# Wavelets Entropy and Zero-Crossing White-Noise Test Applied to Ultrasonic Classification of Degrading Adhesive Joints

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**Abstract.** Composite adhesive joints were exposed to harsh environmental conditions and subjected to destructive and non-destructive ultrasonic testing. The signals were subjected to numerous wavelet transforms in an attempt to decipher a means of monitoring the degradation of the joints. The application of the wavelet transforms does not seem to contribute significant features for the classification of the joints according to their fitness for use. However, entropy calculations based on either the wavelet transforms or the Higher Order Crossing white noise test provide a mean for monitoring the degradation and reveal a cusp pattern which provides an alarming indication whenever the strength of the joints had been reduced by 20%.

## 1. Introduction

One approach for the quantitative acquisition of discriminatory information for the classification of bonded specimens is feature-based analysis: Representative features are derived from the signals, which are used to evaluate and compare classes of specimens, by means of statistical tests, pattern-recognition and cluster-analysis techniques. It turns out, that features derived from the frequency-domain representation of the signals, following a Fourier transform, provide useful contributions to the classification schemes [1].

In the last decades new transforms were developed, namely the Wavelet Transforms. The idea of examining signals at various scales and analyzing them with various resolutions has emerged independently in many fields of mathematics, physics and engineering. Wavelet decomposition introduces the notion of scale as an alternative to frequency and maps a signal into a time-scale plane. Each scale in the time-scale plane corresponds to a certain range of frequencies in the time-frequency plane. [2].

The goal of this study was to examine the possibility of obtaining useful information or sensitive features from the presentations of the signals in the wavelet domain. To achieve this goal, two different classes of composite adhesive joints were immersed in circulating hot water and tested periodically both destructively and non-destructively by means of ultrasonics. The ultrasonic signals digitized and recorded in the experiments were subjected to numerous wavelet transforms and algorithms, as well as to some Higher Order Crossing (HOC) analyses, based on the zero-crossings of the signals [3,4]

## 2. Theoretical background and methods

*2.1Water Diffusion and Degradation of Structural Adhesive Joints*

Among the environmental factors that influence to degradation of structural adhesive joints the most commonly encountered is water. [5,6]. The rate at which the mechanical properties of a structural adhesive joint deteriorate is a function of the rate of moisture ingress and the inherent resistance of the joint to the presence of water. The latter is a function of the choice of adherents, pretreatment, primer, adhesive and curing procedures. Water ingress may significantly affect the condition of adherends in composite-to-composite joints, unlike the metal-to-metal joints, in which the water effect on the adherends is negligible, compared to the effect on the adhesive layer. The important parameters governing the environmental degradation of composites are the exposure conditions, the chemistry of the material and the mode of loading. These issues are discussed in detail in [7].

*2.2 Techniques for detecting Ultrasonic Anomaly Signals, using Wavelet analysis*

S.Legendre and co. [8] proposed a wavelet-based method to perform the analysis of NDE ultrasonic signals received during the inspection of reinforced composite materials. The non-homogenous nature of such materials induces a very high level of structural noise, which greatly complicates the interpretation of the NDE signals. To construct a C-scan image from the wavelet transform of the A-scan signals, a selection process of wavelet coefficients, followed by an interpretation procedure, based on a windowing process in the time-frequency domain were proposed. The proposed NDE method was tested on cryogenic glass/epoxy hydrogen reservoir samples.

In the research of Gang Qi [9] the acoustic emission (AE) signals from glass fiber reinforced (GFR) composites are collected during the standard quasi-static tensile testing and transformed by the Daubechies discrete wavelets. The results verify that the wavelet-based method better approximates residual strength relative to the classical AE techniques.

Nikolaou and Antoniadis proposed a method for the analysis of vibration signals resulting from bearings with localized defects using the wavelet packet transform (WPT) as a systematic tool. A time-frequency decomposition of vibration signals is provided and the components carrying the important diagnostic information are selected for further processing. [10].

A new approach for analysis of transient waves propagating in anisotropic composite laminates was presenting by H. Jeong [11]. The wavelet-transform (WT) using the Gabor wavelet is applied to the time-frequency analysis of dispersive flexural waves in these plates. It was shown that the peaks of the magnitude of WT in a time-frequency domain are related to the arrival times of the group velocity. A method was developed to obtain the group velocity of the flexural mode as a function of frequency.

In this work we apply Wavelet techniques to experimental ultrasonic signals from composite adhesive joints exposed to harsh environmental conditions.

## 3. Experiment

Composite adhesive joints of the single lap-shear configuration were used in the experiment. The samples were 25.4 mm wide, with a 12.7 mm overlap between the adherends. The total thickness of each joint area is just over 3 mm, consisting of two adherends of thickness 2 mm each, and a bond thickness of approximately 0.15 mm. Each laminated adherend was a 16 ply graphite/epoxy structure in a $[0_3, +45, -45, 0_3]_2$ sequence (2 sets of: 3 plies at $0^0$, 1 ply at $45^0$, 1 ply at $-45^0$, and 3 plies at $0^0$). The material used for the individual plies was a unidirectional prepreg, type 3502/AS-4, manufactured by Hercules Aerospace. The adherends were fabricated from the individual plies in an autoclave process at $177^0$C and 700 kPa.

A 100% nylon peel ply covered the surface of the adherend during its fabrication, and was removed before commencement of the adhesive bonding sequence.

Two different types of surface pre-treatments were applied to pairs of adherends used to manufacture the adhesive joint specimens: a standard treatment used in the Aeronautical industry for the adhesive bonding of composite materials denoted treatment P, and an inferior non-industrial treatment, denoted 'F".

Bonding of the pairs of adherends was accomplished with the film adhesive FM-300, 0.1 PSF, manufactured by American Cyanamid. Curing of the adhesive was carried out at $177^0$C and 300 kPa. A more detailed description of the specimens and their preparation is provided in [1]

The ultrasonic experimental set-up consisted of a standard ultrasonic transducer, with a nominal central frequency f = 1 MHz, a pulser / receiver, a monitor, a digitizer, a computer and a X-Y bridge.

Each group of specimens included initially 15 samples. Three samples from each group were destructively tested to assess the initial strength of the joints. The remaining samples were immersed in a tank of circulating tap water at $72^0$C together with a group of reference composite adherends. Periodically thereafter all of the specimens were taken out of the bath to be weighed and subjected to an ultrasonic A-scan, using pulse-echo mode with the ultrasonic beam at normal incidence to the specimens. Each digitized ultrasonic signal was averaged over 64 readings to improve the signal-to-noise ratio. The measurements were taken after 0, 285, 1115, 1927, 2290, 3405, 3641, and 6624 hours of immersion in the circulating hot water.

One specimen from each group was then destructively tested, while the rest of the specimens were put back into the water tank until the next periodic examination.

During the destructive tests, the samples were tested to failure, parallel to the $0^0$ direction of the adherends. Both loading grips were free to swivel, so as not to induce external bending moments. The breaking loads and failure modes were recorded. The aim of destructive tests was to determine the strength of the bonds corresponding to each type of adherend surface pre-treatment (P and F) as a function of time.

## 4. Experimental Results and Data Analysis

### *4.1 Breaking Load and Mode of Failure*

The results of the destructive testing of the composite adhesive joints from the groups P and F are presented in figure 1. [1]

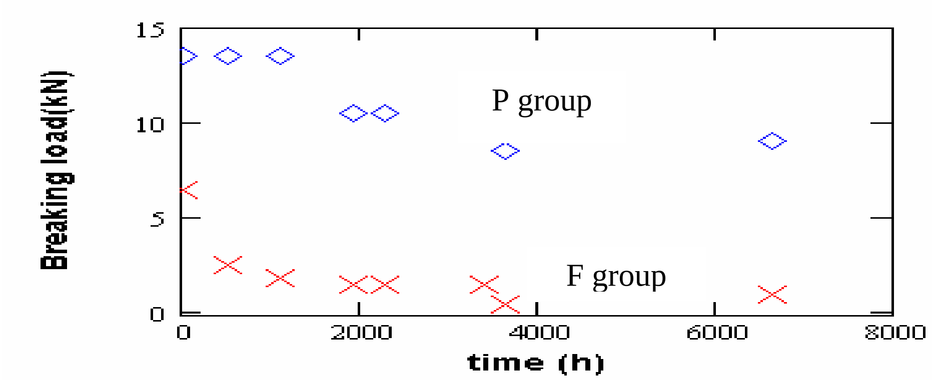


**Figure 1**: The breaking load of the specimens versus the time of exposure to the hot water

In Figure 1 the breaking loads are plotted against the time of exposure to the circulating hot water. The specimens from class F lost almost completely their initial strength, which was initially inferior compared to the P specimens. All the F specimens underwent an adhesive failure, i.e. the failure occurred at the interface between one of the adherends and the adhesive layer. This was expected, due to the pretreatment of these specimens.

The P specimens, that represent standard surface treatments, exhibited a monotonic reduction in the breaking loads, resulting in a loss of about 30% of the initial strength after 2000 hours of exposure and about 50% of the initial strength after 6624 hours of exposure. The broken specimens exhibited different modes of failure, which were dependent on the time of immersion and the surface pretreatment provided to the specimens. The variety of the observed failure modes included a cohesive failure within the adhesive layer, an adhesive failure at the interface between the adherends and the adhesive, a mixed mode of failure (partly cohesive and partly adhesive), and a failure in the composite fibers in the plies adjacent to the interface between the adherends and the adhesive.

### *4.2 Application of Wavelets to Ultrasonic Signals from the Joints*

Each of the ultrasonic signals obtained from the P and F specimens following their immersion in circulating hot water for periods of time of 0, 285, 1115, 1927, 2290, 3405, 3641 and 6624 hours was subjected to both discrete and continues wavelet transforms of several mother-wavelets families. The wavelets applied consisted of the db2, db4, db8 [2] and Morlet [12]. The transforms were performed by means of Matlab program (version 6.1) and Wavelet toolbox of this program [13]. A full description of the ultrasonic signals and their corresponding transforms are detailed in [14]. Some samples are demonstrated in Figures 2,3.

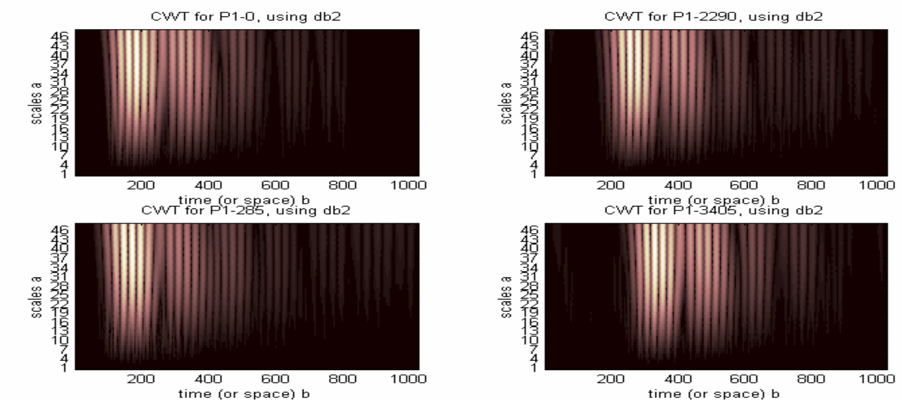


**Figure 2**: CWT of the signals received from one of the P-specimens following different times of exposure to hot water (0, 285, 2290, 3405 hours), using db2 Wavelet

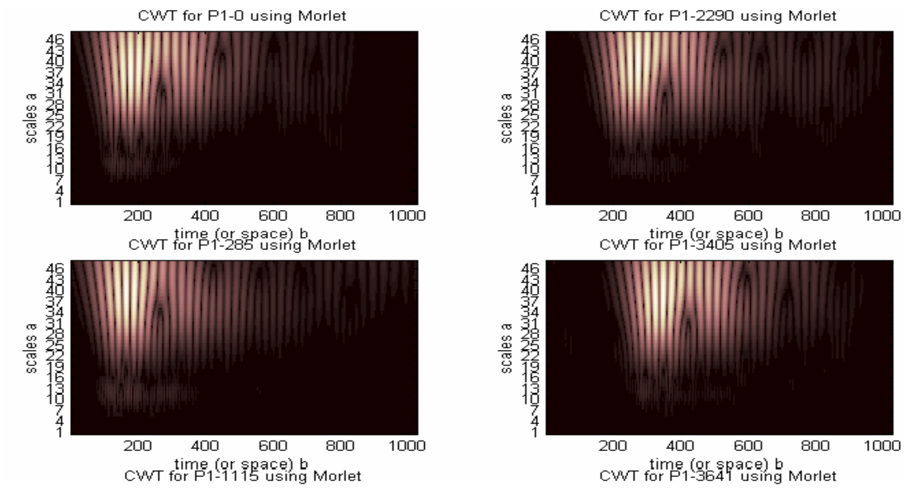


**Figure 3:** CWT of the signals received from one of the P-specimens following different times of exposure to hot water 0, 285, 2290 and 3405 hours) using Morlet Wavelet

As shown from the above figures, in the case of DWT, like in the case of CWT, there is no apparent correlation between the transforms outcome and the degradation of the specimens. During this work many different Wavelet transforms were applied, and many different parameters from the transformed signals were studied (statistical parameters, FFT spectrum, residuals, Local Maxima Lines and so on) in an attempt to find a correlation with the degradation of the specimens, under inspection. The results of this study imply that the wavelet transforms do not provide additional significant information for the evaluation of the joints' degradation. However, applications of Wavelet transforms enable significant data compression with ability of fast and reliable reconstruction. It is demonstrated in figure 4.

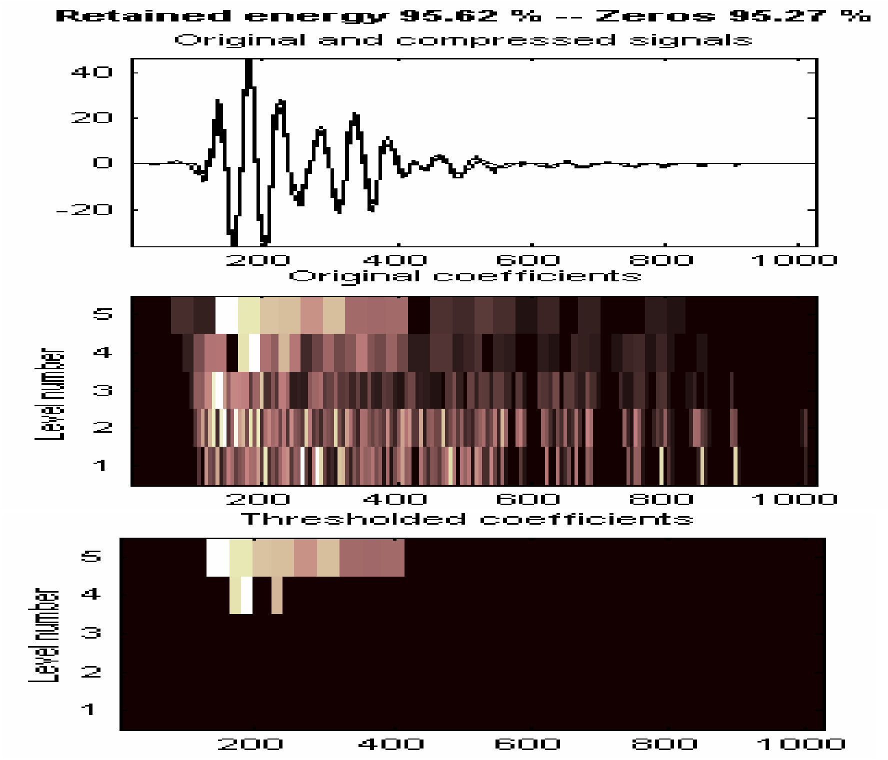


**Figure 4.:** Compressing after DWT of one of the Ultrasonic signals from one of the P specimens

The graphical tool of Matlab 6.1 provides an automatically-generated threshold. Values under the threshold are forced to zero, achieving more than 95% zeros (it is possible to reconstruct the initial signal using less than 5% from the initial data) while retaining almost all (more than 95%) the energy of the original signal, as seen from figure 4. The automatic threshold usually achieves a reasonable balance between number of zeros and retained signal energy [13].

### *4.3 Evaluation of wavelet entropy for Ultrasonic Signals from the Joints*

There are different definitions of entropies in various fields each with its own special interpretation such as thermodynamic entropy, information-theoretic entropy, economo-dynamic entropy and ecological entropy. The information-theoretic entropy was introduced by Claude Shannon in 1948 [15].

Since information reduces uncertainty, Shannon was looking for a measure of uncertainty. For a process with *n* possible outcomes, the uncertainty of the outcome is related to a probability distribution $P = (p_1, p_2, p_3, \ldots, p_n)$. thus finally Shannon defined the entropy as:

$$S = -k\sum_{i=1}^{n} p_i \cdot \log p_i \qquad (1)$$

The information-theoretic entropy S can be linked to thermodynamics through ***k*** as Boltzmann's constant. For convenience the constant ***k*** is set to 1 and the base of the logarithm is taken to be natural. Therefore:

$$S = -\sum_{i=1}^{n} p_i \cdot \ln p_i \qquad (2)$$

We calculated the Shannon's entropy of the ultrasonic signals on the basis of the Matlab subroutines [13].

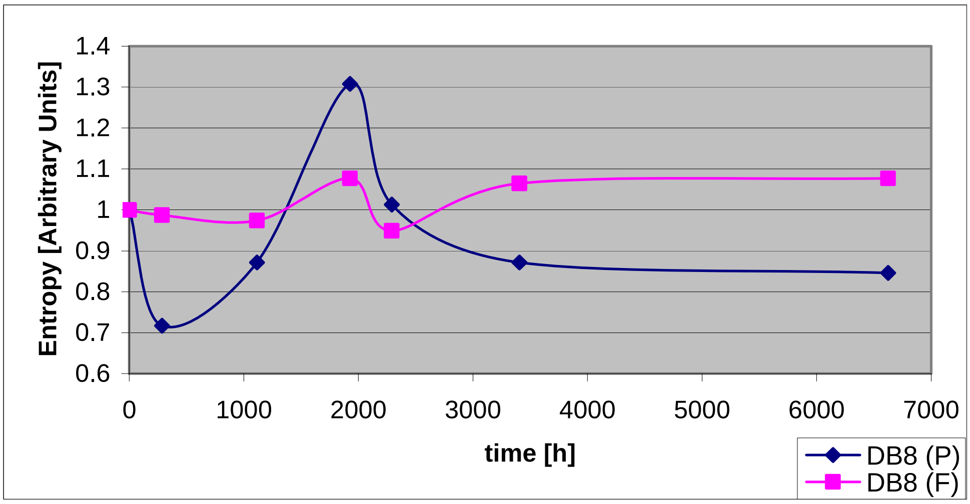


**Figure 5:** The values of average Shannon entropy for the signals from P and F specimens, using DB8 discrete wave transform versus the time of immersion in hot water.

Figure 5 demonstrates the values of the signal's average entropy as a function of the immersion period for the P and F specimens. The entropy units in the figure are arbitrary.

This pattern of the entropy for the P can be explained as follows: at the beginning of the immersion process the entropy of the signals decreases, possibly due to water induced stress relaxation. After about 300 hours of immersion in circulating hot water, the entropy of the signals increases gradually, due to increased microscopic disorganization, because the ingress of water changes the morphology of the interface, causing it to become less uniform, reducing the mechanical interlocking and disrupting chemical bonds between the adhesive layer and adherend.

The turning point occurs in approximately 2000 h of immersion, when the interface between the adherents and the adhesive becomes so weak that the incident ultrasonic beam starts to "see" only the upper adherent rather than the three layers of the joint compound. The shape of the signal is then determined by the very well defined modes of vibrations of the upper adherent plate, so the entropy of the signal decreases.

Concerning the F specimens, we see minimal entropy changes versus the time of exposure to the hot water comparing to the P specimens, that has the following explanation: since the quality of the F specimens at the beginning of the experiment was not satisfactory and not according to the industry standards, the incident ultrasonic beam "sees" only the upper adherent of the joint already at the beginning of immersion.

According to the breaking loads plotted against the time of immersion (Figure 1), the P specimens exhibited reduction in the breaking loads, resulting in a loss of about 30% of the initial strength in about 2000 hours of exposure that coincides with the turning point (maximum entropy) in the entropy pattern (Figure 5). On the other hand, the specimens from class F lost almost completely their initial strength, which was initially inferior compared to the P specimens that coincide with minimal entropy changes in the entropy pattern.

*4.4 Comparison of the results from wavelet entropy analysis and HOC analysis*

This section demonstrates the results obtained from the application of HOC analysis to the ultrasonic signals from P specimens [16]. In Figure 6, the Breaking-loads (BL) and the entropy calculations through both HOC and DB8 wavelet transform of the ultrasonic signals are presented.

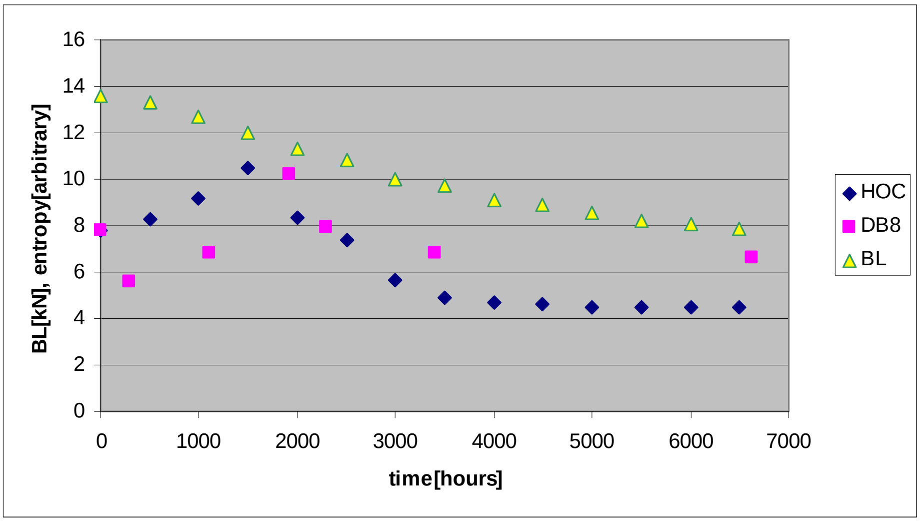


**Figure 6:** The entropy's turning-point pattern obtained from both the DB8-transorm and the HOC white-noise test. The breaking-loads of the specimens are plotted as well, as a function of the immersion time.

For each ultrasonic signal from P specimens the signal's entropy was calculated by both HOC and DB8 wavelet transform to show the "turning-point" pattern with time of immersion. Both “turning points” correspond to a loss of about 30% of the initial strength in about 2000 hours of exposure. After that a relatively sharp monotonic decrease of the entropy is observed. Periodical and successive measurements of in-service composite joints may provide an alarm whenever the "turning point" is reached.

## 5. Summary and Conclusions

In this study experimental ultrasonic signals from composite adhesive joints with different types of surface preparation were studied in order to evaluate their environmental degradation, through the application of Wavelet transforms.

We can summarize the conclusions of this study as follows:

- The application of Wavelet transform doesn’t seem to improve the capabilities of deciphering the condition of the adhesive joints exposed to harsh environmental conditions,
- The application of Wavelet transform enables significant data compression with the ability of fast and reliable reconstruction,
- Calculations of entropy parameters of the signals through Wavelets provide a mean to follow up the relative degradation of the composite joints and an alarming cusp indication whenever the joints had lost 20-30% of their nominal strength. Similar pattern and quantitative results were obtained through the application of the HOC analysis.

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