INSPECTION OF COMPLEX COMPOSITE AEROSPACE STRUCTURES USING AUTOMATED 3D ULTRASONIC SCANNING

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ABSTRACT

The introduction of automated ultrasonic inspections had benefited the NDT field in terms of imaging capabilities, repeatability of inspection data and speed. Ultrasonic immersion tanks and squirter systems are now widely used for flaw detection in aerospace components, while portable automated systems are mounted to aerospace structures for corrosion mapping. In either case, reliable inspections must be accomplished in order to benefit from the advantages of the automation of the process.

An important requirement for reliable ultrasonic inspections is to maintain a constant ultrasonic beam entry angle throughout the whole inspection. In addition, the distance between the transducer and the part (water path) must also be carefully controlled, either to maintain a constant focus depth, to properly control the position of the near field or to use DAC curves to overcome transducer beam spread. While this can be easily achieved on simple geometries (flat, cylindrical, etc.), complex 3D shapes require more advanced scanning schemes in order to be properly inspected and record reliable data. Inspecting complex aerospace parts such as composite turbine blades requires scanners that can reliably follow the part surface and satisfy the aforementioned scanning conditions.

This paper focuses on 3D inspection of parts using ultrasounds. Surface and contour following methodology including mechanical requirements will first be covered, as well as the effects of curvature on ultrasounds. Inspection data obtained on a specially designed calibration block as well as on curved simulated aerospace samples will be presented.

Keywords: NDT, Ultrasounds, Inspection, Composite, Contour following, 3D Scanning.
INTRODUCTION

Most of the components inspected with ultrasonic immersion or squirter systems have simple geometries (flat, cylindrical, etc.) and can be either inspected in a rectangular pattern or with the use of a turntable. Controlling the wave’s incidence angle and water path is then mostly related to the mechanical alignment between the scanner’s axes and the surface to be inspected. However, complex shapes that present inclined, curved or multiple surfaces of interest require more advanced scanning schemes in order to be properly inspected. Three options are then available: (1) scanning the part in multiple passes if it is composed of multiple simple shapes, (2) performing a manual inspection on the surfaces that could not be covered from simple scan patterns, (3) or using advanced surface and contour following capabilities to inspect the whole part as a single surface. The last option represents the most interesting one since it provides a controlled and repeatable mean for performing the required inspections. On the other hand, its realization is the most challenging as it requires advanced scanning and analysis capabilities.

Two distinct types of surface following inspection can be defined depending on the complexity and geometry of the specimen: 3D and 2D contour following inspection. The 3D surface following is used for complex parts that do not present any axis of symmetry (e.g. curved composite components, turbine blades, etc.). Such geometries require a full tridimensional knowledge of the component in order to control the transducer orientation. On the other hand, parts that do have an axis of symmetry (e.g. extrusions) represent a simplified case of the latter 3D inspection since they can be defined as the repetition of a 2D contour along the extrusion axis. Surface following inspection of such parts can be achieved with an axis aligned with the axis of symmetry of the specimen and a 2D surface follower. This type of surface following is sometimes referred to as 2½D scanning, or simply contour following. In either situation, scanning movements involving multiple automated axes are necessary to properly control both the water path and incidence angle during the scan.

This paper presents the methodology behind automated contour following and 3D ultrasonic scanning of composite aerospace and power generation parts. Surface following strategies, mechanical requirements and the effects of part curvature on ultrasounds will be covered. A calibration block specifically designed for 3D scanning training is used to illustrate some aspects of the inspection of complex shapes using 3D surface following. Finally, results from the inspection of curved aerospace composite samples and power generation turbine blade are presented.

SURFACE FOLLOWING

Ultrasonic surface following can be described as a scanner’s ability to do a controlled displacement of one or multiple axes, with the objective to move around a curved, round, or inclined surface while maintaining constant transducer orientation and distance (water path). When contact inspection is performed, this can be relatively well achieved by a spring loaded swivelling head provided that the part surface does not present large variations, as illustrated in Fig. 1a). However, when it comes to performing an inspection with an immersion or squirter system, the orientation of the transducer must be controlled with a high degree of
precision in order to adequately follow the part contour and maintain probe orientation. Of course, this must be accomplished without any collisions between the scanning head and the inspected specimen.

Performing a 3D inspection must be based on the knowledge of the part geometry. This can be achieved using different techniques ranging from manual teaching of the surface coordinates by using ultrasonic signals, optical or mechanical apparatus, or through the use of the part mechanical drawings (CAD, CATIA, etc.). Once the surface coordinates and orientation are known, the motion control software calculates a scan path that allows displacing the ultrasonic transducer across the part with a controlled water path and orientation and without collisions. Scanning the part is then possible by defining an inspection area within the system of coordinates of the surface following paths.

**MECHANICAL REQUIREMENTS**

The automated scanning system must comprise of a minimum number and types of axes to perform 3D surface scans. While three linear axes (X, Y and Z) is the minimum to control the position and distance of the probe relative to the part, rotational axes are necessary to properly control the relative orientation between the transducer and the part surface.

Components presenting an axis of symmetry such as an extrusion require a minimum of one rotational and two linear axes to properly follow the contoured surface, while a third linear axis allow to move across the extrusion axis. As illustrated in Fig. 1b), the purpose of the linear axes is to move the transducer at the proper locations while the rotational axis is used to maintain the proper angle entry of the ultrasonic waves. Alternately, a rotary table could be used to rotate the part while linear axes serve to orient the probe with the surface.

When 3D surface following is required, a second rotational axis probe that is perpendicular to the first one is required to adjust the transducer at any angle in a three

![Fig. 1: Illustration of a surface following movement using (a) a spring loaded swivel head in contact with the part (b) immersion system with constant water path and beam entry angle.](image)
dimensional space. Depending on the part geometry and orientation, probe manipulators such as swivel/gimbal or gimbal/gimbal manipulators maybe required (see examples in Fig. 2).

![Fig. 2: Pictures of two types of probe rotational manipulators. (a) Swivel/Gimbal assembly. (b) Gimbal/Gimbal assembly.](image)

Aligning the transducer with the part surface is not enough to guarantee valid results. As in any ultrasonic inspection, the alignment must be performed on the ultrasonic beam itself and not the transducer casing since they are not necessarily aligned (Fig. 3). For this reason the selection of the probe rotational manipulator must be carefully selected to make sure that alignments of the ultrasonic beam are possible on all portions of the part.

![Fig. 3: Illustration of the misalignment between a transducer casing (dash-dot line) and its ultrasonic beam (bold line).](image)

**DEFINING A SURFACE FOLLOWING PATH**

Before a surface following inspection can be completed, the displacement path of all the involved axes must be properly defined. Since the purpose of this procedure is to maintain constant water path and wave incidence angle, the surface location and shape must be known accurately before a propagation path can be defined. Methodologies that can be used to define the part surface are either to import part geometry from an external source (CAD file, scanning device, etc.) or to use the ultrasonic scanner to define the surface geometry point-by-point. In either case, coordinates and orientation (normal vectors) of points on the surface of the part must be sufficiently sampled. A mean of locating the part within the coordinates of the axes of the scanner is also mandatory. The second methodology, which is often referred to as a *Teach and Learn* procedure, presents the advantage of defining the part surface, orientation and location as a whole using the ultrasonic inspection scanner itself. This method can be tedious to teach the full 3D surface of a test piece. However, it is a method of choice when scanning extruded parts.
3D SURFACE SCANNING

Once the part has been properly defined, the ultrasonic inspection can be performed by scanning the 3D surface. Scanning coverage, resolution and consistency of data is not the same on a 3D surface as it is on a part with no or constant curvature.

Part curvatures have a significant effect on both the ultrasonic response and the scanning resolution requirements. When an ultrasonic beam is generated in water, it enters the part with a different sound velocity. Waves are being refracted and the ultrasonic beam directivity and amplitude pattern can be affected in different ways. Concave surface tends to focus the ultrasonic beam as it enters the material surface while convex has the opposite effect (Fig. 4).

![Fig. 4: Illustration of the beam pattern modifications caused by wave refraction for a (a) flat, (b) concave and (c) convex surface.](image)

Example 1: 2½D inspection of a specially designed calibration block

An example of 3D inspection is shown for an aluminum calibration block specifically designed for training purposes. It consists of a curved sample presenting an axis of symmetry. Its surface integrates flat, concave and convex surfaces, as well as sharp corner angles. Individual groups of five identical side-drilled holes (SDH) were machines at the same depths below each surface type (Fig. 5).

![Fig. 5: Teach and learn calibration block. Dotted lines indicate transitions between different curvatures. The rectangles on top represent the unwrapped surfaces.](image)
This sample was designed to display some geometric characteristics that can be encountered when performing 3D scanning being the presence of flat and curved sections (convex and concave), as well as discontinuities in the surface where surface orientation is not defined (sharp corners). Plus, the presence of SDH underneath each surface serves as a good example of the expected variations in ultrasonic response to defects as well as how data is recorded and interpreted for different curvatures.

The complex surface of the part was defined using the teach and learn methodology and the inspection was performed using TecScan’s 5 axes industrial immersion tank and TecView™ UT with TecView™ 3D (Fig. 6). This block was inspected using a 10 MHz focused transducer (F=1.75”) with a diameter of 0.25” and with a constant scanning resolution of (0.5 mm) defined along the surface of the block. The presence of an axis of symmetry allows representing the C-Scan image resulting from the inspection as a flat surface by unwrapping the curvature. All points scanned along the part contoured surface are then displayed side by side (see Fig. 5). Since the scanning step is constant, conventional rectangular C-Scans and associated B-Scan views can be built from simple gates covering a given depth range below the surface.

**Fig. 6:** Example of a part contour displayed in TecView™ 3D software. The surface of the calibration block (left) is represented by point coordinates and their normal direction on the software screen (right - yellow lines) as well the interpolated part contour (white curve). Transducer location and orientation is also displayed on the software screen.

**Fig. 7** shows the C-Scan obtained on the sample. The horizontal B-Scan (identified as *Contour B-Scan*) shows the unwrapped cross-section of the sample, i.e. depth inside the material relative to the surface. The B-Scan illustrates how data is rectified since groups of SDH appear at the same depths regardless of the curvature.

The effects of curvature on the ultrasonic response previously discussed can be observed in these results. Fig. 8 displays the amplitude of the C-Scan plotted as a function of position along the block curved surface (corresponds to a horizontal cross section of the C-Scan image of Fig. 7). A comparison of the echo amplitude returning from the two shallowest rows of SDH leads to the same conclusions as previously discussed. The amplitude of the SDH of interest recorded in the first two flat sections (labeled 1 and 2 in Fig. 5, 7 and 8) is used as a level of reference and is identified by a red dotted line for the SDH immediately below the surface and by a blue dotted line for the second rows of SDH. As expected, echoes recorded in the concave area are above the reference level while those recorded in the convex area are clearly below the reference level.
Fig. 7: Screenshot of TecView™ UT showing the results obtained from the 3D scanning of the calibration block: C-Scan of the SDH and B-Scans at the cursor position. Transitions between curved sections are indicated by dotted lines. Echoes corresponding to a direct reflection on the SDH are encircled.

Fig. 8: Lateral plot of the amplitude of the C-Scan across the surface of the block (bottom) compared to the position of the SDH and the different curvatures (top). Peaks identified in red represent the SDH that is closest to the surface. Peaks identified in blue represent the second shallowest set of SDH. Red and blue dotted lines represent the expected echo amplitude of these SDH referred to the areas 1 and 2 (both flat). Peaks identified by a circle correspond to SDH in flat areas, while square are for convex and concave areas.
Example 2: Inspection of a simulated aerospace composite panel

Three simulated aerospace composite panels were also inspected. The first sample is a flat, 300mm x 300mm x 5.6 mm thick CFRP sample ([0/45/-45/90]s, 40 layers) containing artificial defects (folded square Teflon® inserts of 2.5 mm, 5 mm, 10 mm and 15 mm) and serves as a flat reference. The second sample is a panel having the same dimensions and artificial defects as the flat sample, but presenting a radius of curvature of 417 mm and a thickness of 6 mm. Finally, the third sample is identical to the second one but without any artificial defects. While the flat panel was inspected with a conventional rectangular raster scan pattern using TecView™ UT, the second and third samples were both scanned by performing surface following. All three samples were inspected using a 0.5”, 5 MHz focused transducer (F = 2.0”) and with a scanning resolution of 0.5 mm. The focal spot was adjusted to lie close to the backwall. Both curved samples were inspected from their convex side.

Fig. 9: C-Scan images of the internal structure of the CFRP panels containing artificial defects. (a) Flat panel. (b) Curved panel (inspection from convex side).

Fig. 10: C-Scan images (enhanced contrast) obtained on the curved sample without artificial defects with gate located on (a) the first half and (b) the second half of the sample thickness.
As illustrated in Fig. 9, results obtained on the flat and curved samples presenting the same defects are almost identical. Some natural porosity appears on the curved sample amongst the artificial defects. This result is expected considering the large radius of curvature, which should not have notable effects on wave propagation. Such a result points to the efficiency of 3D scanning to properly inspect curved panels.

Another inspection was carried out on the sample without artificial defects. Once again natural porosities are clearly visible in the C-Scan images (Fig. 10), where the C-Scan on the left shows the porosities found within the first half of the sample thickness while the C-Scan on the right shows the porosity on the second half of the thickness.

**Example 3: Inspection of turbine blade**

Contour following inspection was performed on a turbine blade with 11 cooling channels. The objective was to map the thickness of the blade at multiple locations and display it on a C-Scan image. The contour of the blade at a representative section was first performed. The ultrasonic wave frequency was selected to provide good axial resolution for thickness measurements while allowing a good sound penetration in the blade. A 10MHz transducer was therefore used for the tests.

![Fig. 11](image)

**Fig. 11:** (a) Blade contour definition prior to the scan. (b) Sketch of the blade (end view) with the defined blade contour identified with a red dashed line

**Fig. 11** shows the blade contour profile defined on the pressure (concave) side prior to performing the scan. With this contour properly defined, a C-Scan of the blade was performed with stable water path and probe orientation throughout most of the blade length.

C-scan images were collected from the concave surface, where blade thickness information was obtained. The C-Scan result (Fig. 12 and 13) show a thickness variation mapping of the structure, as well as the 11 cooling channels and their depth relative to the full thickness. Variations in depth of the channels and the full thickness are observed by color variations in the thickness mapping C-Scan image.
CONCLUSION

A 3D contour following procedure based on an ultrasonic definition of the part contour has been covered in this paper. The example of a calibration block manufactured for contour following training illustrated each step of the process as well as how to interpret resulting B and C-Scan. The effects of surface curvature on the ultrasonic response were explained and demonstrated with scan results. We have shown that a properly conditioned surface following scanning, C-Scans (complete thickness mapping) of complex curved samples can be achieved.