Ultrasonic Non-Destructive Inspection of Localised Porosity in Composite Materials

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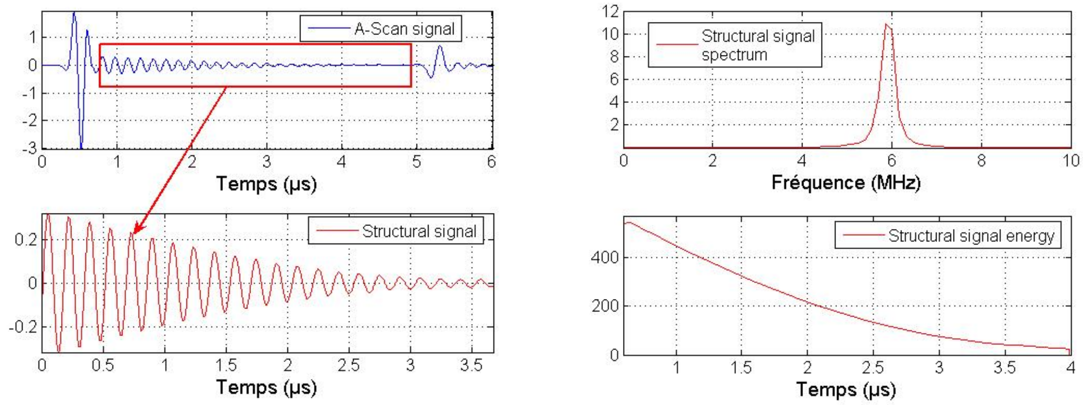
Abstract. Ultrasonic non-destructive inspection of thick composite parts is a major issue as regards to the increasing use of such materials in the aerospace transportation industry. The problem of porosity being inherent to the manufacturing of CFRP, it is necessary to provide inspection methods to evaluate it suitably. Here we propose analysis methods allowing to characterise localised porosity through the thickness. A combined time-frequency, time-energy analysis is used to localise eventual enclosed zones of porosity in otherwise safe parts. Both modelling and experimental results are presented that show the relevance of the proposed method.

Introduction

The increasing use of composite materials in the aeronautical industry implies new non destructive testing issues. In particular high thickness carbon-epoxy composite parts give rise to challenging problems such as inhomogeneous distribution of porosity through the thickness. High thickness makes more difficult the homogenisation of the curing parameters (temperature and pressure) within the part, possibly resulting in zones with concentrated porosity enclosed in an otherwise safe part. The inspection of porosity in composite parts is usually addressed by ultrasonic attenuation measurements. A significant amount of work has been proposed by Rose, Hsu, Nair, Adler, and Jeong [1-4] about the quantification of the porosity volume content by means of attenuation versus frequency and dispersion (phase velocity change) analyses. However all these procedures and studies only give access to a global information about porosity into the specimen. Yet a homogeneous through thickness distribution of porosity can yield the same attenuation result as a localised porosity concentrated in a few plies among otherwise safe plies, despite their dramatically different mechanical properties. The present paper aims at addressing the issue of detection of localised porosity through the thickness by means of non-destructive evaluation with ultrasound. The presence of localised porosity being a disturbance of the continuity of the medium, the idea is to look for such disturbances into the temporal signals (A-Scans) recorded in pulse-echo measurements. To do so we use the generally dropped "structural signal" generated by the stratified nature of these materials as a source of information. We propose to perform a time-frequency and time-energy analysis of the backpropagated signals. Combined experimental and modelling works are presented to show the relevance of the proposed analysis.
Section 1 presents the approach used, from the features looked for to the combined modelling and experimental methodology. Section 2 presents the manufacturing method used to create reference carbon-epoxy parts containing localised porosity. Section 3 presents results underlining the ability of the analysis method to detect the presence of localised porosity in different configurations.

1. Identification of analysis parameters

First, it is essential to identify continuous parameters among the discontinuous signal backscattered from the structure of the material. The periodicity of the layering gives rise to a backscattered resonant signal whose frequency depends on the time an ultrasonic wave takes to undergo a one way and return in one layer. Typically, for our materials with layers of 250 µm thick and speed of compressional waves of about 2950 m/s, this resonant frequency is around 5.8 MHz (**FIGURE 1**).



(a) (b)

FIGURE 1. (a) A-Scan signal backscattered by a stratified carbon-epoxy composite material, (b) Frequency spectrum and energy content of the structural signal

Since this signal results from successive scattering on the layers interfaces, the energy contained decreases continuously (**FIGURE 1**).

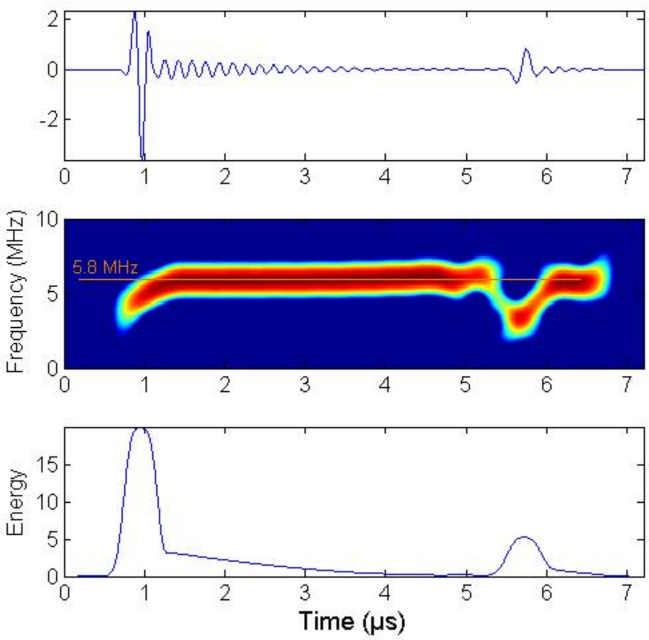


FIGURE 2. Time-frequency-energy analysis of the A-Scan of a perfectly safe stratified composite material for an emitted central frequency of 5 MHz

This structural signal is significant provided the excitation frequency is of the order of the resonant frequency, or higher. If the material is perfectly safe, the part of the signal that is flanked by the front and backwall echoes is only constituted by the resonant signal that yields a continuous time-frequency diagram and a monotonic and continuous decrease of energy (**FIGURE 2**). Thus, in what follows, we will be looking for discontinuities of the frequency and/or energy content of the structural signal.

2. Manufacturing of reference materials

The porosity content in the material is directly linked to the pressure applied during the curing. Tuning the pressure can then roughly control the volumic void content. The lower the applied pressure the higher the porosity rate. The manufacturing of materials with locally concentrated porosity has been achieved as follows.

1. A few layers are stacked and cured with a modified pressure cycle (lower pressure), giving a thin material with distributed porosity
2. Fresh pre-pregs are then stacked on this pre-cooked material and the whole is cured following the recommended cycle.

The resin being thermoset, the re-curing do not modify the porous structure of the pre-cured material and the material obtained is constituted of a set of porous plies among other safe plies. The re-stacking can be done either on one side of the pre-cured material or on both sides yielding an entrapped zone of porous plies. **FIGURE 3**(a) presents a photomicrograph, orthogonal to the fibres, of a unidirectional material with 8 porous plies in the middle.

The 8 porous plies have been cooked without pressure in this particular case and the resulting porosity content is about 10 % in volume (measured by image analysis) in those plies. One can observe on this sample that the pre-cured zone is separated from the safe ones by thicker resin interfaces. These interfaces can be avoided by omitting the peel ply for pre-curing. Materials with local porosity content of 3 % (pre-curing at 3 bars) and no thicker interface have been manufactured that way.

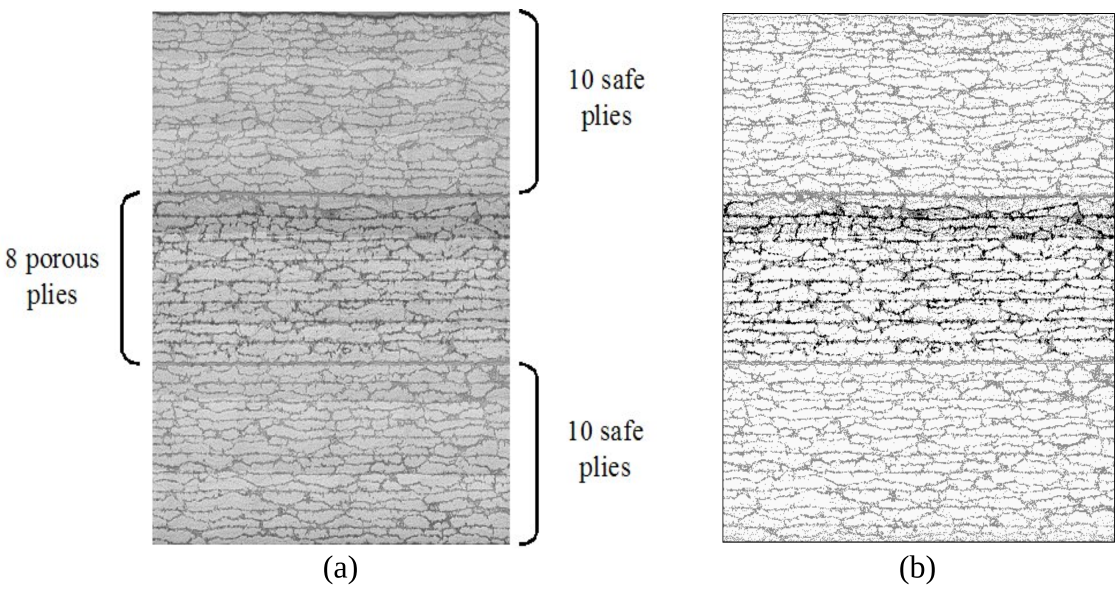


FIGURE 3. (a) Microphotograph of a carbon-epoxy material with a localised porous zone (8 central plies),
(b) Propagation medium for the modelling.
White = homogenised carbon-epoxy, grey = pure epoxy , black = voids

3. Approach and Analysis

3.1 Approach of the study

The approach of the study was to manufacture a small set of materials containing locally concentrated porous zones, and for each sample:

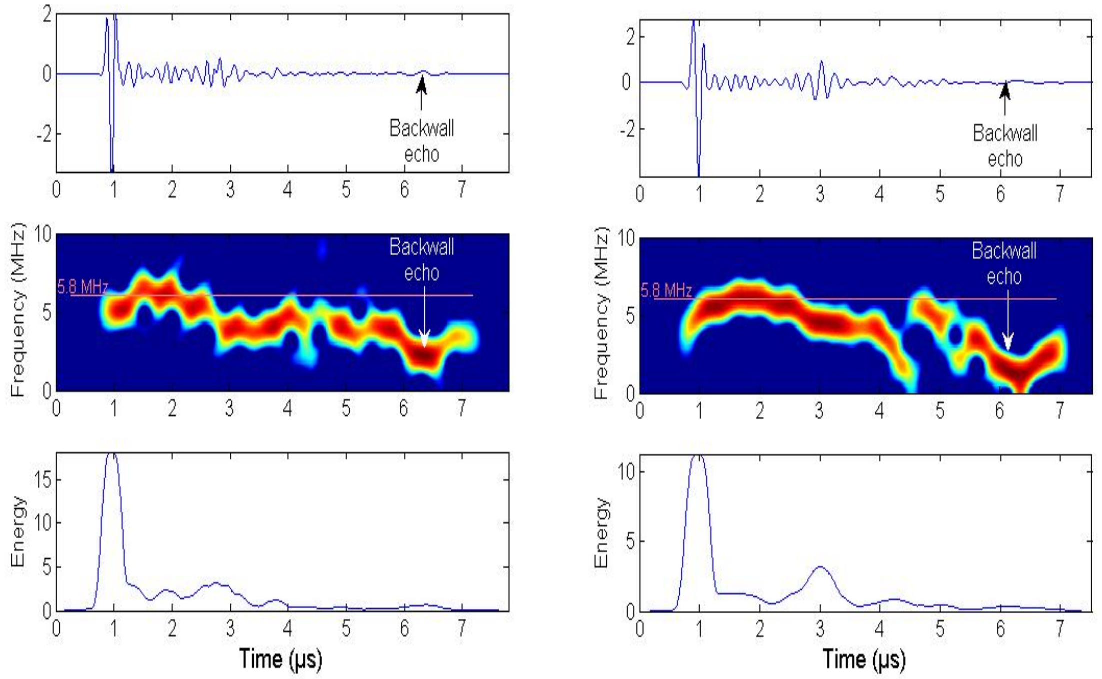
1. Inspect it by ultrasonic pulse-echo measurement
2. Cut it and take a photomicrograph of a slice of the material
3. Evaluate the porosity content by image analysis in the porous zone
4. Use the photomicrograph as a modelling propagation medium. The photomicrograph is thresholded and numerised in three colours, the white corresponds to homogenised carbon-epoxy, the grey to pure epoxy and the black to voids. For instance, the propagation medium of **FIGURE 3** (b) corresponds to the photomicrograph of **FIGURE 3** (a).
5. Exploit the measured and simulated ultrasonic results using the time-frequency-energy analysis tool
6. Correlate the analysis results with the photomicrograph data

The manufacturing of reference samples with totally controlled porosity (geographic distribution and quantity) being inaccessible experimentally, the use of modelling turns out to be very helpful. The systematic comparison between experiments and modelling will allow, in case of agreement, to test other configurations with totally controlled porosity distribution with modelling only, and thus extend the range of the study.
To simulate the propagation of ultrasonic waves into this medium, we use a Finite-Difference code (ACEL [5]) allowing to simulate the propagation of elastic waves in complex media in 2D or 3D. In order to get closer to the experiment, this numerical medium is “immersed” in water to simulate an inspection in immersion. The data about the medium being 2D (a cut), the simulations performed are 2D. A 3D description of the structure of the material would make it possible to do the simulations in 3D but this has not been done in the present study.

3.2 Analysis

- *Porosity at the centre of the material*

The above procedure applied to the material of **FIGURE 3** with an emitted central frequency of 5 MHz leads to the analysis results of **FIGURE 4**. One can clearly see that, on this particular sample, the porosity rate is so high (about 10%) that the porous zone generates an echo. The energy curve then shows a bump at the time corresponding to the presence of the porous zone. Moreover one can see that the time-frequency diagram is also affected by the presence of the porous zone. The resonant frequency is well observed just behind the front echo, but when the wave meets the porous zone, one observes a frequency drop due to the presence of localised porosity. In that case, the frequency shift can be interpreted as the result of the backscattering of the wavefront by the porous zone, yielding an echo whose frequency is around the emitted frequency minus the filter effect of the intrinsic attenuation of the material. On another hand one observes that porosity plays a filter role since the backwall echo has lower amplitude and frequency content compared to the case of the safe material.



(a) (b)

FIGURE 4. Time-frequency-energy analysis on a stratified composite material with 8 central porous plies. (a) Measured signal, (b) simulated signal

- *Porosity at one side of the material*

The material tested is composed of 8 porous plies and 20 safe plies stacked above the 8 porous ones. The volumic void content in the 8 porous plies is about 3% (measured by image analysis).

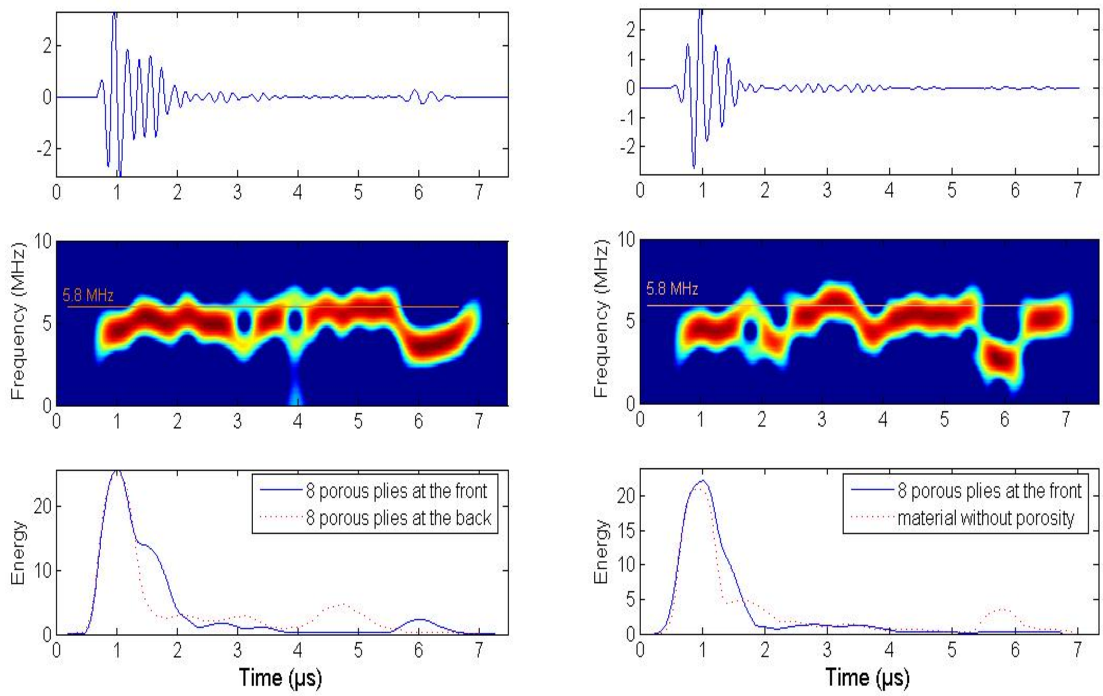


FIGURE 5. Time-frequency-energy analysis on a stratified composite material with 8 porous plies at the front. (a) Measured signal, (b) simulated signal

The inspections performed with the transducer positioned in front of the porous zone with a central frequency of 5 MHz give the results of **FIGURE 5**. One observes that the front echo is followed by a high amplitude signal that suddenly decreases after a while. The energy analysis confirms this fact. One also observes that the resonant frequency is not reached at the times corresponding to this highly energetic signal. This phenomenon is interpreted as the dominance of the scattering by the voids in the first plies with respect to the resonant system created by the periodicity of the layers. Then the signal recorded at that time has the frequency content of the emitted signal, and not the one of the resonant system. This last observation led us to propose the use of an emission frequency sufficiently shifted from the resonant frequency to be able to clearly observe this phenomenon when it is occurring. However the emitted frequency must be sufficiently close to the resonant frequency to be able to excite the resonant system. This trade-off leads to a frequency around 4 MHz as a good candidate. Results obtained with a central frequency of 4 MHz are proposed on **FIGURE 6**. One can see that the use of the central frequency 4 MHz makes the interpretation of the time-frequency analysis clearer.

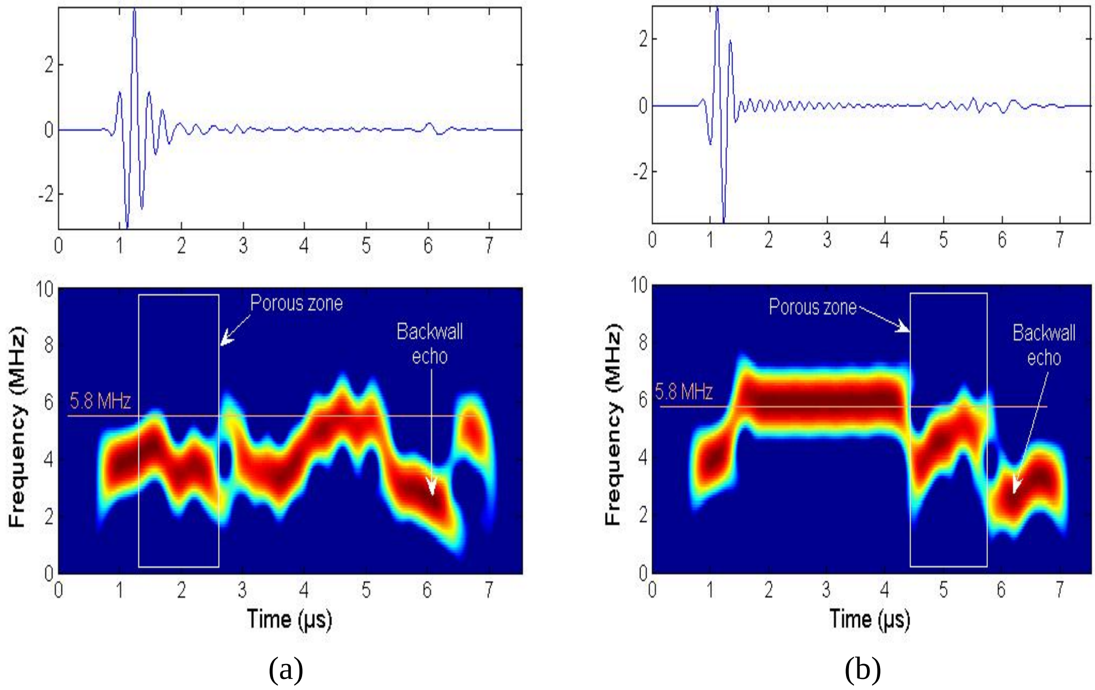


FIGURE 6. Time-frequency analysis on a composite material with 8 porous plies with a emitted central frequency of 4 MHz. (a) Porosity in the front of the material, (b) Porosity at the back of the material

- *Low rate localised porosity*

It turned out difficult to create low controlled rates of localised porosity. Relying on the good agreement between experimental and modelling results, we performed the inspections numerically on totally controlled porosity populations. For instance, a synthetical population of voids have been created, yielding a volumic porosity rate of 2.1 % (Table 1). Synthetical means that it is not extracted from a photomicrograph, but created numerically.

Table 1. Population of synthetical voids for low level localised porosity

Diameter (µm)	**Voids number / mm ^{2}**	**Volumic rate (%)**
50	8.47	2.1

These voids have been inserted in the 8 central plies of a (numerical) 28 plies carbon-epoxy composite material. Within the 8 porous plies, 12 geographical distributions of voids have been computed, chosen at random. Every arrangement of voids simulate a different position of the transducer in front of a randomly distributed porosity.

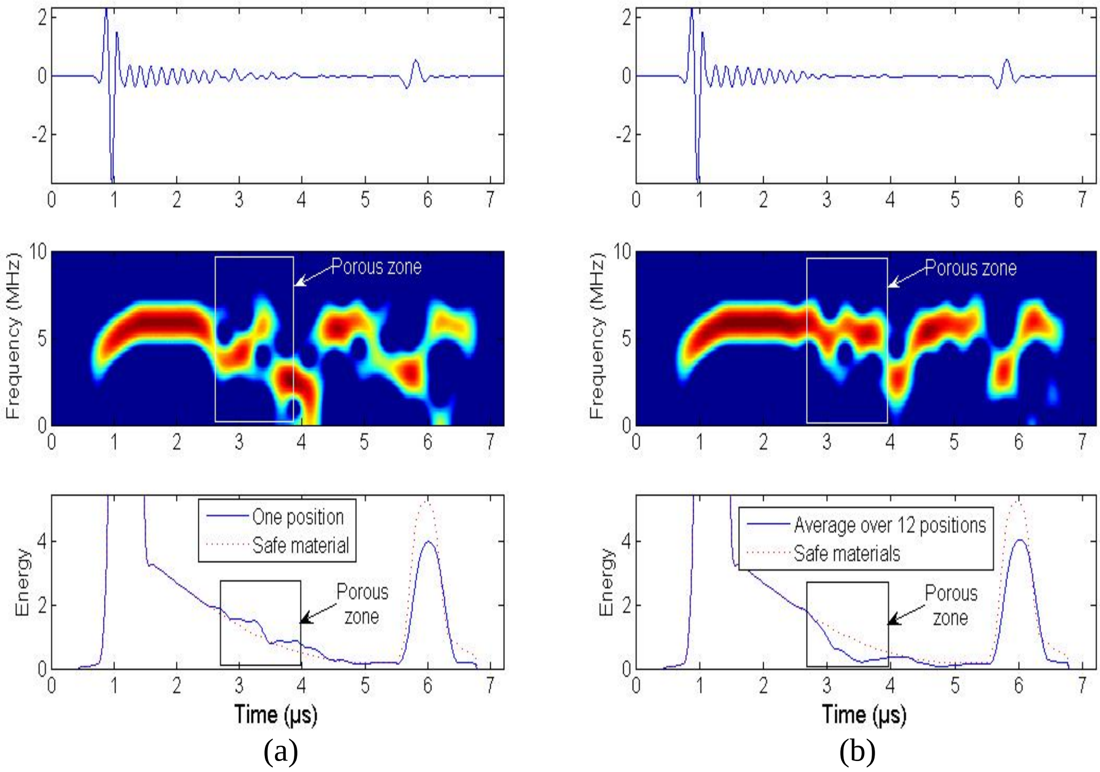


FIGURE 7. Time-frequency-energy analysis on a stratified composite material
with 8 central porous plies with 2.1% of voids in volume.
(a) Signal for one position of the transducer, (b) Signal averaged over 12 positions of the transducer

What appears is that for one position of the transducer (one arrangement of the voids), the porous zone almost do not disturb the energy content of the A-Scan. On the contrary, when an average over the 12 positions is performed, a sudden decrease of the energy content is observed, due to the spatial incoherence of the ultrasonic fields backscattered by the porous zones. On the other hand, the frequency content seems to be strongly affected for one position, and less affected for the averaged signal. These phenomena come from the cancellation of the incoherent contributions to the scattered fields when averaging. This results in an energy loss and in the recovering of the coherent frequency content.

Conclusion

The problem of detection of localised porosity through the thickness in composite materials has been considered following a coupled experimental and modelling approach. Samples with porous plies among otherwise safe materials have been manufactured using a pre-curing technique. A Finite-Difference model allowing the propagation of waves in a medium extracted from photomicrographs has been used for simulations concurrently to ultrasonic measurements on the manufactured samples. The simulation and experimental results turned out to agree on the main characteristics of the recorded signals, which gives confidence into the model. The characteristics of the presence of localised porosity have been found to be discontinuities of the frequency spectrum of the structural signal, and ruptures of the regular and monotonic decrease of the structural signal. The signature of localised porosity depends on the local rate of porosity. High rates yield echoes and an energy bump, low rates yield an energy decrease when averaging over different transducer positions. As for the frequency content, porosity in the bulk of the part yields a frequency disturbance, and porosity at the front of the material forbids the reaching of the resonant frequency after the front echo.

References

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