Advanced Automated NDT Solutions for Composite Aerospace Structures: Modular and Large-Scale Platforms for 3D Inspection and Enhanced C-Scan Interpretation

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1. Abstract

The increasing use of composite materials in aerospace structures presents significant challenges for Non-Destructive Testing (NDT), driven by anisotropic behavior, multilayer architectures, bonded interfaces, and complex geometries. Reliable detection of defects such as delaminations, porosity, disbonds, and impact damages requires inspection solutions that go beyond conventional manual methods in terms of repeatability, coverage, and data interpretation. As a result, automated NDT systems are increasingly adopted to meet the rigorous quality and safety requirements of composite aerospace components.

This paper presents advanced automated NDT solutions specifically developed for composite aerospace applications, ranging from modular portable scanners to large-scale gantry and immersion inspection platforms. The ARMANDA system is introduced as a unique modular and lightweight automated NDT solution, designed for flexibility and rapid deployment. It supports ultrasonic testing (UT), phased array ultrasonic testing (PAUT), and bond inspection, making it well suited for complex composite parts and localized inspections in both manufacturing and MRO environments.

For larger composite structures and production-scale inspections, gantry-based and immersion NDT systems provide high-precision multi-axis motion control and surface-following capabilities, enabling true 3D scanning of complex geometries. These platforms support advanced ultrasonic techniques, including 3D phased array scanning, full matrix capture, and Total Focusing Method (TFM), producing high-resolution volumetric data and depth-resolved C-scan results. Software-driven features such as adaptive scan path generation, CAD-to-as-built correction, and advanced C-scan interpretation enhance flaw detectability and inspection consistency by compensating for geometric deviations and material attenuation.

Representative composite aerospace applications demonstrate how combining modular and large-scale automated NDT platforms improves inspection reliability, defect characterization, and overall quality assurance, contributing to enhanced structural integrity and flight safety.

2. Introduction

The increasing use of composite materials in aerospace structures has created inspection requirements that are more demanding than those associated with simpler, flat, or metallic components. Composite parts can combine anisotropic material behavior, multilayer architectures, bonded interfaces, local thickness variation, and complex three-dimensional geometries [1,2]. These characteristics influence ultrasonic propagation, defect response, and the quality of the final C-scan representation used for interpretation.

The inspection objective is therefore twofold. First, the inspection system must reliably detect defects such as delaminations, porosity, disbonds, and impact damage. Second, the inspection process must provide repeatable coverage and consistent data interpretation despite variations in geometry, material attenuation, and accessibility. Conventional manual inspection remains valuable in many situations, but operator-dependent probe positioning, variable coupling, and limited repeatability can become significant limitations when complex aerospace composite structures must be inspected at production or MRO scales.

Automated NDT systems respond to these challenges by combining controlled mechanical motion, software-defined scan execution, synchronized data acquisition, visualization, and interpretation [3,4]. For composite aerospace structures, the most effective approach is not a single universal scanner, but a set of automated scanner solutions matched to the inspection scale, component geometry, coupling requirements, and deployment environment. Table 1 summarizes the role of the scanner solutions considered in this work.

Table 1. Automated NDT platform roles for composite aerospace structures.

Inspection Context	Scanner Solution	Main Framework Implementation	Expected Contribution
Localized inspection, MRO, manufacturing checks, or parts not suited to large systems	ARMANDA modular portable scanner	Automated 2D X-Y UT, PAUT, and bond testing with C-scan mapping and interpretation	Repeatable portable inspection with improved coverage and localized C-scan analysis
Medium to large composite structures with curved or complex surfaces	Immersion or gantry-based NDT systems	Multi-axis motion with contour-following and true 3D scanning	Controlled inspection of complex geometries with accurate motion-to-data correlation
Components requiring advanced ultrasonic acquisition or volumetric results	Immersion or gantry-based NDT systems	3D PAUT, FMC / TFM, and advanced interpretation	High-resolution volumetric data and improved defect characterization

This paper presents automated NDT solutions for composite aerospace structures through three complementary elements: the ARMANDA modular portable solution, immersion and gantry inspection systems, and the software-driven platform that supports contour following and 3D scanning, advanced inspection capabilities and enhanced C-scan interpretation. These systems address different inspection scales and deployment environments, but they share a common inspection approach implemented through an Automated NDT Solution Framework.

3. Automated NDT Solution Framework

The Automated NDT Solution Framework combines software-driven motion control, data acquisition, data visualization / C-scan mapping, and C-scan interpretation. In practice, this framework is implemented through TecView®-based tools and adapted to the mechanical architecture of each scanner system [3,4].

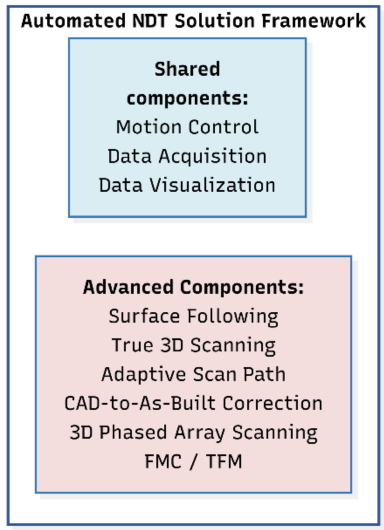


Figure 1. Automated NDT Solution Framework.

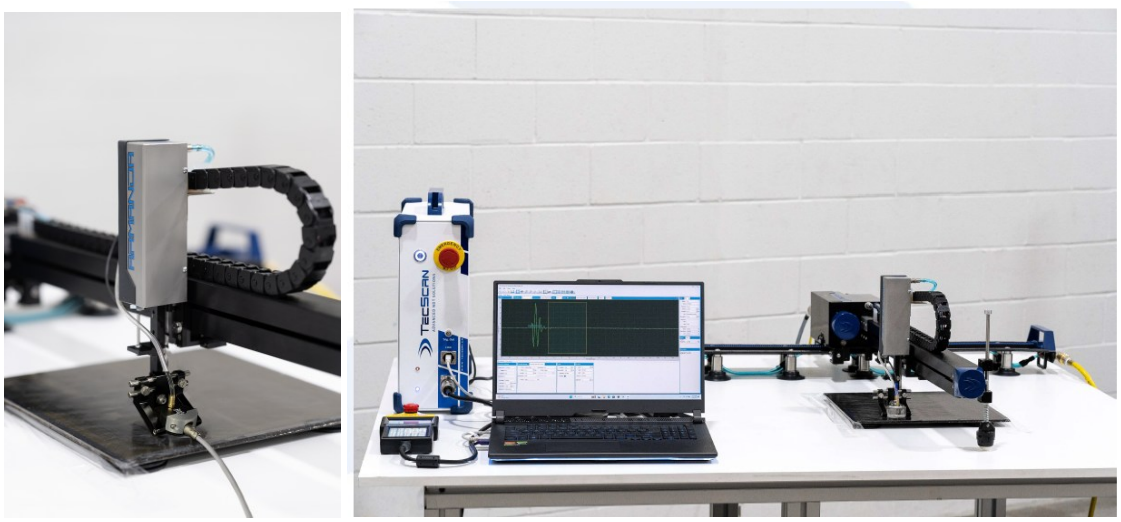
In this context, **motion control** refers to the generation and execution of programmed scanner axes trajectories. The software defines the inspection motion, while the mechanical scanner executes the commanded path. For a portable X-Y scanner, this corresponds to automated 2D encoded scanning. For immersion and gantry systems, the same principle extends to multi-axis contour-following and true 3D motion.

Data acquisition refers to the collection and storage of digitized inspection signals during scanner motion. This includes the synchronized acquisition of UT, PAUT, or bond-testing data with preset probe positions as the scanner executes the programmed trajectory. **Data visualization / C-scan mapping** converts position-referenced inspection data into C-scan representations [3]. C-scan interpretation supports flaw detection, defect characterization, and quality assurance decisions.

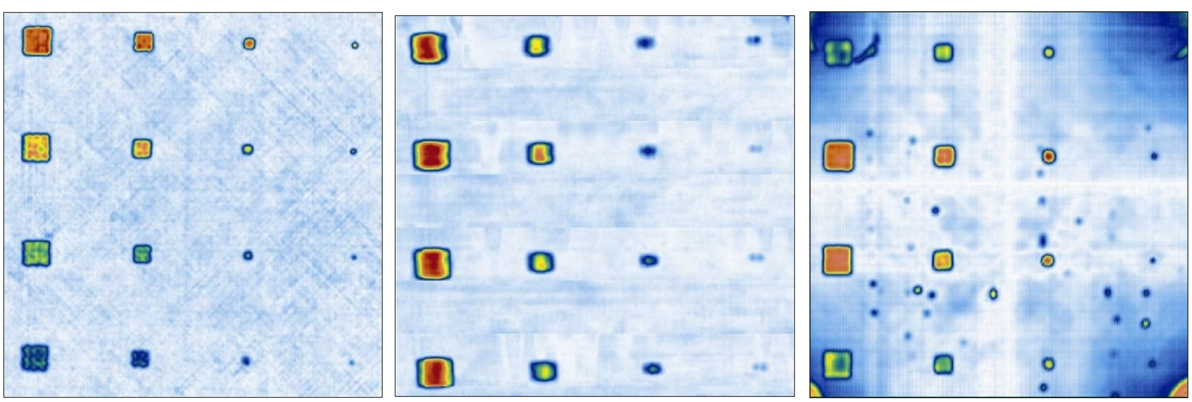
The framework is implemented according to the mechanical architecture and inspection role of each scanner system. ARMANDA implements the framework for automated 2D X-Y inspection. Immersion and gantry systems extend the same framework to multi-axis motion and advanced inspection capabilities, including surface-following, true 3D scanning, adaptive scan path generation, CAD-to-as-built correction, 3D phased array scanning, and full matrix capture / TFM.

4. ARMANDA: Modular Portable Automated NDT Solution

ARMANDA is presented as the modular portable implementation of the Automated NDT Solution Framework for automated 2D inspection [5]. It is a lightweight X-Y scanning platform designed for flexible deployment when a large immersion or gantry system is not practical. Typical applications include localized inspection of composite panels, aircraft wings, flaps, booms, bonded regions, repair areas, and MRO inspection zones.



(a)



(b) *(c)* *(d)*

Figure 2. (a) ARMANDA modular portable automated NDT solution: composite plates C-Scan examples – (b) UT, (c) PA and (d) BT

The system supports ultrasonic testing, phased array ultrasonic testing, and bond testing [5]. This multi-technique capability is important for aerospace composite structures since different flaw types and structural configurations may require different inspection modes. UT supports general composite inspection and C-scan generation. PAUT provides improved coverage and beam-control flexibility. Bond testing is directly relevant to bonded interfaces and disbond detection.

In ARMANDA, the software defines the 2D X-Y scan, the scanner executes the encoded motion, and the acquisition system stores the digitized UT, PAUT, or bond-testing signals. The resulting data are visualized as C-scan maps for interpretation. ARMANDA therefore improves repeatability and coverage compared with purely manual inspection while maintaining portability for manufacturing and MRO environments.

5. Immersion and Gantry Systems for Contour-Following and 3D Inspection

Immersion and gantry systems extend the Automated NDT Solution Framework beyond portable 2D scanning [3,4]. Depending on the application, either platform type can be configured for medium or large-scale inspection. The selection depends on part geometry, coupling requirements, scanning envelope, production constraints, and the ultrasonic technique required.

Figure 3. Gantry and Immersion platforms for inspection of complex composite aerospace structures.

Immersion systems provide a controlled ultrasonic coupling environment and are well suited to components requiring stable coupling and high-quality ultrasonic acquisition. Gantry systems are often selected when large or complex aerospace structures require wide scanning envelopes, water-jet or squirter configurations, and controlled access to extended surfaces. In both cases, the value of the platform is not only the mechanical structure, but the ability to execute software-generated trajectories while maintaining the required relationship between probe position, part geometry, and acquired data.

For complex composite aerospace structures, immersion and gantry systems can perform automated 2D scanning, 2D contour-following, and true 3D scanning [3,4]. In these systems, contour-following is achieved through software-generated multi-axis trajectories defined relative to the component geometry. True 3D scanning extends this approach by defining scan positions on the inspected surface and converting them into coordinated scanner-axis motion. Using virtual scan axes defined on the component surface, probe motion, acquisition, and C-scan mapping remain referenced to the actual part geometry rather than to a planar raster grid [6]. These capabilities are essential when complex curvature prevents a planar scan from maintaining adequate probe orientation, stand-off, coupling, or coverage.

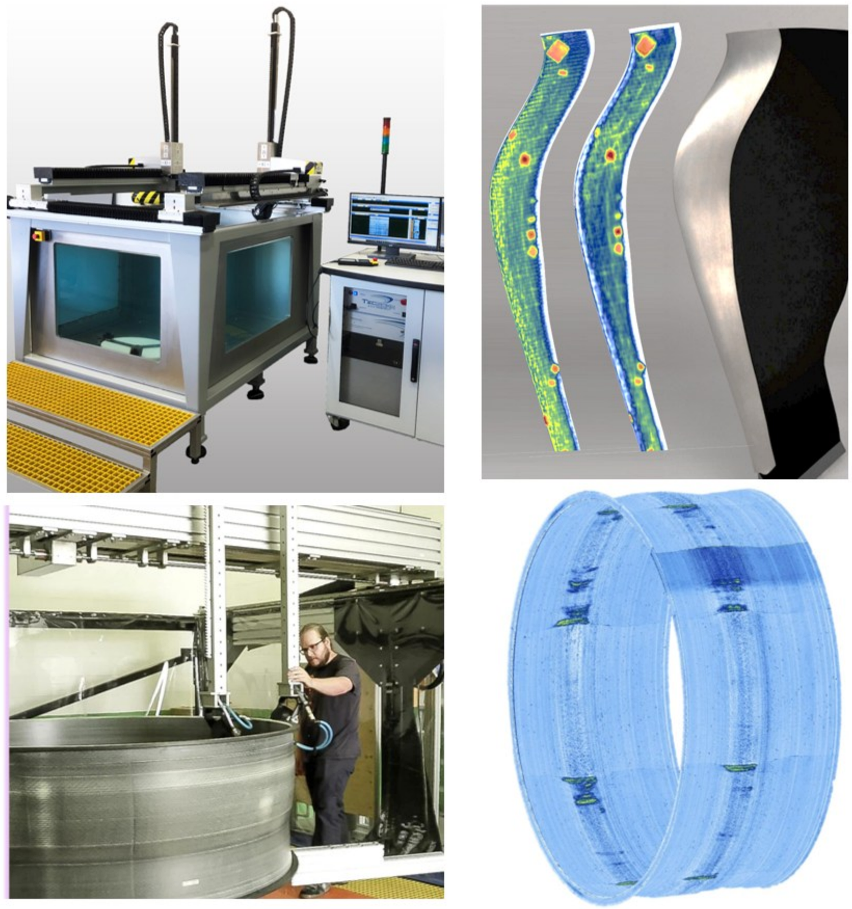


Figure 4. Gantry and Immersion platforms: 2D contour-following and true 3D scanning.

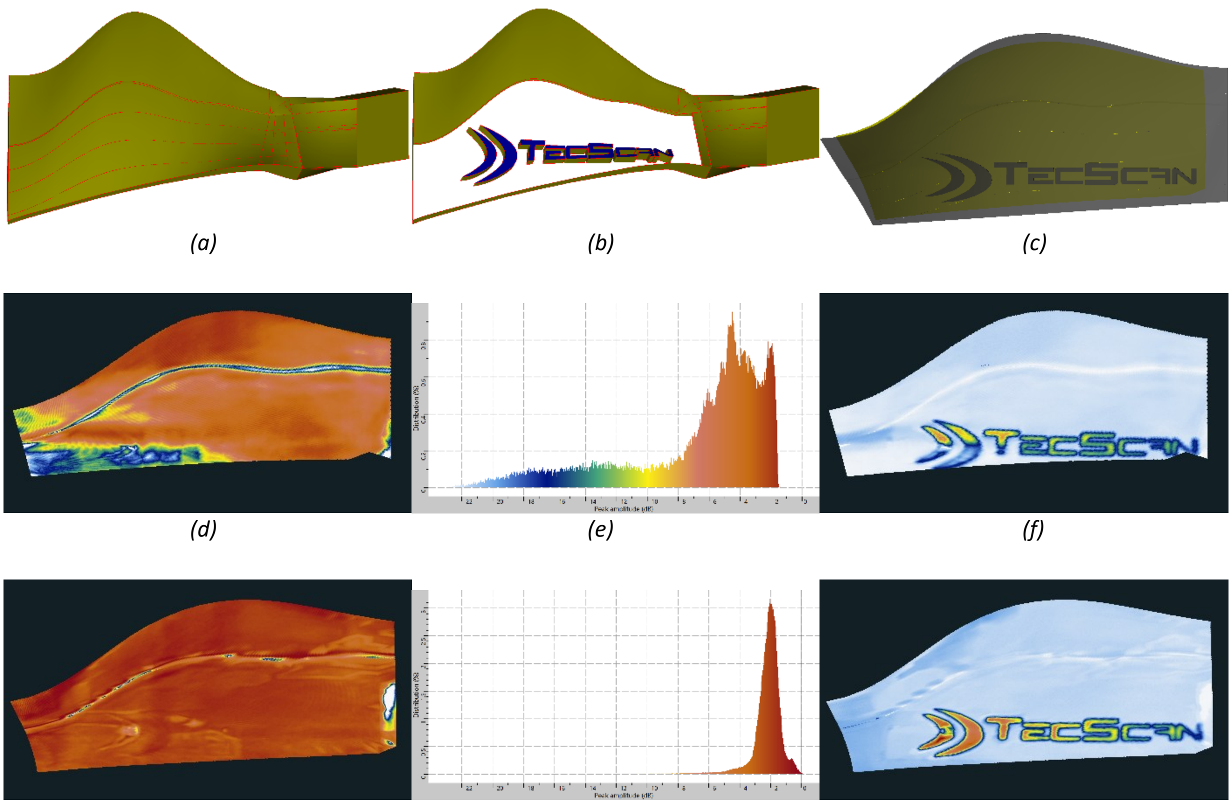
6. Advanced Components of the Automated NDT Solution Framework

With the multi-axis 3D scanning capability established, the advanced components considered in this work include scan-path adaptation, CAD-to-as-built correction, adaptive 3D phased array scanning, and full matrix capture / TFM [3,4].

6.1 Scan-Path Adaptation and CAD-to-As-Built Correction

Scan-path adaptation enables the inspection trajectory to be adjusted according to the actual geometry of the component rather than relying solely on the nominal CAD model [6]. In this work, it is implemented through adaptive scan path generation and CAD-to-as-built correction. This capability represents the motion-adaptation layer of the advanced inspection process: it determines where the probe should move and how it should be oriented relative to the physical inspected surface.

Figure 5 compares nominal CAD-based scan planning with corrected scan execution on the actual component geometry of a 3D printed, scaled down blade with internal reflectors. The difference in front surface echo amplitude stability, as well as the increased amplitude observed on the internal reflector echoes clearly illustrate the improved probe alignment, better surface following, and more consistent inspection response obtained from the scan path adaptation.



(a) (b) (c)
(d) (e) (f)
(g) (h) (i)

Figure 5. Scan-Path Adaptation and CAD-to-as-built correction for geometry-conforming inspection. (a) CAD part model ; (b) CAD model showing internal reflectors ; (c) Expected image from C-scan ; CAD based scanning trajectories - Front surface echo C-Scan (d), histogram distribution of surface echo amplitude (e), and C-Scan image of internal reflectors (f); Scan Path Adaptation trajectories - Front surface echo C-Scan (g), histogram distribution of surface echo amplitude (h), and C-Scan image of internal reflectors (i).

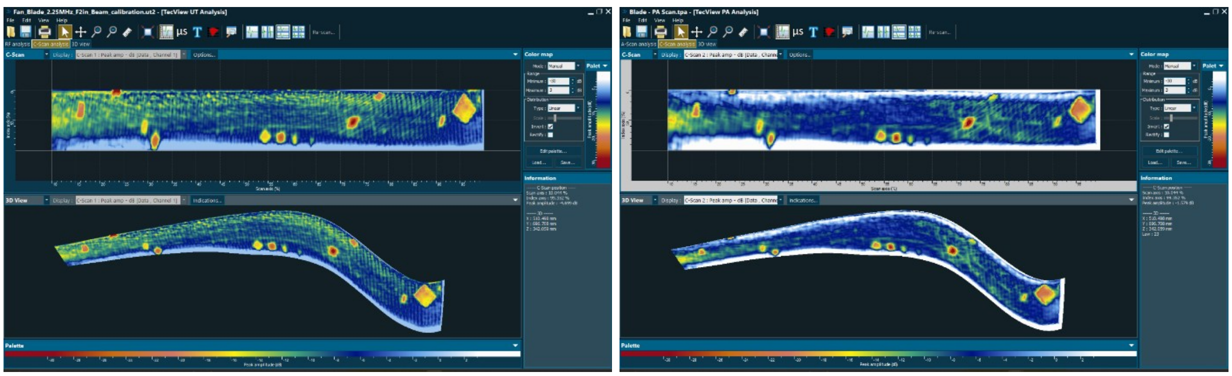
The CAD model is first used to define the initial inspection surface, scan boundaries, and nominal probe poses. Measured reference points or surface feedback are then used to correct local and global deviations between the CAD model and the as-built component. These deviations may result from manufacturing tolerances, assembly conditions, spring-back, or deformation, all of which are particularly relevant for composite aerospace structures.

If these deviations are not considered, the programmed trajectory may no longer maintain the desired relationship between the probe and the part surface. This can lead to improper probe alignment, unfavorable beam-entry conditions, signal loss, or inconsistent C-scan response. By regenerating the scan path on the corrected geometry, the probe can maintain improved alignment with the local surface normal and preserve more consistent inspection conditions over curved or geometrically complex regions.

Scan-path adaptation therefore provides the geometric foundation for advanced automated inspection. It allows immersion and gantry systems to execute contour-following and true 3D trajectories based on the actual component geometry, improving the consistency of ultrasonic data acquisition and supporting more reliable C-scan mapping and interpretation [3,6].

6.2 Adaptive 3D Phased Array Scanning

Adaptive 3D phased array scanning combines geometry-conforming scanner motion with adaptive phased array beamforming [3,7]. The scan path follows the corrected component geometry, while the phased array aperture and focal laws are adjusted according to the local surface curvature. This is particularly important for curved aerospace composite structures, where a fixed aperture may cause some array elements to insonify the surface at unfavorable incidence angles, reducing transmitted energy, focusing quality, and defect sensitivity.



(a) (b)

Figure 6. Comparison of 3D transmission scans on a composite fan blade metallic leading edge: (a) single-element 3D scan and (b) adaptive 3D phased array scan.

A master element or focal law is defined to define the scanning trajectories. At each scan pose, the local surface normal is parallel to the nominal beam direction of the master element or law. Neighboring elements are then evaluated against calibration-derived angular tolerances. Only elements satisfying these incidence-angle limits are retained for focal-law generation. The effective aperture therefore contracts in high-curvature regions, expands in lower-curvature regions, and may use the full aperture on nearly flat surfaces.

This converts phased array beamforming from a fixed-aperture operation into a geometry-aware, curvature-constrained aperture synthesis process. The acquired volumetric PAUT data are mapped into the corrected component coordinate system, allowing C-scan, B-scan, and volumetric results to be interpreted relative to the true inspected geometry. Figure 6 shows a comparison of a 3D transmission scan performed on the metallic leading edge of a composite fan blade using a pair of focused single element transducers (a) with an Adaptative 3D Phased array scan (b). All indications are clearly resolved in both cases.

6.3 Full Matrix Capture and Total Focusing Method

Full Matrix Capture records a rich set of transmit-receive phased array data, which can be processed using the Total Focusing Method to generate high-resolution volumetric information. In automated NDT, FMC and TFM complement the motion framework by providing advanced ultrasonic data for defect characterization and C-scan results extracted from selected depths or reconstructed volumetric regions. Figure 7 presents C-scan images obtained from contour following PAUT scans of a porous, curved carbon composite plate acquired using a 5 MHz cylindrically focused linear array. FMC/TFM scan results are compared with conventional depth focusing in this exploratory study. Interestingly, while scanning results are mostly similar for both focusing types, FMC/TFM appears to be more sensitive to the fiber layout and, as well as presenting a better near-surface resolution, pointing at potential use of TFM for composite materials.

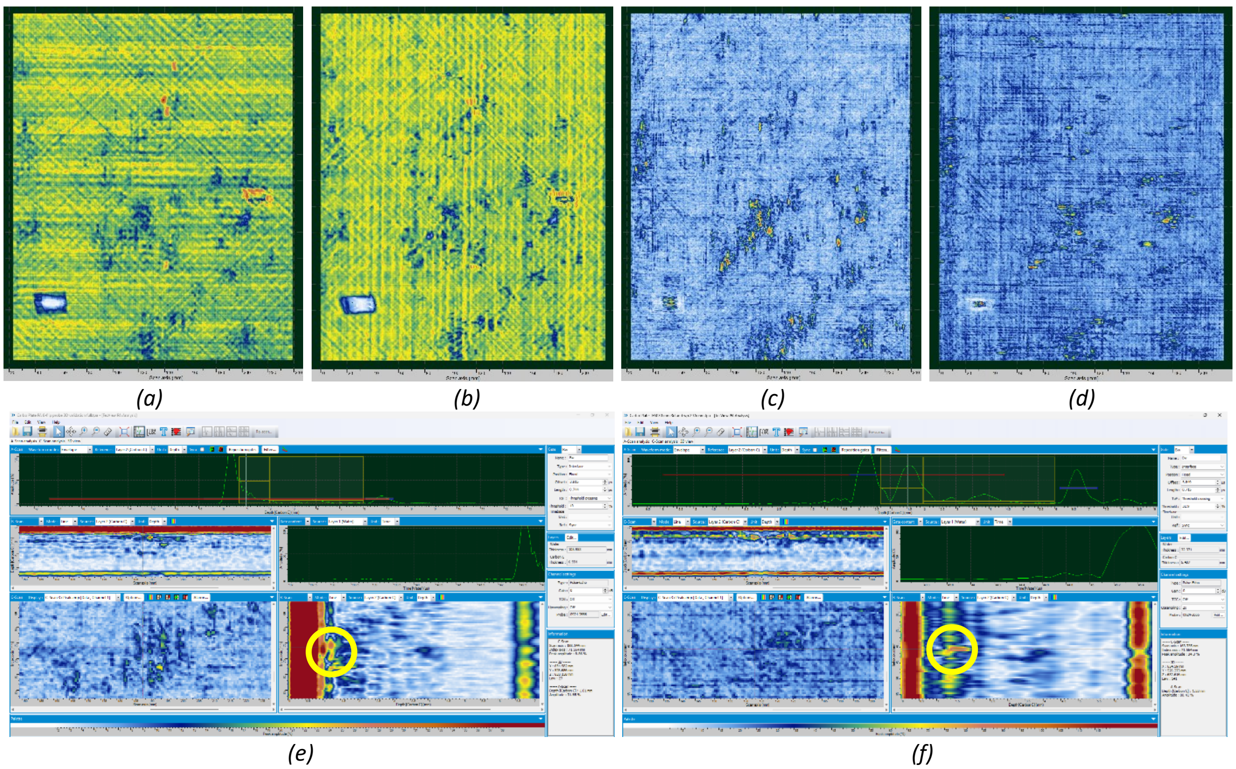


Figure 7. Example of FMC/TFM reconstruction and C-scan results extracted from selected depths or reconstructed volumetric regions, representing the backwall echoes of (a) dynamic depth focusing (DDF) and (b) TFM, as well as echoes recorded between 2 and 6 mm within the sample from (c) DDF and (d) TFM. (e) and (f) respectively show the A, B, and C-scan results of the same area for DDF and TFM; circled features correspond to the same reflector as captured by both focusing techniques.

7. Conclusions

Composite aerospace structures require rigorous NDT because anisotropic behavior, multilayer architectures, bonded interfaces, material attenuation, and complex geometries can complicate both data acquisition and interpretation. Reliable detection of delaminations, porosity, disbonds, and impact damage requires inspection solutions that provide repeatable coverage, consistent C-scan mapping, and reliable interpretation.

This paper presented modular and large-scale automated NDT solutions for composite aerospace inspection. ARMANDA demonstrates the portable automated 2D implementation of this approach, supporting UT, PAUT, and bond testing for localized inspection in manufacturing and MRO environments. Its value lies in improving repeatability, coverage, and C-scan-based interpretation when a large, fixed inspection system is not practical.

Immersion and gantry systems extend the same software-driven inspection approach to contour-following and true 3D inspection of larger or more geometrically complex composite structures. These systems are suited to applications requiring controlled coupling, multi-axis motion, geometry-conforming scan paths, advanced ultrasonic acquisition, and selected-depth C-scan results.

The advanced capabilities demonstrated with immersion and gantry systems include scan-path adaptation with CAD-to-as-built correction, adaptive 3D phased array scanning, FMC/TFM, and enhanced C-scan interpretation. Together, these capabilities improve the relationship between scanner motion, part geometry, ultrasonic acquisition, and final inspection results.

By combining portable 2D automated inspection with large-scale contour-following and 3D inspection platforms, the presented solutions improve inspection repeatability, flaw detectability, defect characterization, and quality assurance for aerospace composite structures. These improvements contribute to enhanced structural integrity and flight safety.

8. References

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