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## Investigation of Structural Integrity of Composite Materials using Wavelet Packet Transform

Claudia Barile<sup>a\*</sup>, Caterina Casavola<sup>a</sup>, Giovanni Pappaletta<sup>a</sup>, Carmine Pappaletta<sup>a</sup>,  
Paramsamy Kannan Vimalathithan<sup>a</sup>

<sup>a</sup>*Dipartimento di Meccanica Matematica e Management, Politecnico di Bari, Viale Japigia 182 – Bari 70126, Italy*

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### Abstract

Carbon Fiber Reinforced Plastic (CFRP) laminates are tested using Acousto-Ultrasonic approach. The materials are subjected to out of plane impact and the Acousto-Ultrasonic approach is used to test the materials both before and after the impact event. The Waveform of the recorded signal before and after the impact is used to characterize the structural integrity of the material. Wavelet Packet Transform (WPT) analysis was used to decompose the Wavelets. The WPT analysis is preferred over the conventional Discrete Wavelet Analysis (DWT) owing to the possibility of analyzing both the approximation and details of the decomposed Wavelet. From the WPT results, the spectral energy in the time domain associated with each of the recorded wavelets are analyzed. The spectral energy is successfully used to characterize the integrity of the CFRP material before and after the impact event. The magnitude of the spectral energy in both the longitudinal and transverse direction of the specimen is observed to be lowered after the impact event. Using this technique, it is possible to characterize the integrity of the material even before it is subjected to loading.

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*Keywords:* CFRP; Acoustic Emission (AE); Acousto-Ultrasonic; Wavelet Analysis; Wavelet Packet Transform (WPT)

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\* Claudia Barile Tel.: +39 080 5962812  
*E-mail address:* [claudia.barile@poliba.it](mailto:claudia.barile@poliba.it)

## 1. Introduction

Non-destructive evaluation (NDE) techniques have provided a variety of ‘active’ and ‘passive’ tools for monitoring the structural integrity of a structure. Despite the versatility in the active NDE tools (such as Ultrasonic Testing, Ultrasonic Tomography and Impact Echo methods), the passive tools (Acoustic Emission, Thermographic Techniques, Laser Static and Dynamic Techniques etc.) were deemed to be appropriate for analyzing the structural integrity. [Grosse et al. (2008)] The passive tools can provide information about the integrity of a material or a structure during its entire load history. In other words, with the aid of this online monitoring, precautionary measurements can be taken before the structure fails entirely. [Dahmene et. al (2015)]

One of the most promising, yet, uncommon passive technique is the Acousto-Ultrasonic approach. As quoted by the forerunner of this approach Vary (1988), “It complements the other NDE approaches to material characterization and offers advantages to make it the preferred one to use in other cases”. When a material is subjected to damage progression, transient elastic waves are produced as a result of different damage mechanisms. Conventional Acoustic Emission (AE) technique records these transient elastic waves as they represent an acoustic event. Based on the acoustic descriptors such as Energy, Amplitude, Duration, Count, Rise Time and Peak Frequency, the different damage mechanisms can be categorized. [Bakhtiary Davijani et. al. (2011)] In the Acousto-Ultrasonic approach, pressure waves are induced into a material through an external piezoelectric source and are received by another piezoelectric transducer. This pressure wave is transformed into elastic wave inside the material and is received at the other end. [Finkel et. al (2000)] The propagation of these waves is based on the material properties such as microstructure, porosity and shear modulus. In case of Fiber Reinforced Plastics (FRPs), the propagation is affected by the curing pressure, fiber orientation, shear modulus, layer thickness among many other characteristics. In principle, a flaw in the structural integrity of a material is reflected in the wave propagation, which is the basic principle of Acousto-Ultrasonic approach. [Vary (1988)]

One of the limitations of the otherwise efficient Acousto-Ultrasonic and Acoustic Emission techniques is the difficulty in identifying false signals. The waveforms of the recorded signals can be used effectively than the conventional AE descriptors such as Amplitude, Energy, Counts and Rise Time. In the past decade, Yousefi et. al. (2014) and Saeedifar et. al. (2018) among many other researchers have analyzed the waveforms recorded in FRPs and have estimated the frequency band at which the different damage mechanisms are recorded. Similar to that, the stress wave propagation during the Acousto-Ultrasonic approach has different frequency bands. Each frequency band of the recorded waveform may represent the signal transmitted along the fiber or matrix. Moreover, the energies of these frequency band are affected by several parameters such as stiffness of the fiber/matrix, fiber orientation or flaws in the interlaminar structure. By analyzing the frequency band, the integrity of the structure can be identified. To decompose the waveforms into different frequency bands, normally Discrete Wavelet Transform (DWT) is used. However, the DWT decomposes the signal into its lower and higher frequency bands to several levels but discards the low frequency content. In this research work, Wavelet Packet Transform (WPT) has been used. WPT decomposes the signal into various levels of energy content and provides detailed information on the energy content in each level.

The aim of this research work is to perform Acousto-Ultrasonic tests on specimens before and after a drop-weight impact. The WPT analysis was performed on the specimens both before and after the impact event. Using the energy content obtained from the WPT analysis, the integrity of the material has been characterized.

## 2. Materials and Methods

Carbon Fiber Reinforced Plastic (CFRP) specimens were prepared using Resin Film Infusion, while the reinforcement fibers are fabricated into mats using stitching process. Totally five specimens, each of dimension, 100 x 150 x 5 mm<sup>3</sup> were tested. The average resin content of the specimen is 39% and they were cured at temperature and pressure of 135 °C and 1.5 bar, respectively, for 2 h. The details of the Fabric (F) and Tape (T) related to layup and fiber orientation are as follows: [45F/0T/0T/45F/0T/0T/0F/0T/0T/0F/0T/0T/45F/0T]<sub>s</sub>. The drop-weight impact damage in the specimen was created according to ASTM D7136 - Standard Test Method for Measuring the Damage

Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event. The test was conducted in INSTRON CEAST 9350 drop weight impactor with an impactor radius of 16 mm. The drop weight 2.781 kg was dropped from a height of 1835.50 mm at a velocity of  $7.151 \text{ ms}^{-1}$  to create an impact energy of 50 J. This low velocity impact event creates a Barely Visible Impact Damage (BVID). The force-deformation curve was recorded and the peak force, energy at peak force was calculated by the data acquisition system integrated with the testing machine. Since the results of peak force or energy is beyond the scope of this presented work, more details about the method of impact, information on the materials properties and results can be seen in the authors' previous research work [Barile et. al. (2019)].

The Acousto-Ultrasonic tests were performed using a pair of R30 $\alpha$  general purpose, 300 kHz resonant frequency Acoustic Emission sensor was placed on the surface of the specimen. The sensors were coupled to the surface of the specimen through silica grease and were positioned 30 mm from the center of the specimen along the transverse axis. The sensor outputs were amplified by 40 dB through 2/4/6 AST pre-amplifier and the acoustic events were recorded in PAC PCI2 system. To create the stress waves through the specimen, a pulse of 28 V spike (approximately 100 dB bump) was sent through the specimen and the structural response was recorded. The width of the pulse is kept at 5  $\mu\text{s}$  and 10 number of pulses were sent through the specimen with the interval of 100 ms between the consecutive pulses. The threshold for the receiving signals is kept at 35 dB. More details regarding the Acousto-Ultrasonic approach can be seen in the authors' previous research work [Barile et. al. (2019)]. The schematic of the specimen and how the sensors' location is coupled to the specimen is are provided in Figure 1.

Wavelet packets are linear combinations or superpositions of wavelets which retains the orthogonality, smoothness and localization properties of their parent. WPT decomposes the wavelets into approximation (low-frequency content) and detail (high-frequency content). The total number of components that can be obtained from WPT is based on the level of decomposition ( $i$ ). For each level of  $i$ ,  $2^i$  components can be obtained. In the present work, the decomposition level was set to 3 to obtain 8 components.

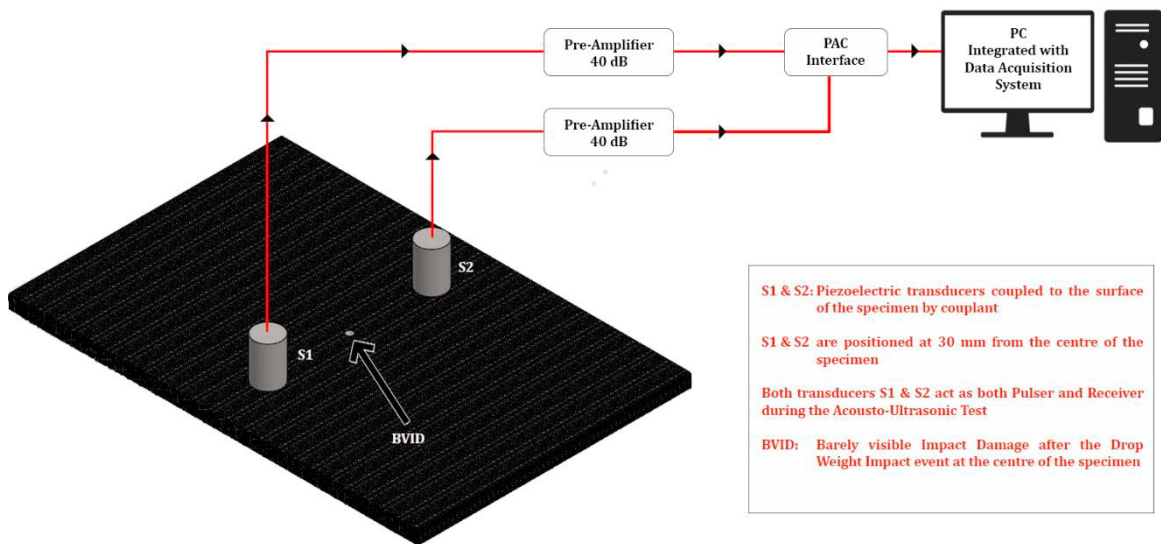


Figure 1. Schematic of Acousto-Ultrasonic setup on CFRP specimen

### 3. Results and Discussions

The Acousto-Ultrasonic tests were conducted in two modes. First, the specimens were tested before the drop-weight impact event and secondly, the specimens were tested again after the impact event. The residual indentation of the BVID was measured using a digital depth gauge. After the impact event, although the interlaminar damage could

not be observed in the naked eye, the obvious fiber breakage along the transverse direction can be observed. This means that, during the impact, majority of the load was transmitted along the transverse direction which lead the breakage of fibers. The BVID, conventionally, is not symmetrical; however, it is a parameter to understand the interlaminar stiffness of the material. On that regard, the maximum load in the specimens were deemed to be transferred along the transverse direction. Initially, the stress waves are created by sending a burst of 28 V peak through the specimen and the wavelet of the sent signal is recorded. The Wavelet Packet Transform (WPT) of the sent signal is presented in Figure 2. The dominating frequency with high spectral energy lies in the 312.5-375 kHz frequency band. In addition to that the frequency between 0-62.5 kHz also has a considerable amount of spectral energy. The duration of the signal in 312.5-375 kHz frequency band is around 100 samples, whereas, the 0-62.5 kHz frequency signal is decaying rather gradually over the period of time.

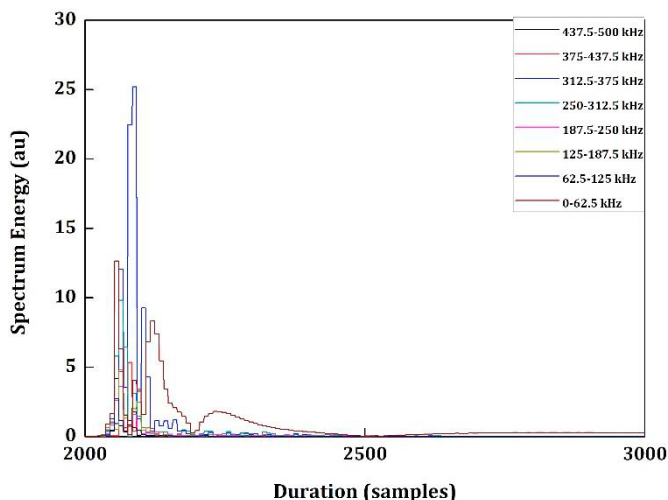


Figure 2. WPT results of the sent signal

It can be observed from Figure 3 that, in specimens AU2 and AU5, the frequency with dominating spectral energy lies in the 312.5-375 kHz frequency band. Moreover, it can be observed that the duration of these dominating frequency is around 150-200 samples. The portion of sent signal in 125-187.5 kHz band cannot be observed in the received signals. It was observed in Figure 2 that the 125-187.5 kHz signal was decaying and probably had decayed completely before reaching the receiver. The evidence for decaying can be assessed by the loss in spectral energy in the received signal. The sent signal has a maximum spectral energy of 25 au in the 312.5-375 kHz band, whereas, the received signal has a maximum of 5 au. It is a well-known phenomenon that a stress wave or acoustic wave propagation is affected by the material structure and properties leading to the loss in energy.

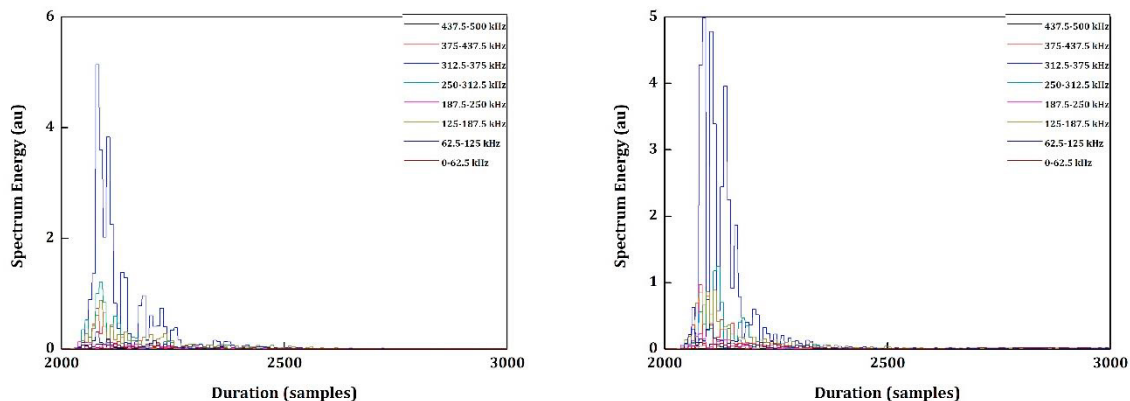


Figure 3. WPT results of received signals in specimens AU2 and AU5 before impact event

The variation in the spectral energy of the received signal can be related to the material properties. As indicated earlier, the spectral energy of the frequency content tends to decay over the propagation length. The propagation of the acoustic waves is affected by various properties such as bond strength, interlaminar strength, curing pressure, etc. Although the specimens taken for this study have same geometrical dimensions, the variation in their material property is the reason for the variation in spectral energy between the different specimens. After testing the specimens, they were subjected to drop-weight impact and the results are presented in Table 1. The specimen AU1 and AU5 has responded poorly to the impact event and sustained the most damage. The respective Peak Force during impact and the Energy peak absorbed at the impact event proves the same.

Table 1. Drop-Weight Impact Test Results

Specimen Denomination	Residual Indentation <i>mm</i>	Peak Force <i>N</i>	Energy at Peak Force <i>J</i>
AU1	-0.59	9849.16	26.84
AU2	-0.41	11095.55	37.57
AU3	-0.46	10652.33	36.23
AU4	-0.39	10393.53	47.72
AU5	-1.74	9090.62	32.20

After the impact event, the specimens are once again tested using the Acousto-Ultrasonic approach along the transverse direction and the WPT results of Specimen AU2 and AU5 are presented in Figure 4. In our previous research work, the Acousto-Ultrasonic approach was tested along both the longitudinal and transverse direction. However, most of the damage was observed along the transverse direction as the fibers along that direction are broken and projected outside the external laminate. Based on that observation, the WPT analysis was performed for the signals received along the transverse direction.

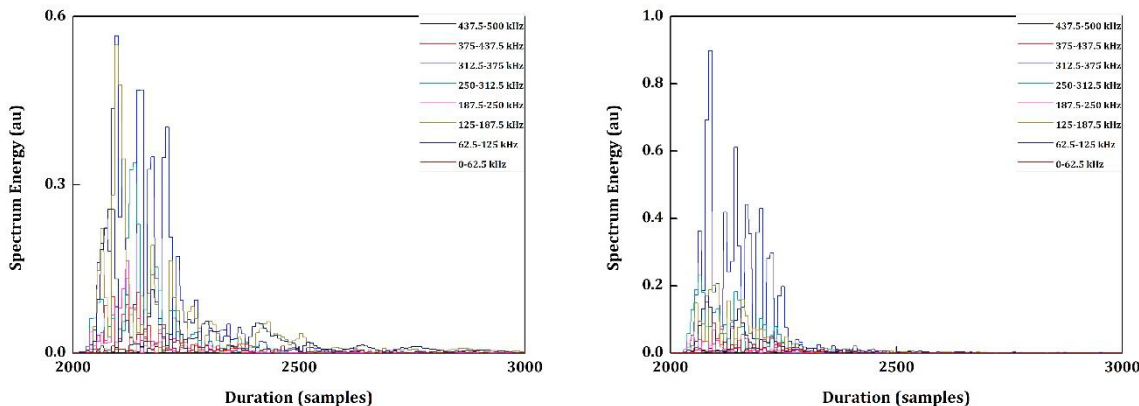


Figure 4. WPT results of Received Signals in Specimens AU2 and AU5 After Impact Event

From Figure 4, it is quite obvious that the signal received after the impact event has decayed even further when compared to both the original signal sent (Figure 2) and the signal received before the impact event (Figure 3). The spectral energy of the signal in 312.5-375 kHz band has dropped from 25 au to 0.575 au and 0.9 au, respectively in specimens AU2 and AU5. This drop in spectral energy is lower than the energy of the same frequency band received before the impact event. This suggests that the material is subjected to damage resulting in the disruption of the wave propagation path.

Another important result that can be observed is the spectral energy of the frequency band 125-187.5 kHz. In specimen AU2, comparing Figure 3 and Figure 4, some interesting observation in the spectral energy in 125-187.5 kHz frequency band can be observed. Before the Impact Event (Figure 3) the spectral energy of the band is 0.75 au in Specimen AU2 and After the Impact Event (Figure 4) the spectral energy drops slightly to 0.55 au. However, in Specimen AU5, the spectral energy before and after the impact event in the same band are 0.85 au and 0.2 au respectively. While comparing this observation with the drop-weight impact results in Table 1, it becomes more intriguing. Specimen AU2 has lower residual indentation and absorbed the maximum force during the impact event in comparison, while Specimen AU5 has exhibited poorly in both the cases.

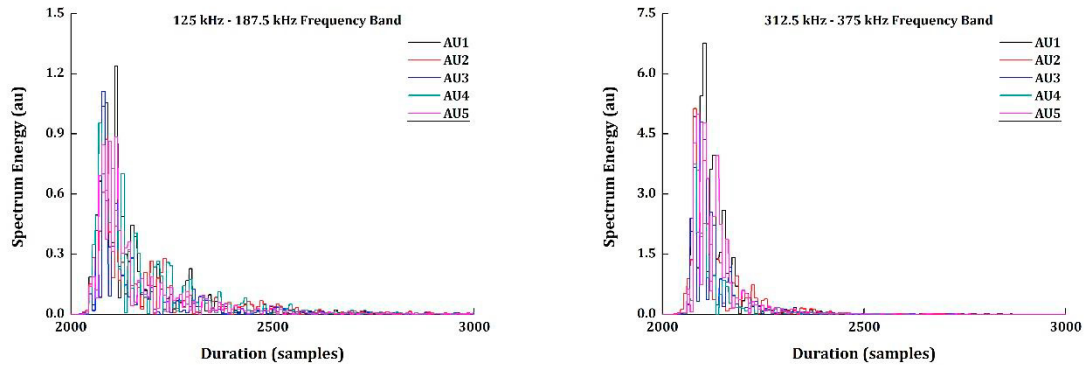


Figure 5. WPT Spectral Energy of 125-187.5 kHz and 312.5-375 kHz Frequency Band – Before Impact

In our previous research work, for CFRP materials, the authors have proved a hypothesis that the different frequency band of the stress waves generated in the material can be related to the wave propagation along the matrix and fibers, respectively. On that regard, it can be assumed that the signals of frequency band 125-187.5 kHz were not affected largely after the impact event resulting the loss of spectral energy to only 26.67% in specimen AU2 (while the loss in AU5 is 76.47%). The same material has shown promising results to the drop-weight impact event. This means that, the frequency band 125-187.5 kHz represents probably the signals transmitted along the fiber and the fiber has sustained only small damage when compared to the specimen AU5. For better identification of these two significant frequency bands, the spectral energy of 125-187.5 kHz and 312.5-375 kHz frequency bands, before and after the impact event are presented in Figure 5 and Figure 6, respectively.

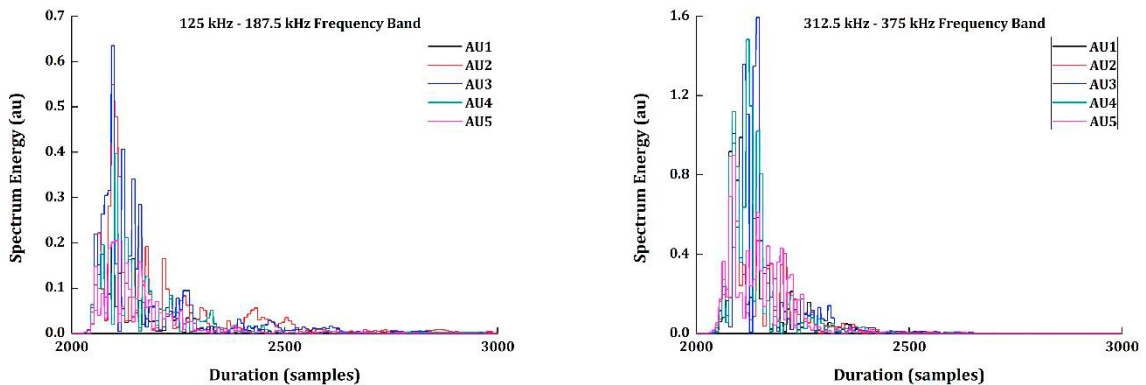


Figure 6. WPT Spectral Energy of 125-187.5 kHz and 312.5-375 kHz Frequency Band – After Impact

The spectral energies of the other frequency bands are not of major significance as they are relatively low when compared to the other frequency bands. That is the reason why the frequency bands 125-187.5 kHz and 312.5-375 kHz are given more importance. The results presented in Figure 5 and Figure 6 are significant enough to prove that the lower loss in spectral energy in frequency band 125-187.5 kHz for each specimen can be directly related to the amount of damage the fibers in the specimens have sustained after the impact event. Similarly, by comparing the percentage of the spectral energy loss in each different band, the integrity of the specimen in all aspects can be identified.

From the above observations and the discussions, it is quite evident that the Acousto-Ultrasonic approach is an interesting and powerful tool in evaluating the integrity of the material. By improving the analytical tools and automizing the process, the integrity of small to large structures can be monitored using this technique.

#### 4. Conclusion

In the presented research work, the authors have tried to investigate the structural integrity of the CFRP using the Acousto-Ultrasonic approach. CFRP specimens before and after the drop-weight impact event were taken for this study. The Wavelet Packet Transform (WPT) has been employed to decompose the recorded waveforms and to measure the spectral energy associated with each band. The waveforms were decomposed into eight frequency components; however, the frequency bands 125-187.5 kHz and 312.5-375 kHz in particular are of major significance. The material which has sustained less damage by the drop weight event, AU2, has a relative loss of 26.67% in spectral energy in the 125-187.5 kHz frequency band. Whereas, the specimen AU5, which suffered the most damage has a loss of 76.47%. By properly analyzing each frequency band and their spectral energy before and after the impact event, the structural integrity of the specimen can be analyzed properly. This can be developed as a powerful tool, provided the spectral energy of the Acousto-Ultrasonic has been studied for a reference material of similar curing properties, resin and fiber content and fiber orientations. Thereby comparing the results of the Acousto-Ultrasonic with the reference material, extensive knowledge of the material integrity can be predicted.

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