# Air-coupled ultrasound inspection of complex aluminium-CFRP components


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***Abstract*— Composite Overwrapped Pressure Vessels (COPVs) are widely used to contain high-pressure fluids. COPVs consist of a thin metallic liner covered with a composite material based on structural fibres. The main function of the liner is to avoid direct contact between composite and chemical agents which can degrade the resin matrix. In the filament winding process for COPV production, a metallic core is wrapped with impregnated carbon filaments. After that, the matrix can be cured at ambient temperature without use of an autoclave. The COPV's structural integrity can be assured using suitable designs, controlled manufacturing processes and effective Non Destructive Evaluation (NDE) methods. However, the ultrasound inspection of these components is challenging by several factors. Because no vacuum compaction process is applied, the sound attenuation in the laminate is high. Moreover, the strong reflection at the liner-fibre interface avoids inspecting from the metallic-side using conventional techniques. This work explores the possibility of inspecting COPVs by air-coupled ultrasound after the manufacture process.**



***Keywords*— *Air-coupled ultrasound; COPV vessels; COPV manufacture; NDE for aerospace***


## I. INTRODUCTION

COPVs are progressively replacing all-metal pressure vessels. Composite vessels are used as storage tanks for liquid or gaseous fuels, achieving an important weight reduction. Therefore, warranting a high integrity level is mandatory to improve safety factors, especially if COPVs are used in aerospace applications.

In general, COPV's design is supported on metal vessels, with cylindrical, spherical, and also conical shapes. A COPV consists in a non-structural liner used as a mandrel for wrapping high-strength fibres embedded in polymeric matrix resin, which forms the composite structure. Depending on the application requirements the liner can be covered with filaments of glass, aramid, Kevlar® or carbon. The liner avoids fluid permeation and reduces the composite degradation. In order to minimize weight, liners can be made of polymers, integrated composite materials, or thin ductile metal structures [1-3].

The COPV composite structure and mechanical behaviour is more complex than in all-metallic vessels. Therefore, specifics standards have been published for manufacturing and inspecting these components [4-5].

### A. *Damage types in COPVs.*

The development of a COPV involves a winding process of several steps, such as fibre configuration, winding tension, wrap pattern, and resin drying and hardening [6]. Therefore, COPVs may have different damages that can be introduced during the manufacturing process. Metallic liners may have leaks, cracks, and discontinuities on welds. Delamination is the typical composite damage, which can be described as disbonds (between laminates or overwrap-liner). Areas not properly bonded can produce blisters and voids compaction. Porosity and inclusions of foreign object debris can be also found. The winding system can introduce errors not holding the fibre tension constant causing a non-uniform compaction or even fibres breakage. The winder can also present errors of slippage and misalignment, which yield to depressions and wrinkling on the composite, matrix-rich or fibre-rich regions, fibre-matrix unbonding, and fibre scrolling and splitting [7]. Incorrect matrix curing can also produce cracking and delamination. Moreover, liner-overwrap disbonding can be formed after pressure proof testing. Definitely, any kind of delamination leads to lose the COPV mechanical properties [8].

### B. *NDE Methods.*

Quantitative and qualitative NDE techniques have to be applied before and after wrapping liners. Metallic liners are inspected by traditional NDE methods prior to the overwrapping process. Particularly, for finding leakages and discontinuities in welds. In order to evaluate the cured composite vessel, standards recommend the applications of methods such as, Acoustic Emission (AE), Eddy Current (EC), Laser Shearography (LS), Radiologic Testing (RT), Thermographic Testing (TT), Ultrasonic Testing (UT), and Visual Testing (VT) [4, 8-9].

UT can be suitable for detecting and sizing sub-surface imperfections after the manufacture process as, for example, inclusions, delaminations, voids, porosity, and unbonded overwrap-liner, or possible liner separation (disbond) that can be induced after pressure proofs.

However, there are several limitations for implementing UT as NDE method of COPVs. The overwrapped composite tends to be inhomogeneous, anisotropic, and very attenuating. These are problems that worsen with thickness. Moreover, contact inspection techniques require a relatively flat surface for an efficient acoustic coupling, but the composite overwrap texture is in general irregular, which reduces the transferred acoustic energy. COPVs inspection can be improved by using immersion tanks or jet coupling methods. In both cases, the ultrasonic couplant can be water or low contaminant liquids for avoiding the composite degradation. Nevertheless, some COPVs cannot be wetted for this can induce moisture in the composite and induce corrosion in the metal liners

Phased array technology can also be used for enhancing the scanning speed and assisting in the beam orientation into the COPV surface. However, the non-uniform surface is an issue for beam focusing. In such cases, a precise alignment of the array with respect to the primary ply is required, and strategies for performing beam auto-focus should be considered [10].

### *C. Air-coupled ultrasonic transducer (ACT).*

Advancements in new materials and manufacturing processes have made possible the development of more efficient ACTs. These transducers have their acoustic impedance well matched to the impedance of the air to ensure high sensitivity and provide an adequate signal-to-noise ratio (SNR) [11]. In consequence, the great potential of ACT has led to a large variety of emerging non-contact NDE applications and material characterization methods [12-13].

This work proposes to take advantage of the ACT capabilities to reduce the exposure of the composite to liquid couplants, and to overcome the problems associated with complex geometries of COPVs.

## II. MATERIALS AND METHODS

### *A. Studied sample.*

An aluminium cylindrical liner of 130 mm length with 114 mm of outer diameter and 3 mm of wall thickness was used to produce a reduced mock-up of a COPV. The aluminium surface was manually sandpapered and cleaned using isopropyl-alcohol to improve the liner-composite adhesion. The manufacturing process method to overwrap the liner was filament winding. The COPV sample was winded with carbon fibres in a 4-axis machine prepared to work with two TORAY T700S carbon fibre tows and an epoxy resin system (Kohlenia, Argentina). The fibres tension was set to 1 kgf each [7]. The 4 axes movement during production was programmed by FILWIND software (Kohlenia, Argentina). The fibres were impregnated with epoxy resin through a drum type impregnator incorporated on the moving carriage, just before being wrapped on the liner. The lamination sequence incorporates 10 hoop layers (fibres oriented at 88°), and 4 low angle layers (fibres oriented between 5° and 20° depending on the layer). The resin curing was at ambient temperature and no autoclave was used.

Rectangular polypropylene inserts of 130 mm length, 38 mm width and 0.1 mm thickness were introduced on the sample (Fig.1). Defects were located at 90° intervals. One artificial defect was placed at liner-overwrap interface to simulate disbond. The other three inserts were disposed between layers $4^{th}$ and $5^{th}$, $8^{th}$ and $9^{th}$, and $13^{th}$ and $14^{th}$, to simulate delaminations at different depths.

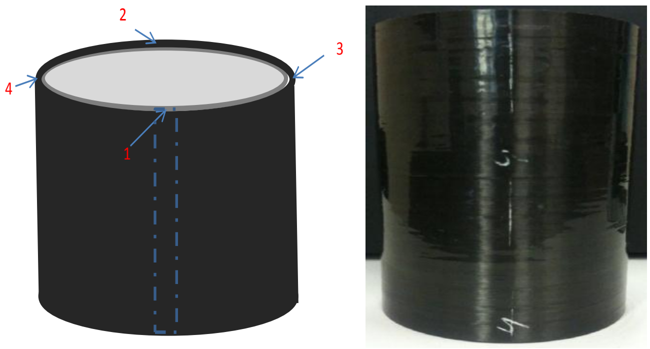


Fig. 1. Diagram of insert locations and picture of the test tube with aluminum liner overwrapped with carbon fibre used in the experimentation.

### *B. Experimental Setup.*

The test sample was mounted on a pair of motorized turning rolls, which provide the cylinder rotation around its axis. The non-contact inspection was performed using two pairs of ACT developed by CSIC, Spain [14], in through-transmission and pitch-catch configurations. The transducers were moved using the *xyz* positioning system DIS-500 (Dasel SL, Spain) for exploring the sample. The 4 channels pitch & catch acquisition system AirScope (Dasel SL, Spain) was used for recording the ultrasonic signals.

### *C. Through – transmission configuration.*

This arrangement consists of using a pair of ACT to pass through the cylinder wall a beam oriented along the radial direction, i.e. with quasi normal incidence to the tube surface. Both transducers are aligned and faced, the transmitter placed on the outer wall of the sample and the receiver positioned behind the cylinder wall (Fig. 2). Transducers central frequency is 250 KHz, with narrowband response and 25 mm aperture diameter. In order to improve the spatial resolution, each transducer was mounted with SonoJet focusing device, obtaining a collimated beam of 1.5 mm diameter [15].

In this configuration, the ultrasound passes through the sample thickness. Thus, it is possible to evaluate the material inhomogeneity by comparing the emitted and received acoustic energy. If defects (i.e. delamination, disbonds, etc) exist on the beam path, the received signal decreases due to reflection on the obstacles. The signal attenuation can be partial or total (loss of transmission) depending on the size and type of the defect.

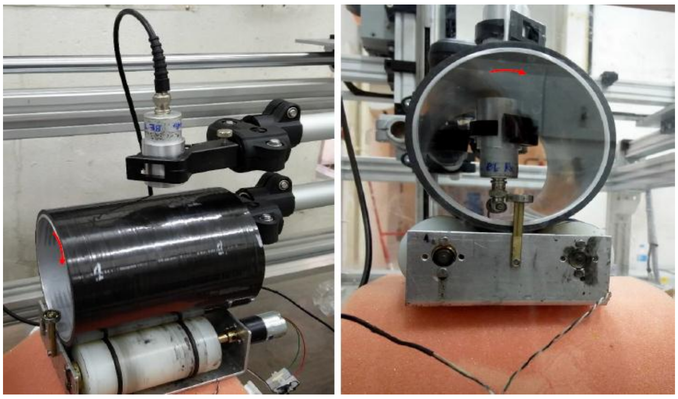

Fig. 2. Arrangement for scanning the sample under test in through-transmission mode. At the top is the emitter transducer, inside the receiver.

### *D. Single side, pitch – catch configuration.*

This configuration presents the main advantage of avoiding the necessity to have access to both sides of the test sample. In this particular case, both ACTs are placed on the outer side of the cylinder with oblique incidence over the surface. A pair of 250 KHz wideband transducers was used, with square section of 12x12 mm (Fig. 3). In particular, the pitch-catch configuration allows the generation and detection of guided waves for testing the composite structure.

The optimal angle of both the transmitter and the receiver can be determined using the coincidence principle [16], although in this case, the generated guided waves are not simple Lamb waves as the COPV wall is a complex, anisotropic and layered structure. The generated guided waves interact with the wall thickness and structural damages, such as delaminations, disbonds, and other mechanical degradation conditions [17].

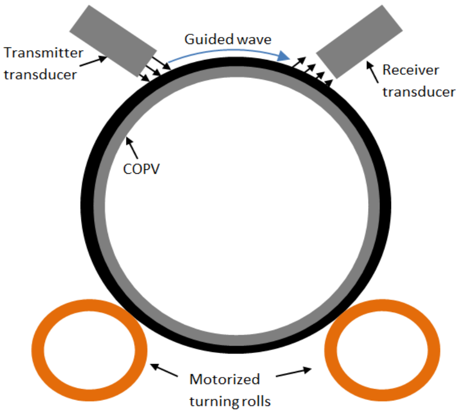


Fig. 3. Setup for the pitch-catch configuration mode.

## III. RESULTS

In both inspection configurations, the scanning was performed turning the cylinder in a direction such that the defects sequence is 1-4-2-3. Moreover, scanning was restricted to the sample centre zone (away from the cylinder edge) to prevent that the signal received through the air masks the wave that propagates through the sample wall. Amplifier gain was set to 48 dB and, in order to improve the SNR, a real-time averaging of 8 signals was applied.

### *A. Through-transmission results.*

In through – transmission mode, the pair of ACT was moved in tandem along the cylinder axis 2 mm steps, after three turns of the cylinder each time. The scan starts at 22 mm from the edge and extends about 46 mm long.

Information was plotted on a C-Scan format image of the transmitted echoes amplitudes. The abscissa-axis expresses the cylinder turn number and the ordinate-axis indicates the transducers position over the generatrix (Fig. 4). The linear colour scale is expressed in % of full screen height (FSH). The artificial flaws are detected when the signal amplitude falls below 30% due to the acoustic energy reflection on the inserts. The defects sequence (1 to 4 - 2 - 3) is coherent and repeated for the three turns that were acquired at each longitudinal position of the cylinder. The scan image revels that inserts 1 and 4 are slightly separated, while defects 2 and 3 are very close together. Moreover, the laminate between inserts 3 and 1 has a better adhesion to aluminum (more signal amplitude) that region between 4 and 2. Finally, some misalignments in the image can be appreciated as a consequence of cylinder slip over the rollers.

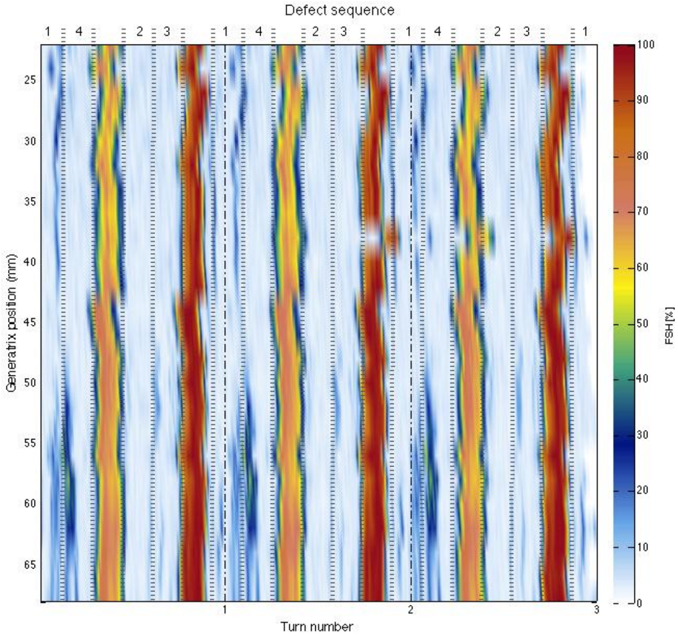


Fig. 4. C-Scan image obtained using the configuration mode 1.

### *B. Pitch-catch results.*

In this case, a qualitative analysis of the laminate condition can be performed from the behaviour of the guided wave. The pair of ACT was positioned at 36 mm from the cylinder edge. The optimal angle for the transducers was approximated by the coincidence principle and later optimized by manually tuning the incidence angle until the highest signal amplitude was obtained.

The A-Scan information is plotted together with the transmission signal obtained at the same scanning position (Fig. 5). The first noticeable difference is that signals are noisier than through-transmission mode. This is because the sound path on the fibres is longer than in transmission, besides that guided waves are sensitive to the material anisotropy. However, the maximums of the guided waves are correlated with the inserts position. In fact, inserts allow the laminate to vibrate more easily than if it is bonded to the liner. Therefore, indications obtained using normal incidence and transmission mode and using oblique incidence and pitch-catch guided waves are complementary. In effect, guided waves show a local maximum when through-transmission is minimal.

The pitch-catch transducer separation has also been studied to analyse how the defect size resolution is affected. For this purpose, the sound path in the laminate was modified to the following values: 15 mm, 25 mm, and 35 mm (Fig. 6). In all cases, the peaks corresponding to the inserts positions remain constant. In addition, the smaller path on the fibre the better SNR and the higher peak definition are achieved.

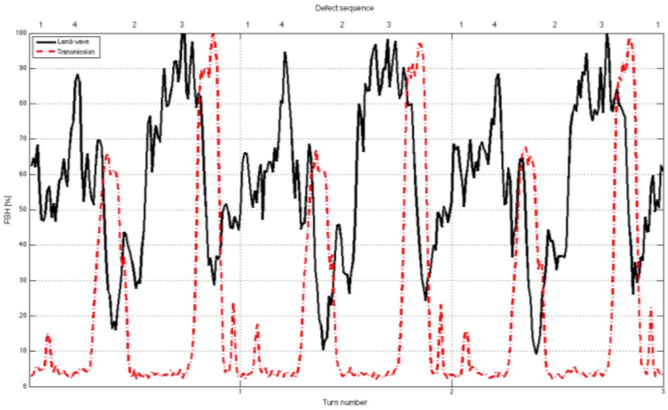


Fig. 5. Comparison between data obtained using guided waves and through-transmission mode. Signals were taken at 36 mm from the cylinder edge.

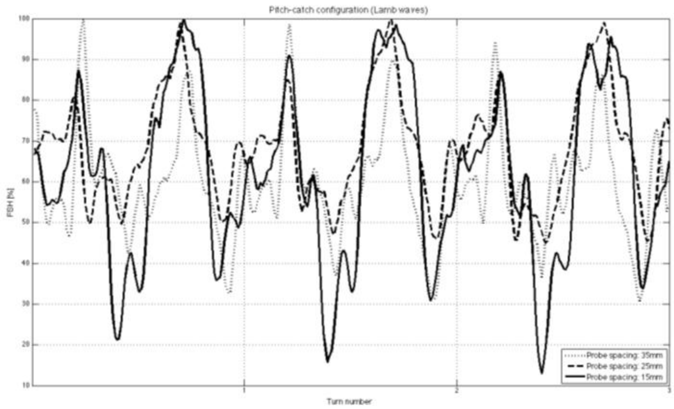


Fig. 6. Test adjusting the sound path on the cylinder wall at 15 mm, 25 mm, and 35 mm. Each response corresponds to three turns of the cylinder, acquired at 36 mm from the edge. The defects sequence is 1-4-2-3.

## IV. Conclusions

This work has presented the use of ACT for the non-contact evaluation of COPVs. This alternative offers a great potential for rapid inspection taking into account the wide range of COPV sizes, as well as reduces the exposure of the composite to liquid couplants. The single probes allow a relatively easy automation and to perform an inspection without interfere in the winder machine. Both configuration modes are complementary and provide a qualitative detection of defects. Through-transmission mode offers a good sensitivity and SNR. However, requires to access to both sides of the test sample. On the other hand, the single-side, pitch-catch mode allows using guided waves and performing the inspection from outside, which reduces the scanning system complexity. The guided wave test also enables the possibility of characterizing material properties such as fibres orientation, and resin cure temperature. However, in both cases, no quantitative analysis can be performed.

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