DISCRETE WAVELET ANALYSIS OF ACOUSTIC EMISSIONS
DURING FATIGUE LOADING OF CARBON FIBER
REINFORCED COMPOSITES

by

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A THESIS

IN

MECHANICAL ENGINEERING

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

MASTER OF SCIENCE

IN

MECHANICAL ENGINEERING

/ Approved ^ ^

May, 1996

ACKNOWLEDGMENTS

I would like to convey my immeasurable gratitude, whole hearted thanks and sincere respect to my advisor Dr. Javad Hashemi for his guidance, support and encouragement during this thesis work. I would like to express my sincere thanks and esteem respect to my co-advisors Dr. Alan Barhorst and Dr. Jaime Cardenas for reviewing my work and offering useful suggestions and guidance during the course of this thesis. I would also like to thank all my friends for putting up with me during my stay here and helping me during the course of this research. I would like to take this opportunity to honor the three most important people in my life, my parents and my grandmother, with the deepest love and respect. For, without their support, encouragement and blessings, I would never have achieved what I have today.

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ABSTRACT

Acoustic Emissions (AE) are generated during operational loading of Fiber Reinforced Composite (FRC) materials due to various sources of fracture. These sources which include matrix fracture, fiber fracture, splitting and delamination could be generated individually or simultaneously. The multiplicity of defects and failure modes creates problems in identifying and distinguishing various sources of emissions. This analysis is further complicated due to the friction related emissions (generated during grating of newly generated damage surfaces and fretting of broken fibers with matrix) that mask the actual signal and in most cases, exceeds the emissions from actual damage. The purpose of this thesis is to investigate the applicability of discrete wavelet transforms in the analysis and time-frequency breakdown of AE signals detected during fatigue loading of FRC materials. The first objective is to decompose the AE signals into different levels based on the central frequency around which the emissions are generated. The second objective is to identify the frequency at which friction based emissions are generated. The final objective is to determine if a possibility exists to associate various failure modes with specific frequencies.

Through utilization of wavelet transforms, it became possible to present the spectral composition of a transient signal (AE signal) in a time-frequency map which is not easily achieved through conventional spectral analysis techniques. Application of discrete wavelet analysis to the AE signal resulted in various wavelet levels (11 in all). These correspond to the various frequency bands ranging from 0-2000 kHz, with each

level acting as a digital filter. It was further determined that most of the acoustic energy (95%) was localized in levels 7, 8 and 9 corresponding to central frequencies of 120, 250, and 310 kHz. Results indicate friction related emissions are associated with levels 8 and 9 and have a frequency range of 250-300 kHz. Also, there are indications that matrix related emissions are generally concentrated in level 7 corresponding to a central frequency of 120 kHz. The results indicate that wavelet analysis would be an effective tool in the analysis of AE by providing information relative to the frequency of the emissions. Consequently, in contrast to conventional AE analysis techniques which are generally based on amplitude analysis, an alternative AE methodology has been identified that will provide additional frequency related information. This development could serve to assist the researchers in determining the extent and type of damage during on-line inspection of components.

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CHAPTER I

ACOUSTIC EMISSION

1.1 Introduction

Acoustic Emissions (AE), also called stress wave emissions, are transient elastic stress waves generated by the rapid release of energy from a localized source within a material. Acoustic emission is a passive monitoring technique and it differs from most other non-destructive testing (NDT) methods in two key aspects. First, the signal has its origin in the material itself and not in an external source. Second, this technique detects movement, while most other methods such as Ultra-sonic based techniques detect existing geometrical discontinuities.

Acoustic emission signals cover a wide range of energy levels and frequencies and are considered to be of two basic types : burst emissions and continuous emissions as shown in Figure 1.1. The term burst emissions is a qualitative description of emission signals corresponding to individual emission events such as crack initiation. Continuous emission is a qualitative term to describe an apparently sustained signal level from rapidly occurring emission events such as dislocation motion.

Acoustic emission technique has been extensively used to monitor and analyze stress wave emissions in fiber reinforced composite materials in order to determine the location and the extent of damage in such structural components. Some classical sources of AE in composite materials are fiber breakage, matrix cracking, splitting, delamination, and friction. There exists a great deal of literature on AE analysis of

(a) Continuous Emissions

(b) Burst Emissions

Figure 1.1 : Burst and Continuous Emissions (Courtesy PAC)

fracture in composites. Many of these research efforts concentrated on developing methods that enable the researchers to distinguish the different modes of failure in composites. Majority of the existing research related to differentiating emissions due to various modes of failure has relied on amplitude analysis and event counting techniques. No attempt has been made to break down the AE signals based on frequency.

Major benefits of the Acoustic Emission technique are: (i) allowance for the whole volume of the structure to be inspected non-intrusively in a single loading operation, (ii) real time recording of progressive damage in a material, (iii) ability to locate AE sources to identify regions of stress concentration, (iv) dynamic detection of flaw and (v) cost effectiveness in comparison to other conventional NDT techniques. The first systematic study of damage detection in materials using AE was performed by Josef Kaiser (1950). He measured emissions from conventional engineering materials and related the data to the constitutive behavior of the material. The technology and its uses have since continued to grow and have become an integral part of NDT damage detection practices.

The focus of this research is on the application of the AE technique to distinguish acoustic emissions from actual damage based on the frequency of the emissions. Analysis of AE signals from composite materials is quite complex due to multiplicity of defects, variety of failure modes, and existence of friction related emission capable of overshadowing the actual damage related emissions. The defects exist due to variation of fiber strength, matrix properties and the adherence between

fibers and matrix. This increase in the volume of defects leads to an increase in the friction related emission. Thus, it is a challenging task to analyze the AE signals to distinguish the friction related emission from the various failure. In this thesis, the Wavelet transforms will be used to breakdown the AE signals collected during fatigue testing of unidirectional CFRC into various frequency bands with the objective of identifying friction related emissions. In the next section a brief background of the existing AE work in composites will be given.

1.2 Literature Review

A vast amount of literature on the application of AE to fatigue of composites is available, a small sampling of which is discussed in this section.

Application of AE to fatigue was initiated by Dunegan, Harris and Teleman (1970, 1973). Acoustic emission technique was applied for the detection of fatigue-crack propagation in 7075-T6 aluminum and 4140 steel. The authors present a relationship between crack-growth rate, cyclic stress-intensity factor, load-cycling rate and the observed AE behavior. Investigation on effects of instrumentation sensitivity and frequency bandpass were also investigated. Conventional AE parameters such as ringdown counts, event counts, peak amplitude distribution, and root mean square value were used to describe the initiation and propagation of cracks.

Bertheholt utilized AE analysis in composites (1986) and reported that matrix cracking produced AE of low amplitudes, but the delamination and fiber breakage

produced signals of higher amplitude. The author's conclusions were purely based on peak amplitude characterization of the AE signal.

Eckles and Awerbuch (1988) and Awerbuch and Ghaffari (1988), monitored AE in graphite epoxy laminates during fatigue loading. The main emphasis of their research was to distinguish the emission caused by new damage from friction generated emission by identifying the characteristic intensities associated with friction. The authors attributed AE generated below the maximum dynamic stress level to friction. Friction Emission Threshold (FRET) values based on energy counts, duration and counts per events were determined and used as a basis to distinguish friction related emission. Spatial filtering was carried out to eliminate all emissions from the specimen grips and the machine hydraulics.

Chefarouni et al. (1989) adopted a statistical data analysis approach, called the multivariate data analysis, to classify AE signals into three groups. Using this technique they divided the emissions into three groups: the first group was classified as the high energy, medium frequency signals representing emissions from fiber breakage. The second group was classified as the low energy, high frequency signals representing emissions due to fiber matrix debonding. The third group was classified as the low energy signals, with high or low frequency emissions representing matrix cracking.

Experimental investigations were carried out on unidirectional Glass-Fiber-Reinforced Plastic (GFRC) by Bhat and Murthy (1989), to explore the feasibility of identifying the damage stages using acoustic emission techniques. The authors divided the fatigue life of composites into three stages, the first was associated to matrix

cracking, the second to crack propagation and the third stage was associated with fiber breakage. The role of friction in the analysis of the results was not discussed in this study.

Jacobs et al. (1990) conducted fatigue tests on CFRC laminates. The main emphasis of their investigation was to determine the influence of several system components on fretting wear and fretting fatigue performance of composite laminates. The authors conclude that interaction of surface damage due to fretting and fatigue drastically reduces the fatigue life of a structural component.

Prosser et al. (1995) conducted studies on waveform analysis of AE from composite materials. The authors conclude that identical source mechanisms produce a wide range of AE signal amplitudes. The distance of the source from the sensor, dispersion and attenuation of the signal adversely affect the signal amplitudes.

Generally, the review of the literature indicates that the AE technique has been extensively used in relation to damage mode prediction in composites by a great number of researchers. However, the review shows that a vast majority of the analysis is based on event counting techniques and majority of the conclusion are based on amplitude analysis of the results. No attempt has been made to distinguish the various damage mechanisms and friction related emissions based on a frequency break down of the AE signals.

In this thesis, the time frequency break down of AE signals collected during fatigue testing of CFRC composites will be presented. The next section describes in

brief the objective of this thesis and the steps that will be initiated in overcoming some bottlenecks in the analysis of AE data.

1.3 Objective

The proposed research is aimed at providing an alternative frequency based AE analysis methodology in the area of nondestructive testing of materials using discrete wavelet analysis of AE signals. The main objective of this research is to identify the AE emissions due to friction and associate the friction related emissions with their specific frequency ranges.

During fatigue loading, the multiple fracture surfaces in a composite laminate, grate or rub against each other repeatedly resulting in a large volume of emission due to friction. Acoustic emissions are also generated due to various sources of fracture, which include matrix fracture, fiber fracture, splitting and delamination. Therefore, as the acquired AE signals are masked by the friction related events, it is necessary to obtain a clean signal in order to predict the various failure modes. Thus, it is proposed to adopt the wavelet analysis methodology to remove friction related emission from the actual signal. It is also proposed to use this methodology as an inspection tool.

The work proposed herein consists of five chapters. The first chapter gives a brief introduction to acoustic emissions, a literature review of relevant AE efforts and a description of the objectives of this thesis. The second chapter details the wavelet analysis approach and explains the significant differences among the different Wavelets and between the Wavelet and the Fourier transforms. The third chapter explains in

detail the steps involved in the fatigue and tensile testing of carbon composite specimens including the steps involved in the preparation of the specimen, their testing, data acquisition and the various instrumentation and tools used. In the fourth chapter, the results and the methods adopted to analyze the signal has been presented in detail. The fifth chapter details the conclusion and the recommendations for future research.

CHAPTER II

WAVELET TRANSFORMS

2.1 Introduction

Wavelet transform was first introduced in the early 1980's (Grossman and Morlet, 1984) as a theoretical tool. It was applied to an arbitrarily square summable real function and transformed into a series of shifted and dilated sum of wavelets. Wavelet analysis has proven to be a powerful and reliable tool in areas related to analysis of transient signals (Martinet et al., 1987; Aussel and Monchalin, 1989; Loe et al., 1982). Researchers have recently developed new wavelets, faster algorithmic transforms, and have started to apply wavelet analysis to new and more complicated problems (Mallat, 1987; Daubechies, 1988; Chui, 1992). The application of wavelets to non-communications engineering problems however is still in its infancy. Newland (1993) was one of the pioneering researchers to describe wavelets in the engineering language and suggest its application to the field of Mechanical Engineering. His work related to the application of wavelet transforms to the analysis of mechanical vibrations. Qi, et al (1996) applied wavelet transforms to the AE signals from quasi-static tension tests on CFRC with the objective of identifying the various failure modes and for residual strength prediction.

This chapter provides a brief introduction to the concept of discrete wavelet transform and the formulation of the wavelet based acoustic emission analysis method. Wavelet transforms are being applied to problems that previously were solved using

the Fourier transforms. A major disadvantage of the Fourier analysis is that frequency information can only be extracted for the complete duration of a signal $f(t)$. The integral in the Fourier transform extends over the duration and the information it provides is an average value over the whole length of the signal. If, at sometime during the lifetime of the signal $f(t)$, a local oscillation representing a particular feature occurs, it will contribute to the calculated Fourier transform $F(\omega)$, but its location on the time axis will be lost. Thus, there is no way of knowing whether the value of $F(\omega)$ at a particular ω derives from frequency present throughout the life of $f(t)$ or during one or a few selected periods. On the contrary, wavelet analysis transforms a signal in the time domain into the time-frequency domain. The decomposed parts of the signal are resolved such that the higher the frequency, the finer the resolution.

2.2 Mathematical Background

It is easier to understand the concepts of the wavelet transforms by comparing it with classical the Fourier transform. Presented below is a review of classical the Fourier transforms.

2.2.1 Continuous Fourier Transform

Let $f(t)$ be a continuous function, applying the Fourier transform we get the following expression

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{i\omega t} dt \quad (2.1)$$

the function $f(t)$ can be recovered via

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{i\omega t} d\omega \quad (2.2)$$

provided the following conditions are satisfied. (a) $f(t)$ should satisfy the Dirichlet conditions in a finite interval and, (b) $f(t)$ is absolutely integrable in a finite domain, which means

$$\int_{-\infty}^{\infty} |f(t)| dt < \infty \quad (\text{is a finite number}). \quad (2.3)$$

2.2.2 Discrete Fourier Transform

let $f(n)$ be a time sequence, then the discrete Fourier transform is defined by

$$F_K = \sum_{n=0}^{N-1} f(n) e^{-ik\omega n} \quad \text{for all } k. \quad (2.4)$$

The inverse of the above equation is given by

$$f(n) = \sum_{k=0}^{N-1} F_k e^{ik\omega n} \quad \text{for all } n \quad (2.5)$$

provided that $f(n)$ is square summable, which means

$$\int |f(n)|^2 dx < \infty.$$

Equations 2.1 and 2.4 are called the spectra of the input (in frequency domain), or the coefficients of the Fourier transform. They indicate the spectral distribution of the input signal.

2.3 Continuous Wavelet Transform

Let $f(t)$ be a continuous function such that $f(t) \in L^2(R)$, then the continuous wavelet transform of input function $f(t)$ is

$$FW(a, \tau) = \frac{1}{\sqrt{a}} \int f(t) \phi\left(\frac{t - \tau}{a}\right) dt \quad (2.6)$$

where a represents scale level equivalent to frequency (relative) and t is shift (time), Function $\phi(\cdot)$ is called the wavelet function. If $\phi(\cdot)$ is chosen such that the above equation is invertible, then recovery of $f(t)$ is determined by (Chan, 1995)

$$f(t) = \frac{1}{C_\phi} \int_{-\infty}^{\infty} \int_0^{\infty} FW(a, \tau) \frac{1}{\sqrt{a}} \phi\left(\frac{t - \tau}{a}\right) \frac{1}{a^2} da d\tau \quad (2.7)$$

where the constant C_ϕ is given by

$$C_\phi = \int_{-\infty}^{\infty} \frac{\phi(\omega)}{\omega} d\omega < \infty \quad (2.8)$$

with $\phi(\omega)$ being the Fourier transform of $\phi(t)$.

The wavelet function ϕ , should be chosen such that

$$|\phi(\omega)| < \infty \quad (\text{is finite for any value of } \omega) \quad (2.9)$$

and

$$\int_{-\infty}^{\infty} \phi(t) dt = 0 \quad (2.10)$$

which implies that $\phi(t)$ must have zero dc.

One of the major advantages of using the wavelet transforms is that the wavelet function $\phi(t)$ is user-defined; any function can be chosen as the wavelet

function, as long as the chosen function, satisfies the conditions defined in Eqs. 2.8 through 2.10.

The following are a few examples of wavelet functions

1. Morlet wavelet (Modified Gaussian)

$$\varphi(t) = e^{i\omega t} e^{-\frac{t^2}{2}} \quad (2.11)$$

$$\varphi(\omega) = \sqrt{2\pi} . \quad (2.12)$$

2. Second Gaussian derivative wavelet

$$\varphi(t) = (1 - t^2) e^{-\frac{t^2}{2}} \quad (2.13)$$

$$\varphi(\omega) = \sqrt{2\pi} \omega^2 e^{-\frac{\omega^2}{2}} . \quad (2.14)$$

The wavelet functions defined in Eqs. 2.11 and 2.13 are plotted in Figure 2.1.

The corresponding Fourier transforms are plotted to the right of the wavelet functions.

From the plots, the following conclusions about wavelet properties can be made

1. The wavelets have zero dc;
2. They act as bandpass filters (signal can be passed only in a particular range);
3. They decay rapidly in both the positive as well as the negative directions.

2.4 Discrete Wavelet Transform Algorithm

The first discrete wavelet function was developed by Daubechies (1988), using a Haar function as a scaling function in the interval of $0 \leq x < 1$. She used a linear combination of shifted and dilated versions of the scaling function to construct the

Figure 2.1 : Examples of Continuous Wavelets

wavelet function. The coefficients of each of these linear combinations is well defined in her published works.

2.4.1 Wavelet and Scaling Functions

The most commonly used wavelet called the Daubechies wavelet (Daubechies, 1988), is based on the Haar function

$$\phi(x)=1 \quad 0 \leq x < 1. \quad (2.15)$$

A weighted sum of Eq. 2.15, called the scaling function of the wavelet, is given by

$$\phi_j(x) = \sum_{k=0}^{N-1} c_k \phi_{j-1}(2x - k) \quad (2.16)$$

The above equation defines an iterative algorithm to determine the scaling function of Daubechies wavelet. A scaling function, is the backbone of the wavelet function. A properly chosen set of coefficients c_k (Eq. 2.16) was determined by Daubechies. Therefore, the wavelet function can be defined as

$$\varphi(x) = \sum_{k=0}^{N-1} (-1)^k c_k \phi(2x + k - N + 1) \quad (2.17)$$

where N is the total number of coefficients chosen. The plots of D2, D14 and D20 are shown in Figure 2.2. The corresponding spectral plots, are shown to their right.

2.4.2 Discrete Wavelet Transforms

The study and application of discrete wavelet transforms is the main focal point of this research. AE signals generated due to fatigue testing of CFRC are transient signals. Further, Eq. 2.17 can be dilated and shifted such that

Figure 2.2 : Examples of Discrete (Daubechies) Wavelets

$$\varphi(t) = \sqrt{2^j} \varphi(2^j t - k). \quad (2.18)$$

Then the discrete wavelet transform is defined as

$$DW(j, k) = \sqrt{2^j} \int_{-\infty}^{\infty} f(t) \varphi^*(2^j t - k) dt \quad (2.19)$$

where j is the relative frequency term, k relates to time, and $\varphi^*(\cdot)$ is the complex conjugate of $\varphi(\cdot)$. Using the conditions defined in the previous section, we can reconstruct the input signal $f(t)$ from

$$f(t) = c \sum_j \sum_k DW(j, k) \varphi(t) \quad (2.20)$$

where c is a constant dependent on $\varphi(\cdot)$ only.

Consider an example; if $k = 1, 2, 3, 4$, $f(t)$ is decomposed into its wavelet series with the first order, second order and so on. Expressed as,

for $j = -1$, $f^{(\phi)}(t) = a_0 \phi(t)$ is the wavelet component of order -1, if

$j = 0$, $f^{(0)}(t) = a_1 \varphi(t)$ is the 0^{th} ordered wavelet component, and if

$j = 1$, $f^{(1)}(t) = a_2 \frac{\varphi(2t)}{a_3 \varphi(2t-1)}$ is the 1^{st} ordered wavelet component, and if

$f^{(j)}(t)$ is the j^{th} ordered wavelet component .

For a signal $f(t)$ with finite length N (N has to be a power of 2), the wavelet transform will shift the signal k times, the number of chosen coefficients c_k , and dilate the signal at different energy levels ' j ', where $j = -1, 0, 1, 2, \dots, n$. At each level the number of wavelet coefficients are $2^0, 2^1, 2^2, \dots, 2^j$.

2.5 Wavelet based Acoustic Emission Analysis

The AE signals emitted from materials (composites, metals, wood, etc.) are in a wide frequency range (10 KHz - 1.0 MHz). Dividing this range into a number of consecutive frequency bands allows each band in this range to represent different AE signals from the material under stress. The representative frequency bands of the different failure modes in composites can be quantified and shown that each has certain differing values according to the material properties (Yamaguchi et al., 1986; Chefarouni et al., 1987). In this work, the representative frequency bands were obtained by decomposing the AE signal into different wavelet levels. Each wavelet level corresponds to a certain frequency band.

Let $f(t)$ be the digitized signal in the time domain with length N , the value of N must be a power of two. Based on Eq 2.20, it is possible to decompose the signal as

$$f(t) = f^{(\phi)}(t) + f^{(0)}(t) + f^{(1)}(t) + \dots + f^{(j)}(t) + \dots$$

where $f^{(\phi)}(t)$, $f^{(0)}(t)$, ..., and $f^{(j)}(t)$ are the levels of the decomposed signal.

Therefore, $f(t)$ is grouped according to the frequency component during a period of sampling length. The algorithm used for discrete wavelet transform was developed by Newland (1993).

Let $E^{(\phi)}(t)$, $E^{(0)}(t)$, ..., and $E^{(j)}(t)$ be defined as different levels of energy, that is the decomposed accumulative energy of different levels at any time t during the test. Namely

$$E^{(\phi)}(t) = \sum_{\tau=1}^t (f^{(\phi)}(\tau))^2 \quad (2.21)$$

$$E^{(0)}(t) = \sum_{\tau=1}^t (f^{(0)}(\tau))^2 \quad (2.22)$$

$$E^{(1)}(t) = \sum_{\tau=1}^t (f^{(1)}(\tau))^2 \quad (2.23)$$

$$E^{(j)}(t) = \sum_{\tau=1}^t (f^{(j)}(\tau))^2 \quad (2.24)$$

the total energy is given by

$$E^{(t)}(t) = \sum_j E^{(j)} \quad (2.25)$$

The ratio of energy in different levels to the total energy is an important factor and is given by

$$R^{(i)}(t) = \frac{E^{(i)}(t)}{E^{(t)}(t)} \quad i = \phi, 0, 1, 2, \dots, j. \quad (2.27)$$

The above expression gives a relative energy distribution in each level.

CHAPTER III

EXPERIMENTAL SETUP AND AE DATA ACQUISITION

3.1 Introduction

The aim of this chapter is to explain in detail the specific steps taken in fatigue and tensile testing of CFRC specimens. An overview of the steps involved from the preparation of the specimens, their testing, data acquisition and the various instruments and tools used is presented in detail.

3.2 Specimen Preparation

3.2.1 Fatigue Specimen

Standard fatigue specimens were machined according to ASTM guidelines D3479-76 (Reapproved 1990) (ASTM, 1994) from the 300x300 mm square 12-ply unidirectional CFRC panel using a diamond impregnated circular cutting saw. Specimen dimensions are 19.1 mm width, 250 mm length and thickness of 1.1 mm as shown in Figure 3.1. Tabs were prepared from Aluminum, and diamond patterns were machined on their surface to offer a rough contact surface between the specimen and tabs as well as between tabs and the machine grips. The objective of using tabs was to prevent the slippage of specimen during loading, minimize the noise signals originating from the grips and reduce stress concentration in the regions where the specimen is

Dimensions not to scale

Figure 3.1 : Standard Fatigue Specimen

held by the grips. The tabs were glued onto the specimens using ¹G-5 epoxy resin-hardener. A one-to-one mixture of resin-hardener was allowed to cure for 48 hours as recommended by the manufacturers for 100% effectiveness.

V-notches with a notch length-to-width ratio (a/W) of 0.2 and circular notches with diameters ranging from 2 mm to 4 mm were machined using diamond tipped cutting tools to study the effects of notches on the failure analysis of CFRC specimens under fatigue loading.

3.2.2 Tensile Specimen

Standard tensile specimens were machined according to ASTM guidelines D3039/D3039 M (ASTM, 1994) from the 300x300 mm square 12-ply unidirectional CFRC panel using a diamond impregnated circular cutting saw. Specimen dimensions are 15 mm width, 230 mm length and the specimen thickness was 1.4 mm as shown in Figure 3.2. V notches and circular notches were machined using diamond tipped cutting tools. The specimen edges were finely ground to avoid regions of stress concentration and to remove any flaws on the edges due to machining.

3.3 AE Instrumentation

3.3.1 Sensors

Two $\mu 30$ sensors with resonant frequency of 300 KHz manufactured by Physical Acoustics Corporation (PAC) were used. The frequency response spectrum

¹ Guogeon Brothers, Inc.

Dimensions not to scale

Figure 3.2 : Standard Tensile Specimen

of the sensor, is shown in Figure 3.3. The key element in a AE sensor/transducer is the piezoelectric disk, that converts the mechanical energy carried by the elastic wave into an electrical signal. A typical construction of an AE transducer is shown in Figure 3.4. The piezoelectric transducers have a limited bandwidth and will not reproduce accurately the signal amplitudes outside of their response range.

3.3.2 Couplant

High vacuum grease, a silicon couplant manufactured by Dow Corning was used as a couplant. It has an operating temperature range from -40 to 100 deg C. A sensor simply placed on the surface to pick up AE signals does not pick up any of the low amplitude signals. Thus, there is a need to use some kind of a viscous medium between the sensor and the material surface. A couplant is best suited for this job and aids in the transmission of acoustic waves between the two surfaces.

3.3.3 Pre-amplifiers

A PAC manufactured pre-amplifier model 1220 A, with a 40 dB gain was used to amplify the signal generated by the sensor. The piezoelectric sensor generates a very low output voltage, this signal will be lost before it reaches the data acquisition system. Therefore, it is necessary to use a pre-amplifier to amplify this signal. The main components of the 1220A pre-amplifier are a plug in filter of bandwidth 100-300 KHz (can be changed as per user specifications) and a basic amplifying circuit as shown in Figure 3.5.

Figure 3.3 : AE Transducer Description (Courtesy PAC)

Figure 3.4 : Frequency Response Spectrum of Sensor (Courtesy PAC)

A pre-amplifier was placed as close to a sensor as possible to minimize pickup of electromagnetic interference. A pre-amplifier can drive a signal over a long length of cable so that the instrumentation can be placed at a safe distance from the test setup. The filter is a high pass or band pass type to eliminate mechanical and acoustical background noise that prevails at low frequencies. Some sensors have built-in pre-amplifiers, but are rarely used due to their bulky size. Pre-amplifiers are also used to condition signals.

3.3.4 A/D Board

The heart of AE systems is the Data Acquisition board. The AE data was acquired using a PAC AEDSP-32/16 PC based two-channel high sampling frequency (8 MHz) A/D data acquisition board. This A/D board is completely software controlled. A block diagram of the board is shown in Figure 3.6.

In addition to acquiring AE data, the A/D board is capable of filtering data, extracting signal shape features, frequency features and pulsing the sensor that allows for extra information on the sensors coupling and sensitivity. As can be seen from Figure 3.6 AE signals from the pre-amplifier are fed to the A/D board through the 2 BNC connectors at the rear of the board. The AE signal is then buffered and sent to a plug-in filter module. The filter module contains multiple high and low pass filters that are user selected. The output of the plug-in filters is fed to an 8th-order low pass filter for anti-aliasing and then sent to the Analog to Digital filter (ADC) module for digitization. The output of each ADC module is fed to the TMS320C40 Digital Signal

Figure 3.5 : Amplifying Circuit of Pre-Amplifier (Courtesy PAC)

Figure 3.6 : Block Diagram of A/D Board (Courtesy PAC)

Processor for waveform processing and control, and to the feature extractor for real time feature extraction. The output of the feature extractor is fed directly to C40-DSP, which is the main controller of the AE digital PC card. The C40-DSP reads all the extracted features from each channels feature extraction hardware, normalizes the data and performs front end filtering. In addition, it also processes AE waveforms and parametric inputs. A cooling fan that fits into a slot next to the A/D board is provided to re-circulate air around the data acquisition board to help dissipate heat.

3.4 AE Test Parameters

Physical Acoustic Corporation AE application software Massively Instrumented Sensor Technology for Received Acoustic Signals (MISTRAS) was used to acquire the raw data and for basic data processing and conventional AE analysis.

MISTRAS is a combination of several modules and has the capability to control the A/D board, source location analysis, conventional AE parametrization, clustering methodology and time ordering utility. In order to successfully acquire data a series of parameters have to be set. These hardware settings were determined after much trial and error. A series of trial tests were performed in order to select the proper AE test parameters. Table 3.1 details all the AE test parameters used.

Table 3.1 Setup AE Test Parameters

Parameter	Set Value / Option
Threshold type	Float
Threshold	75 dB
Peak Definition Time (PDT)	200 μ sec
Hit Lockout Time (HLT)	300 μ sec
Hit Definition Time (HDT)	400 μ sec
Sample Rate	4 MHz
Filter on Board (low)	10 KHz
Filter on Board (high)	1200 KHz
Pre-trigger	20 μ sec
Hit Length	4 K
30 Hz low Pass Filter	No
Cycle Counter Threshold	1.0 Volts
Front End Filters	No
Delta-T Front End Filters	Yes

3.4.1 Spatial Filtering

During fatigue tests, a lot of acoustic energy is generated by the specimen grips and the loading machine. This unwanted noise was eliminated by spatial filtering of the raw signal. Delta-T-Front end filters (software option) were used and all the emissions originating from beyond the sensor location at either end were filtered by eliminating all independent hits and setting up an Event Definition Time (EDT) of 100 μ sec's. Thus, AE from sources within 30-70% of the gage length were collected and processed.

3.4.2 Wave Reflections

As an effective method to minimize the AE events from reflections of emission waves from edges of the specimens, and alternate paths, a very low value of Hit Lockout Time (HLT) of 400 μ sec was used. This measures only the main part of the wave that originates from the source event and the AE events from reflections are not recorded. Figure 3.7a describes a recorded hit with reflections and Figure 3.7b shows a recorded hit without reflections.

3.5 Experimental Procedure

The fatigue testing of the CFRC specimen was carried out in 2 steps. A series of tensile tests were conducted on the CFRC specimens, in order to determine their Ultimate failure load. Tests were performed under a quasi-static uniaxial tensile loading condition on a closed-loop servo-hydraulic Material Testing System (MTS)

Figure 3.7 : AE Hit with and without Reflections

machine. The experiments were carried out in stroke control mode at a rate 0.1 in/min. (2.54 mm/min.). The specimen were loaded to failure. The load displacement parameters were acquired using an application module written in ²LabView. The A/D board used was a National Instruments AT-MIO-16 series. Continuous AE data was recorded in order to reproduce and verify existing results. It also helped in correcting and fine tuning the set AE parameters. The tensile tests were repeated on the double V-notched and circular notched specimens.

A series of fatigue tests were conducted on the CFRC. The specimens were subjected to a constant amplitude uniaxial tension-tension fatigue loading under load control mode at a frequency of 10 Hz. All tests were conducted on a closed loop servo-hydraulic Materials Testing System (MTS) machine. The specimens were subjected to a static load of 50% ultimate failure load and in addition constant amplitude sinusoidal loads at different load ranges was applied, ranging from 10% to 30% of the ultimate failure load. The loading pattern is shown in Figure 3.8. Shown in Figure 3.9 is the experimental setup.

Acoustic Emission (AE) was monitored using PAC's MISTRAS instrumentation. Two micro(μ) 30 transducers of 300 KHz resonant frequency were mounted 6 cm apart, about the center, on either ends of the specimen, using suitable hold downs. High vacuum silicone grease was used as couplant. Aluminum tabs were glued to the specimen to prevent unwanted noise from the grip regions and also prevent slipping of the specimens. Spatial filtering was performed to eliminate

² Product of National Instruments, Inc.

Figure 3.8 : Fatigue Loading Pattern

Dimensions not to scale

Figure 3.9 : Experimental Setup

unwanted noise from the grips and the hydraulics. Emission from only 30-70% of the gage length was acquired and analyzed. Hit Lockout Time of 400 μ sec's was set to eliminate reflection hits. A 1220A pre-amplifier manufactured by PAC with a fixed gain of 40 dB was used. A floating threshold of 75 dB was applied, in addition to a cycle counter threshold of 0.8 Volts. Post amplifier gain of 10 and a dead time of 1 msec was used. AE data was not acquired during the quasi-static loading of the specimen to 50% of its ultimate failure load.

The main objective of the above experimentation and analysis is to distinguish and separate using the wavelet based technique the emission from fretting and friction from emission resulting from an actual damage, for example matrix failure, matrix cracking, crack propagation and fiber related events.

The above tests were repeated on double V-notched and circular notched 12-ply unidirectional specimens. The notched specimens were tested using the same procedure as the unnotched specimens explained above. The procedure adopted for the wavelet and conventional AE analysis is explained in the following chapter.

CHAPTER IV

IDENTIFICATION AND SEPARATION OF FRICTION RELATED EVENTS THROUGH WAVELET-BASED AE ANALYSIS

4.1 Introduction

Fatigue can be theoretically defined as “ the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations” (ASTM E1150-85).

4.2 Test Series

Fatigue and tensile tests were conducted on CFRC specimen. The objective of the tests was to replicate the loading sequences and patterns a material has to go through during its entire operating period. Quasi-static tensile tests were conducted to determine the ultimate failure load of the specimen. The specimens were subjected to fatigue loading in a tension-tension mode. A predetermined static load of 50% ultimate failure load was applied. In addition, a constant amplitude sinusoidal loading sequence was adopted as it was simple to simulate on a Material Testing System (MTS) and also replicates the loading sequence carbon composite structures undergo. A series of

tests were performed under identical loading conditions to assure consistency of results. A selected sampling of the tests performed is tabulated in Table 4.1.

Table 4.1 Test Series

Test Type	Test Number	Specimen	Number of cycles	Load Sequence	Failure mode
Tensile	T2.dta	Un-notched	-	Max St 10,200 lb	F & M
Tensile	T3.dta	Un-notched	-	Max St 9,960 lb	F & M
Tensile	T11.dta	Un-notched	-	Max St 10,467 lb	F & M
Fatigue	fat1..13.dta	Un-notched	31,200	St = 5000 lb Cyc = 10 %	II stage
Fatigue	f1.. 14.dta	Un-notched	2,00,000	St = 6000 lb Cyc = 20 %	III stage
Tensile	F4g.dta	Circular Notch 4 mm	-	Max St 5400 lb	M
Fatigue	F4g1..6.dta	Circular Notch 4 mm	18,000	St = 3000 lb Cyc = 20 %	M, II stage
Fatigue	F4a1..8.dta	Circular Notch 4 mm	23,000	St = 3400 lb Cyc = 20 %	M, II stage
Tensile	FF.dta	Double V- notch (a/w=0.2)	-	Max St 4200 lb	F & M
Fatigue	FF1..7.dta	Double V- notch (a/w=0.2)	11,100	St = 2000 lb Cyc = 20 %	M, II stage
Fatigue	FK1..3.dta	Double V- notch (a/w=0.2)	3,000	St = 2000 lb Cyc = 20 %	M, I Stage
Fatigue	FQ1..5.dta	Double V- notch (a/w=0.2)	9,700	St = 2000 lb Cyc = 20 %	I stage

F - Fiber Failure, M-Matrix Failure, St - Static Load, Cyc - Cyclic load as % of Ultimate Load

Figure 4.1 describes a typical fatigue curve of a CFRC specimen subjected to constant amplitude cyclic loading. The total AE counts are plotted with respect to the number of fatigue load cycles for the test series FS (Table 4.1). The fatigue life cycle of a CFRC specimen can be described by three predominant stages. A very short duration stage I accounts for 5-10% of the total fatigue life. Lot of AE activity was observed in the I stage and this short period of high activity could be attributed to the large number of new damages occurring in the weaker component of the CFRC specimen, i.e., the matrix. Stage II was found to be more dormant in comparison to stage I with very little AE activity. It was observed that the slope of the fatigue curve during stage II was fairly constant. This stage accounts for about 75-80% of the total fatigue life. Stage III or the final stage was observed to be of a very short duration with high AE activity. This stage was attributed to the final failure of the test specimen. This has been explained later in this chapter.

Continuous monitoring of AE during the fatigue test was not possible due to limitation of disk space on the computer. Therefore, 200-300 AE hits were acquired at intervals of every 3,000 fatigue cycles. The sensor response was deconvolved from the acquired AE signal as explained in the next section.

4.3 Discrete Wavelet Analysis

Wavelet analysis of AE is still in its infancy. The need to use discrete wavelet analysis instead of continuous wavelets can be explained by the fact that AE signals are of transient nature. Before application of the discrete wavelet transforms to AE

Typical Fatigue Curve

Figure 4.1 : Typical Fatigue Curve

signals, the sensor and pre-amplifier responses were deconvolved from the collected AE signal. Discrete wavelet analysis was performed on the deconvolved acoustic emission signal.

4.3.1 Deconvolution of Sensor and Pre-amplifier response

Deconvolution of the sensor and pre-amplifier response from the acquired AE signal was carried out to remove any contribution from these sources to the actual signal. Let $f(t)$ be the AE signal from the material that reaches the sensor, $h(t)$ be the sensor and pre-amplifier response and $g(t)$ be the signal that is acquired by the A/D board. Hence, we have

$$g(t) = h(t) \cdot f(t) \quad (4.1)$$

taking the FFT, we have

$$G(\omega) = F(\omega) H(\omega) \quad (4.2)$$

rewriting eq. (4.2), we have

$$F(\omega) = \frac{G(\omega)}{H(\omega)}. \quad (4.3)$$

Eq (4.3) is called point-by-point spectral division. This can be used to remove the sensor and the pre-amplifier effects. Taking the inverse FFT, we get

$$f(t) = IFFT(F(\omega)) \quad (4.4)$$

where, $f(t)$ is the deconvolved AE signal.

The signal $H(\omega)$, is obtained by taking the Fourier transform of the calibration signal $h(t)$, obtained from the pencil break (impulse response) test on the composite laminate. Figure 4.2 shows the original and the reconstructed deconvolved signal.

4.3.2 Wavelet Analysis of Deconvolved AE Signal

The application of discrete wavelet analysis to the deconvolved AE signals, resulted in eleven different wavelet levels. As explained in Chapter II, the hit length analyzed was 1024 points (1 Kbytes), and this resulted in 11 wavelet levels. Each level represents a specific frequency range, the frequency increases with the increasing wavelet level.

The frequency spectra of levels 6 through 11 for AE data from the I, II and III stages of the fatigue cycle has been presented in Figures 4.3, 4.4 and 4.5. From the figures, it is possible to infer that the frequency of level 7 is centered at about 120 kHz, the frequency of level 8 is centered at about 250 kHz, and the frequency of level 9 is centered at about 300 kHz. There is an accumulative energy associated with each energy level. The results revealed that the total energy in levels 1 through 6, 10 and 11 account for less than 5% of the total energy, and their frequencies are also beyond that of the operating range of the sensor and the pre-amplifier. Therefore, the results from these levels were ignored and the results from the levels 7, 8 and 9 are discussed in detail.

Figure 4.2 : Original and Reconstructed Signals

Figure 4.3 : Frequency Spectrum in Different Wavelet Levels (Stage I)

Figure 4.4 : Frequency Spectrum in Different Wavelet Levels (Stage II)

Figure 4.5 : Frequency Spectrum in Different Wavelet Levels (Stage III)

4.3.3 Test Results and Analysis

The results of the wavelet analysis applied to AE data from the stages I, II and III (levels 7, 8, and 9) for a typical unidirectional specimen are shown in Figures 4.6, 4.7 and 4.8. Figures 4.6a, 4.7a and 4.8a represent the energy change rate per event versus event count and Figures 4.6b, 4.7b and 4.8b represent the accumulative energy versus event counts in level 7 (centered at a frequency of about 120 kHz). The figures (all 4.x a) show extensive non-repetitive activity and account for about 5-10% of the total AE energy.

Figures 4.6c, 4.7c and 4.8c represent the energy change rate per event versus event count and Figures 4.6d, 4.7d and 4.8d represent the accumulative energy versus event counts in level 8 (centered at a frequency of 250 kHz). Figure 4.6c, which corresponds to data from the I stage of the fatigue cycle, shows similar non-repetitive activity as in level 7, but have a higher energy content. As this data is from the early stages and there is not much activity due to friction, we can conclude that this should relate to matrix related failures, this has been explained in the later part of the chapter. Figures 4.7c and 4.8c (stages II and III) show predominantly low amplitude repetitive activity and can be speculated as friction related activity. The total energy in level 8 is about 20-30 % of the total AE.

Figures 4.6e, 4.7e and 4.8e represent the energy change rate per event versus event count and Figures 4.6f, 4.7f and 4.8f represent the accumulative energy versus event counts in level 9 (centered at a frequency of 300 kHz). Figure 4.6e, which corresponds to data from the I stage of the fatigue cycle, shows similar non-repetitive

Figure 4.6 : Energy Distribution of Unidirectional CFRC (Stage I)

Figure 4.7 : Energy Distribution of Unidirectional CFRC (Stage II)

Figure 4.8 : Energy Distribution of Unidirectional CFRC (Stage III)

activity as in levels 7 and 8, but has a higher energy content than all the other energy levels. As this data is from the early stages and there is not much activity due to friction, we can conclude that this should relate to matrix related failures, this has been explained in the later part of the chapter. Figures 4.7e and 4.8e (stages II and III) show predominantly low amplitude repetitive activity and can be speculated as friction related activity. The total energy in level 9 is about 60-70 % of the total AE.

4.3.4 Differentiate Friction Related Emission

Friction related emission contributes a major amount to the total emission. Thus, it becomes necessary to distinguish the friction related emission, in order to analyze the emission from the actual damage. As levels 7, 8 and 9 correspond to about 95% of the total energy, only these levels have been analyzed for friction related emission. Figures 4.6a, c and e, 4.7a, c and e and 4.8a, c and e represent energy change per events plots inclusive of friction related emission.

Friction generated emission was eliminated through the setting up of filters (some kind of bandpass) in the wavelet levels 7, 8, and 9 based on event duration, event amplitude any energy count. All events below energy count of 50 and time duration of 250 μ sec were filtered from the original signal, before the signals were subjected to wavelet analysis. Figures 4.9, 4.10 and 4.11 describe the energy distribution plots after the removal of friction related events.

Figures 4.9a and b, 4.10a and b and 4.11a and b represent level 7. The change in accumulative energy after removal of the friction related emission is about 0.4%.

Figure 4.9 : Energy Distribution after Removal of Friction (Stage I)

Figure 4.10 : Energy Distribution after Removal of Friction (Stage II)

Figure 4.11 : Energy Distribution after Removal of Friction (Stage III)

Therefore, we can conclude that level 7 essentially corresponds to emissions from matrix related damages.

Figures 4.9c and d , 4.10c and d and 4.11c and d represent level 8. The change in accumulative energy after removal of the friction related emission is about 7.2% in the I stage of fatigue (corresponding to Figures 4.9c, d). This phenomenon can be explained by the fact that not many friction related events occur in the initial stage of the fatigue cycle. On the other hand a change in the accumulative energy of about 68% in the intermediate stage and 65% in the final stage was observed. This clearly explains that a major amount of emissions are friction related in the intermediate and the final stages of the fatigue cycle.

Figures 4.9e and f, 4.10e and f and 4.11e and f represent level 9. Similar trends as in level 8 is observed here. The change in accumulative energy after removal of the friction related emission is about 1.3% in the I stage of fatigue (corresponding to Figures 4.9e and f). The change in the accumulative energy of about 39% in the intermediate stage and 32% in the final stage was observed. This clearly explains that a large amount of emissions are friction related in the intermediate and the final stages of the fatigue cycle. Therefore, it can be concluded that friction related emissions occur at a frequency range of about 250-300 kHz. The energy change per event plots clearly show that once friction related events are removed, only a few peaks were observed, this again confirms the conclusion that friction accounted for a major amount of emission in levels 8 and 9.

Another point of interest is that as the frequencies of levels 8 and 9 are very close, they might correspond to the same source of emission. This has to be investigated further, by breaking up the events in level 8 and 9 into further more sub-levels.

CHAPTER V

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusion

Discrete wavelet based analysis of acoustic emission from carbon composites, offers a new dimension to the field of non-destructive testing. Discrete wavelet analysis, although in its infancy to its application to AE, offers distinct advantages in terms of time saving, analysis of results, flaw criticality determination, separation of emission from different sources, as compared to conventional AE analysis. Described below are the main conclusions:

1. The discrete wavelet transforms decompose an AE signal into different wavelet levels. Each level corresponds to the components of the decomposed AE signal in a certain frequency range and also captures any local disturbances in its dominant level. This facilitates the investigation of internal defects in the material. Therefore, wavelets could be compared to bandpass digital filters in their working principle, as they allow signals in only a specified frequency range to pass through (in a particular wavelet level).
2. In the series of tests performed, the energy carried by the AE signal, is predominantly concentrated in levels 7, 8, and 9, with 70% of total energy in level 9, 20% of total energy in level 8 and about 8% of total energy in level 7. The reconstructed signals from levels 7, 8, and 9, were identical to the original signal,

with only a small change in amplitude. This, further verifies the author's claim that 7, 8 and 9 are the predominant levels in the AE signals analyzed.

3. Levels 7, 8 and 9 correspond to a frequency range of 100-300 kHz, and also contain about 95% of the total emission. Therefore, it can be concluded that most of AE energy from carbon composites is in the 100-300 kHz range.
4. As a resonant sensor was used for data acquisition, the sensor response was deconvolved from the acquired signal, using a point-by-point division spectral method to overcome any skewing of the signal in the resonant frequency band.
5. Friction emission threshold (FRET) values were used to eliminate the friction related emission from the acquire signal. Friction related emission, in some cases corresponds to about 80% of total emission as can be seen from stages II and III. Therefore, friction related emission has to be eliminated from the acquired data in order to analyze the AE from any damage sources.
6. Friction related emission corresponds to wavelet levels 8 and 9 (II and III stages of the fatigue cycle). Therefore, it can be concluded that friction related emission corresponds to a frequency range of 250-300 kHz.
7. It can be seen from the energy plots that there is almost no visible friction related emission in level 7 (centered at 120 kHz). The results clearly indicate that level 7 is essentially matrix related emission.
8. The results indicate the presence of large amplitude, non-repetitive events in the initial stages of the fatigue test, this phenomenon could be attributed to matrix related emission. During the intermediate stage, repetitive low amplitude events

were observed and can be explained as emissions from friction and due to crack propagation. During the final stage, large amplitude signals, along with repetitive low amplitude events were observed. Therefore, it could be concluded that final stage is a combination of friction related emission and emission from fiber related damage.

5.2 Recommendations for Future Work

The following recommendations for future research in this area are recommended in addition to the on going process to develop a more effective and faster method for wavelet analysis of AE.

1. Use of faster wavelet transform algorithms to minimize AE analysis time.
2. Use of broad band sensors instead of resonant sensors in order to remove any effects of the sensor response on the acquired signal.
3. Use of different configurations and lay-ups of carbon composite laminates to confirm the repetitiveness of the above results.
4. Use of this method (discrete wavelet analysis of AE) for online inspection of processes and components.
5. Simulation of the fatigue process on a computer using a finite element code and verify both experimental and theoretical results.
6. Relating level energy to the parameters of fracture mechanics.
7. Identify various failure modes on-line using wavelets.

8. Obtain microscopic scans of the damaged area to correlate a specific event to any damage.
- 9 Modify existing software (¹ mi2asc), to obtain more points than the existing 1024 (the number of points should also be a power of 2). This, would help in adding more wavelet levels and lead to a more accurate analysis. Addition of more wavelet levels would also cause a shift in central frequencies of the different wavelet levels.

¹ Registered product of PAC.

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APPENDIX

MATLAB CODES (Wavelet Transforms)

```

%      Module for the energy analysis of the acquired AE signal
%      Code Developed by Qi Gang and Girish
%      Algorithm Developed by Newland (1993)
clear
t0 = clock;
file = [0 0 0 0 0 0];
k = 0;
M = 196;
lines = 9;
while k < M
    k = k+1;
    clear e_in_L;
    clear A;
    if k < 10
        datak = ['fk300' int2str(k)];
    elseif k >= 10 & k <= 99
        datak = ['fk30' int2str(k)];
    else
        datak = ['fk3' int2str(k)];
    end
    y = j_fscanf(datak, lines);

    %
    % Following is the discrete wavelet transform
    %
    A=displayn(y,16);
    %
    % calculate the energy carried by different
    % level of wavelet transform

    % n is the starting number of rows in A wanted
    % to be analyzed.
    %
    n = 6;
    for i = n:10
        e_in_L(i-n+1) = energy(A(i,:));
    end
    e_in_L(6) = sum(e_in_L(1:5));
    %
    % put the value of energy in level into a matrix file
    % of name <file> with first column having energy in level
    % 7th, second in level 8th, ..., fifth in level 11th and
    % the last column is the total energy summed from all levels.
    file1 = [file1;e_in_L];

```

```
end  
t_used = etime(clock, t0)/60
```

```

% This module performs the data arrangement and draws the related figures
%     Code Developed by Qi Gang and Girish
%     Algorithm Developed by Newland (1993)
clear

% Load the result data file from e_anasys.
load fs12n.dat /ascii;
file = fs12n;

% Creat a new file named file_cum which is the corresponding acumulative energy in
% each column of file.

% Input the number of levels and the number of hits which are considered, n is the
% level and m is the hits.

m = size(file(:,1));
n = 5 + 1;
% where 5 is levels and 1 is the sum at certain time.

for j=1:n
    for i=1:m
        file_cum(i,j) = sum(file(1:i,j));
    end
end
%
% Next, it is ready to make figures to compare and analyze the results

for j=1:n
    figure(j);

    subplot(211),plot(file(:,j)),...
    if j==6
        title('total energy change rate'),...
    else
        title(['energy change rate in level ' int2str(j+5)]),...
    end
    ylabel('energy change rate /hit'), grid;

    subplot(212),plot(file_cum(:,j),'.'),...
    if j==6
        title('total energy in all levels'),...
    else
        title(['accumulative energy in level ' int2str(j+5)]),...
    end
end

```

```

    xlabel('event'),...
    ylabel('accumulative energy'),grid;
end
% Calculate the energy percentage contained in each level corresponding to the total

for i=1:5
    file_p(:,i) = file_cum(:,i)./file_cum(:,6);
end

figure(j+1);
hold on
hold off

```

```

% Module for Wavelet Transform of AE signal
% Code Developed by Qi Gang and Girish
% Algorithm Developed by Newland (1993)
function a = wavedn(f,N)
%
% This is a trial programming of wavelet transform
%
M = length(f);
n = round(log(M)/log(2));
c = dcoeffs(N);
clr = fliplr(c); % This function flip matrix c
for j=1:2:N-1, clr(j) = -clr(j); end
a = f;
for k = n:-1:1
    m = 2^(k-1);
    x = [0]; y = [0];
    for i = 1:1:m
        for j = 1:1:N
            k(j) = 2*i-2+j;
            while k(j)>2*m, k(j)=k(j)-2*m;end
        end
        z = a(k);
        [mr,nc] = size(z);
        if nc>1, z=z.';end
        x(i) = c*z;
        y(i) = clr*z;
    end
    x = x/2; y = y/2;
    a(1:m) = x;
    a((m+1):2*m) = y;
end
end

```

```

% Module for Inverse Wavelet Transform of AE signal
% Code Developed by Qi Gang and Girish
% Algorithm Developed by Newland (1993)
function f = iwavedn(a,N)
%
% This fragment is to reconstruct the signal
%
M = length(a);
n = round(log(M)/log(2));
c = dcoeffs(N);
f(1) = a(1);
for j = 1:1:N/2
    c1(1,j)=-c(2*j);
    c1(2,j)=c(2*j-1);
    c2(1,j)=c(N-2*j+1);
    c2(2,j)=c(N-2*j+2);
end
for k=1:1:n
    m = 2^(k-1);
    for i=1:1:m
        for j=1:N/2
            k(j) = m+i-N/2+j;
            while k(j)<m+1,k(j)=k(j)+m; end
        end
        z = a(k); [mr,nc] = size(z); if nc>1,z=z.'; end
        x(2*i-1:2*i) = c1*z;
        zz = f(k-m);[mr,nc]=size(zz);if nc>1,zz=zz.';end
        xx(2*i-1:2*i) = c2*zz;
    end
    f(1:2*m) = x + xx;
end
end

```



```

% Module to display the reconstructed AE signal
%      Code Developed by Qi Gang and Girish
%      Algorithm Developed by Newland (1993)
function A = displayn(f,N)
%
M = length(f);
n = round(log(M)/log(2));
% subplot(211)
% plot(f),grid,title('signal f')
a = wavedn(f,N);

b = zeros(size(1:M));
b(1) = a(1);
A(1,:) = iwavedn(b,N);
for i=2:1:n+1
    b = zeros(size(1:M));
    b(2^(i-2)+1:2^(i-1))=a(2^(i-2)+1:2^(i-1));
    A(i,:)=iwavedn(b,N);
end

```

```

% Module to Compute the Coefficients of the Wavelet Transforms
% Code Developed by Qi Gang and Girish
% Algorithm Developed by Newland (1993)
function c = dcoeffs(N)
%
% This fragment is to generate the N coefficients required by the
% wavelet transformation.
%
% Format of using this function is c = dcoeffs(N)
% where N is the number of Daubechies'wavelet coefficients
%
if N == 2,
    c(1) = 1;
    c(2) = 1;
end
if N == 4,
    c(1) = (1+sqrt(3))/4;
    c(2) = (3+sqrt(3))/4;
    c(4) = (3-sqrt(3))/4;
    c(4) = (1-sqrt(3))/4;
end
if N == 6,
    s = sqrt(5+2*sqrt(10));
    c(1) = (1+sqrt(10)+s)/16;
    c(2) = (5+sqrt(10)+3*s)/16;
    c(3) = (5-sqrt(10)+s)/8;
    c(4) = (5-sqrt(10)-s)/8;
    c(5) = (5+sqrt(10)-3*s)/16;
    c(6) = (1+sqrt(10)-s)/16;
end
if N == 8,
    c(1) = .325803428051;
    c(2) = 1.010945715092;
    c(3) = .892200138246;
    c(4) = -.039575026236;
    c(5) = -.264507167369;
    c(6) = .043616300475;
    c(7) = .046503601071;
    c(8) = -014986989330;
end
if N == 10,
    c(1) = .226418982583;
    c(2) = .859343542705;
    c(3) = 1.024326944260;

```

```

c(4) = .195766961347;
c(5) = -.342656715382;
c(6) = -.045601131884;
c(7) = .109702658642;
c(8) = -.008826800109;
c(9) = -.017791870102;
c(10) = .004717427938;
end
if N == 12,
    c(1) = .157742432003;
    c(2) = .699503814075;
    c(3) = 1.062263759882;
    c(4) = .445831322930;
    c(5) = -.319986598891;
    c(6) = -.183518064060;
    c(7) = .137888092974;
    c(8) = .038923209708;
    c(9) = -.044663748331;
    c(10) = .000783251152;
    c(11) = .006756062363;
    c(12) = -.001523533805;
end
if N == 14,
    c(1) = .110099430746;
    c(2) = .560791283626;
    c(3) = 1.031148491636;
    c(4) = .664372482211;
    c(5) = -.203513822463;
    c(6) = -.316835011281;
    c(7) = .100846465010;
    c(8) = .114003445160;
    c(9) = -.053782452590;
    c(10) = -.023439941565;
    c(11) = .017749792379;
    c(12) = .000607514996;
    c(13) = -.002547904718;
    c(14) = .000500226853;
end
if N == 16,
    c(1) = .076955622108;
    c(2) = .442467247152;
    c(3) = .955486150427;
    c(4) = .827816532422;
    c(5) = -.022385735333;

```

```

c(6) = -.401658632782;
c(7) = .000668194093;
c(8) = .182076356847;
c(9) = -.024563901046;
c(10) = -.062350206651;
c(11) = .019772159296;
c(12) = .012368844819;
c(13) = -.006887719256;
c(14) = -.000554004548;
c(15) = .000955229711;
c(16) = -.000166137261;
end
if N == 18,
    c(1) = .053850349589;
    c(2) = .344834303815;
    c(3) = .855349064359;
    c(4) = .929545714366;
    c(5) = .188369549506;
    c(6) = -.414751761802;
    c(7) = -.136953549025;
    c(8) = .210068342279;
    c(9) = .043452675461;
    c(10) = -.095647264120;
    c(11) = .000354892813;
    c(12) = .031624165853;
    c(13) = -.006679620227;
    c(14) = -.006054960574;
    c(15) = .002612967280;
    c(16) = .000325814672;
    c(17) = -.000356329759;
    c(18) = .000055645514;
end
if N == 20,
    c(1) = .037717157593;
    c(2) = .266122182794;
    c(3) = .745575071487;
    c(4) = .973628110734;
    c(5) = .397637741770;
    c(6) = -.353336201794;
    c(7) = -.277109878720;
    c(8) = .180127448534;
    c(9) = .131602987102;
    c(10) = -.100966571196;
    c(11) = -.041659248088;

```

```
c(12) = .046969814097;  
c(13) = .005100436968;  
c(14) = -.055179002335;  
c(15) = .001973325365;  
c(16) = .002817686590;  
c(17) = -.000969947840;  
c(18) = -.000164709006;  
c(19) = .000132354366;  
c(20) = -.000018758416;
```

```
end
```

```

% Module that reads a sequential set of files
%     Code Developed by Qi Gang and Girish
%     Algorithm Developed by Newland (1993)
function y = j_fscanf(datak,lines)
%
    filename = [datak '.da1'];
    fid=eval(['fopen( "' filename ' "',"r")']);

    if fid < 0
        filename = [datak '.da2'];
        fid=eval(['fopen( "' filename ' "',"r")']);
    end

    if fid < 0
        filename = [datak '.dat'];
        fid=eval(['fopen( "' filename ' "',"r")']);
    end

    frewind(fid);
    byets = lines*20;
    fseek(fid,byets,-1);
    y=fscanf(fid, '%d');
    fclose(fid);
%
% end

```

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