Non-Contact Ultrasonic Inspection of CFRP Prepregs for Aeronautical Applications During Lay-Up Fabrication.

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***Abstract*—The possibility to inspect laminates of prepreg carbon fiber reinforced polymer (CFRP) laminates during lay-up fabrication is studied. First ultrasonic properties of the uncured material are determined, this information is used to design an inspection system that is tested during the fabrication of laminates with up to 30 layers, following different compaction schemes and including some Teflon insertions to simulate the presence of delaminations. The paper shows that for the chosen selection of parameters (transducers sensitivity, centre frequency and mold configuration), the inspection is possible, opening a new field of application of air-coupled ultrasonic techniques.**

***Keywords*—Non contact NDT, air-coupled transducers, uncured CFRP.**

I. Introduction

Use of composite materials in the aeronautical industry is in continuous advance due to the increasing demand of materials able to meet economic, security and design goals that are also becoming more demanding. In a similar way, challenges faced by the inspection techniques are growing at the same pace. For example, for thermosetting polymers, inspection before curing is being considered as an alternative as it offers the possibility to repair or discard unsound material before the autoclave stage with a potentially significant cost reduction.

One of these applications is the inspection during prepreg lay-up fabrication. A prepreg is a fabric or tape that has been previously impregnated with a resin. The resin system is already mixed and is in an uncured stage. The material is typically placed on a roll. The prepreg material is sticky and adheres to other plies easily during the lay-up process. Inspection during this fabrication process is extremely challenging for a number of reasons. First, in order to prevent any material contamination, fabrication procedures determine that contact with the material is prohibited; this excludes the possibility of using conventional ultrasonic techniques. Second, though there is a significant lack of knowledge of the properties of the uncured CFRP prepreg, it is expected that the attenuation of ultrasound waves in the uncured material be extremely high. Third, the ultrasonic properties of the material are expected to be strongly affected by the presence of lacks of compaction that may appear during the fabrication. However, most of them are not real defects as they are completely removed during curing in an autoclave, but they will seriously affect the inspection before curing. Fourth, the material has to be inspected along with the mold or lay-up surface where it is fabricated.

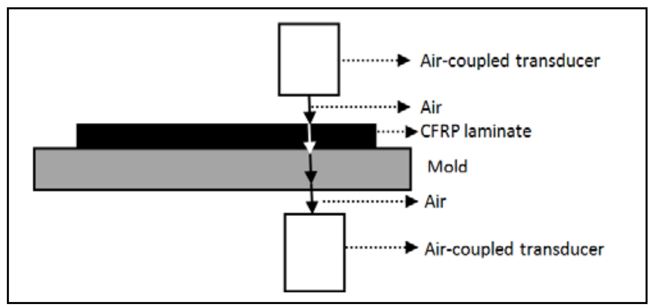

Fig. 1. Proposed configuration for the non-contact inspection of lay-up laminate of CFRP composite on the fabrication mold using a through transmission technique and air-coupled piezoelectric transducers.

The objective of this paper is to propose a non-contact ultrasonic technique for the inspection of CFRP prepreg laminates during lay-up fabrication. A through transmission technique is proposed using air-coupled transducers to transmit ultrasonic signals through the prepreg laminate and the mold where it is fabricated using normal incidence, see Fig. 1.

Apart from some investigations to propagate shear waves in uncured FRP using EMAT transducers and some studies using ultrasonic techniques to monitor the curing of the epoxy in a FRP, [1], [2]; there are no information available about the ultrasonic properties of the uncured CFRP. Therefore, a detailed experimental study of the properties of the uncured laminated prepregs was first performed in order to determine ultrasound velocity and attenuation. Then, these properties were used to model the ultrasonic propagation through the system as shown in Fig 1 to determine the optimum inspection configuration. Finally, an inspection system built following these design criteria was tested on real conditions. Several samples were fabricated following different compaction schemes. Some of them included Teflon insertions to simulate the presence of defects. Inspections were carried out during the

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fabrication to test the influence of both the number of layers and the compaction processes.

II. ULTRASONIC PROPERTIES OF UNCURED LAMINATES.

A 1 mm thick uncured CFRP laminate were used for the characterization of the material. For comparison purposes a 2 mm thick cured CFRP laminate were also characterized. Towards this end, the technique described in [3] was used. This consists on measuring the magnitude and phase spectra of the transmission coefficient around the first order thickness resonance using a through transmission technique and air-coupled wide-band transducers [4], [5] and then solving the inverse problem.

The plates were measured in ten different points to determine the spatial variability. Two representative measurements are shown in Fig. 2. Averaged obtained parameters and standard deviation are collected in Table I. The more remarkable difference between both materials is the attenuation coefficient that is much larger in the uncured laminate, seriously limiting the inspection possibilities. The other differences are a slightly lower density in the uncured CFRP, a significantly lower velocity, due to the comparatively lower velocity in the uncured resin, and a larger variability of the measured properties. Acoustic impedance of the uncured CFRP laminate is lower (2.16 MRayl) compared with the cured material (5.27 MRayl).

TABLE I. PROPERTIES OF CURED AND UNCURED CFRP LAMINATES

Material	Density (kg/m^3)	Ultrasound velocity (m/s)	Ultrasound attenuation @ f_{res} (Np/m)
Uncured	1580 ± 120	1370 ± 175	540 ± 80
Cured	1850 ± 120	2840 ± 40	20 ± 2

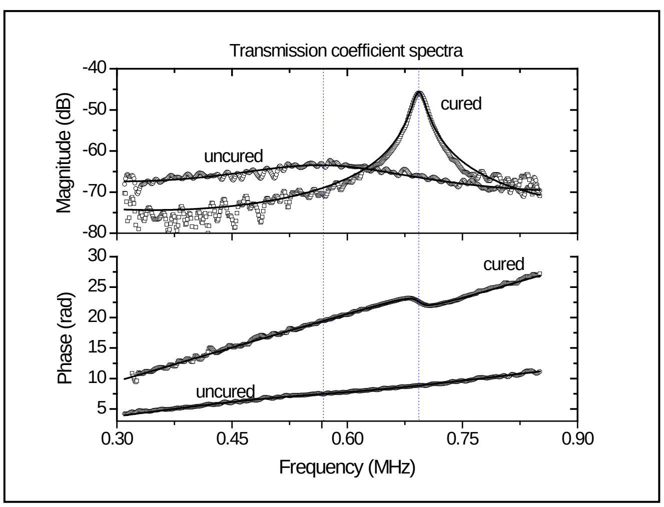

Fig. 2. Measured and calculated magnitude and phase spectra of the transmission coefficient for two FRPC plates, cured (2mm thick) and uncured (1 mm thick).

III. DETERMINATION OF THE INSPECTION POSIBILIITIES USING AIR-COUPLED ULTRASOUNDS: DESIGN PARAMETERS FOR THE INSPECTION SYSTEM.

As the material must be inspected along with the mold where it is fabricated, the design variables of the inspection system to be considered are: 1) Mould material and thickness, and 2) Transducers centre frequency and bandwidth. A theoretical simulation of the ultrasound transmission is performed using the material parameters previously obtained and varying these design variables to find out the best configuration. A 1D problem was considered: plane waves and normal incidence, and a linear variation of the attenuation with the frequency. It is assumed a thickness of the CFRP laminate of 7 mm in all cases. Following our previous experience, the maximum acceptable through transmission losses is set to 100 dB, i.e. beyond that value it is considered that the inspection is not possible with the available technology.

As the mold has to be made of a metal, the selected option was aluminum because of its relatively lower acoustic impedance, and cost. Fig. 3 shows the calculated Insertion loss (IL) vs. frequency for three different mold thicknesses: 2, 6 and 13 mm. The first conclusion is that working frequency must be limited below 0.55 MHz, the second one is that a significant increase of the transmitted signal amplitude can be achieved if the working frequency is tuned to the thickness resonance of the mold. So, with the 6 mm thick mold the thickness resonance appears at 0.52 MHz, minimum IL= -92 dB, for the 13 mm thick mold, the thickness resonance appears at 0.25 MHz with a minimum IL of -78 dB. Therefore, the proposed configuration consists on a 13 mm thick mold and a pair of 0.25 MHz air-coupled transducers.

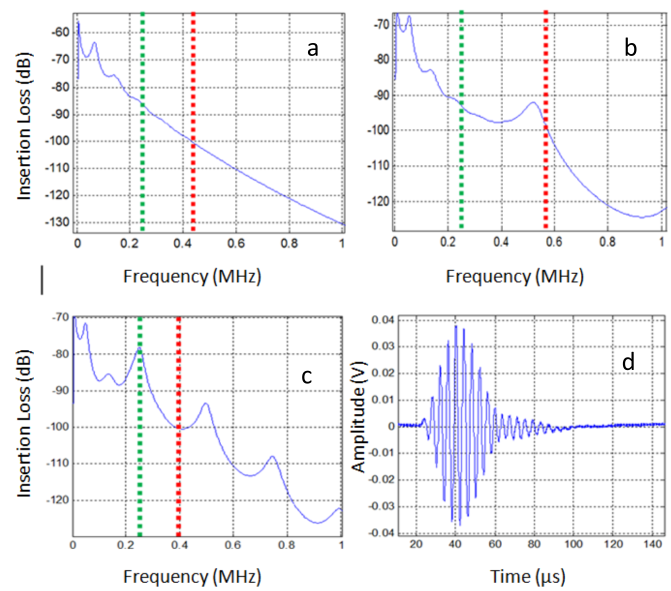

Fig. 3. Calculated spectra of the Insertion loss of the FRCP laminate and the aluminum mold for three different mold thicknesses (a: 2 mm; b: 6 mm; c: 13 mm). Green line indicated the location of the 0.25 MHz frequency and the red line indicates the maximum inspection frequency for the -100 dB limit. 3. d: simulated transmitted pulse for the 13 mm mold using a pair of 0.25 MHz air-coupled transducers.

IV. ULTRASONIC INSPECTION SYSTEM.

A. *Transducers.*

The impulse response and sensitivity obtained with the pair of transducers used for this work, operated in through transmission, separated 2 cm in air, using a Panametrics Pulser/Receiver (PR 5058), with spike amplitude set to 200 V and receiver gain set to 0 dB, and a Tektronix Oscilloscope DPO7054 is shown in Fig. 4. Sensitivity is calculated as the ratio of the FFT of the electric voltage measured on the receiver terminals to the one measured on the transmitter terminals. Peak sensitivity is -24.6 dB, this figure is the key to set the limit of the maximum acceptable insertion losses for a through transmission test at -100 dB.

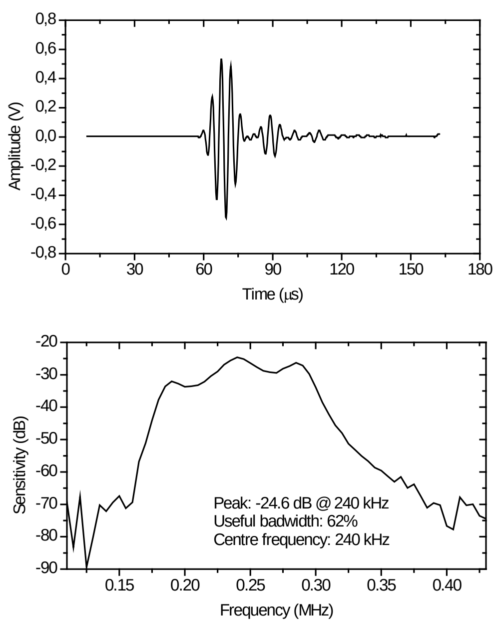

Fig. 4. Measured impulse response and sensitivity of the 0.25 MHz air-coupled transducers employed for the tests.

B. *Electronics.*

Two different pulser/receiver systems were successfully used. A Panametrics P/R 5058, and a DASEL USB-ultrascope that provide a tone burst (square wave, we used between 1 and 5 cycles) up to 400 V and 60 dB gain in reception.

C. *Mechanics.*

The transducers were mounted on a U shaped holder as shown in Fig. 5. The holder was fitted into an automatic and portable scanning system, developed by Tecnatom, to perform both punctual through transmission measurements and C-Scans. This system can be put in place to perform the tests and then taken away to allow for the space for the machine that puts the layers of prepreg CFRP.

D. *Materials and inspection scheme.*

Several samples (300 x 300 mm and up to 30 layers) of CFRP, equal to others used in the aeronautical industry, were fabricated at FIDAMC (Getafe, Spain) following different compaction scheme. Some samples were fabricated without compacting them, and some other were compacted at different stages. The compactions were performed using conventional vacuum bags. Two different compaction times were used: short (15-30 min) and large (from 4 to 8 hours). In addition, some of them included 10 x 10 mm Teflon insertions at three different depths (2, 15 and 28 layers) to simulate the presence of local defects (delaminations).

Fig. 5. Picture of the aluminum mold with the CFRP, the transducers and the scanning system.

V. RESULTS.

A. *Transmission of airborne ultrasonic signals through the CFRP laminate and aluminum mold system.*

Fig 6. shows the transmitted signal from Tx to Rx for several cases. The transmitted signal through the CFRP-mold system is clearly identified and the SNR figure is pretty good (>30 dB). Reverberations in the airgaps between transducers and sample are clearly appreciated revealing the importance of using wideband transducers.

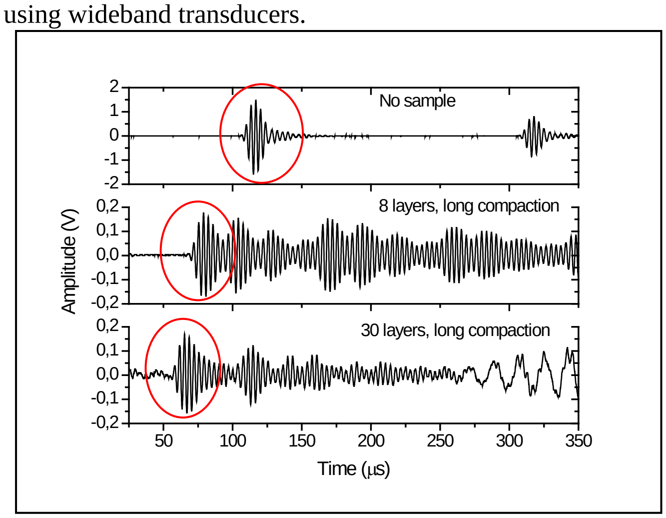

Fig. 6. Transmitted signal from Tx-transducer to Rx-transducer for three cases: Up: no sample between Tx and Rx. Middle: CFRP laminate (8 layers) and 13 mm aluminum mold. Bottom: CFRP laminate (30 layers) and 13 mm aluminum mold.

For the inspection of the 8 layers laminate the pulse amplitude of the Panametrics 5058 were set to 400 V and the gain in reception to 40 dB. For the 30 layers laminate, the configuration was 400V and 50 dB, respectively.

The measurement of the variation in the time of flight as the number of layed layers increased permitted to us to determine the ultrasound velocity , which turned out to be slightly smallerthan the values obtained in the preeliminary study, about 950 m/s.

B. *Influence of compaction.*

To determine the influence of the compaction degree on the inspection possibilities several laminates were fabricated (up to 30 layers) following different compaction schemes. In all these cases layers were put manually, which is the worst possible scenario because in this case, the degree of compaction is comparatively smaller compared with the case when layers are put by a machine. Comparing the amplitude of the signal received with different number of layers after the same compaction procedure it was possible to estimate the attenuation coefficient in the laminate which results to be extremely dependent on the degree of compaction. Results are summarized in Table II. These, along with the estimation of the level of noise permit to determine the maximum number of layers that can be inspected with this configuration. For example, after a short compaction, the results suggests that the inspection limit is about 12 layers, for non compacted material, the limit is reduced to about 3 layers, while after a long compaction it would be possible to inspect up to 90 layers.

TABLE II. AVERAGED VALUE OF THE MEASURED ATTENUATION PER LAYER FOR DIFFERENT TYPES OF COMPACTIONS FOR ALL THE TESTED CASES.

Compaction	Attenuation (dB/layer) @ 0.25 MHz
Long	0.3-0.75
Short	2.5-3.0
None	7-10

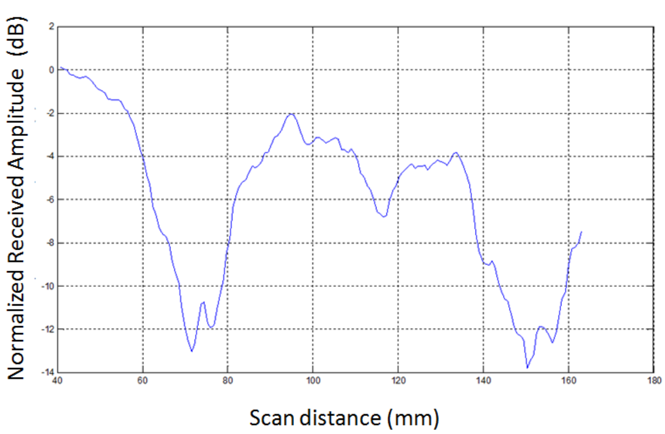

Fig. 7. Linear scan along two Teflon insertions, laminate with 24 layers measured after a long compaction.

C. *Detection of Teflon insertions.*

Fig. 7 shows the result of a liner scan over two 10 x 10 mm Teflon insertions located at a distance of 75 and 150 mm, respectively, from the scan origin. The drop of signal amplitude due to the presence of the insertions is between 7 and 12 dB and the actual size of the insertion is consistent with the size of the amplitude drop.

VI. CONCLUSIONS.

This paper studies the possibility to use an air-coupled and through transmission ultrasonic technique to inspect prepreg CFRP laminates during lay-up fabrication (i.e. before the resin cures). The main challenges of this application are the impossibility to touch the material during the inspection, the large attenuation coefficient in the uncured CFRP laminate and the need to perform the inspection together with the fabrication mold. An air-coupled and through transmission technique is proposed. To minimize the effect of the very large insertion loss, a pair of wide band and low frequency (0.15-0.35 MHz), high sensitivity (-24 dB) transducers with active area diameter of 25 mm were employed together with a conventional pulser/receiver. In addition, a mold of aluminum, 13 mm thick, was proposed, so the mold presented a thickness resonance within the transducers bandwidth so transmission of energy is enhanced. With this configuration it was possible to inspect well compacted laminates with up to 30 layers, and the estimation is that the maximum thickness that can be inspected is about 90 layers. It was also possible to detect the presence of Teflon (10 x 10 mm) insertions at different depths, with an amplitude loss about 7-12 dB compared with insertion-free areas. Finally, the paper reveals that one of the key factors to determine the possibility to inspect prepreg lay-up CFRP laminates is the ultrasound attenuation. This attenuation is largely determined by the degree of compaction of the laminate; it can be more than one order of magnitude larger in the case of poorly compacted laminates compared with well compacted ones.

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