Air-coupled Ultrasonic Inspection of Thermoplastic Composite Structures for Aerospace Vehicles

Armin Huber
German Aerospace Center (DLR), Germany, armin.huber@dlr.de

Abstract

Composites have become the most important type of material used in the manufacturing of aerospace vehicle components. One focus of the German Aerospace Center is to develop cost-efficient manufacturing processes for large-scale composite components such as liquid hydrogen tanks, rocket booster pressure vessels, and aircraft fuselages. To enable a high degree of automation in the manufacturing, robot-assisted tape-laying processes with flash lamp consolidation of thermoplastic prepregs are preferred. Non-destructive inspection is crucial to monitor manufacturing quality, and various forms of ultrasonic inspection have become standard. Air-coupled ultrasonic inspection is applied at the German Aerospace Center, and since access to the component is usually available only from one side, Lamb waves are excited and detected in focused slanted reflection mode. Like the manufacturing process, air-coupled ultrasonic inspection has been automated as well to avoid a significant pause during or after manufacturing. The paper demonstrates the robot-assisted air-coupled ultrasonic inspection of a liquid hydrogen tank. The robotic program is generated using offline programming software, based on the topography of a CAD model of the hydrogen tank. The inspection is carried out by scanning the component while ultrasonic pulses are triggered on a regular grid. The ultrasonic A-scans together with the measurement coordinates are monitored simultaneously. The data are used to generate and evaluate a three-dimensional C-scan.

KEYWORDS: H2 Tank; CAD model; Robot; Automation; Off-line Programming

1. Introduction

Guided waves have been used for the non-destructive inspection (NDI) for many decades. An early description of the flaw detection in sheets and tubes immersed in water by means of Rayleigh and Lamb waves was given by Viktorov (1) already in 1967. Only a few years later, Luukkala et al. (2) proposed a contactless test method for metal plates based on Lamb waves. Many applications have been established since then, and the advent of composite materials in automotive and aerospace industries, which took place in the early 1990s, has added significant complexity to the non-destructive testing and evaluation processes. The ability of guided waves to propagate many meters in a waveguide is utilized for pipe inspection (3). They are also used for the inspection

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of bonding (4). Air-coupled ultrasonic testing (ACUT) plays an important role in future production lines. Often, the presence of a liquid coupling medium is unwanted because it might inflict damage to unsealed composite structures, beside other drawbacks. Furthermore, ACUT is more suitable for inline NDI, thereby improving the cost-efficiency of the manufacturing process. Castaings et al. (5) have done significant work on the single-sided ultrasonic testing of composites by using Lamb waves, while Solodov et al. (6) have used them for transmissive inspection. The Spanish company Tecnatom (7) has achieved remarkable progress in the automation of ACUT and other NDI methods. Huber (8) demonstrated the automated inspection of a rocket booster pressure vessel demonstrator by means of Lamb waves in 2016, and Schönheits et al. (9) in 2019 developed a system enabling the automated inspection of composite components with varying thicknesses and curvatures. The most recent advance in contact-less inspection technology is laser-excited ultrasonic inspection, developed by the Austrian company XARION. This method was used for the detection of porosity in composite parts in 2021 (10).

2. Air-coupled ultrasonic inspection of a hydrogen tank

2.1 Liquid hydrogen tank

A liquid hydrogen tank demonstrator was manufactured from thermoplastic pre-impregnated carbon fiber reinforced epoxy (CFRP) at the DLR Augsburg. The manufacturing was conducted using an in-situ automated fibre placement (AFP) process with flashlamp heating. The fibre placement end-effector was carried by an industrial robot, and the layup was performed on a rotatable tooling. The tank has a diameter of 1.3 m and a length of 2.2 m. As shown in Fig. 1, the main parts are the cylindrical midsection, which is closed by the two domes, and two skirts. The subparts were joined by thermoplastic welding using a continuous ultrasonic welding process. More details about the tank and its manufacturing are given in Ref. 11.

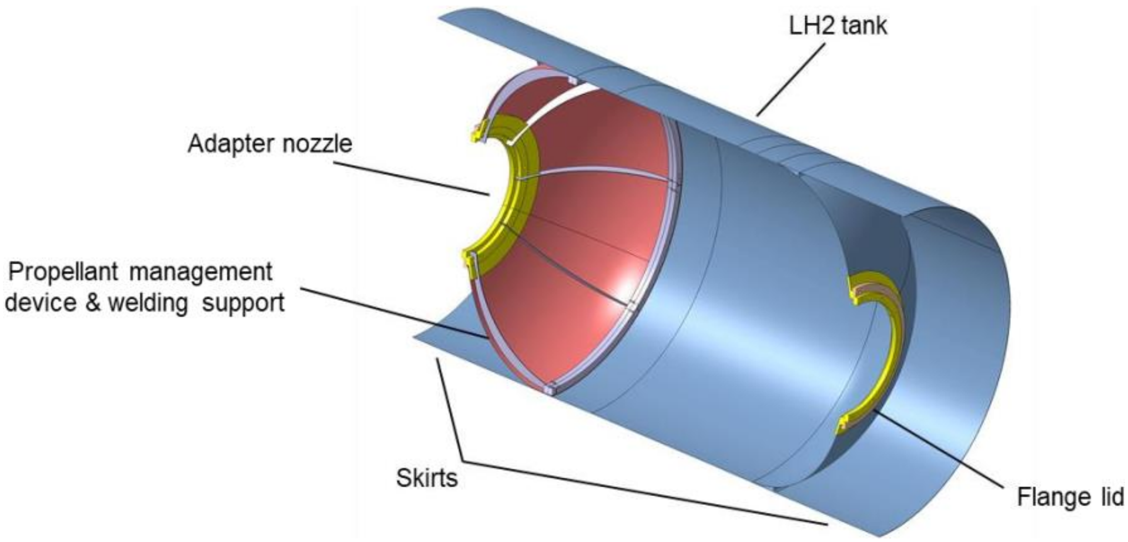

Figure 1. DLR design for a cryogenic liquid hydrogen tank (11).

2.1 Experimental setup

The objective was to fully inspect the cylindrical area of the tank. Since there was limited space inside the skirts, the domes should be spared from inspection. The inspection process should be fully automated and contactless. Figure 2 shows the experimental setup of air-coupled ultrasonic inspection in the focused slanted reflection mode (FSRM). The meander-like scanning of the tank was performed using a KUKA KR 120 industrial robot. The KR 120 carried a dedicated end-effector holding two ultrasonic transducers (sender and receiver) with centre frequencies of 200 kHz. These were designed for the excitation of Lamb waves with high power, and were purchased together with the air-coupled ultrasonic testing device from INOSON GmbH, St. Ingbert, Germany. Excitation of Lamb waves is enabled by sending ultrasound under the appropriate angle with respect to the component’s surface. This coincidence angle depends on the thickness and on the stiffness of the laminate. It is also frequency dependent due to the dispersive nature of Lamb waves. Although dispersion diagrams can be calculated using the open-source Dispersion Calculator (DC) (12), in the present case, the angle of excitation (and reception) was obtained by changing it manually until a maximum of the Lamb wave amplitude was found in the measurement software. The whole tank was scanned with this fixed angle in both the sender and the receiver.

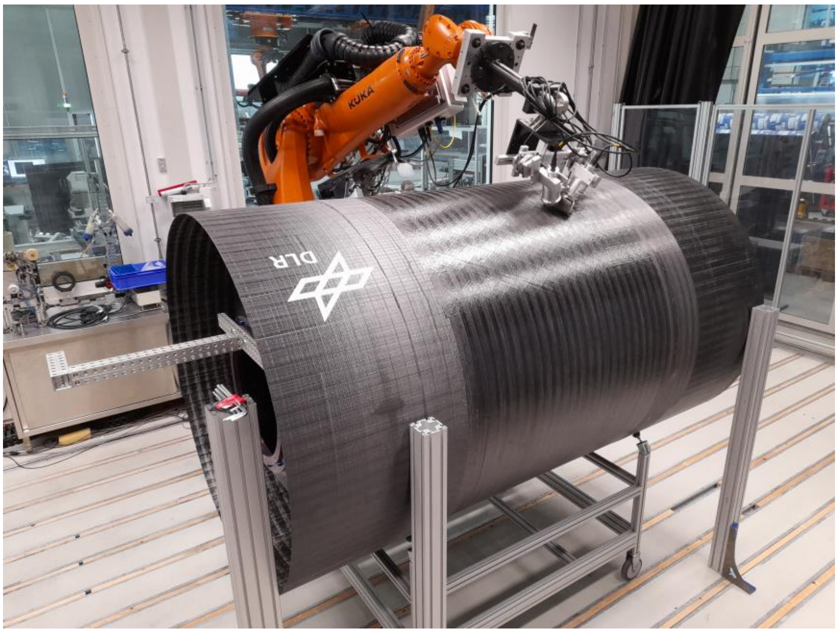

Figure 2. Robot-assisted air-coupled ultrasonic inspection of a hydrogen tank at the DLR Augsburg.

As shown in Fig. 3, the robot offline programming was performed in the FastSuite Edition 2 R2022.1 (Cenit AG, Stuttgart, Germany), based on CAD models of the robotic cell and of the hydrogen tank. The ultrasonic testing device was integrated into the robotic system such that ultrasonic pulses could be triggered at equidistant points along the scanning path. During the scanning, the ultrasonic data (A-scans) and the measurement positions (X, Y, Z-coordinates) were monitored simultaneously with a resolution of 2×2 mm. A low scanning speed of 150 mm/sec was used for better data quality. The tilt-turn-table, which was used in the previous study (10) to rotate the tank, was not available this time. Therefore, due to reachability issues, the tank was scanned in eight segments. Between each scan, the tank had to be rotated by forty-five degrees, in order to cover the whole circumference. The three mechanical stops seen in Fig. 2 enabled the reproducible positioning off the tank. The L-shaped beam mounted on the left dome had a reference marker (base) used to match the positioning in the real word and in the FastSuite Edition 2.

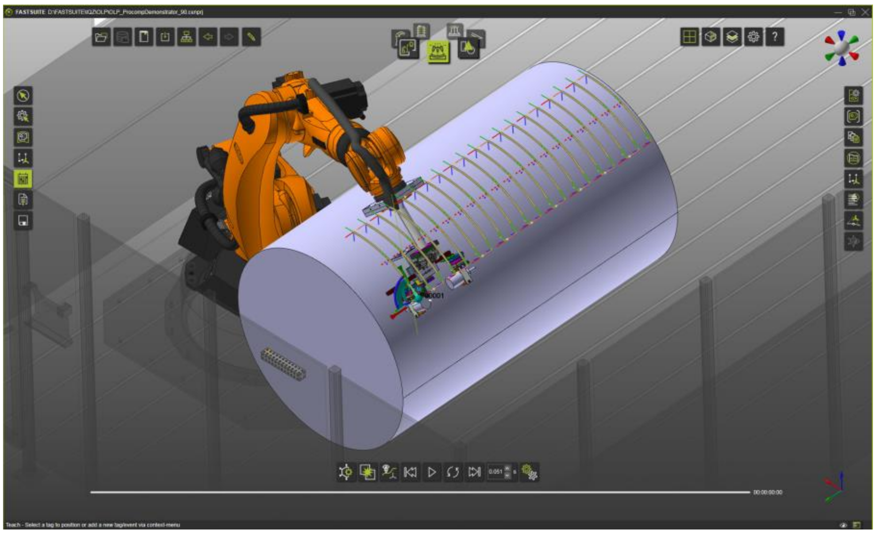

Figure 3. Robot offline programming in the FastSuite Edition 2.

2.2 Inspection results

As a result of the inspection, a cloud of 2.5 million measurement points was obtained, each containing the X, Y, and Z-coordinates and the corresponding ultrasonic A-scan. The data processing and plotting was performed in MATLAB (The MathWorks, Natick, MA, USA). Since the tank was inspected by measuring only a forty-five degrees segment, and then rotating and measuring the tank another seven times, a total of eight coinciding point clouds was obtained. To generate the 3-D C-scan shown in Fig. 4, seven of those were rotated about the length-axis of the tank into the positions they belonged. The colour in this C-scan represents the Lamb wave amplitude. The maximum peak-to-peak amplitude was extracted from each A-scan such that a single amplitude value could be allocated to each measurement position. By unwinding the point cloud, the flat C-scan depicted in Fig. 5 was obtained, for convenience. This representation allows interpretation of the results. The first impression is that the laminate is rather inhomogeneous. This is seen from the inhomogeneous colour distribution. Only a homogeneous and well-consolidated laminate allows continues Lamb wave propagation with high amplitude. However, the present picture is expected with the chosen material and manufacturing process. The reader should be reminded that the tank was only a manufacturing technology demonstrator, not a component of serial production. The two dark stripes (A) indicate the connections between the domes and the skirts. In these areas, the laminate changes its thickness so that Lamb waves could not be excited with the incidence angle adjusted on the sender. Thus, the low amplitudes in these areas do not indicate flaws in this case. The remaining area reveals details of the layup structure. Zero degrees layers (aligned in the Z-direction) are predominant in the skirts, whereas 45° and 30° layers stand out in the midsection. However, there can also be identified a number of distinct flaws. The areas marked by

(B) come from bridging effects, which occurred at the crossover from the midsection to the upper dome. The consolidation roller, which pressed the thermoplastic tape against the underlying tooling, lost contact occasionally. The marker (C) indicates two severe delaminations. These may result from instabilities in the process parameters such as reduced output power of the flash lamp, causing incomplete matrix melting and consolidation. Finally, marker (D) indicates a lengthy, circumferential anomaly caused by a somewhat extruding structure on the tooling. The laminate is slightly thinner here than in the surrounding area. As discussed above, Lamb wave propagation depends on the thickness of the waveguide. Since the incidence angle of the sender was adjusted to excite Lamb waves in the slightly thicker laminate, Lamb waves were excited with reduced efficiency in the thinner area.

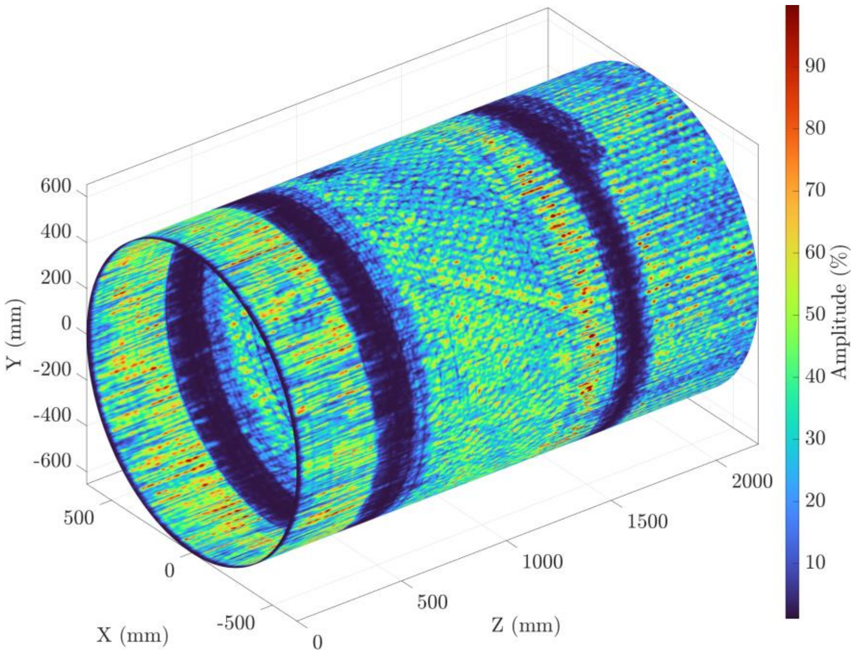

Figure 4. 3-D C-scan of the tank. The colour represents the amplitude of Lamb waves.

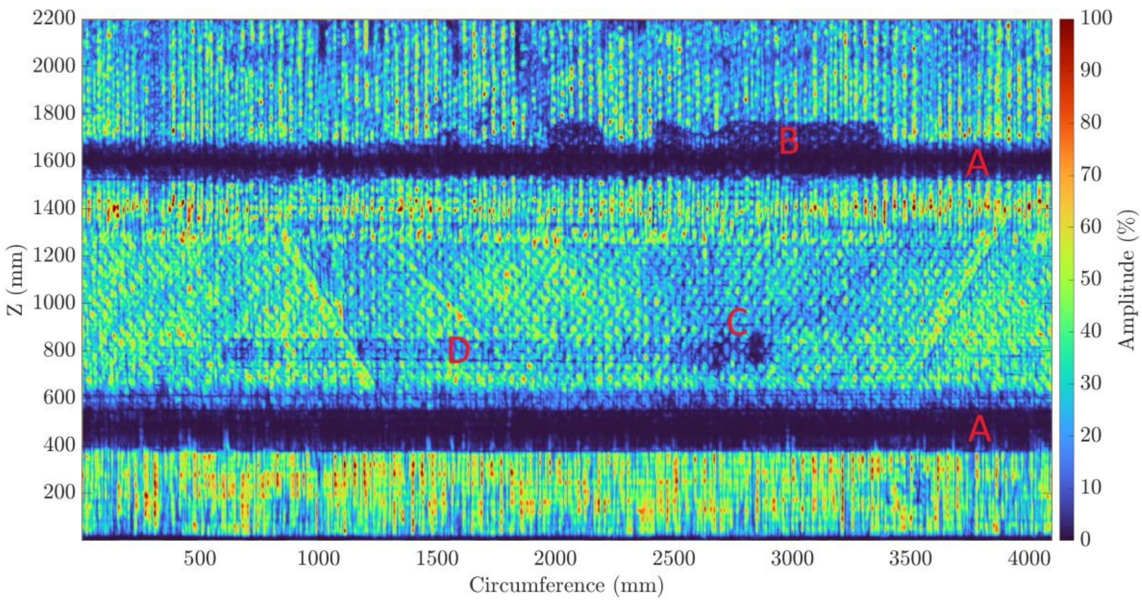

Figure 5. 2-D C-scan obtained by unwinding the point cloud.

3. Conclusions

Robot-assisted air-coupled ultrasonic inspection of a liquid hydrogen tank was reported. The robotic programme was obtained using the FastSuite Edition 2 offline programming software, based on CAD models of the robotic cell and the tank. The scanning of the full circumference was achieved without a tilt-turn-table. The ultrasonic C-scan showed that air-coupled ultrasonic testing is suitable to reveal details in the laminate structure as well as delaminations with sufficient resolution. However, the trend in contact-less non-destructive inspection technology points towards laser-excited ultrasonic testing.

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