Fibre optic sensor for continuous health monitoring in CFRP composite materials

Laurent Rippert [a]*, Jean-Michel Papy [b]**, Martine Wevers [a]*, Sabine Van Huffel [b]**
Katholieke Universiteit Leuven, [a] Department MTM, Research Group MP&NDT,
and [b] Department ESAT, Division SCD-SISTA

ABSTRACT

An intensity modulated sensor, based on the microbending concept, has been incorporated in laminates produced from a C/epoxy prepreg. Pencil lead break tests (Hsu-Neilsen sources) and tensile tests have been performed on this material. In this research study, fibre optic sensors will be proven to offer an alternative for the robust piezoelectric transducers used for Acoustic Emission (AE) monitoring. The main emphasis has been put on the use of advanced signal processing techniques based on time-frequency analysis. The signal Short Time Fourier Transform (STFT) has been computed and several robust noise reduction algorithms, such as Wiener adaptive filtering, improved spectral subtraction filtering, and Singular Value Decomposition (SVD) -based filtering, have been applied. An energy and frequency -based detection criterion is put forward to detect transient signals that can be correlated with Modal Acoustic Emission (MAE) results and thus damage in the composite material. There is a strong indication that time-frequency analysis and the Hankel Total Least Squares (HTLS) method can also be used for damage characterisation. This study shows that the signal from a quite simple microbend optical sensor contains information on the elastic energy released whenever damage is being introduced in the host material by mechanical loading. Robust algorithms can be used to retrieve and analyse this information.

Keywords: health monitoring, composite material, fibre optic, acoustic emission, time-frequency analysis, noise reduction, STFT, SVD, HTLS

1. INTRODUCTION

In comparison with metals the main advantage of composite materials lies in their high mechanical properties for a significantly lower density. But their mechanical behaviour and in particular the fracture mechanisms involved are quite complex. Research studies are still required before they can be used at their maximum efficiency. 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.

Indeed fibre optic sensors have several advantages compared to the electronically based sensors like piezoceramics such as all passive configurations, low power utilisation, immunity to electromagnetic interference, compatibility with optical data transmission and processing. The difficulties to overcome in obtaining reliable data are the embedding procedure of the optical fibre (influence on the host material properties and connections with the outside world) and the complex signal processing.

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-modulated sensors. They have been successfully used for acoustic

* Laurent.Rippert@mtm.kuleuven.ac.be; Martine.Wevers@mtm.kuleuven.ac.be; phone (+32) 016 32 12 45; fax (+32) 016 32 19 90; http://www.mtm.kuleuven.ac.be; Katholieke Universiteit Leuven, Faculty of Applied Sciences, Department of Metallurgy and Materials Engineering (MTM), Kasteelpark Arenberg 44, 3001 Heverlee (Leuven), Belgium
** jmpapy@esat.kuleuven.ac.be; Sabine.VanHuffel@esat.kuleuven.ac.be; phone (+32) 016 32 17 08; fax (+32) 016 32 19 70; http://www.esat.kuleuven.ac.be; Katholieke Universiteit Leuven, Faculty of Applied Sciences, Department of Electrical Engineering (ESAT-SCD-SISTA), Kasteelpark Arenberg 10, 3001 Heverlee (Leuven), Belgium

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wave detection [1, 2, 3, 4] and damage detection in various materials and in particular composite materials [1, 5, 6]. Phase-modulated sensors are usually very sensitive but also very complex and fragile. Main applications for Bragg grating sensors are found in civil engineering with very accurate measuring of physical quantities like strain and temperature.
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 [7, 8, 9, 10]. Several intensity-modulated sensors have been successfully used to measure damage but they usually rely on the optical fibre fracture [11, 12].
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.

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 curvature radius in the order of centimeters this is called macrobending. Microbending is related to 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).
Microbending is typically caused by defects in the optical fiber, but it has been proven [13] that small geometrical perturbations can also produce some microbending. ***Figure 1*** illustrates the microbending concept. The transducer used to bend the optical fiber can be a mechanical component such as a wire wrapped around the fiber. It is also possible to use a microbending sensitive optical fiber embedded in a material with random or nearly random perturbations such as the reinforcing fibers in a composite material. The amount of intensity loss depends on the amount of bending and thus on the amount of displacement.
This method can be used to measure, for instance, the strain field in a composite material but it is now well known that microbender sensors are not accurate enough for precise stress measurements. Nevertheless, this concept can find other applications such as damage detection in composite materials. The stress field in a damaged layer is not the same as in an undamaged layer and this may cause the optical fiber to bend in the material [14]. This concept can be explored to correlate it with the onset of the different kinds of damage.
Damage created in composite materials can also be characterised by 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. This paper will focus mainly on the signal analysis tools.

3. EXPERIMENTAL

Laminates were produced from a VICOTEX carbon-epoxy prepreg. The prepreg was cut and stacked into a $[0_2°, 90_4°]_s$ 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.
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.
A 10 mW HeNe laser has been used as light source. A beamsplitter has been used to connect both optical fibers. In

some cases, one optical fiber had been damaged during the sample fabrication and so only one optical fiber was connected. 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 [15, 16, 17, 18]. 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 fiber that has been used is very fragile and thus requires some handling precautions especially if it is to be used for field applications.

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. The optical signal post-processing was performed on a workstation using MATLAB® software, in particular the Signal Processing Toolbox. A program was written to denoise the signal and detect transient features. Additional tools were developed to extract damage related information from the time-frequency analysis.

To detect and identify damage in the composite material specimens an AE system has been used (WAVE EXPLORER® from DIGITAL WAVE CORPORATION). It requires broadband sensors with a nearly flat frequency response in the 50–3000 kHz frequency range. This AE technique is called Modal Acoustic Emission (MAE) [19, 20] because it uses the plate wave theory as a theoretical background and analyses the waves according to their mechanical nature, namely extensional and flexural waves. The MAE technique allows a more convenient way to identify the damage mode by looking at the frequency content of the acoustic waves produced by the damage. The presence and relative importance of extensional and flexural modes is the key to the damage mode characterisation. According to M. Surgeon [14, 21], who tested carbon-epoxy laminates of the same kind and thickness, a flexural mode is typically found below 140 kHz and an extensional mode between 400–800 kHz. This method has been proven to work in an efficient way for matrix cracking and fiber fracture. It also allows for a clear recognition of grip noise and EMI.

4. RESULTS AND DISCUSSION

4.1 Tensile tests: global analysis and first results

Tensile tests were performed on ten 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. Several standard Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filters have been tested and this one produced the best results in term of frequency response and signal quality. A typical loading curve from the tensile machine (upper curve) and the corresponding filtered optical attenuation curve (middle curve) are shown in ***Figure 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).

a - *From 0 to 2.5 seconds:* the load is not yet applied and the optical curve is constant.

b - *From 2.5 to 132 seconds:* the attenuation increases linearly when the loading increases and so can be directly related to the loading curve. A low frequency oscillation can be seen on the curve and is caused by vibrations from the tensile machine. It is difficult to filter it without reshaping too much the signal.

c - *From 132 to 159 seconds:* the optical signal is quite erratic. It is a transition part. In most tests, there is a dip in the attenuation curve at the beginning of this part.

d - *From 159 to 217 seconds:* the attenuation is slightly decreasing (in some other tests, it is approximately constant).

e - *After 217 seconds:* close to the final fracture, this part won't be analysed here.

At the beginning of the test (part b) the stress is uniformly distributed in the sample. The first types of damage to appear, transverse matrix cracking and delamination, occur in 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 all the stress is carried by the 0° plies. It explains why after 132 seconds 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

seconds. Some studies are still going on to check more precisely the occurrence of the different kind of AE events related to delamination, matrix cracking and fiber breaking and will be addressed in another publication.

A close look at the optical signal shows some particularities as illustrated by ***figure 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 [22]. So more advanced noise reduction and signal processing methods are required to proceed further.

4.2 Noise reduction

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 Hz, 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 [23]. This kind of filter is very efficient to remove specific frequencies but the algorithm is quite consuming in terms of computation 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 S.F. Boll for speech processing [24]. It is assumed that significant noise reduction is possible by removing the effect of noise from the magnitude spectrum only. The noise is estimated just before that an interesting transient is expected. To overcome this limitation, an improved version of the spectral subtraction method has been used [25]. 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 those due to damage. This technique happens to be quite fast and robust.

An example of the application of the filtering techniques is given by ***figure 4***. The AC-coupled amplifier first filters 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 [26]. 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. This is illustrated in ***figure 5***. The upper curve shows the filtered signal in the time domain and the lower curve shows it in the time-frequency domain (STFT). 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 in a previous research study [26]. 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 [27]. This very robust method is used to filter data that are arranged in an Hankel matrix. The algorithm uses the Singular Value Decomposition (SVD) [28, 29] and the Total Least Squares (TLS) [30] 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.
Figure 6 illustrates results that are obtained with the HTLS method. The upper left curve displays a transient produced by a pencil lead break on the surface of the sample. The model parameters have been computed with K equals 200 (i.e. 200 quadruplets of parameters). Since the signal is real only the 100 quadruplets corresponding to positive frequencies values have been kept and then the signal have been reconstructed (lower left curve). The relative error between the original signal and the reconstructed one can be evaluated as given by ***equation 1*** where E_0 and E_{HTLS} are respectively the energy estimates of the original and the reconstructed signals. The right curve in the figure displays the model accuracy in function of K for the pencil lead break test. Computations with the HTLS method can be quite time consuming for high order values. The order 200 corresponds to less than 1% of error. One of the main advantages of this application of the HTLS method is a very important data reduction. The information of interest that was, for instance, captured in 5000 samples (half a second of signal with SR equals to 10 Hz) is now found in 400 values (for a real signal and K equals to 200). This allows further processing on small amounts of data. Moreover, a model of the transient is obtained with a very good accuracy. For instance the frequency accuracy is typically lower than 1 Hz (0.1 Hz or better can be obtained) [27, 30].

$$\Delta E_r = 100 * \frac{E_0 - E_{HTLS}}{E_0} \tag{1}$$

The detection method has been evaluated on several tensile tests and first on pencil lead break tests performed at several locations on a composite specimen. The quadruplets have been sorted by increasing amplitudes and only the 20 quadruplets corresponding to the highest amplitudes have been kept. It would have been possible to directly compute only 20 quadruplets (K equals to 40), it would have been faster in terms of computation time but at the expense of the precision on the results.
For instance, 41 pencil lead breaks have been performed during a test. The detection method detects 58 transients that are illustrated in ***figure 7*** (upper plot). After the HTLS computation, it appears clearly that some transients have common features such as three particular frequency bands (around 840 Hz, 1055 Hz and 1290 Hz). Correlation with MAE shows these events (illustrated on the second plot on the figure) correspond to the pencil lead breaks while the other events (illustrated on the lower right plot on the figure) are false detections.
The HTLS model has been applied to 171 pencil lead breaks performed at different locations on a sample. The parameters are displayed in ***figure 8*** versus the distance between the optical fiber and the pencil lead breaks. No effect of the location could be measured on the parameters. This is not too surprising since the maximum distance tested is 50 mm and that the SR is only 10 kHz. This might not be enough to detect modal dispersion or high frequencies attenuation. Three frequency bands are clearly seen, their values are found to be slightly different for different samples but they are in the same frequency domain (between 700 Hz and 1400 Hz).
Figure 9 and ***figure 10*** display respectively the histograms of the HTLS parameters for 171 pencil lead breaks and 17 false detections. It is found that the phase distribution is nearly flat and that the damping coefficients distribution is close to a gaussian distribution. The frequency distribution of the false detections is very different from the frequency distribution of the pencil lead breaks: most of their frequency content is above 2 kHz and it is more randomly distributed. It is thus shown that the HTLS method can be used to decrease the number of false detections.
The method has also been applied on tensile tests but the results are not conclusive yet. The frequency content of damage related 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.

4.4 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 [21]. 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 damage related events is illustrated in the time-frequency domain by ***figure 11***.

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.

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FIGURES

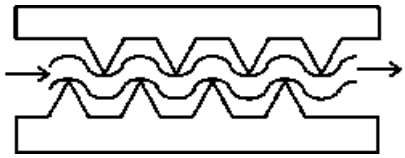


Figure 1: *The microbending concept.*

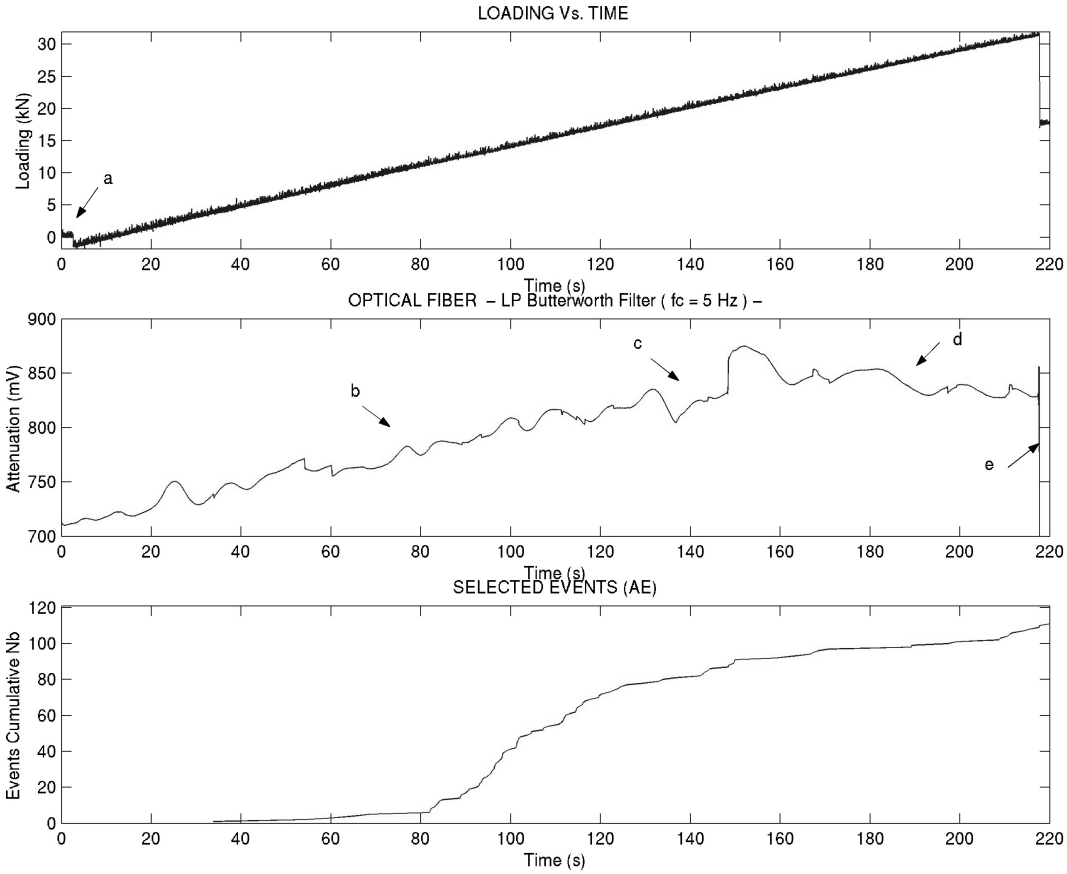


Figure 2: *The loading (upper), the measured optical signal (middle) and the cumulative number of MAE events (lower).*

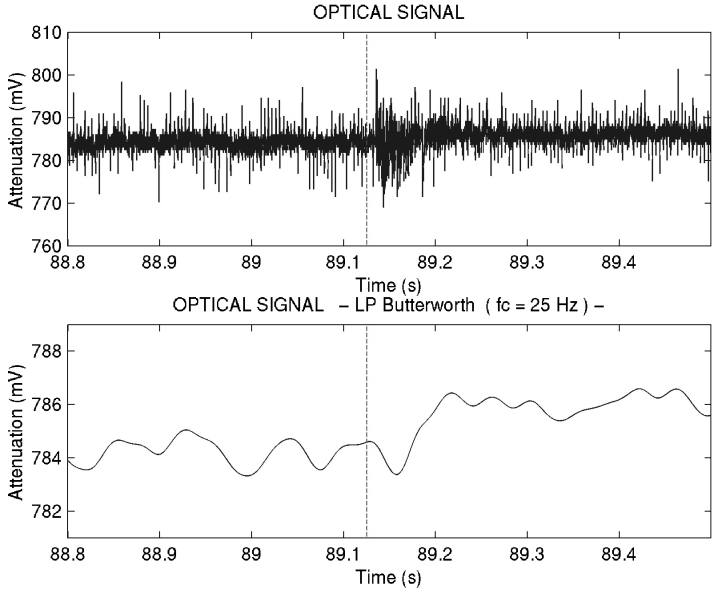


Figure 3: *The measured optical signal (upper) and the filtered optical signal (lower).*

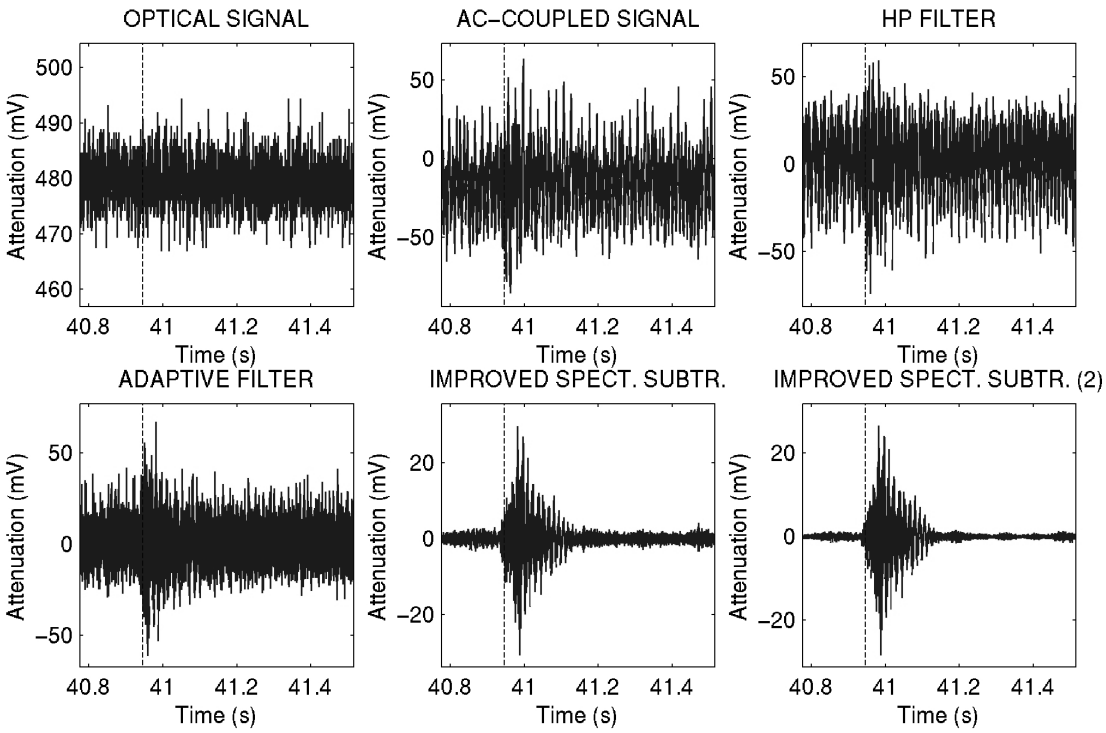


Figure 4: *The different filtering techniques that are applied on the optical signal to detect a pencil lead break.*

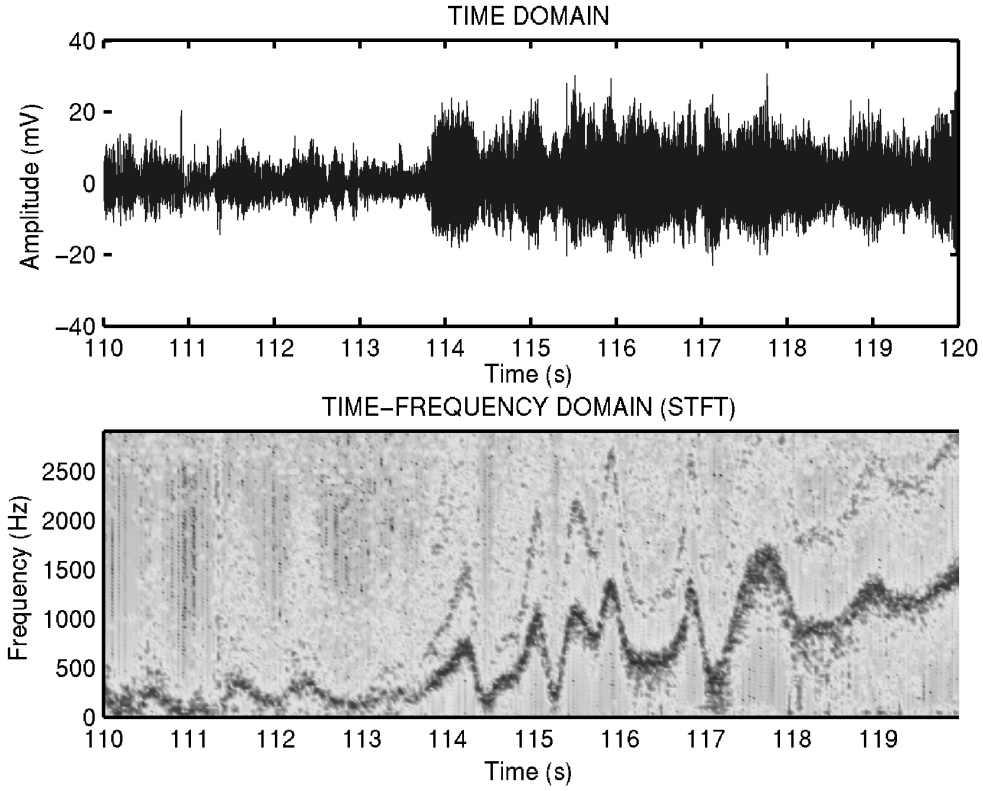


Figure 5: *The filtered optical signal in the time domain (upper) and in the time-frequency domain (lower).*

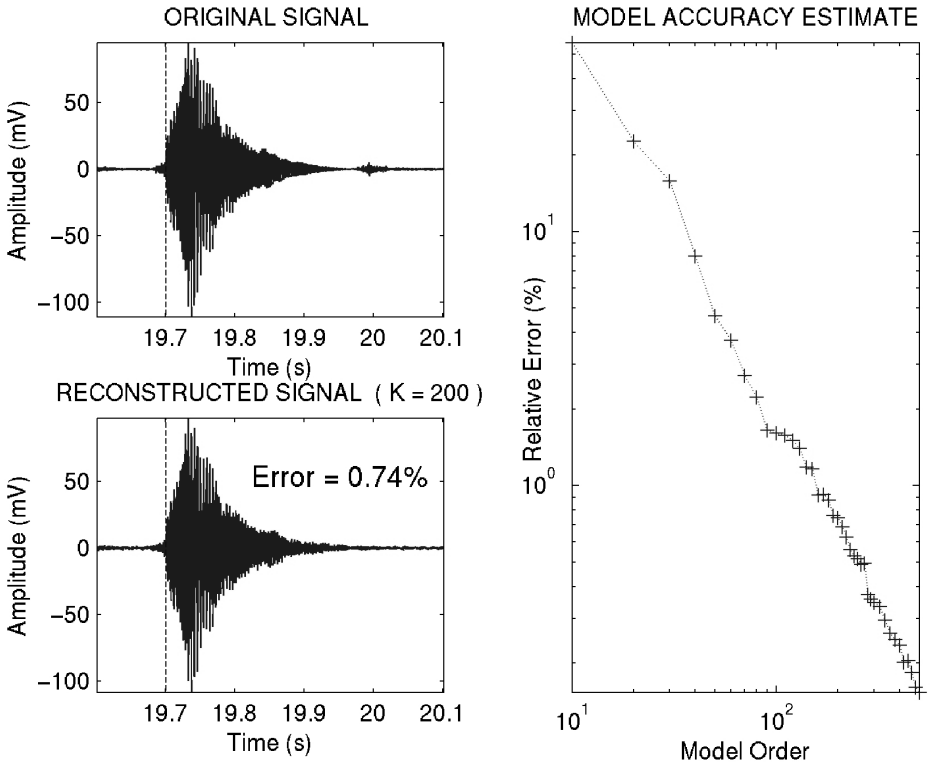


Figure 6: *A pencil lead break (upper left) modelled with the HTLS method (lower left) and the error vs. the model order(right).*

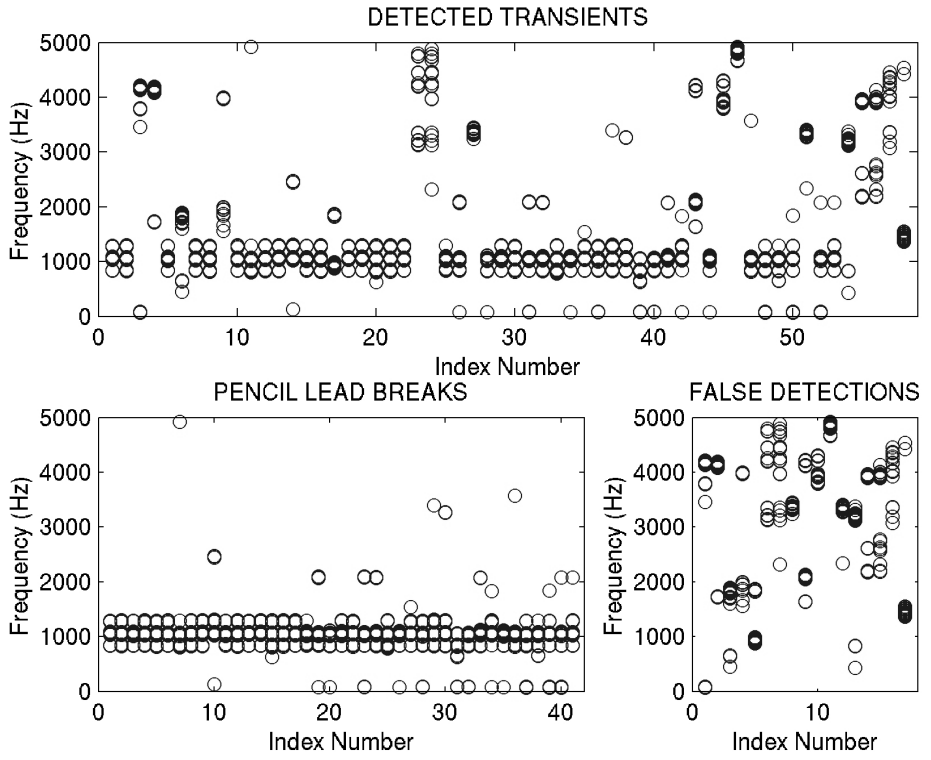


Figure 7: *The frequency content (HTLS) of the detected transients.*

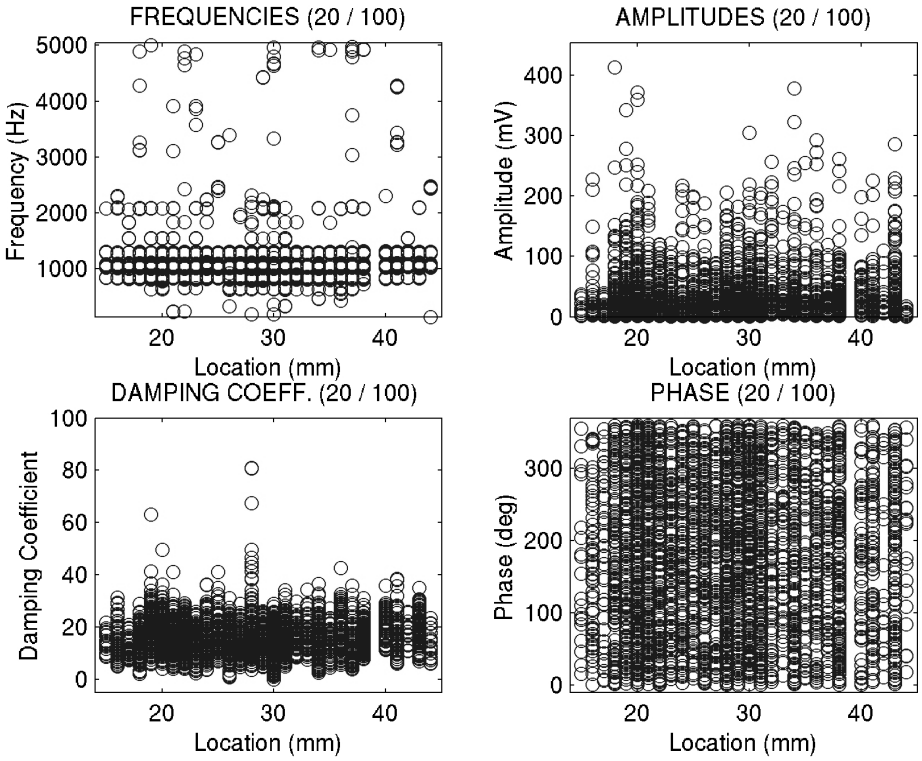


Figure 8: *The HTLS parameters in function of the location of the pencil lead breaks.*

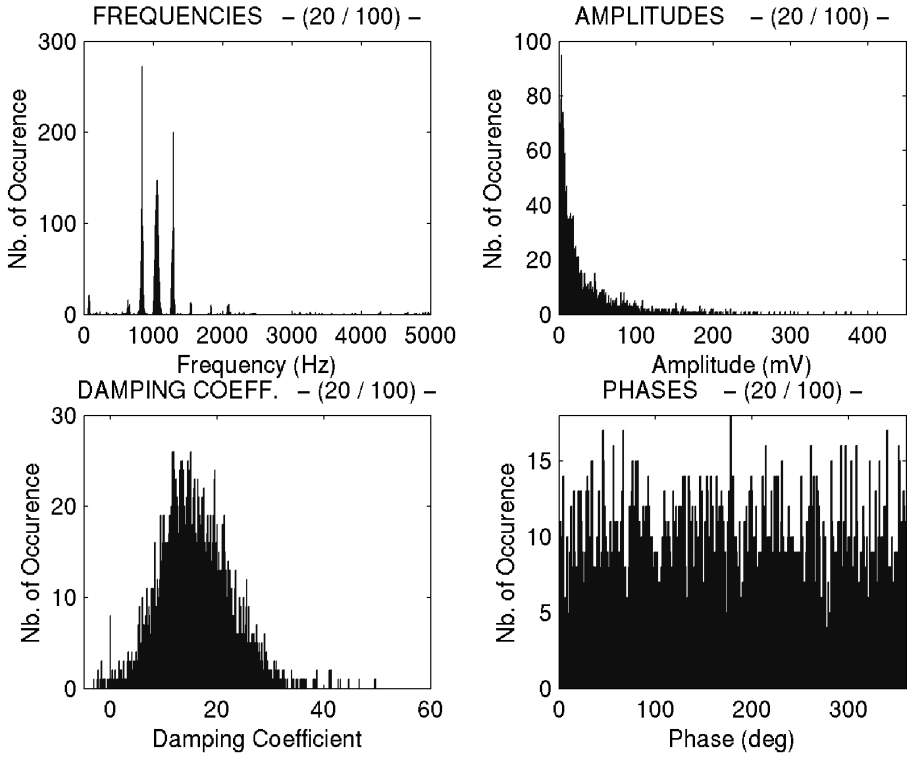


Figure 9: *The histograms of the HTLS parameters for 171 pencil lead breaks.*

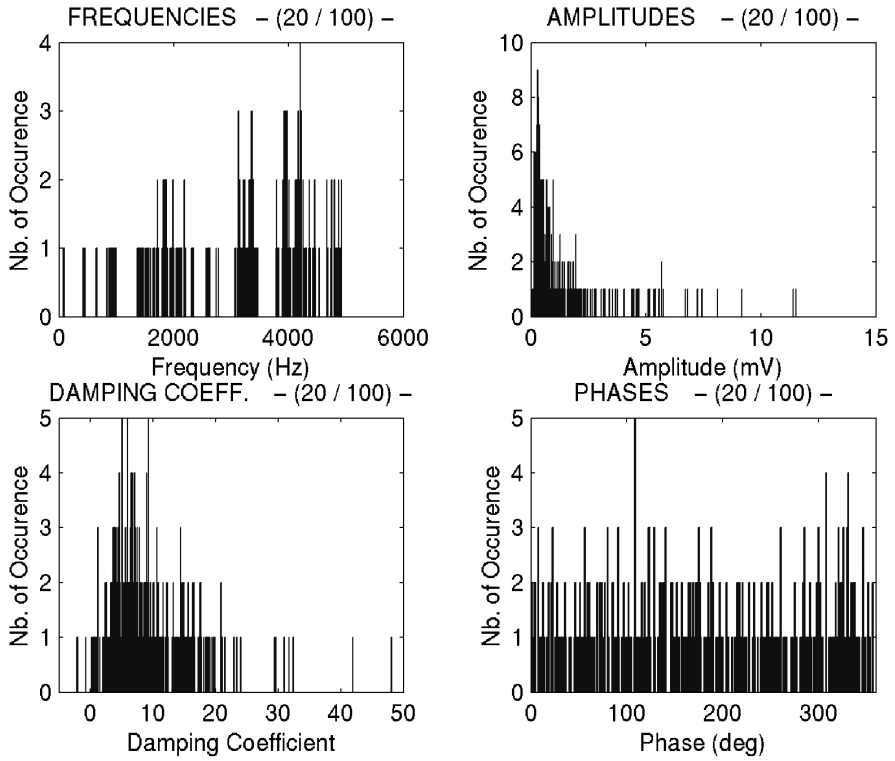


Figure 10: *The histograms of the HTLS parameters for false detections.*

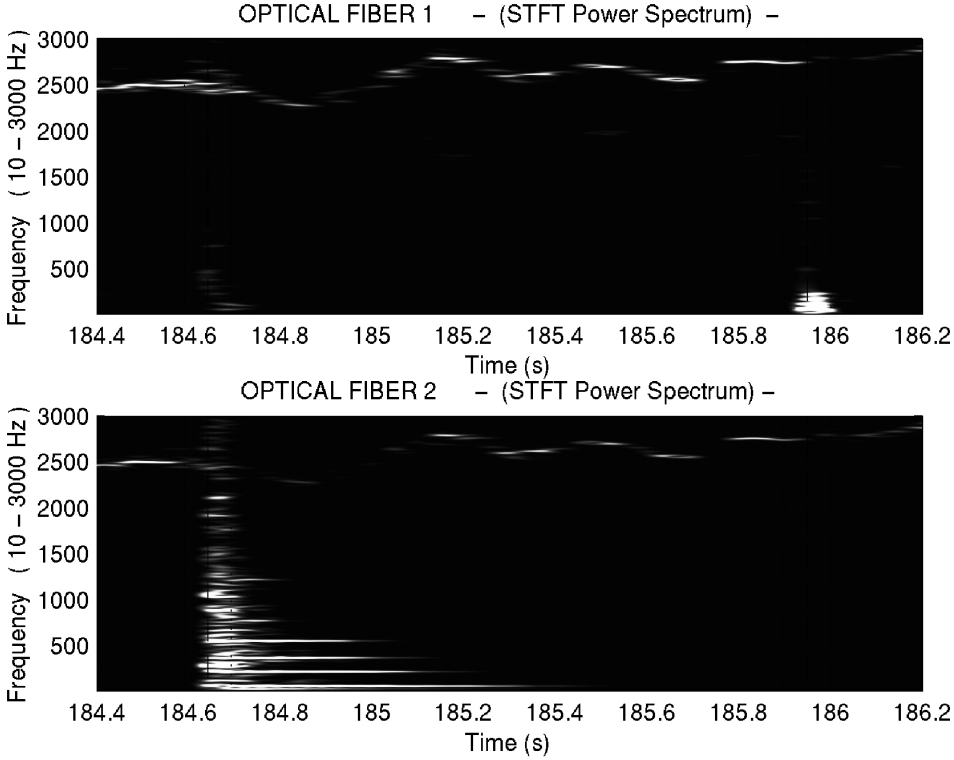


Figure 11: *The STFT analysis.*