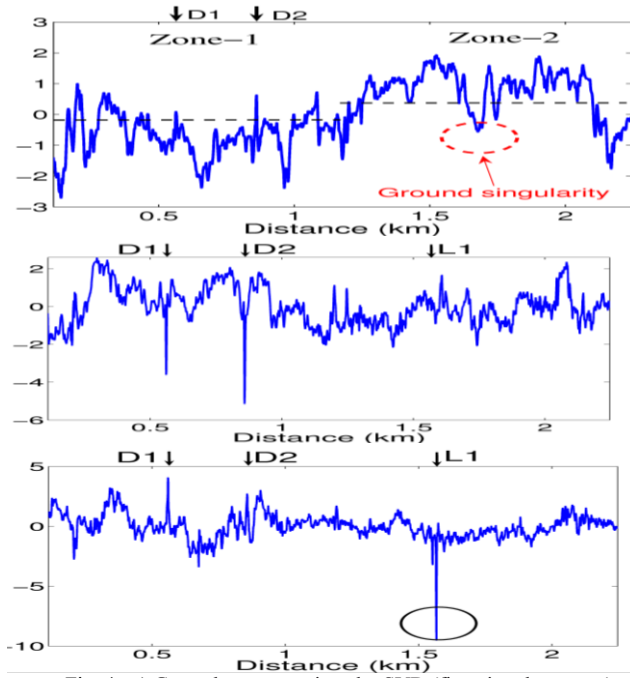


Fig. 4. a) Ground response given by SVD (first singular vector); b) Drain responses given by ICA (first independant vector); c) Leakage L1 detected by ICA (second independant vector).

In Fig. 5a, final result of the detector on distance axis is proposed. We can identify, each element as drain 1 and 2, leakages 1, 2 and 3 and hot spot. Applying same processing two years latter (2007) on the same site, we find (Fig. 5b), the existing structures (D1, D2) and some real leakages (concentrated around D2) confirmed after visual inspection.

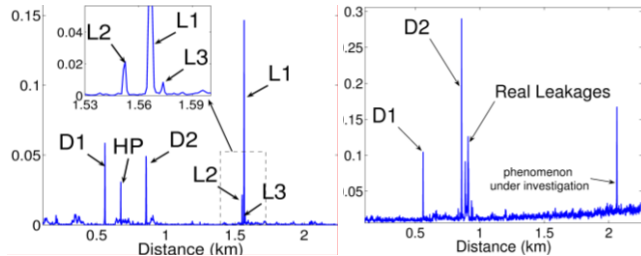


Fig. 5. a) Results on simulated leakages, b) Result on real data (2007)

IV. THE DISTRIBUTED BRILLOUIN SENSORS CASE

The Distributed Brillouin Sensor (DBS), in comparison with other sensing sensors, has the advantage of combining temperature **and** strain measurements over few meters to kilometers. This device launches two counter propagative lightwaves into the fiber, one has a fixed frequency, whereas the other is frequency-modulated. An energy transfer, called Brillouin gain, occurs when the two lightwaves encounter each other. The maximum energy transfer occurs when difference between two frequencies equals the Brillouin frequency ν_B in the optical fiber. This frequency is linearly dependent on the temperature and strain [18]. The spatial resolution w of this device is defined by the wavelength of lightwave pulse. Estimation of strain in the optical fiber is based on the determination of the Brillouin frequency, defined as the abscissa of the maximum of Brillouin spectrum and calculated by fitting Lorentzian or pseudo-Voigt curves [19]. The numerical Brillouin spectrum $G_z(\nu)$, within the spatial resolution, w , is modelled as the integral of all the elementary spectra $S_e(\nu)$ centered in the local Brillouin frequencies:

$$\tilde{G}(\nu, z_i) = \sum_{z_i-w/2}^{z_i+w/2} S_e(\nu - \nu_B(x)) dx \quad (3)$$

If local strains or loads are applied on the fiber at position z , the Brillouin spectrum is distorted [20] and several spectral components $S_e(\nu)$ appear. Their central frequencies and amplitude are related to the strains. Decomposition of a distorted Brillouin spectrum allows determining these spectral components and an estimation of a strain profile at each position z . Several unmixing techniques exist to decompose spectra. Therefore methods like nonnegative matching pursuit [21], Nonnegative Matrix Factorization (NMF) [22] can be used as a Brillouin spectrum is positive.

A. Spectral source separation

The problem can be expressed as: from three real and positive matrices, $\mathbf{M} \cong \mathbf{S}\mathbf{A}$ where $\mathbf{M} \in \mathbb{R}_+^{N_f \times N_d}$ the data, $\mathbf{S} \in \mathbb{R}_+^{N_f \times N}$ the sources and $\mathbf{A} \in \mathbb{R}_+^{N \times N_d}$ their weight and N the number of sources to estimate, the NMF technique allows to estimate $\mathbf{A}$ and $\mathbf{S}$ minimizing F [22] as: $F = \|\mathbf{M} - \mathbf{S}\mathbf{A}\|_F^2$. When strain is uniform, the Brillouin spectrum is an elementary spectrum $S_e(\nu)$. The matrix $\mathbf{S}$ is shifted versions of the elementary spectrum with a $\Delta\nu$ step. The update rules from Lee and Seung [22] are used to minimize F . To be efficient, we regularize the number of possible N sources through a sparsity criterion [23] defined as:

$$spa(\mathbf{A}_n) = \frac{\sqrt{N_d} - \left(\frac{\sum_{x=1}^{N_d} |a_{nx}|}{\sqrt{\sum_{x=1}^{N_d} |a_{nx}|^2}} \right)}{\sqrt{N_d} - 1} \quad (4)$$

So the proposed algorithm enables to find a weight vector $\mathbf{a}$ for each k^{th} Brillouin spectrum.

B. Real example

A controlled experiment has been carried out to validate our methodology. The experimental bench enables to pull the cable constantly between two fixed points (10.5m and 14m), with two measurements: 1) cable relaxed; 2) cable pulled. Output of device estimate the strain profile with a fixed rate sample distance $\Delta z = 40\text{cm}$ (Fig 6.b purple curve). By applying the proposed NMF source separation, we obtain the sparsity criteria curve along the distance (fig 6a) based on [24]. This curve highlights 2 points at $z_1 = 10.4\text{ m}$ and $z_2 = 14.2\text{ m}$ (distances with the highest strain). As we can choose our rate sample in the NMF procedure (1cm instead of 40 cm), we obtain a better resolution strain profile (fig 6b. black curve). The relative error between a reference strain and the source separation procedure is given in fig. 6c (5%).

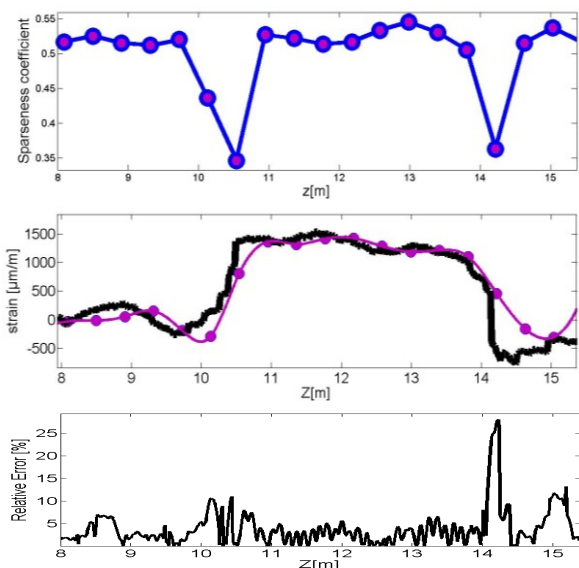


Fig. 6. a) Sparsity criteria curve along the distance (Real data)
b) Strain profile from the device (purple), from the NMF processing (black)
c) Relative error between reference and the output of NMF

V. CONCLUSION

The optical fiber sensing acts as an array and allows detection, location and discrimination of events depending on temperature and/or strain measurement over distance. Source separation processing is proposed to highlight the wanted signature. We prove by SVD-ICA and NMF algorithm on Raman based (temperature) recordings and Brillouin spectrum (strain) that leakage detection, strain profile estimation strain profile and resolution of the result are highly enhanced.

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