Acoustic emission monitoring using a polarimetric Single Mode optical fibre sensor

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Abstract: Since the hydrocarbon reservoirs in Europe are rapidly depleting, there is a need for new 'intelligent' technology for the efficient commercial exploitation of the remaining hydrocarbon reservoirs: an intelligent and high-temperature, corrosion and fatigue resistant thermoplastic composite coiled tubing. This paper describes the polarimetric Fibre Optic Sensor and accompanying advanced transient signal detection techniques for an early detection of damage in this new type of intelligent composite tubing built for drilling and exploiting hydrocarbon reservoirs. The capabilities of the new optical system for detecting growing damage are demonstrated by carrying out bending tests on short test models of the tube.

Keywords: optical fibre sensor; acoustic emission monitoring; polarimetric setup; power data transmission coil.

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1 Introduction

Fibre Optical Sensors (FOSs) are emerging for many applications. The use of FOSs for Structural Health Monitoring (SHM) is particularly interesting because of its corrosion resistance, immunity to electromagnetic interference and light-weight. For monitoring large structures with a distributing sensing system, an interesting type of FOS is the intrinsic fibre sensor where the sensing takes place in the fibre itself. Developing damage often causes high-energy, high-frequency acoustic waves. The light in the sensing fibre will be perturbed by these high-frequency pressure variations. The intrinsic optical fibre sensor can be configured as an intensity, an interferometric or a polarimetric sensor (Udd, 1991). The interferometric sensor is reported to be much more sensitive than the intensity modulated sensor (Bucaro et al., 1977), but requires a well-isolated and undisturbed reference arm, which is difficult to yield.

In this paper, a polarimetric approach is adopted. Polarimetric sensors require a simpler setup than the interferometric sensors, though, generally, a lower resolution is achieved. The polarimetric sensors will detect the perturbation of the acoustic field by monitoring the change in the State of Polarisation (SOP) of the light propagating

through the fibre. This type of sensor has been widely used to measure properties for many applications, for instance hydrostatic pressure (Frank et al., 2003), ultrasonic fields (Chan et al., 1989), weight (Liu and Chuang, 1998), damage (Ma and Asundi, 2001; Lee et al., 1997; Thursby et al., 2003), current (Lee et al., 1998) and biochemical measurements (Heideman et al., 1993).

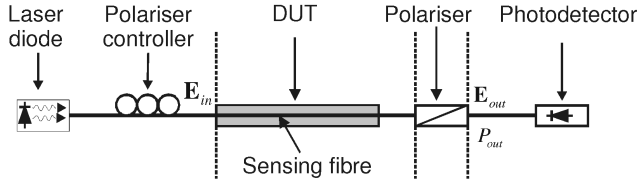
These sensors are based on the birefringence properties of SM optical fibres. For an ideal circular SM-fibre, the birefringence can be introduced in optical fibres by many physical parameters leading to optical anisotropy. This means that the two polarised optical waves that are able to propagate in an ideal SM fibre encounter different refractive indices and thus propagate at different velocities with, as a consequence, a phase shift appearing between the two polarisation eigenmodes. Since in an ordinary SM fibre the polarisation state fluctuates rapidly as the light propagates, often polarimetric sensor configurations are elaborated with Polarisation-Maintaining (PM) fibres (Chan et al., 1989; Lee et al., 1997; Heideman et al., 1993). Nevertheless, for the coiled tubing application the cheaper classical SM fibre is chosen in order that the same fibre can be shared with a parallel optical fibre system (Thévenaz et al., 1999) to monitor strain and temperature along this fibre during operating.

Thursby et al. (2003) describes a polarimetric setup for detecting Lamb waves through the measurement of the changes of SOP of an optical fibre embedded or bonded onto the plate to be tested for damage. A novel but simple method is applied. At the input of the sensing fibre a polarisation controller is positioned to optimise the SOP. At the other end of the sensing fibre a polariser and detector are installed. The working principle of this sensor relies on the phenomenon that when stress or strain is applied on a photoelastic element along a certain direction, the photoelastic element acts like a linear retarder with fast axis along that direction (Udd, 1991). Notice that, for SHM of a composite tube during a drilling operation, the optimal SOP at the input of the embedded sensing fibre changes continuously. What's more, the direction of the acoustic emission waves can not be predicted in advance and the actual SOP in the fibre at the place where the interaction with the acoustic waves occurs is unpredictable. Consequently, the polarisation controller at the beginning is redundant for this type of application.

2 The polarimetric sensor configuration

The polarimetric sensor configuration is depicted in Figure 1. Although for the considered acoustic emission monitoring application the polarisation controller is redundant, the polarisation controller is added for controlling purposes. For example, it is used to verify if the amplifiers are not saturated for some polarisation states. The working principle of the polarimetric sensor is explained below.

Figure 1 Diagram of configuration for polarimetric sensor for detection of acoustic emission events



If $\mathbf{E}_{in} = (E_x, E_y)^t$ and $\mathbf{E}_{\text{out}} = (E'_x, E'_y)^t$ represent the complex electric field vectors along two chosen arbitrary orthogonal transverse axes x and y at the input of the sensing fibre and at the output of the polariser, the Jones matrix (Jones, 1941) $\mathbf{M}_{\text{sensor}}$ is elaborated to describe the transformation of light as it propagates through the optical system:

$$\mathbf{E}_{\text{out}} = \mathbf{M}_{\text{sensor}} \mathbf{E}_{in} \tag{1}$$

It is known that an optical fibre showing both birefringence and polarisation dependent loss can be described as an optical system composed of cascaded retardation plates and partial polarisers with different principal directions. This means that the Jones matrices for the forward-lead can be expressed as Yamashita et al. (1996):

$$\mathbf{F}_F = \prod_{n=1}^{N} g_n \mathbf{R}(-\phi_n)\mathbf{C}_n \mathbf{R}(\phi_n)\mathbf{R}(-\theta_n)\mathbf{D}_n \mathbf{R}(\theta_n) \tag{2}$$

with g_n the polarisation-averaged amplitude in the nth portion of the fibre, $\mathbf{R}$ the rotation matrix

$$\mathbf{R}(\theta) = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}, \tag{3}$$

$\mathbf{C}_n$ and $\mathbf{D}_n$ the Jones matrices of the nth retardation plate and partial polariser. The latter have their principal directions in the x and y directions and can be expressed as Yamashita et al. (1996).

$$\mathbf{C}_n = \begin{pmatrix} e^{i\delta_n/2} & 0 \\ 0 & e^{-i\delta_n/2} \end{pmatrix}, \tag{4}$$

and

$$\mathbf{D}_n = \begin{pmatrix} \gamma_n & 0 \\ 0 & 1/\gamma_n \end{pmatrix}, \tag{5}$$

with δ_n the degree of retardance and γ_n the degree of polarisation dependent loss. It is hereby assumed that the changes in fibre birefringence are small during the transit time of the light.

Notice that the degree of polarisation dependent loss γ_n barely changes when the light in the fibre interacts with an acoustic wave.

Ignoring the polarisation dependent loss and using the Galilean coordinate frame, it is shown that equation (2) can be rewritten as Yamashita et al. (1996):

$$\mathbf{F}_F = g \begin{pmatrix} a & b \\ -b^* & a^* \end{pmatrix} \tag{6}$$

with

$$|a^2| + |b^2| = 1 \tag{7}$$

and where ()* denotes the complex conjugate.

The matrix in equation (6) is unitary and the complex values a, b, depending on the birefringence in the fibre, change when the acoustic wave interacts with the light beam in the optic fibre. g accounts for the fibre loss:

If the x-axis is chosen to be the transmission axis of the polariser, the Jones matrix $\mathbf{P}$ for the polariser can be written as:

$$\mathbf{P} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}. \tag{8}$$

The Jones matrix $\mathbf{M}_{\text{sensor}}$ for the complete system defined in equation (1) can be simply expressed as:

$$\mathbf{M}_{\text{sensor}} = \mathbf{P}\mathbf{F}_F. \tag{9}$$

The light intensity at the output of the polariser can now be written as:

$$\mathbf{P}_{\text{out}} = |\, g(aE_x + bE_y)\,|^2 . \tag{10}$$

It should be noted that $\mathbf{P}_{\text{out}}$ depends on the birefringence of the fibre. The output of the polariser is led to the photodetector, amplified, filtered and digitised. Advanced transient detection techniques are then applied on this signal to detect the acoustic events.

3 Transient online detection algorithm

The signal processing technique that is described in this section aims at the detection of events occurring with unknown energy, at unknown time, that might be buried in the noise. These events can be seen as bursts of short duration, modifying abruptly the signal properties or state.

The analogue filtering stage which takes place before the acquisition process aims to remove the unnecessary low frequency components (e.g., originating from mechanical movement) as well as the high frequency components which might create unwanted aliasing effects.

Nevertheless the bandlimited, digitised output signal resulting from the acquisition stage remains very noisy after this filtering process. Moreover, some noise properties[1] might be slowly varying. Consequently, the detection of transient signals cannot be achieved by only applying a simple thresholding method to the raw signal whether it is in the time or in the frequency domain. Previously, a very fast and efficient detection technique (Papy et al., 2003) has been applied to multimode sensors. Since in the present case the output signal is of the same nature, this technique achieves comparable performances when it is applied to signals issued/stemmed from the polarimetric SM setup. For sake of clarity we explain briefly the philosophy of the method as well as the mathematical background. Then we give an outline of the algorithm.

The information to be detected is related to small perturbations of the light intensity at the output of the optical fibre. This results in changes of the properties of the digitised signal. However, these artefacts are more or less visible, depending on the noise level. In order to detect these changes a segmentation of the discrete time signal and processing in the frequency domain are carried out. There are numerous motivations (Papy et al., 2003) for this choice:

- very fast processing (e.g., real-time processing)
- interpretation of the changes in the frequency components is easy
- possibility to separate the signal information from the noise
- the power-law detector achieves very good performances in the frequency domain.

Let $x[m]$, $m \in \mathbb{N}^*$ be the sampled version of the continuous time signal $x(t)$, that is expressed as follows:

$$x[m] = x(m \cdot \Delta t) \tag{11}$$

where $\Delta t \in \mathbb{R}^+$ is the sample time interval and m is called the sample time index. The sampling rate f_s is defined as the inverse of Δt. Note that we make the assumption of additive noise and therefore each element of the signal can be written as $x[m] = s[m] + n[m]$ where s denotes the signal and n the noise. We define the qth frame x_q as a vector containing L adjacent samples of $x[m]$:

$$\mathbf{x}_q = (x[qI+1] \quad x[qI+2] \quad \cdots \quad x[qI+L]) \tag{12}$$

where I is the sample shift between two frames. The index q is called the subsampled time index. An element of x_q is noted as $x_q[l]$.

In fact, the signal is represented as a fixed-size vector whose elements are changing over time. Using the windowed Fourier transform, x_q can be transformed into the frequency domain as follows:

$$X_q[k] = \sum_{l=1}^{L} x_q[l] \cdot w[l] \cdot \exp\left\{-2j\pi \frac{kl}{L}\right\} \tag{13}$$

in which $X_q[k]$ is the frequency component corresponding to the frequency bin k, whose central frequency is $w_k = 2\pi k/L$. The discrete function $w[l]$ is the so-called apodisation window. It is well known that applying an apodisation window different from a rectangular window limits the influence of the strong frequency components on their nearest neighbours. We typically use a Hanning window:

$$w[l] = \cos^2\left[\frac{\pi l}{2L}\right]. \tag{14}$$

Equation (13) is known as the windowed Short-Time Fourier Transform (STFT). Based on the computation of the STFT and Wang's power-law criterion (Wang and Willett, 2001), an efficient extended power-law detector (Papy et al., 2003) has been derived:

$$T(X_q^2[k]) = \sum_{k=1}^{K} \left(\frac{|X_q[k]|^2}{|\hat{N}_q[k]|^2} \right)^v \tag{15}$$

where $|\cdot|$ denotes the spectrum modulus, $\hat{N}_q[k]$ is the estimate of the noise spectral component in the qth frame, and v is an adjustable exponent chosen between 1.5 and 2. The key point in this detection criterion is the estimation of $|\hat{N}_q[k]|$. It was achieved using the recursive noise estimation procedure of the extended spectral subtraction

algorithm (Sovka et al., 1996). This recursive noise estimation is elaborated using an approximate Wiener filter *H*:

$$|\hat{N}_q[k]| = H_{N_{q-1}}[k] \cdot |X_q[k]| = \left(\frac{\overline{|N_{q-1}[k]|}}{\overline{|S_{q-1}[k]|} + \overline{|N_{q-1}[k]|}} \right)^{1/2} \cdot |X_q[k]| \tag{16}$$

where $\overline{|S_{q-1}[k]|}$, the smoothed estimate of the noise free signal, is expressed as follows:

$$\overline{|S_{q-1}[k]|} = |X_{q-1}[k] - \overline{|N_{q-1}[k]|}| \tag{17}$$

and $\overline{|N_{q-1}[k]|}$, the smoothed estimate of the noise spectrum, is calculated as follows:

$$|N_q[k]| = r \cdot |N_{q-1}[k]| + (1-r) \cdot |\hat{N}_q[k]| . \tag{19}$$

The coefficient r is the so-called exponential forgetting factor with $r \in [0, 1]$. In the second member of equation (17), the operation which consists in taking the absolute value is called a Full Wave Rectification (FWR). It prevents the smoothed signal components from having negative values.

Notice that the approximate Wiener filter $H_{N_q}[k]$ is a non-linear weighted function of the past spectral component $X_p[k]$, $p = 1, 2, \ldots q$. In reality, due to the weighing factor r, only a few of the past frames are really taken into account. A second remark is that $H_{N_q}[k]$ is not a causal filter.

Indeed, it is necessary to have a first guess of $\overline{|N_{q-1}[k]|}$, otherwise the recursive estimation cannot be started. There are several ways to get such estimates. For instance, a first STFT can be performed during a short silent period, which is a period in which we are sure that no event occurs. Therefore one can obtain a smoothed estimate of the noise spectrum by averaging along the frequency bins. Another method consists in roughly estimating the noise within the first frame as follows:

$$\overline{|N_1[k]|} = |X_1[k]| \cdot \alpha \tag{19}$$

with α close to 1 since there is a low probability of the presence of an event in the first frame.

Finally, an outline of the used algorithm is given.

Algorithm

1 Perform an initial guess of the noise level (19) and deduce a smoothed estimate of the clean signal (see for instance (17))

2 Start the main loop

   a Compute the instantaneous noise level estimate (16)

   b Compute the smoothed noise estimate (18)

   c Compute the smoothed signal estimate (17)

d Compute the detection criterion (15)

e Take the FFT of the next frame (13) and go to (a).

4 Integration of the optical fibre sensor into a composite tube

In this paper the capabilities of the new system to detect growing damage in the composite tube are demonstrated by carrying out bending tests on short test models of the PDT-coiled tubing.

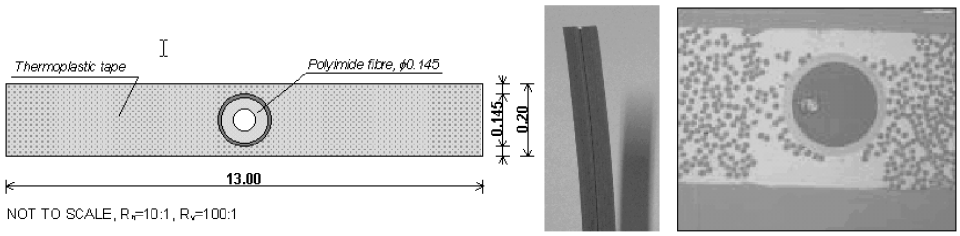
In those test models, it is crucial for the optical fibre to be embedded in such a way that there is good transmission of the acoustic pressure variations. This means that no void or porosity may exist adjacent to the fibre and no slippage occurs along the interface (Surgeon, 1999). For an easy and efficient integration of the optical fibre into the composite tube, the optical fibre is first embedded in a composite sensing tape called SMARTape.

To allow a good bonding and acoustic wave transfer, it is recommended to integrate the optical fibre within the tape in a similar manner as the reinforcing fibres integrated in the composite materials.

For the SMARTape, a glass fibre reinforced thermoplastic PPS matrix has been selected. This material has excellent mechanical and chemical resistance properties. Since its production involves heating to high temperatures (in order to melt the matrix of the composite material), it is necessary for the fibre to withstand this temperature without damage. In addition, the bonding between the optical fibre coating and the matrix has to be guaranteed. Polyimide-coated optical fibres fit these requirements and were therefore selected for this design (Glisic and Inaudi, 2003).

The typical cross-section width of the thermoplastic composite tape that is used for manufacturing composite structures is in the range of 10–20 mm, and therefore not critical for optical fibre integration. The thickness of the tape can be as low as 0.2 mm, and this dimension is more critical since the external diameter of polyimide-coated optical fibre is of 0.145 mm approximately. Hence, only less than 0.03 mm of tape material remains on top or bottom of the optical fibre, with the risk that the optical fibre will emerge from the tape. The scheme of the sensing tape cross-section, with typical dimensions, is presented in Figure 2.

Figure 2 Cross-section picture and micrograph of the sensing tape: SMARTape



The use of such sensing tape is two-fold: it can be used externally, firmly attached to the structure, or embedded between the composite laminates, playing also a structural role.

This type of sensors has been used for example to monitor the strain evolution in a pipeline installed in a landslide area in Italy and for the monitoring of the deformations of a concrete dam in Latvia.

In our experiment, the SMARTape was installed on a PPS liner using a thermoplastic winding machine. Once the SMARTape was bonded to the liner, additional layers of composite were bonded using the same type of tapes, but with no embedded optical fibre inside. Once the winding process was completed, connectors were attached at the end of the sample.

5 Experimental setup and results

The acoustic monitoring capabilities of the developed system are demonstrated by carrying out bending tests on two glass-PPS composite tubes with the embedded SMARTape. These tubes can be considered as short test models of the coiled tubing developed in the EC-project PDT-coil.

A scheme and picture of the experimental setup are depicted in Figures 3 and 4, respectively. The SM optical fibre embedded in the SMARTape is connected to a temperature-stabilised SM diode. At the other side of the tube the SM fibre is connected to a polariser and photodiode. The composite tube is installed on a test bench with a 4-point contact holder of a mounted bending rig. The output of the photodetector is amplified, filtered and digitised. A sample frequency of 1.2 MHz is used. For detection of the acoustic emission transients in the light intensity output (OF events or OF transients), the online transient detection is implemented in LABView and MATLab. The detected OF transient signal and the cumulative number of detected OF events (OF transients) vs. time are hereby displayed online. The detected OF transients are saved to hard disk and can, as such, be further analysed offline with other signal processing tools (Vandenplas et al., 2004).

Figure 3 Scheme of bending setup. Device Under Test (DUT) is glass-PPS composite tube with the embedded SMARTape

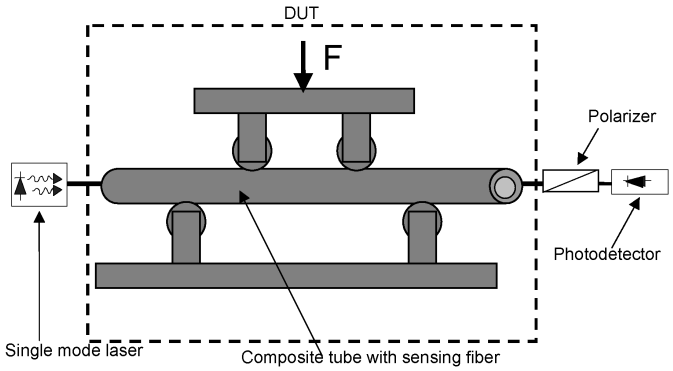


Figure 4 Picture of bending setup



During the bending test the upper contact points move downwards with a constant speed of 2 mm/min. The load vs. time curve for the first tube is depicted in Figure 5. After about 400 s the plasticity region is reached. Beyond this point, removal of the applied load leaves residual deformation and damage is initiated. In the same figure, the cumulative number of detected OF events (OF transients) vs. time is depicted. In the plasticity region, the number of detected events increases sharply, which is related to the different types of damage that occur while bending the tube beyond its elastic limit, i.e., delaminations, matrix cracking and fibre breaking. In Figure 6, as example, the 62nd detected OF transient is presented. For the second tube, the load vs. time curve and the number of detected OF events (OF transients) vs. time are depicted in Figure 7. One can see a sharp increase of cumulative number of detected OF events (OF transients) in the plasticity region after 500 s.

Figure 5 Bending test on first tube. Cumulative number of detected OF events vs. time (black curve) and load vs. time (grey curve)

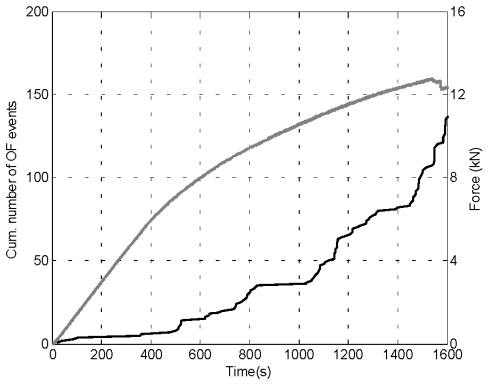


Figure 6 An example of a detected OF transient

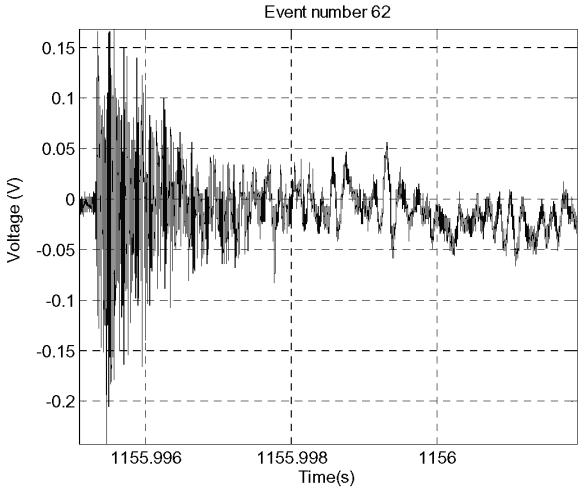
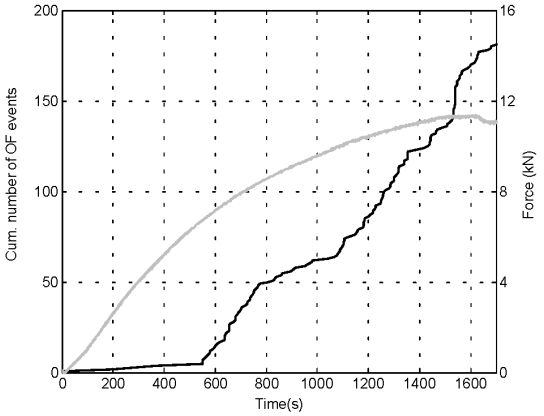


Figure 7 Bending test on second tube. Cumulative number of detected OF events vs. time (black curve) and load vs. time (grey curve)



6 Conclusions

For efficient commercial exploitation of hydrocarbon reservoirs, a thermoplastic composite coiled tubing containing embedded electrical power conductors and optical fibre SHM sensors is elaborated. This paper focuses on the acoustic emission monitoring capabilities of the in the EC PDT-coil project developed composite coiled tubing. The functioning of a simple but efficient optical fibre sensor is demonstrated on a short test model for the coiled tubing. The sensor consists of a SM optical fibre used in a polarimetric configuration. The sensing SM fibre can be shared with a parallel optical fibre system to monitor strain and temperature along the fibre during operation. It is shown that the output of the polariser depends on the birefringence in the fibre, and as such advanced transient detection techniques can be applied to detect acoustic emission events originating from developing damage. A transient online detection method able to

detect small perturbations in a slowly varying noise environment is presented to detect those acoustic emission events. The discrete time signal is therefore segmented and processed in the frequency domain. Recursive noise estimation is carried out using an approximate Wiener filter and the extended spectral subtraction algorithm. The acoustic emission events are then calculated by using an extended power-law detector. An efficient method is presented to integrate the optical fibre sensor into a composite tube. This is done by using a composite tape (SMARTape) within which the optical fibre is embedded. Such a tape can be used externally, firmly attached to the structure, or embedded between the composite layers having as such a structural role too. The acoustic monitoring capabilities of the developed system are demonstrated by carrying out a bending test on two glass-PPS composite tubes with the embedded SMARTape.

A strong increase in the cumulative number of detected acoustic emission events vs. time curve occurs when the plasticity region is reached and damage is initiated. By monitoring this curve online and analysing the OF transients, damage can be detected at an early stage. As such, appropriate action can be taken before the tube fails, which, for drilling applications, could result in serious damage. Further offline processing of the detected OF transients is possible too. Since the sensing fibre is able to sense continuously over large distances, the developed system is potentially a cheap alternative to monitor various types of large structure applications.

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Note

[1]We limit ourselves to the first order and second order statistical moments.