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Processing of transient signals from damage in CFRP composite materials monitored with embedded intensity-modulated fiber optic sensors

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Abstract

In this research study, intensity-modulated fiber optic sensors, whose working principle is based on the microbending concept, are used to monitor the damage in C/epoxy laminates during tensile loading. The use of advanced signal processing techniques based on time–frequency analysis is explained in order to get information on the damage developing in the composite. The signal Short Time Fourier Transform (STFT) has been computed and several robust noise reduction algorithms have been applied. Principally, Wiener adaptive filtering, improved spectral subtraction filtering, minimum-phase FIR (Finite Impulse Response) filtering and Singular Value Decomposition (SVD)-based filtering have been used. An energy and frequency-based detection criterion is introduced to detect transient signals that can be correlated with the Modal Acoustic Emission (MAE) results and thus damage in the composite material. Hints are that time–frequency analysis and Hankel Total Least Square (HTLS) method can also be used for damage characterisation (delamination, matrix cracking and fiber breaking).
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1. Introduction

The damage development in composite materials, which is much more complex than in metals, involves more than one damage type and can cause a degradation in the mechanical properties which jeopardizes the functionality of a composite well before final fracture. Research studies are therefore focussed on the development of tools and techniques to monitor and assess the damage development in those materials while being in use. Thanks to the development of optical fibre communication technologies and the evolution in computer technology, new testing methods emerged. With optical fibres embedded in composite materials and advanced data processing techniques of the optical signals, a Non-Destructive Testing (NDT) system can be integrated into this complex material. In this approach fibre optic sensors may offer an alternative for the robust piezoelectric transducers used for Acoustic Emission (AE) monitoring.

Several kinds of optical fibre sensors have been developed, namely intensity-modulated sensors, phase-modulated sensors (interferometers), and Bragg grating sensors. The Michelson, Mach-Zenhder and Fabry-Perot interferometers are the most widely used configurations for phase-measuring of physical quantities like strain and temperature ([18,22]).

Intensity-modulated sensors detect variations in the intensity of the transmitted light caused by a perturbing environment. The main causes for intensity modulation are transmission, reflection and microbending. Intensity-modulated optical fibre sensors require only a low cost, simple and robust sensing system. The major limitation for these sensors is that any intensity fluctuation in the output not associated with the measurand produces erroneous results, so their repeatability and overall accuracy is not very high. The first intensity-modulated sensors developed, used the microbending concept to detect pressure, acceleration, displacement, temperature and strain ([1–3]). Several intensity-modulated sensors have been successfully used to measure damage but they usually rely on the optical fibre fracture ([4,5]).

In this study it will be shown that the optical signal, collected from an intensity-modulated sensor based on the microbending concept, contains information on the elastic energy and hence strain released whenever suddenly damage is being introduced in the host material. Advanced filtering and signal processing techniques are applied to obtain these results, which are compared with those obtained from an AE monitoring system.

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2. Principle of operation

Bending an optical fiber locally reduces the critical reflection angle and thus a small amount of light leaks in the cladding. For a curvature radius in the order of centimeters this is called macrobending. Microbending is related to a curvature radius in the order of micrometers. Microbends are axial fiber distortions having spatial wavelengths small enough to cause coupling between propagating and radiation modes (leaky modes).

Damage created in composite materials also produces mechanical waves propagating in the material. When a wave hits an optical fiber, the wave displacement bends it locally and so some coupling between propagating and radiation modes may appear. So, transient features in the measured optical signal could be related to stress waves released by matrix cracking, delamination or reinforcing fibers fracture phenomena. To reveal this, signal analysis tools such as filtering (denoising), time analysis and time–frequency analysis have to be used.

3. Materials and experimental set-up

Laminates were produced from a Vicotex carbon–epoxy prepreg. The prepreg was cut and stacked into a $[0^{\circ}_2, 90^{\circ}_4]_s$ lay-up. Two multimode optical fibers were embedded 60 mm apart in the 90° direction, in the middle plane of the specimen. A polymeric bore tube was put around the optical fibers at their exit point from the composite specimen. It shrank around the fiber during the cure and so protected this weak point. The tested specimens had a length of 150 mm, a width of 25 mm and a thickness of 1.2 mm. The gauge length of the sensor was 10 mm (see Fig. 1).

Tensile tests were carried out on the 4505 Instron testing machine with a 100 kN loadcell to introduce damage in the composite. Aluminium end tabs were bonded to the specimens to prevent grip damage, using a two components Araldite 2011 epoxy glue. The load was applied continuously and the tensile machine was operating at a displacement rate of 0.5 mm/min.

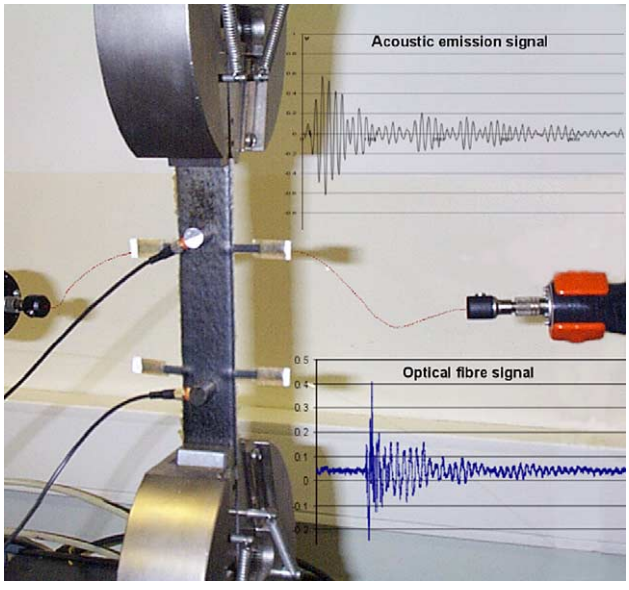

Fig. 1. Photograph of instrumented specimen in tensile test machine.

A 10 mW HeNe laser has been used as light source. A beamsplitter has been used to connect both optical fibers. The optical fiber core diameter was 100 μm, the cladding diameter was 110 μm and the coating diameter was 125 μm. The optical fiber has been chosen to maximise the microbending and the injected light intensity. The polyimide coating maximised the strain/stress transfer from the composite material to the optical fiber and minimised the influence of the optical fiber embedment ([6–9]). The small diameter difference between the core and the cladding increased the loss of light due to bending. Great care was also taken with the different optical connections to try to maximise the Signal to Noise Ratio (SNR).

The optical signal was collected in a photodiode, further amplified and then sent to an oscilloscope card with a 12 bits A/D Converter. A Labview® program has been developed to control the acquisition card and the data collection. An Ac-coupled amplifier was also designed. Basically, it is a first order High Pass (HP) filter with a 1.6 Hz cut-off frequency and an amplifier with a gain equal to 10. For each optical fiber, the output and the Ac-coupled output optical signals are collected. The Sampling Rate (SR) was set to 10 kHz.

To detect and identify damage in the composite material specimens an AE system has been used (Wave Explorer® from Digital Wave Corporation) with broadband sensors B1025 with a nearly flat frequency response in the 50–3000 kHz frequency range.

4. Testing and signal analysis

4.1. Testing and data acquisition

Tensile tests were performed on 10 composite material specimens. A fourth order minimum-phase Low Pass (LP) Butterworth filter was applied (with a 5 Hz cut-off frequency) on the measured optical signal. A typical loading curve from the tensile machine (upper curve) and the corresponding filtered optical attenuation curve (middle curve) are shown in Fig. 2. Events detected by the MAE system are also illustrated in the figure (lower curve). The test can be separated in several parts (a–e).

At the beginning of the test (part b) the stress is uniformly distributed in the sample. Next, the first types of damage appear, namely transverse matrix cracking and delamination, in and around the 90° plies. With the increasing damage, the stress is more and more sustained by the 0° plies. So, close to the optical fiber in the 90° plies, the stress is not increasing any more and some stress relief may even appear. When the Characteristic Damage State (CDS), i.e. a saturation of the transverse matrix cracks, is obtained nearly

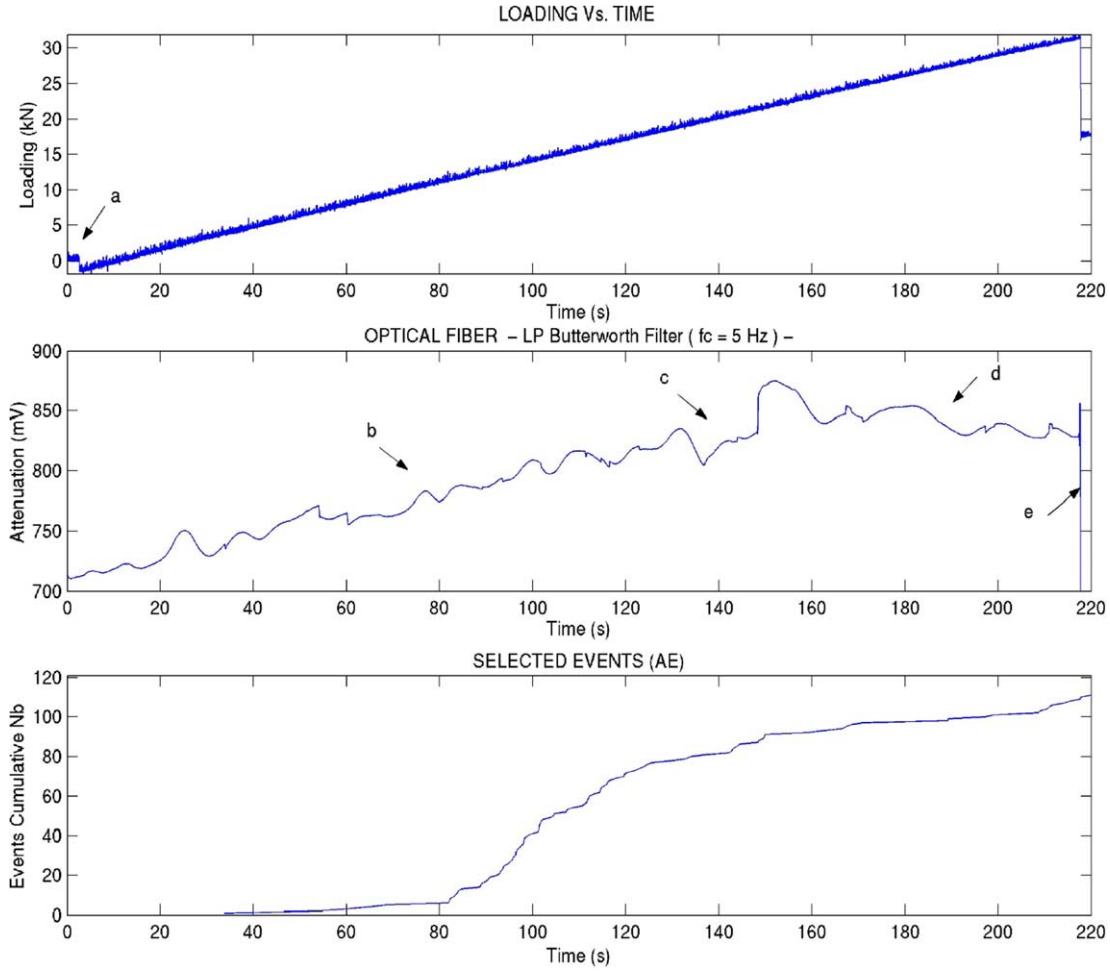

Fig. 2. The loading (upper), the measured optical signal (middle) and the cumulative number of MAE events (lower).

all the stress is carried by the 0° plies. It explains why after 132 s the optical signal does not follow the loading curve. This is also corroborated by the MAE results. The cumulative number of AE events has been plotted (with the very low energy events being filtered out). The shape of the curve is quite typical and it shows that some substantial damage has occurred (and very probably the CDS is obtained) before 132 s.

A close look at the optical signal shows some particularities as illustrated by Fig. 3.

The upper curve shows the attenuation signal whereas the lower curve displays the optical signal filtered by the same LP Butterworth filter (but with a 25 Hz cut-off frequency). The occurrence of this transient feature is correlated with the occurrence of a MAE event (the vertical dotted line) that can be related to damage. So this feature can be related to damage as well. This optical event (i.e. transient detected in the optical signal) is clearly the sum of a step and a high frequency transient feature. The main limitation is the sensitivity; the events detected by this very simple method are only the most energetic ones ([10]). So more advanced noise reduction and signal processing methods are required to proceed further.

4.2. The numerical postprocessing of the optical signals

Several steps were taken to increase the SNR and to look for small transient features in the optical signal. A hardware filter has been designed and several numerical filters were implemented in software (using Matlab®). There is a high static (DC) component in the measured optical signal, therefore a home-made first order analog HP filter has been designed. The cut-off frequency is 1.6 Hz. As the signal is also amplified (by a factor of 10), this kind of system is typically referred as an Ac-coupled amplifier circuit. To further filter the static component, several standard FIR and IIR filters were tested. Finally, a third order minimum-phase Chebyshev HP filter has been chosen (with a 50 Hz cut-off frequency) for its slightly better frequency behaviour.

One of the main noise sources was found to be the laser power supply. It appears in the frequency domain as a high component at 50 Hz and its harmonics at 100, 150 Hz, etc… in the measured signal. A two taps adaptive filter, based on Wiener theory and the Least Mean Squares (LMS) method, was used to remove this noise ([11]). This kind of filter is very efficient to remove specific frequencies but the algorithm is quite consuming in terms of computation

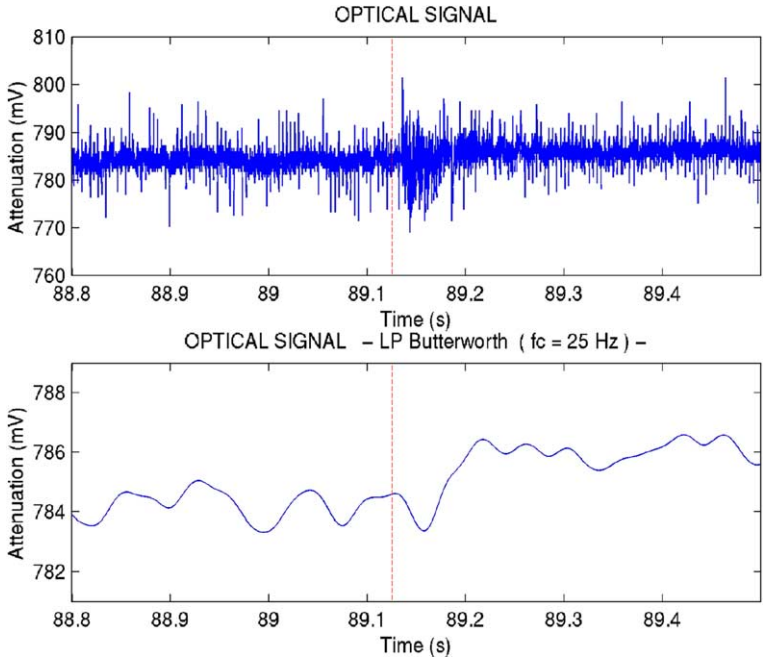

Fig. 3. The measured optical signal (upper) and the filtered optical signal (lower).

time. Therefore, since this noise above 250 Hz was small enough, the filtering was stopped at this frequency. Next, an improved spectral subtraction method has been applied. The spectral subtraction is a filtering technique that has been developed by Boll for speech processing ([12]). It is assumed that significant noise reduction is possible by removing the effect of noise from the magnitude spectrum only. The noise is estimated in a window of the signal just before an interesting transient. To overcome this limitation, an improved version of the spectral subtraction method has been used ([13]). The noise estimate is computed at each time frame using an adaptive Wiener filter. The main requirements are that the useful signal and the noise are uncorrelated and that changes in the optical signal due to noise are slower than the ones due to damage. This technique happens to be quite fast and robust.

An example of the application of the filtering techniques is given by Fig. 4. The Ac-coupled amplifier first filters

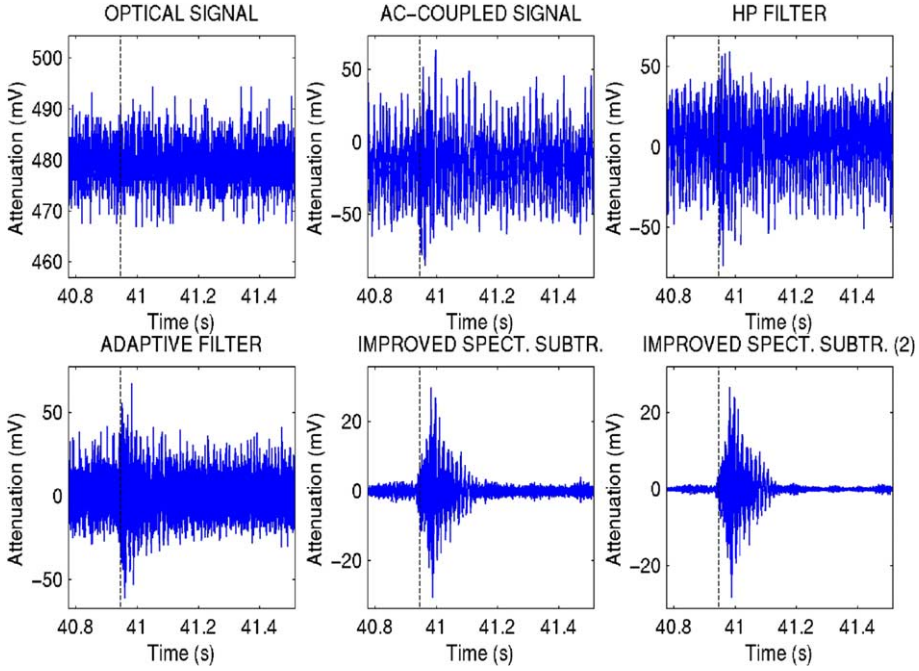

Fig. 4. The different filtering techniques that are applied on the optical signal to detect a pencil lead break.

the optical signal. Both signals are then digitised and are displayed in the upper row (left and middle) of the figure. Then the Ac-coupled signal is filtered by the Chebyshev HP filter (upper right curve), the resulting signal is filtered by the adaptive filter (lower left curve). Then the improved spectral subtraction filter is applied twice (lower middle and right curves). During the time period displayed by the figure, a pencil lead break test had been performed and its occurrence is pinpointed by the vertical dotted line. The SNR improvement is significant, mostly due to the improved spectral subtraction filter. Applying it twice increases slightly the SNR at the expense of a slight increase in computation time.

After the application of these filters, the main source of fluctuations in the optical signal is some noise with a time-varying frequency content ([10]). The source of this non-linear phenomenon is most probably the laser. These fluctuations appear in the time domain as transient features on the signal. Studies are going on to filter this noise but other robust signal processing methods can also be used to distinguish between damage related events and false detections.

4.3. Damage detection

A detection method based on energy tracking has been developed ([10]). Basically, a smooth estimate of the energy is compared to the instantaneous energy estimate. Based on their ratio, a decision factor is calculated during a training period (i.e. a sequence where there is no event, typically a few seconds at the very beginning of the test). This method is quite robust if the noise does not evolve too much during a test. The improved spectral subtraction computes and also uses these energy estimates. So, the additional computation cost of this method is quite low. This method does not require setting a threshold that would depend of the overall light intensity, the decision factor is automatically computed from the statistical properties of the noise in the signal.

Additionally, the Hankel Total Least Squares (HTLS) method has been used ([14]). This very robust method is used to filter data that are arranged in an Hankel matrix. The algorithm uses the Singular Value Decomposition (SVD) ([15,16]) and the Total Least Squares (TLS) ([17]) methods to estimate the parameters of a damped exponential model. So every detected event is modelled as a sum (up to a chosen order K) of damped exponentials and the related parameters (frequencies, damping coefficients, amplitudes and phases) are obtained with a very good accuracy. The method can be used on complex or real signals. Then a classification of the detected transients has been attempted to separate false detections and correct events. The results of this classification have been correlated with the MAE results.

The detection method has been evaluated first on pencil lead break tests performed at several locations on a composite specimen. For the pencil lead break tests a good sorting out of the good and false detections could be obtained (Fig. 5). After the HTLS computation, it appears clearly that some transients have common features such as three particular frequency bands (around 840, 1055 and 1290 Hz). Correlation with MAE indicated that these events correspond to the pencil lead breaks while the other events are false detections.

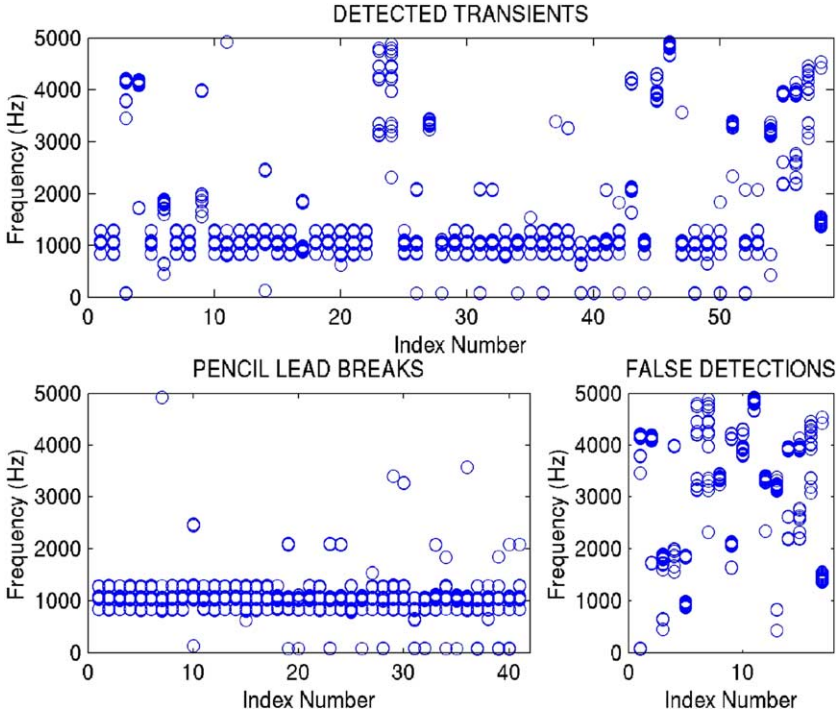

Fig. 5. The frequency content (HTLS) of the detected transients.

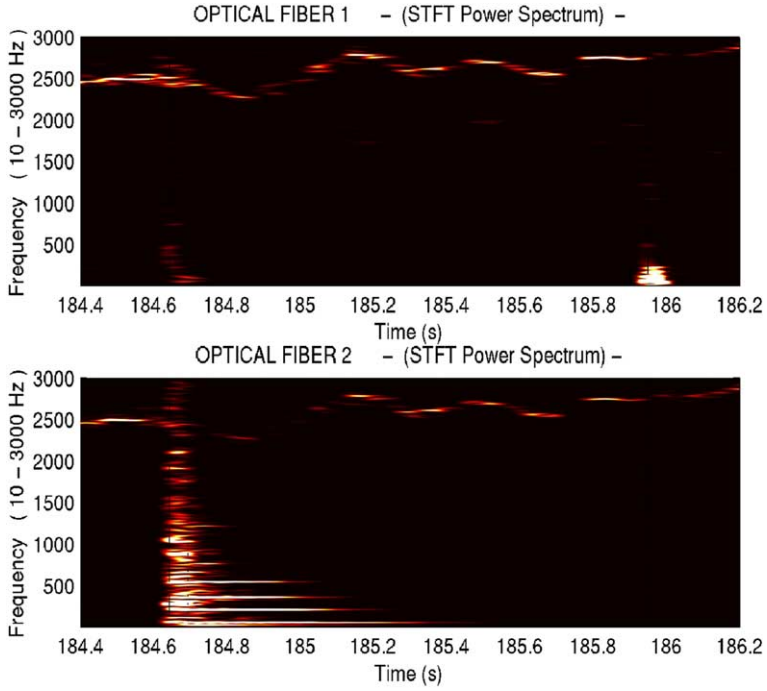

Fig. 6. The STFT analysis.

The method has also been applied on detected events from the tensile tests but the results are not conclusive yet. The frequency content of damage events is quite widespread and so more advanced methods are required to separate events and false detection. Statistical methods or neural networks may be of use to solve this problem.

4.3.1. Time–frequency analysis (STFT) and damage identification

The STFT can be applied on the filtered signal or after the application of the HTLS on the reconstructed signal. Since the pencil lead breaks were performed on the surface of the sample, the predominant mode in these tests should be the flexural mode whereas during tensile tests both modes should be present with relative magnitudes depending on the type of damage that produced the wave. It appears that most of the frequency content that can be identified with the STFT is from the flexural mode. The extensional mode appears at higher frequencies where the level of noise makes it more difficult to identify. The so-called optical events can be clearly localised and characterised in the time domain and in the frequency domain, but no final conclusive results can be produced so far to correlate the wave packages with the type of damage. An example of a damage related event is illustrated in the time–frequency domain by Fig. 6.

5. Conclusion

It has been shown that an intensity-modulated optical sensor based on the microbending concept can be used for continuous damage monitoring. Its sensitivity is less than those of interferometers but it is simple and robust. It requires some advanced signal analysis tools like adaptive filtering, spectral subtraction filtering, exponential data modelling (HTLS) and time–frequency analysis (STFT). Correlation methods between several embedded fibers (or between an embedded fiber and a reference fiber) and frequencies tracking methods are currently under study to enhance the system and more especially when the time-varying frequency content of the noise is in the same frequency range as the damage related events.

The principle has been proven to work. The sensor can detect damage initiation and characterise its frequency content. The similarities between optical and MAE signals and the use of time–frequency analysis (STFT or wavelets for better resolution) should permit damage identification.

Acknowledgements

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