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EXPERIMENTAL WAVELET ANALYSIS OF ACOUSTIC EMISSION SIGNAL PROPAGATION IN CFRP

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Abstract

In this research work, the characteristics of acoustic wave propagation was studied in different Carbon Fiber/Epoxy laminated composites (CFRP). Piezoelectric transducers were used to simulate the acoustic waves through the materials and the effects of ply number, fiber orientation and the material thickness of the CFRP on the propagation of acoustic signals were studied. The relative loss of the Acoustic Emission (AE) signals has been parameterized in terms of the peak amplitude, acoustic energy and duration of the recorded acoustic signals. The effect of the material properties on the relative loss in AE descriptors have been correlated. Waveform analysis was performed for the simulated and received acoustic signals to identify the change in amplitude and waveform. Wavelet analysis for the recorded acoustic waveforms were performed by the Continuous Wavelet Transform. The effect of material properties on the propagation of the acoustic signal was characterized through AE descriptors, Waveform and Wavelet Analysis.

Keywords: *CFRP, Auto Sensor Test, Acoustic Emission, CWT, Wavelet Analysis*

Introduction

The exponential growth in the facilitation of signal processing, high-tech instrumentation and ever-growing advancements in the statistical techniques and procedures has made Acoustic Emission (AE) technique one of the most reliable Non-destructive methods to analyse and characterize the defects and integrity of composite materials [1]. Acoustic signals are transient waves, which are produced by the sudden outburst of stored energy when the material is either deformed or subjected to failure, under loading. In the case of composite materials, the acoustic signals are produced by one or more mechanisms, which includes matrix cracking, fiber failure, delamination, debonding of the matrix from the fibers, fiber pullout and interfacial debonding and sliding. Each acoustic signal produced in the composite material carries useful information, which can be characterized by their amplitude, acoustic energy, counts and hits [2-4].

Many works have reported the successful utilization of acoustic energy and amplitude signal, using different characterization techniques, in evaluating the delamination growth behaviour [5-10]. Some research works have focussed on evaluating the residual strength and fracture toughness of composite materials using AE techniques [11], while the other on the residual fatigue strength [12] and residual torsional strength of the composite materials [13]. Thus, over the past few years, AE Technique has become one of the powerful tool in characterizing damage mechanism and damage growth in the composite materials.

However, most of the studies utilized the AE energy, amplitude, duration and count as the prime descriptors in evaluating the damage in the material. Very less emphasis has been provided to the frequency domain analysis of the acoustic signals. Fourier Transform (FT), Short-Time Fourier Transform (STFT), Continuous Wavelet Transform (CWT), Discrete Wavelet Transform (DWT) can be used in frequency domain analysis of the acoustic signals to interpret the damage mechanism during mechanical testing of composite materials [14-18]. The wavelet analysis in frequency domain can provide more information about the damage evaluation in composite material.

While loading, when the acoustic waves are generated as a result of elastic deformation or by any means of damage mechanism; these transient waves propagate through the material before being sensed by the sensor. These transient waves are passed through a predefined pre-amplifier and filtered through a pair of low pass and high pass band filters. The acquired waves are processed by a data acquisition system, which functionalizes the received signals in terms of amplitude, acoustic energy and duration. Each of the signals produced by the damage mechanisms can be distinguished by their frequency band.

During this highly sensitive process, the acoustic waves pass through the material before reaching the sensor. The properties and the geometry of the material are rather ignored; while they play an important role in affecting the transmitted acoustic signals. Only few research works have been reported on analysing the effect of distance between the sensors and the thickness of the material in the amplitude and acoustic energy of the acoustic signals [19].

The term, which is more related to the analyses of acoustic signals considering the properties of the material, is acousto-ultrasonics [20, 21]. Nevertheless, it is an entirely different technique, which emphasises on detecting the flaws and evaluating the mechanical properties of the material using AE techniques. These techniques involve the numerical modelling of the voltage pulses produced by the acoustic technique to evaluate the flaws [22 – 25]. No detailed reports on how the phase difference between the matrix and the composite, the volume fraction of the matrix, the fiber orientation or the fiber properties affects the acoustic waves recorded by the sensor have been reported. However, it has been reported by many researchers that the acoustic waves are affected by the elastic modulus and shear modulus of the materials [20, 21]. This intrigued the authors to investigate the effect of matrix/fiber phase difference, fiber orientation, ply thickness and material thickness in the transmission of the acoustic signals.

In the present research work, the authors have tried to investigate the propagation of acoustic signals in carbon fiber/epoxy laminated composites (CFRP). The effect of the factors including the ply thickness, fiber orientation and material thickness in the propagation of AE signals has been investigated. The AE descriptors, peak Energy, Amplitude and Counts of the sent and received AE signals have been characterized on different materials. Moreover, wavelet analysis was performed for the sent and received signal using Continuous Wavelet Transform (CWT).

Among the other wavelet analysis, CWT was chosen for this particular study on the basis that, CWT provides more information on the frequency domain analysis when compared to DWT, FT or STFT. In addition to that, CWT facilitates the modification of number of octaves and voices per octave in the frequency domain analysis of the recorded waveform [26]. The possible correlation between the Wavelet transform of the sent and received signals was made to characterize the effect of the material specifications in AE signal transmission.

However, a rather different approach than the acousto-ultrasonic has been followed in characterizing the acoustic signals in this present work. In the conventional approach of acousto-ultrasonics, an ultrasonic transducer is used to simulate acoustic waves inside the material; the parameters, which can be controlled, are the frequency of the ultrasonic signals. In the present work, Auto-Sensor-Test capability, an inbuilt monitoring system provided in the AEWin Software by Physical Acoustics Corporation was used to simulate acoustic signals. This system facilitates the controlling of pulse width of the signal produced. This method also simplifies the data acquisition system, since both the emitter and receiver of the acoustic signals are interfaced to the same system. Moreover, AEWin Software facilitates the utilization of GUI, which is more efficient in controlling the Acoustic signal parameters and obtaining waveform information of the signal.

Experimental

Procedure

In the context of data acquisition system for AE, the software AEWin produced by Physical Acoustics Corporation (PAC) has been widely used by most researchers. So far, only one report has been filed on the AST and how the geometry and the thickness of the specimen affects the AE signals [19].

In this research work, the authors have used the AST, which normally uses two or more sensors, while each of them acts as both the emitter and receiver of the acoustic signals, at the same time. In its own way, during AST, the sensor can simulate an acoustic wave that the other sensors can detect while receiving the signal sent by the other sensors.

The procedure involves coupling the AE sensor/transducers to the surface of the specimen by a suitable couplant. When AST is activated, the piezoelectric crystal in the sensor is excited by a 28 V spike. This inverse piezoelectric effect results in the deformation of the crystal, thus sending pressure waves through the couplant. The pressure waves are transformed into stress waves in the structure, which is essentially the simulated acoustic wave. The simulated acoustic wave not only passes through the material structure, but also ricochets back to the emitter. Once the sensor receives the structural response, it reverts itself to a receiving sensor. In this way, after a time delay, it can receive back the signals sent by the other pulsars [27].

Propagation of these acoustic waves is influenced by the material properties, resonances, geometry of the structure and other material parameters [19, 20]. However, the pulsing produces the main bump which results in the recorded amplitude to be saturated at approximately 100 dB on all occasion. The signals are saturated by a pre-amplifier with a gain of 40 dB. The threshold for the recorded signals were set at 35 dB. Thus, it becomes necessary to analyse the acoustic energy, duration and counts for monitoring the pulse response [19, 27].

The pulse voltage of 28 V spike cannot be altered in the AST, nonetheless, other pulse parameters can be modified. The parameters that can be controlled and modified in the AST using AEWin software are Number of Pulses, Time between Pulses and the Pulse Width. In the present work, the experiments were repeated for the different specimens, whilst keeping the Pulse Width 5 μs, Number of Pulses as 10 and the Time between Pulses as 100 ms.

Two general-purpose narrow band resonant sensor with high sensitivity (Model - R30α; named as S1 and S2), supplied by Mistras were used in this study. The pre-amplifier gain was set as 40 dB and the high pass filter and low pass filter was set between 1 kHz and 3 MHz, respectively. The waveform was recorded for a sample length of 3K.

Materials and Testing Conditions

The materials used in this study were carbon fiber/epoxy laminated composites (CFRP) of different fiber orientation and thickness. The details about the ply number, fiber orientation and the thickness of the specimen are indicated in Table 1.

Table 1. Layup Configuration of Specimen

The two sensors S1 and S2 were held firmly to the surface of the specimens by the coupling agent (silicone grease). The sensors were connected to the PAC data acquisition system through 2/4/6 AST amplifier with 20/40/60 dB gain. The gain of 40 dB was set for all the tests. The distance between the two sensors was kept approximately at 75 mm. All the tests were conducted at room temperature (~22 °C). For each specimen, the experiment was conducted for five iterations. The AE signals were simulated for the pulse widths of 5 μs.

Results

The simulated AE signals were recorded in the two sensors S1 and S2, respectively. Both the sent signals and the received signals were recorded and the average value of the AE descriptors (Peak Amplitude, Energy, Duration and Count) for each specimen is provided in Table 2.

Table 2. AE descriptors for different specimens

The relative variation of the AE descriptors when it is received at the other end of the sensor for each specimen is illustrated in Figure 1. The waveform of the sent signal to all the specimens are identical. Thus, an illustrated waveform of the sent signal is provided in Figure 2, while the signals received by the different specimens are provided in Figure 3. The CWT waveform of the recorded signals are produced in the subsequent figures (Figure 4 and Figure 5). Figure 4 shows the CWT waveform of the AE signal sent during the experiments and Figure 5 shows the Waveform of the different signals received in each specimen.

Figure 1. Relative loss in the Amplitude, Energy and Duration of the Simulated AE signals in different Specimens

Figure 2. Waveform of the Simulated Acoustic Signal sent

Figure 3. Waveform of the Received AE signals in different Specimens

Figure 4. CWT Wavelet Analysis of the Simulated Acoustic Signal sent

Figure 5. CWT Wavelet Analysis of the Received AE signals in different Specimens

Discussions

The results in Table 1 shows the obvious and expected changes in the AE descriptor values between the sent and received AE signals. However, it is quite noteworthy to elucidate the variation in Acoustic Energy, Duration and the Counts of the signals sent while all the signals correspond to the 28 V spike. It was pointed in the previous research work by PAC [19], the incident acoustic signals are affected by the surface roughness of the specimen and the thickness of the couplant. Since, the thickness of the couplant, silicone grease is difficult to measure during the experiments; these small changes in the simulated acoustic signals are unavoidable.

More importantly, the changes between the sent and received AE descriptors must be addressed. As mentioned in the previous reports, the peak amplitude recorded for all the sent signals are 99 dB (~ 100 dB), while the received signals have lower values. The simulated acoustic signal has to pass through the material, which acts as the transmission medium, before reaching the receiving end. It is obvious that the medium of transmission affects the acoustic signal, which results in the loss of Amplitude, Acoustic Energy and Duration when the signal reaches the receiver. The relative loss of amplitude is significantly lesser than the loss of Amplitude, Acoustic Energy and Duration because the amplitude corresponds mostly to the signals, which have propagated through the surface of the material rather than inside the material. It has been advised by PAC to not consider the peak Amplitude while characterizing the AE signals [27].

In Figure 1, the relative loss of the AE descriptors in all the specimens has been provided. On looking upon closely the data provided in Table 1 and Figure 1, a correlation between the material properties and its adverse effects on the acoustic signal can be found. Specimens C1 and C3 have very close material geometry (thickness 2.76 and 2.73 mm, respectively) and same fiber layup. The number of plies in both the specimens are 12 and their fiber orientations are similar (Table 1). In Figure 1, the relative loss in the Amplitude and Energy of the acoustic signals in specimens C1 and C3 have closer values. The relative loss of Amplitude for C1 and C3 are 30.20 and 30.51 %, respectively. Similarly, the loss of acoustic energy is 98.46 and 98.30 %, respectively. While looking at the AE descriptors of the other two specimens, C2 and C4, which have different fiber orientation, thickness and the ply number, it can be inferred that the material properties plays in important role in the transmitted acoustic signal. In the same way, the same rationale can possibly extended to the acoustic signals produced during damage mechanisms.

While considering the specimen C2, which has the thickness of 2.08 mm, it exhibits the lowest relative loss in all the AE descriptors. The Amplitude loss is 22.83 % in C2, while the other specimens has relatively more loss. This begs the question, whether only the thickness plays a major role in the acoustic signal transmission. Is it possible the lower specimen thickness can result in lower loss in AE descriptors during transmission? The results for the specimen C4 suggests otherwise. C4 has a thickness of 2.94 mm but has the relative amplitude, energy and duration loss considerably lesser than C1 and C3. However, the fiber are oriented in a unidirectional manner in C4 with the number of plies is 11. It was reported A. Vary [20], the acoustic wave can run in the direction parallel to the fiber direction. This can be related to the fact that the fiber orientation provides the feasibility of acoustic signal transmission.

The loss in energy, amplitude and duration in all the specimens are accounted for more than 90 %, which can be attributed to the non-isotropic nature of the specimens. The phase difference between the epoxy matrix and the reinforcement, carbon fiber might have played a major role in the relative loss.

More insight on the differences between the acoustic signals in each specimen can be attained by the waveform and wavelet analysis. From Figure 3, it can be observed that the waveform of the received acoustic pulse is not the same in either of the specimens. In case of specimens C1 and C3, the peak amplitude of the waveforms are closer, however, has definite different waveforms. This intrigued the authors to perform the spectrum of wavelet analysis.

The scalogram of the wavelet transform of the sent and received signals can be observed in Figure 4 and Figure 5. It can be observed that the sent signal has a magnitude ranging from 2 to 11 in difference frequency domains but at a very short time interval (Figure 4). However, the received signals has magnitudes in different frequency domains with relatively longer time intervals. This can be related to the increase in Counts of the received signals in all the specimens (Table 2).

In specimens C1 and C4, the waveform can be observed in two different frequency domains, albeit, very indistinctively. The frequency domain in the specimens C1 and C4, for the same sample value in the initial stages, has two undistinguishable frequency domains separated very narrowly. Although, there are two frequency domains obtained, it is quite unclear to separate them on the basis where they begin and end. However, two distinct frequency domains can be observed in specimen C2. The two frequency domains in the specimen C2 have different magnitude values for each domain. Moreover, the frequency pattern of the specimen C2 is almost identical to the Input signal. In relation, specimen C2 exhibited the minimum loss in AE descriptors. On the other hand, the wavelet transform on the specimen C3 is entirely different. Although, the frequency domains above the normalised frequency 0.25 is almost identical in specimens C1 and C3, the entire wavelet is not identical.

Thus, it can be inferred that the different material properties, geometry of the material and the thickness of the couplant plays an important role in the acoustic signal transmission. By analysing the acoustic activity properly and by monitoring the wavelet transforms more details on the acoustic signal transmission can be identified.

Conclusions

The propagation of the simulated acoustic signals through different CFRP specimen having varying specimen thickness and fiber orientations. The effects of the composite material properties such as fiber orientation, ply number and the material geometry has been characterized. The adverse effects of these properties on the loss of the AE descriptors, peak amplitude, energy and the duration of the recorded signals has been related. Continuous Wavelet Transform (CWT) has been used to perform the Frequency Domain Wavelet analysis for the recorded acoustic signals. The results signifies that the material properties such as ply orientation, phase difference between the matrix and reinforcement and the geometry of the specimen affects the acoustic wave propagation. The results prove that with the aid of proper monitoring and data acquisition, more detailed information on the AE propagation and the material properties can be related.

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Table 1. Layup Configuration of Specimen

Specimen Name	Layup Configuration	Thickness mm
C1	$[0/90]_{12}$	2.76
C2	$[45F/0T/0T/45F/0T/0T/0F/0T/0T/0F/0T/0T/45F/0T]_S$	2.08
C3	$[0/90]_{12}$	2.73
C4	$[0]_{11}$	2.94

Table 2. AE descriptors for different specimens

Specimen Name	AE Signal	Amplitude	Acoustic Energy	Duration	Count
		dB	*au*	*ms*	
C1	Sent	99	1015.1	5463.4	53
	Received	69.1	15.6	379	90
C2	Sent	99	1060	5491.3	667
	Received	76.4	32.8	390.6	104
C3	Sent	99	1030	5467.5	60
	Received	68.8	17.5	431.8	105
C4	Sent	99	1011.5	5474	69
	Received	71.5	19.6	517.9	126

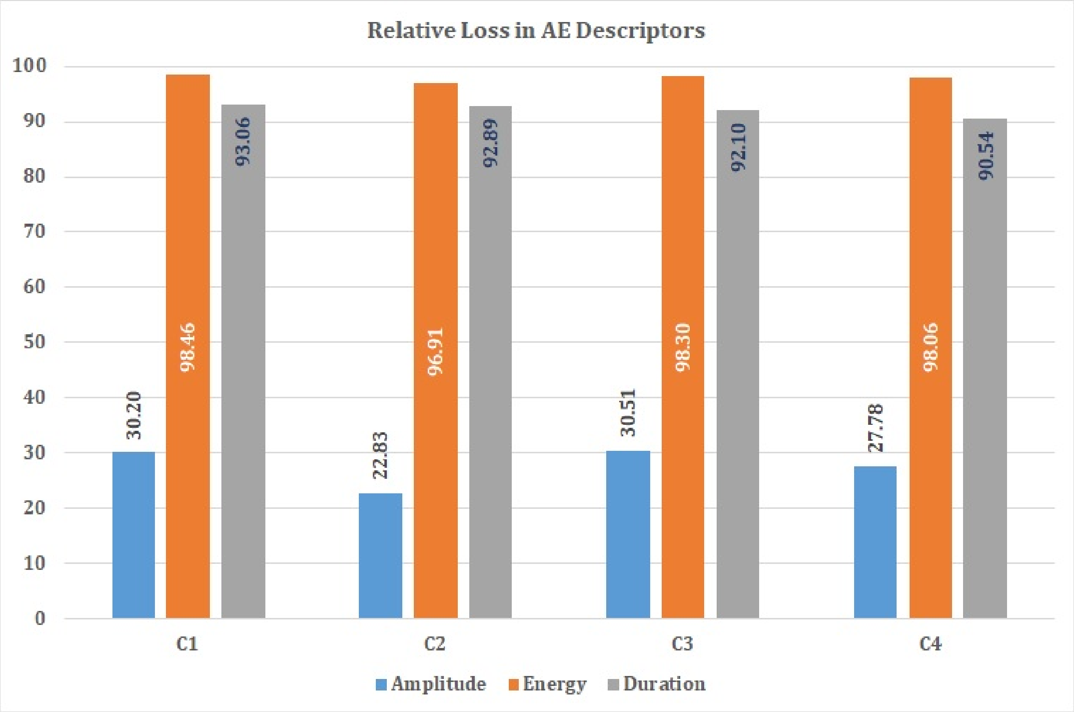


Figure 1. Relative loss in the Amplitude, Energy and Duration of the Simulated AE signals in different Specimens

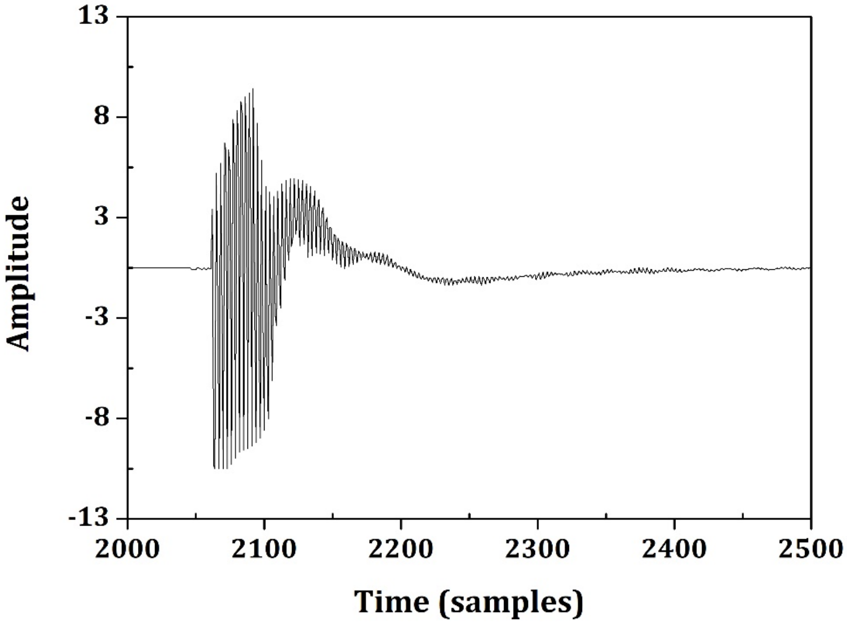
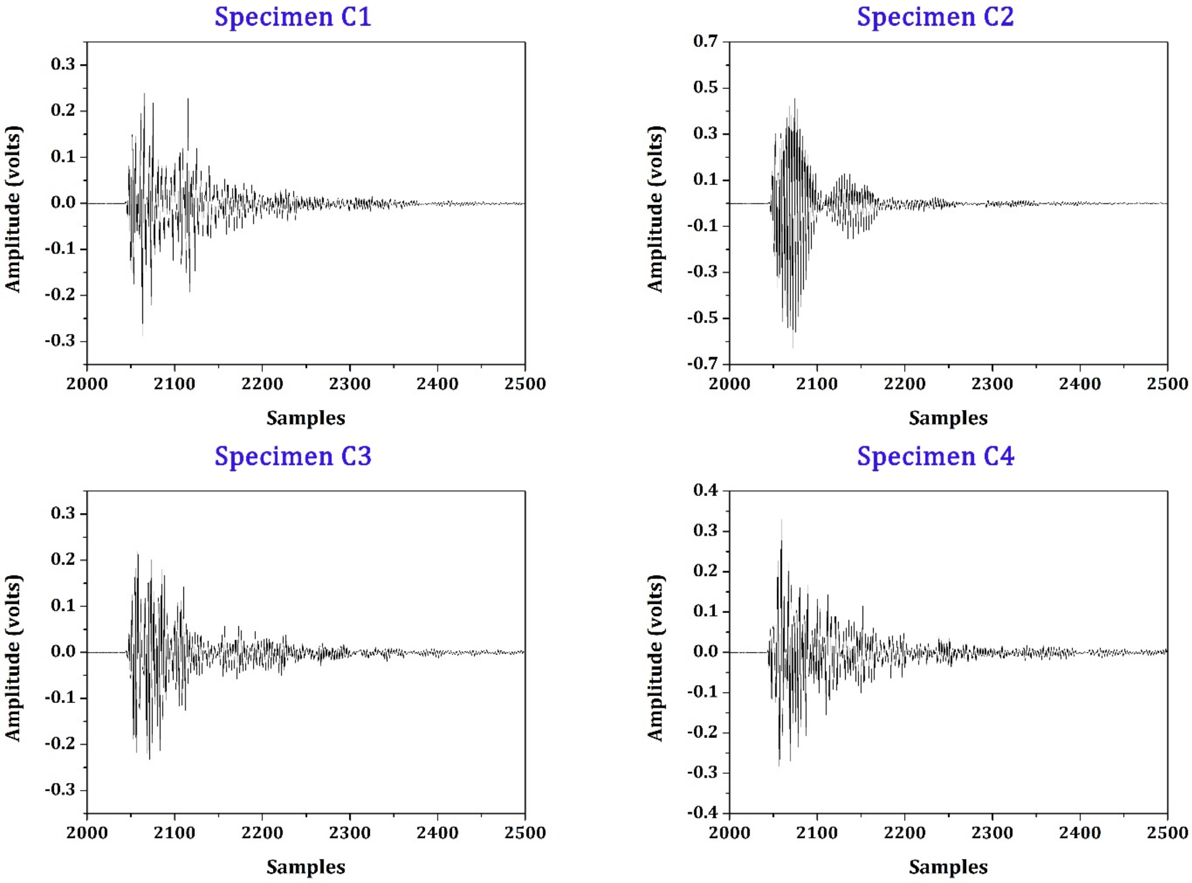


Figure 2. Waveform of the Simulated Acoustic Signal sent


Specimen C1

Specimen C2

Specimen C3

Specimen C4

Figure 3. Waveform of the Received AE signals in different Specimens

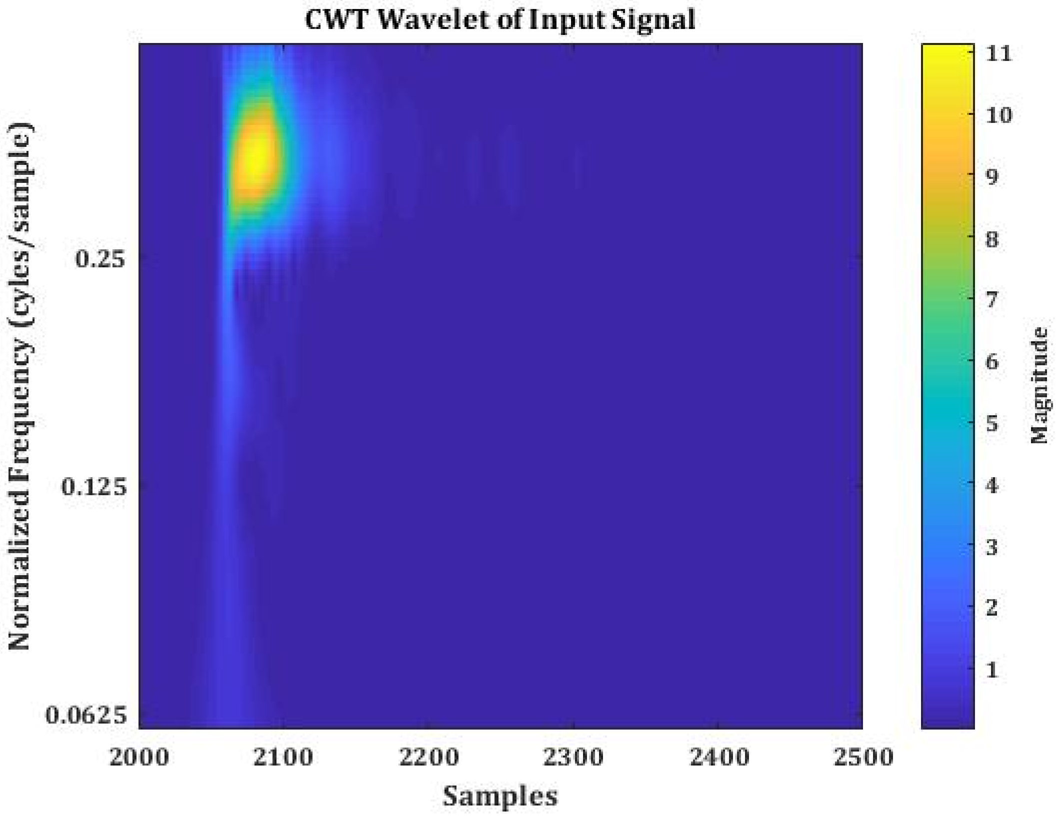


Figure 4. CWT Wavelet Analysis of the Simulated Acoustic Signal sent

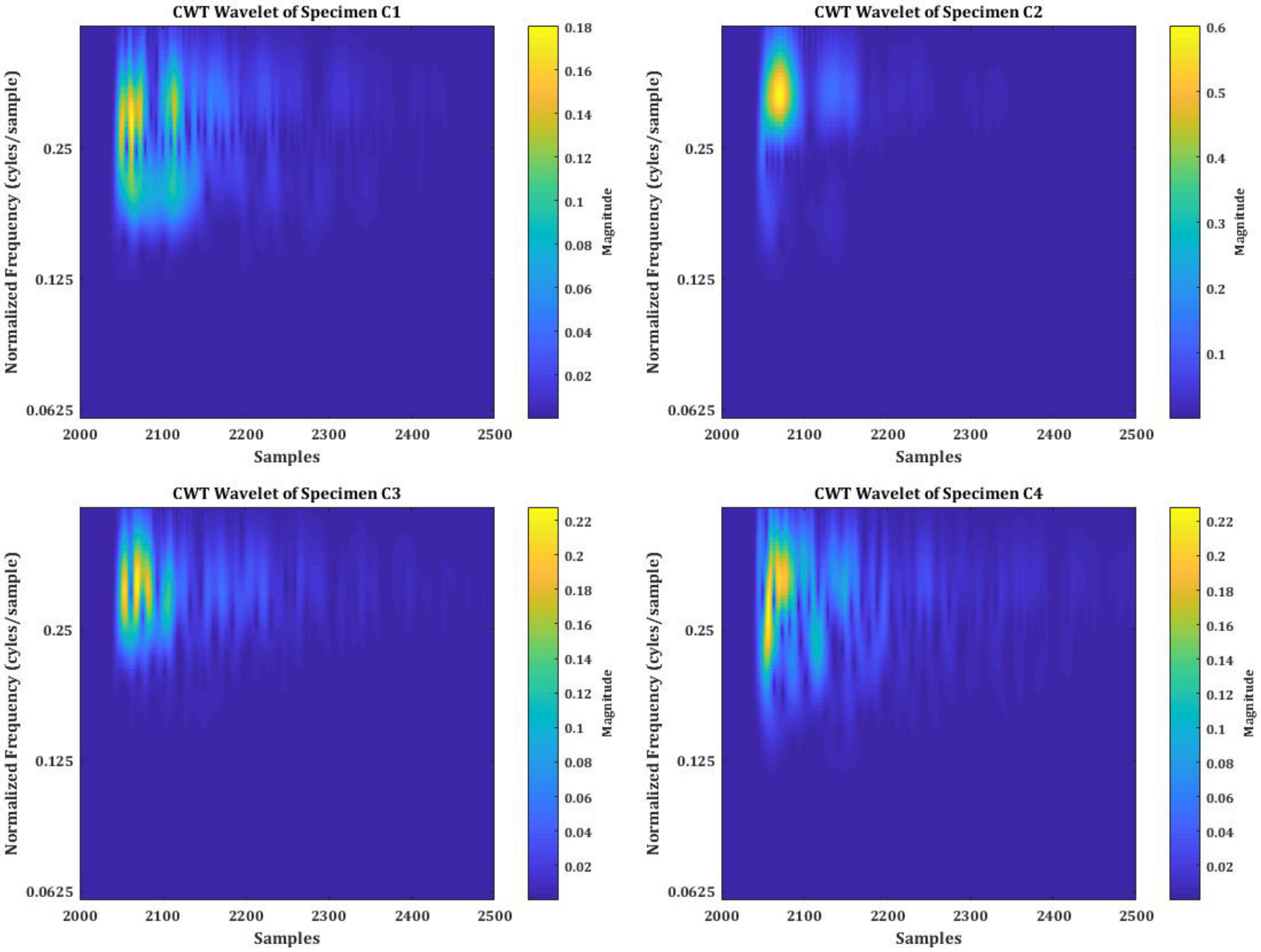


Figure 5. CWT Wavelet Analysis of the Received AE signals in different Specimens