# On the application of wavelet transform of AE signals from composite materials

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## Abstract

Wavelet transform has introduced a plethora of new aspects in signal and image processing over the last twenty years. It has significantly expanded the signal analyst's capabilities and offers certain advantages over classical fourier transform (FFT) or short-time fourier analysis (SFFT). The investigation of the suitability of the wavelet transform to handle Acoustic Emission signals has attracted some effort during the last decade. In the rather limited literature one can find some preliminary results on the use of wavelet transform in AE signal analysis to extract information from AE waveforms. Considering that time-frequency analysis is quite versatile but very powerful for transient signals we have decided to use wavelets for analyzing AE signals monitored during quasi-static testing of composite materials. Primary goal of the present study is to explore the numerous possibilities that wavelet transform offers in terms of optimum wavelet choice, optimum decomposition, de-noising and compressing of AE waveforms. Further on, the identification of the different damage mechanisms appearing within the material structure during testing and contributing in different way into the AE waveforms is also intended. The results are thoroughly discussed and an evaluation of the wavelet method to handle AE transients is attempted.

Keywords: wavelet analysis, acoustic emission, time-frequency domain, failure mechanisms

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## 1. Introduction

Acoustic Emission has been extensively used during the past 30 years for nondestructive evaluation of damage accumulation as well as for the study of fracture behaviour of composite materials. AE monitoring is considered a very attractive NDT method as it provides real-time information on damage progression within the material. Most studies so far have used AE descriptors such as counts, amplitude, energy to characterize the development of failure mechanisms. Efforts have been directed towards the use of multivariate data analysis utilizing statistical pattern recognition algorithms[1,2,3,4,5], with interesting results.

Although descriptor – based AE techniques are relatively easy to perform they ignore AE waveform, which usually carries much more information. So another group of studies were dedicated to the more difficult task of waveform processing of AE signals.

The vast majority of the above studies were performed in the time domain. Some researchers though insisted that valuable information was lying in the frequency domain as well[6,7,8]. The most important outcome of the research in frequency domain was the suggestion that each failure mechanism is distinguished by a different peak frequency obtained by FFT analysis of the acquired waveforms.

Since both time and frequency domains contain valuable information for the source and the medium of propagation of AE waveforms a technique of joint time-frequency analysis is needed. The first candidate tool for such an approach is short-time FFT or windowed FFT. Though relatively easy to apply its precision is limited by the size of the window and all frequencies are analyzed with the same resolution[9,10]. For this reason SFFT has not become popular in AE analysis.

Wavelet transform (WT) is a more sophisticated joint time-frequency analysis method. Wavelets were developed the last twenty years and have become a quite powerful tool in signal analysts' arsenal.

## 2. Wavelet transform (WT)

A wavelet is a localized wave of effectively limited duration that has an average value of zero. Instead of oscillating forever it drops to zero rather quickly. They stem from the iteration of filters and filter banks (with rescaling) so they are inherently orthogonal or biorthogonal. Fourier analysis consists of breaking up a signal into sine waves of various frequencies. Similarly, wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or *mother*) wavelet. Figure 1 depicts six typical mother wavelets. Wavelets db3, db6 and db10 belong to the renowned Daubechies family of compactly supported orthonormal wavelets, the researcher that her pioneering work gave a real boost to wavelets. The coiflet4, meyer and morlet wavelets of figure 1 are three other representatives of the wavelet family and they follow the names of researchers that first introduced them. There is a wide variety of available wavelets with different properties and characteristics. The major advantage of wavelets is their inherent ability to perform local analysis with varying precision. WT treats low frequencies with low resolution and high frequencies with high resolution[9,10,11,12]. Consequently they are ideal candidates to analyse transient signals, reveal trends, highlight noise e.t.c.

Despite their short life (they appeared in the mid 1980's), wavelets have already found numerous applications in signal and image processing. In AE research only a few works have appeared the last ten years[13,14,15,16,17]. The field of wavelets application in AE analysis is quite open and challenging. To this direction we have decided to apply the discrete wavelet transform to AE signals monitored during quasi-static tensile testing of unidirectional $Al_2O_3$-$Al_2O_3$ ceramic composites. In wavelet analysis, a signal is split into an approximation and a detail. The approximations are the low-frequency components of the signal and the details the high-frequency ones. The approximation is then itself split into a second-level approximation and detail, and the process is repeated as many times it is desirable.

Mathematically this procedure is described by the discrete wavelet transform (DWT) which is expressed as:

$$DW(j,k) = \sqrt{2^j}\int_{-\infty}^{+\infty} f(t)\psi^*(2^j t - k)dt \qquad (1)$$

where DW(j, k) are the wavelet transforms coefficients given by a two-dimensional matrix, j is the level representing the frequency domain aspects of the signal and k represents the time domain. f(t) is the signal that is analysed and ψ the wavelet used for the analysis. The inverse discrete wavelet transform can be expressed as:

$$f(t) = c\sum_j \sum_k DW(j,k)\psi_{j,k}(t) \qquad (2)$$

where c is a constant depending only on ψ.

Equation (2) is the backbone of the present work and the whole philosophy of using wavelets for analysis of AE signals, as it states that a given time series signal can be decomposed by the discrete wavelet transform into its wavelet levels, where the summation of these levels represent the original input signal. The decomposed wavelet levels are channeled in such a way that each level corresponds to a certain frequency range of the acquired AE signal.

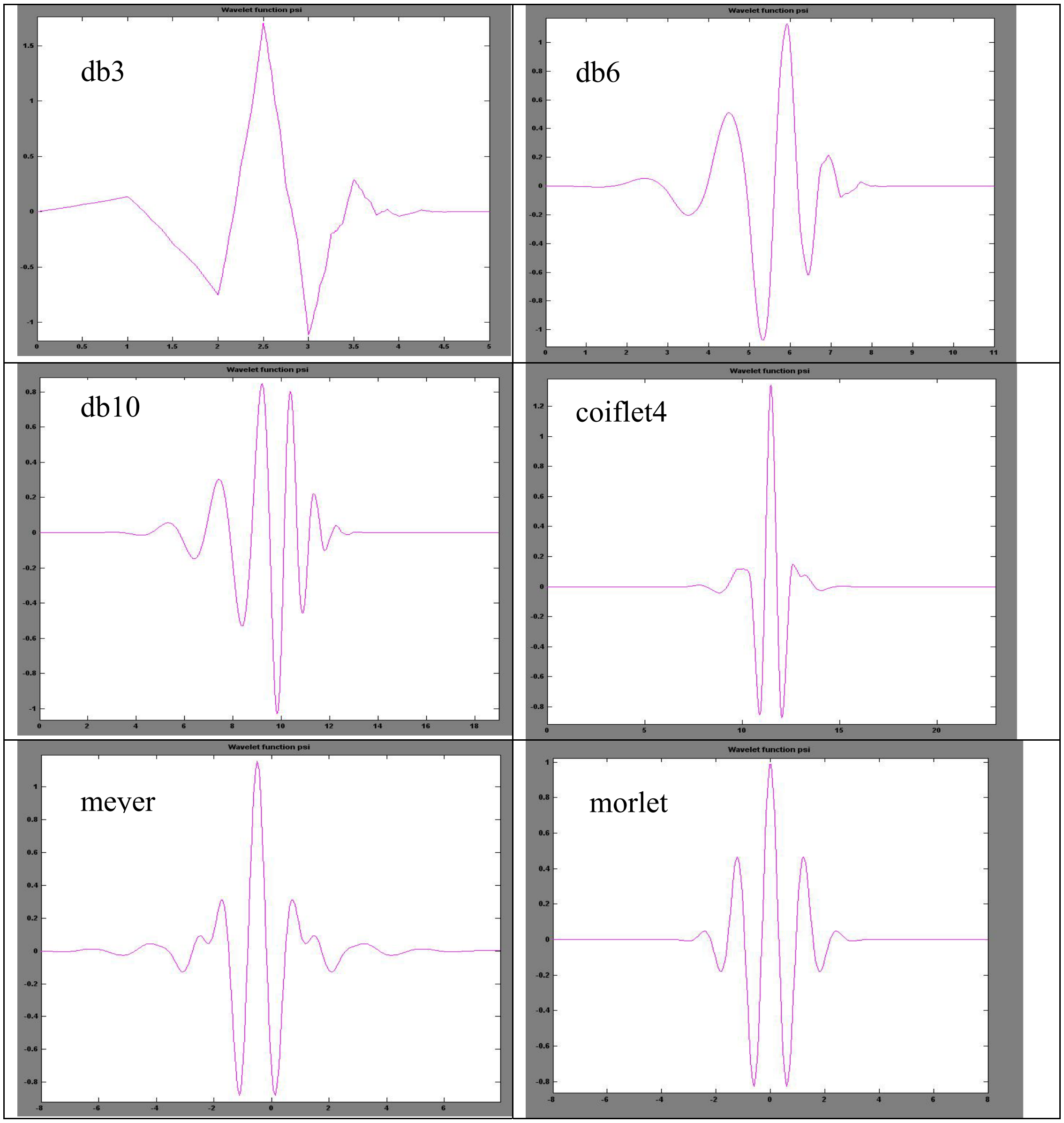

Figure 1: Typical wavelets

## 3. Experimental procedure

Straight edge tensile test coupons of unidirectional $Al_2O_3$-$Al_2O_3$ ceramic composite having dimensions according to EN 658–1[18] and thickness the original plate thickness which was 2,6 mm, were tested following the procedure described in EN 658–1. The configuration of the test coupon geometry and the positions of the two AE transducers are showed in Fig.2.

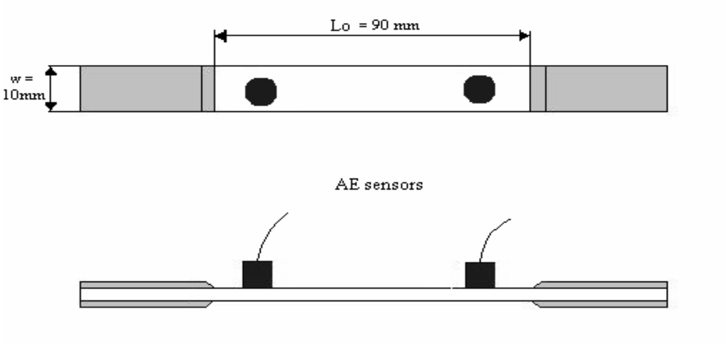

Figure 2: Specimen geometry characteristics

All tensile tests were performed using a MTS Universal Testing Machine equipped with hydraulic gripping system, under displacement control, at controlled environmental conditions of 25 $^{o}$C and 70% relative humidity. AE activity was recorded during the tensile testing of the material. The data acquisition system used was a Mistras 2001 of Physical Acoustics Corporation. The AE signals were monitored by using two resonant transducers (NANO 30), which were attached to each specimen by means of a suitable coupling agent. Pre-amplification of 40 dB and band-pass filtering of 20-1200 kHz was performed by 2/4/6-AST pre-amplifiers. The acquisition parameters for the two active channels were: threshold and gain equal to 40 and 20 dB respectively, while the Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT), were set at 50 μs, 100 μs and 500 μs. Pencil break tests were used for the calibration of the applied set up.

## 4. Wavelet-based methodology for AE analysis

During a typical quasi-static tensile test with continuous AE monitoring a number of AE waveforms are recorded. In the case examined in the present work around 2800 AE waveforms were collected during a typical test. A schematic representation of the in-house developed wavelet-based scheme, which was used for the analysis of AE signals is presented in Fig. 3. The waveforms are loaded in Matlab workspace (Matlab Professional 6.12).

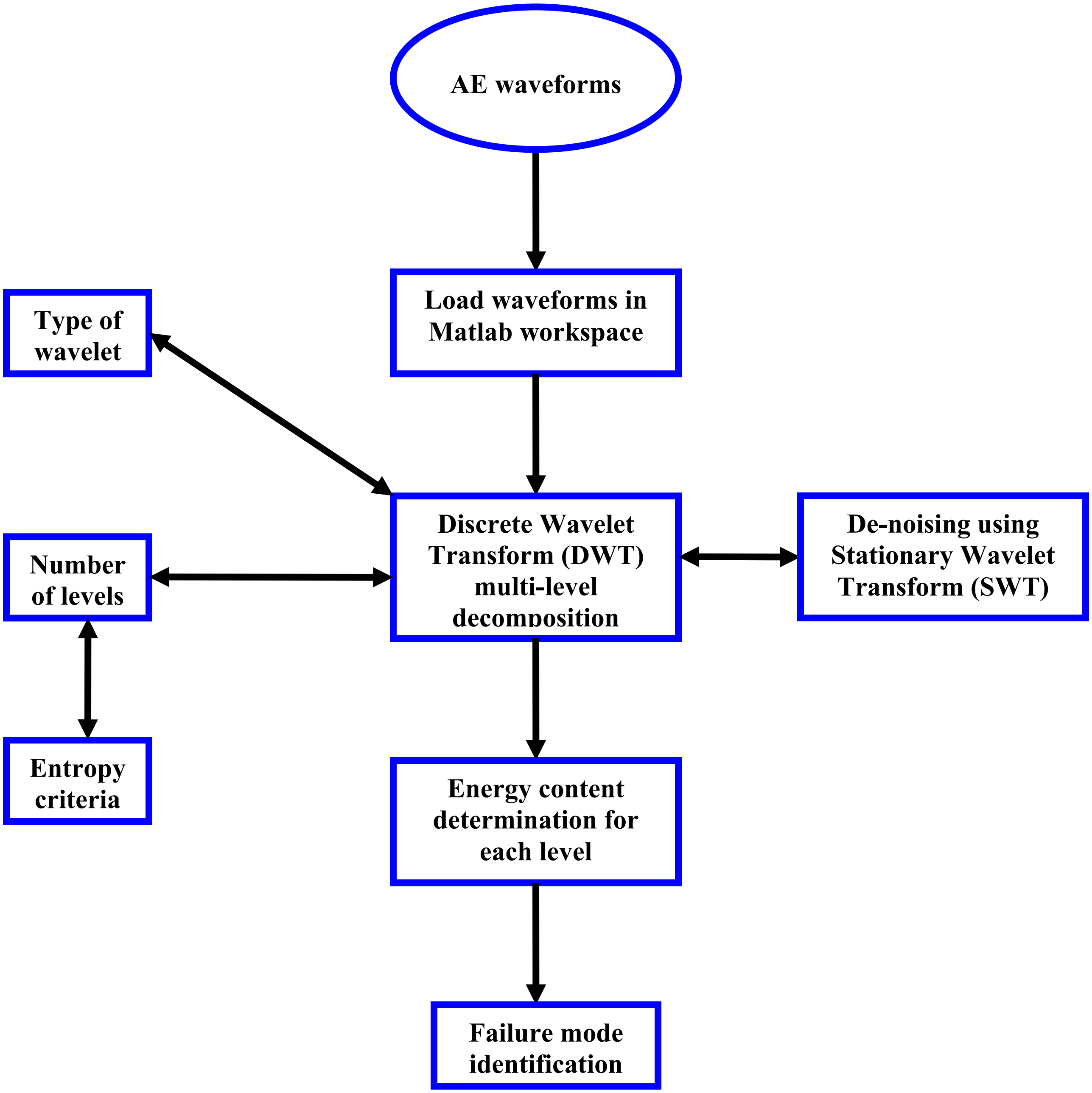

**Figure 3: Wavelet-based scheme for AE signals analysis**

Matlab software was selected since it provides a quite versatile wavelet toolbox with numerous options. It also offers the possibility to program and create routines and codes for any application.

After all AE waveforms were loaded in Matlab, discrete wavelet transform (DWT) is applied for every signal. The application of DWT to each waveform results in the decomposition of the original AE signal into its wavelet levels. Each level represents a certain frequency band and the sum of all levels reconstructs the primary AE signal. In fact the decomposition is the result of a repetitive procedure of filtering the signal with specially designed band-pass filters. The inversion of the transform is quite accurate and full reconstruction of the original signal is feasible. Fig.4 depicts a characteristic example of decomposition of a random AE signal chosen from the given example having 2800 recordings that were available from the given test. The type of 'mother' wavelet chosen for the analysis as well as the number of the levels of decomposition are user defined parameters. Fig.4 decomposition was based on db10 wavelet and five levels of analysis. A discussion at this point may rise concerning the optimum wavelet to be used for a certain application and the number of levels of the decomposition. In fact the question of which is the proper wavelet type to use has not been answered so far in a quantitative and explicit manner. No rules have been set to determine the superiority of one wavelet over another to analyze a given signal. One must comprehend quite well the properties and characteristics of different wavelets, have a profound knowledge of their differences and experience to deal with a certain type of signals. On the other hand for the optimum number of levels there are certain mathematical criteria called entropy criteria[19] that determine if a decomposition is sufficient or more levels are needed. This is easy to check for one signal and define the optimum number of levels. In the case of a large number of signals though, entropy criteria are not easy to apply as it is not obligatory to agree in the same number of levels of decomposition for all waveforms.

In the present work after systematic trials the number of levels was set to five as it was evident that less were insufficient and more were redundant. As far as the type of wavelet is concerned db10 was a very good compromise of smooth function, without sharp edges and not too difficult to create numerically as with db wavelets of higher order. The family of Daubechies wavelets was chosen because it consists of biorthogonal, compactly supported wavelets, satisfactorily regular and not symmetrical. These attributes were considered very important for the analysis of transient signals such as AE activity. Other wavelets having similar properties to the Daubechies family, such as symlets or coiflets were also used with minor differences in the results.

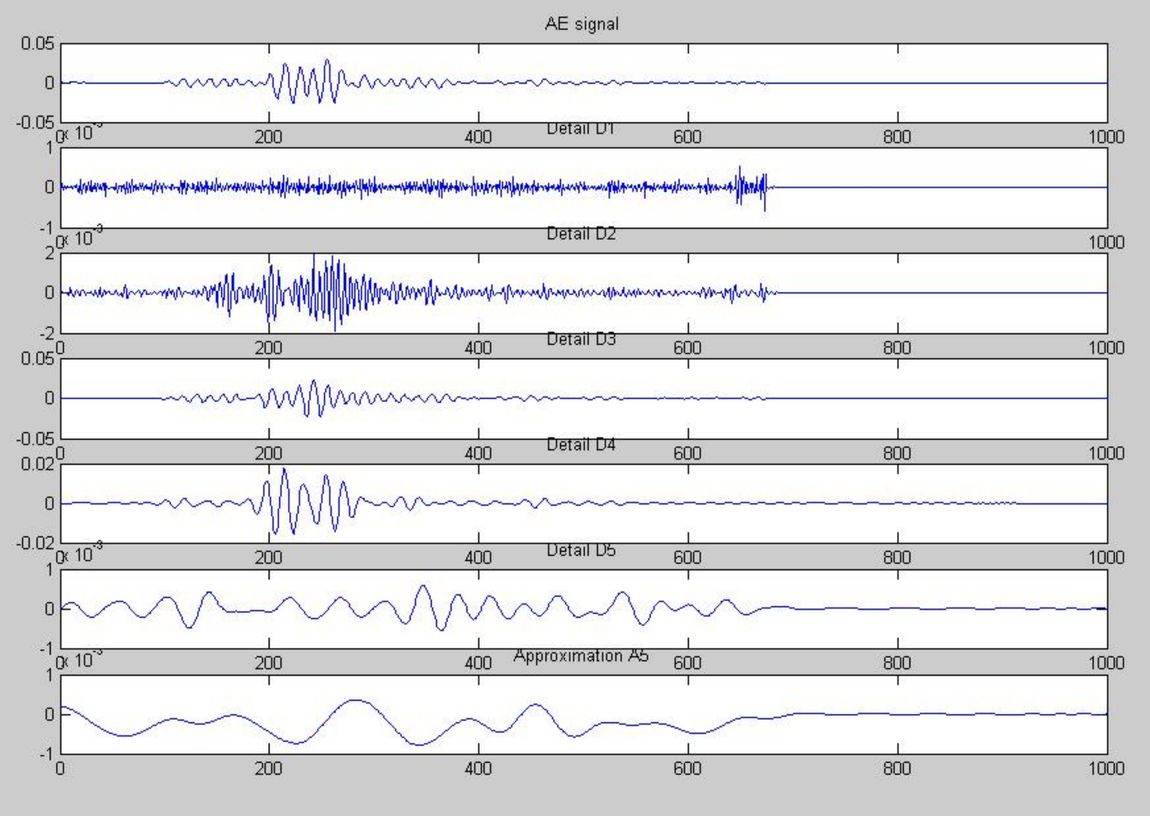

Figure 4: Five level wavelet decomposition of an AE signal

Figure 5 shows the frequency bands for each one of the decomposition levels. The quite important property of wavelets to decompose signals and channel them to different frequency bands is obvious from the graphs. The approximation A5 has the lowest frequency content while the details D5-D1 have increasing frequency bands up to 2 MHz.

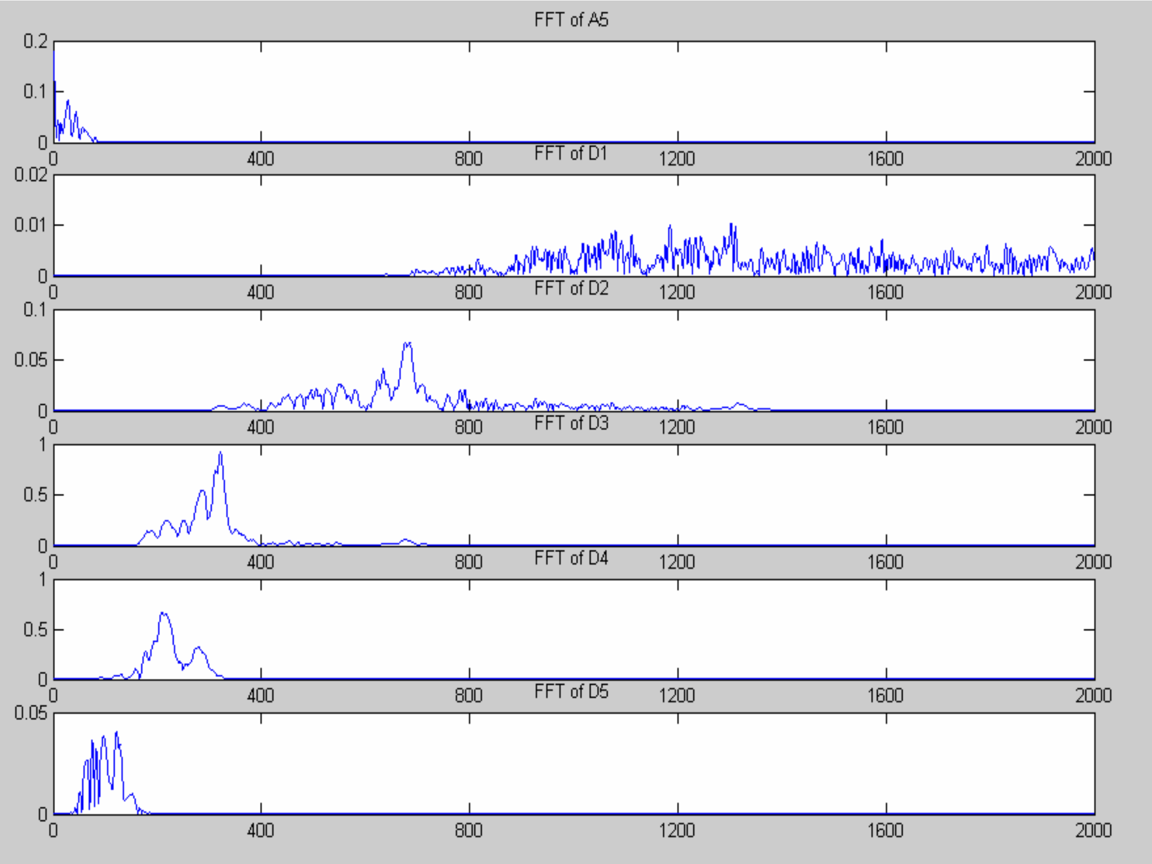

Figure 5: FFT of the decomposition levels

After the decomposition of all AE signals the energy content of each level $f^{(i)}(t)$ is determined. This is mathematically expressed as:

$$E^{(i)}(t) = \sum_{\tau=t_0}^{t} \left(f^{(i)}(\tau)\right)^2 \qquad (3)$$

Where $E^{(i)}(t)$ represents the energy of level i. After completing the calculation of energy of decomposition levels for all waveforms, a summation of the energy of each level for each waveform follows. Figure 6 shows the results of this procedure. The x-axis represents the waveforms as received in time (so it is a measure of time) and the y-axis the energy percentage of the level as compared with the total energy of the AE signal. It is evident from fig.6 that the greatest percentage of energy is gathered in four levels, namely approximation A5 (level 1), detail D3 (level 4), detail D4 (level 5) and detail D5 (level 6). These levels could be directly related to the damage mechanisms of the material as long as they carry more than 95% of the total signal energy and additionally they are characterized by different frequency bands. Level 1 is in the domain of 0-100 kHz, level 4 at 300-400 kHz, level 5 at 200-300 kHz and level 6 at 50-150 kHz. Levels 4 and 5 are dominant between the four levels. The major failure mechanisms in composites are fibre failure, matrix cracking, fibre-matrix interfacial debonding and interfacial sliding. Though at this stage direct corresponding of energy levels with damage mechanisms is not feasible, it is believed that the energy content information obtained by wavelet analysis is crucial for the failure mode identification in composites.

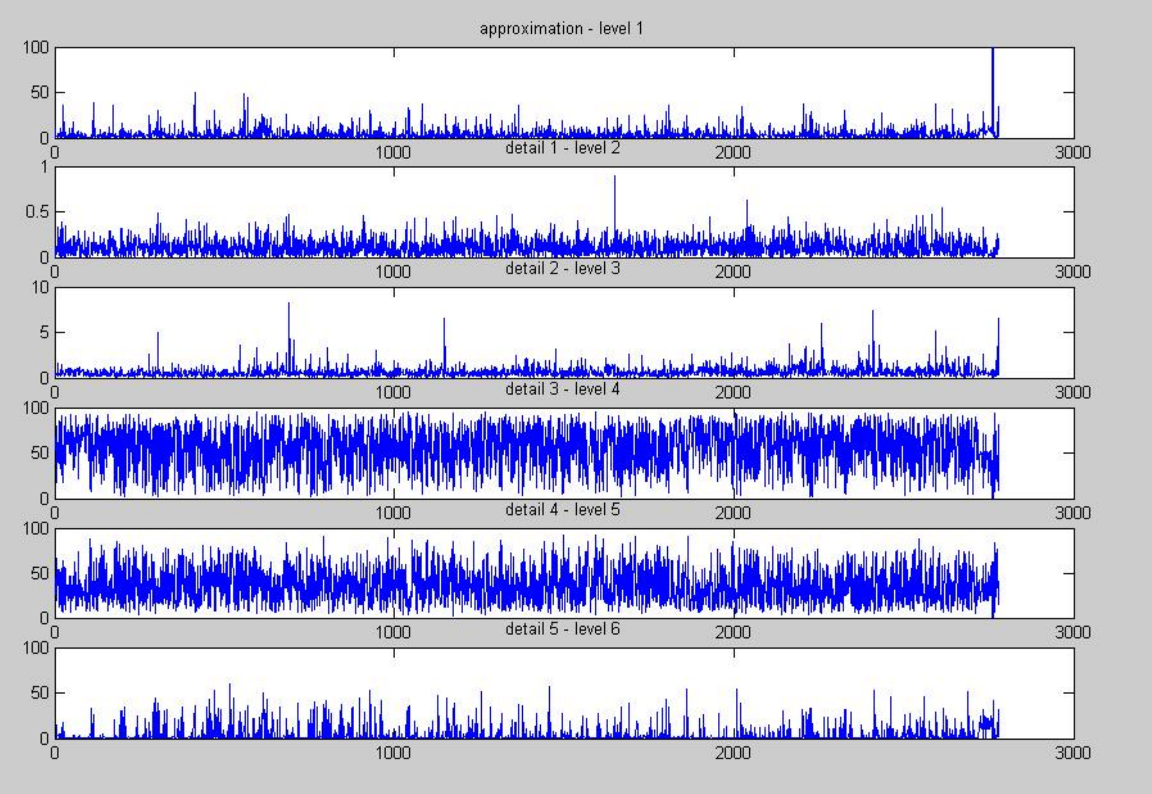

Figure 6: Energy of levels for all waveforms

Continuing with the numerous capabilities of wavelets, de-noising of AE signals is another important application. Fig. 7 depicts the original AE signal in comparison with the de-noised signal. De-noising is succeeded using a special version of wavelet transform called Stationary Wavelet Transform (SWT). It is an averaged slightly different DWT quite useful for de-noising and break-down points detection.
In fact the de-noised signal results from the removal of the high-frequency components of the signal.

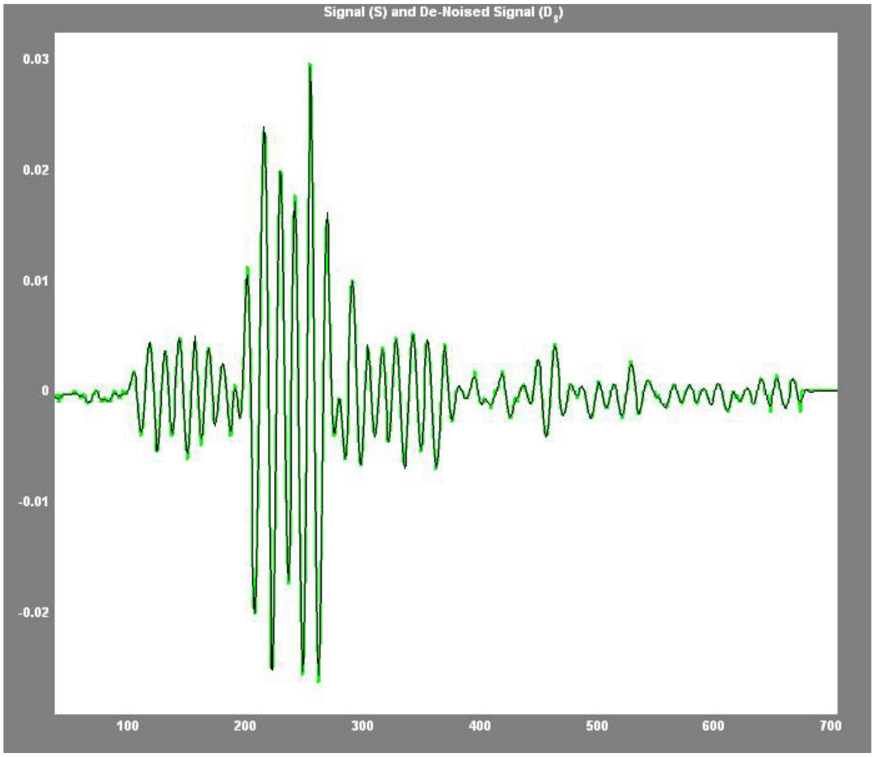

Figure 7: De-noising of AE signals

## 5. Conclusions

The wavelet transform is a new powerful technique with important applications in the field of signal analysis. Since its first appearance in 1980's numerous publications involving the use of wavelet transform in many scientific terrains have appeared. The study of the applicability and usefulness of wavelets in the research domain of Acoustic Emission was the aim of the present work. Although the published works in this field are quite limited it was necessary for an attempt to be made towards a more quantitative application of wavelet transform in AE signals. An innovative wavelet-based scheme for the treating of AE signals was developed in Matlab. Different wavelets have been extensively used and many aspects of the wavelet transform have been examined. The results are rather promising fully justifying the great expectations of the new method in Acoustic Emission research. A lot of work is still to be done in the future and many indications exists that wavelets are an extremely useful tool in the Acoustic Emission analysis.

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