Robotic Inspection of Fiber Reinforced Composites Using Phased Array UT

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Abstract. Ultrasound is the current NDE method of choice to inspect large fiber reinforced airframe structures. Over the last 15 years Cartesian based scanning machines using conventional ultrasound techniques have been employed by all airframe OEMs and their top tier suppliers to perform these inspections. Technical advances in both computing power and commercially available, multi-axis robots now facilitate a new generation of scanning machines. These machines use multiple end effector tools taking full advantage of phased array ultrasound technologies yielding substantial improvements in inspection quality and productivity. This paper outlines the general architecture for these new robotic scanning systems as well as details the variety of ultrasonic techniques available for use with them including advances such as wide area phased array scanning and sound field adaptation for non-flat, non-parallel surfaces.

Keywords: Ultrasound, Composites, Non-Destructive Testing, Robots, Phased Array, Aerospace
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INTRODUCTION

Commercial aircraft have seen a dramatic rise in the use of fiber reinforced composites, replacing metals in structural airframe components. As an example Boeing's 777 platform, first delivered in 1995, contained 12% composite by weight and the newly delivered 787 platform contains 50% composite by weight [1]. The integration of multiple airframe components as single composite structures reduces fastener count by up to 80% over traditional metal skin construction driving geometric complexity of these new integrated structures and posing a non-destructive testing challenge.

Traditionally, mechanized ultrasonic non-destructive testing of composite airframe structures was accomplished using conventional, single channel ultrasonic transducers manipulated with Cartesian based gantry mechanics as depicted in Fig. 1. These testing machines tended to be custom in nature and built for purpose for the airframe OEM's and their top tier suppliers. The growth in composite demand is now driving expansion of the supply base to tier 2 and tier 3 companies and to machines with the capability of increased throughput and flexibility over conventional gantry systems.

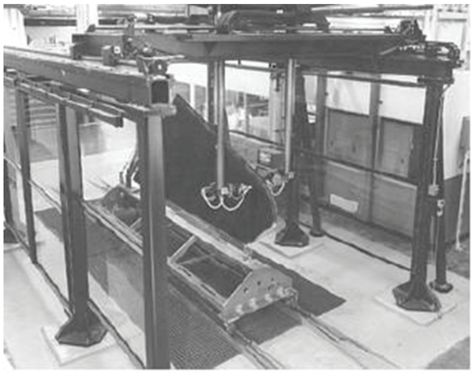

FIGURE 1. Typical Cartesian gantry scanner.

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AUTOMATION CHALLENGES

The challenge in automating ultrasonic inspection of airframe structures exists within the construction and geometric characteristics of the item to be inspected and with the machine design elements to support this inspection. The very nature of building component parts into an integral whole combined with the fabricated shape possibilities afforded by composite construction techniques yields assemblies with complex shapes where all elements of the geometry typically require inspection. A fabricated assembly may include laminate only, laminate with honeycomb core, bonded stiffeners and a host of other configurations. An example of this can be seen in Fig. 2 where an external composite laminate skin includes omega stiffeners bonded to the inside surface of the skin to form an integrated assembly. In this case the skin, omega stringers, and bonding of the stringer to the skin all require inspection with different inspection techniques and tooling.

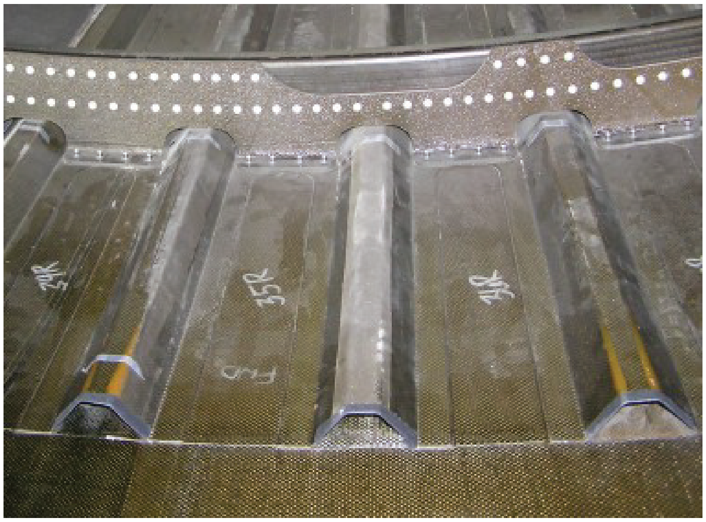

FIGURE 2. Typical composite construction.

With respect to machine design, the challenge comes in the form of the accuracy of the motion and ability to follow complex contoured surfaces. This is true no matter the general ultrasonic method employed whether it is the Through Transmission (TTU) or Pulse Echo (PE) Ultrasound inspection technique. To illustrate the importance of accurately following the contour of a part, Fig. 3 represents the sensitivity of signal loss of a backwall echo with respect to angle of incidence variation for PE inspection of a 6mm thick laminate using a squirter mounted 3.5 MHz conventional transducer and a 4 inch water path.

THE AUTOMATION ALTERNATIVE

Cartesian gantry systems are well established, built for purpose solutions with several well-known suppliers building machines with a high degree of absolute accuracy. The only real drawbacks with this technology are that they tend to be custom designed, expensive and don't provide the overall part inspection flexibility required by the current expanding aerospace composite part supplier base.

Newer generation six-axis robots and new control methods, while not having the absolute accuracy of Cartesian gantries, are proving to have the relative positional accuracy required for both TTU and PE ultrasonic inspection especially when combined with Phased Array Ultrasonic tools and inspection techniques such as Reverse Phasing Contour Adaptation (RPCA) as described in US2006/0195273A1 [2]. These systems provide the benefit of being highly flexible production tools based on a standard proven automation platform.

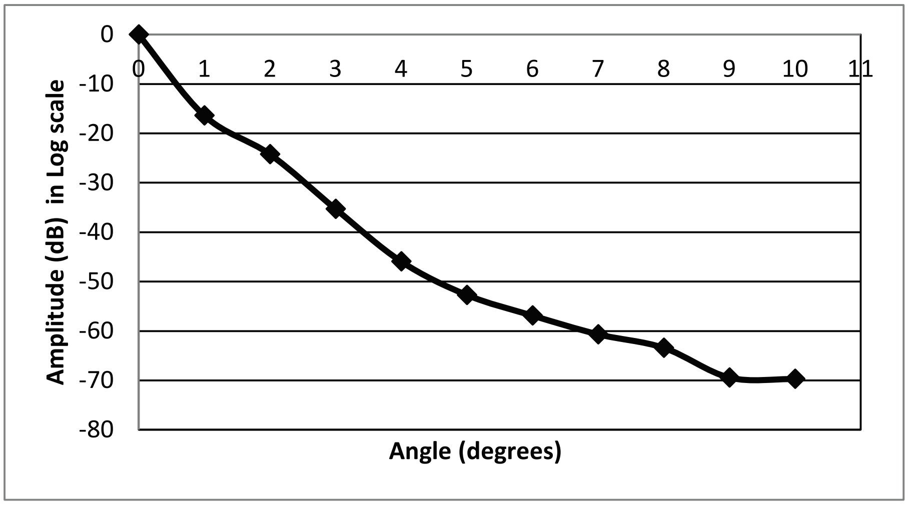

FIGURE 3. Signal amplitude versus angle of incidence of a back wall reflection.

Commercially available six-axis robots are typically constructed with linear slide or turn table axes based on the general part types requiring inspection. The same machine that can follow the contours of a business jet cockpit structure in both TTU and PE modes can be programmed with different end effector tooling to inspect flight surfaces, stringers, and complex composite assemblies. With batch scanning software and the ability to semi-automatically exchange end effector tooling, multiple different parts can be mounted in a scanning area and scanned in one sequence with minimal operator intervention dramatically reducing overall cycle times of automated scans. Figure 4 shows a system composed of two cooperating robots mounted on separate auxiliary linear axes performing TTU inspection of a complex composite flight surface with annular ultrasonic probes pulsing and receiving two different frequencies during the same scan. This configuration allows inspection of both the laminate (with a 5MHz transducer) and honeycomb reinforcement (with a 1MHz transducer) sections of the part at the same time.

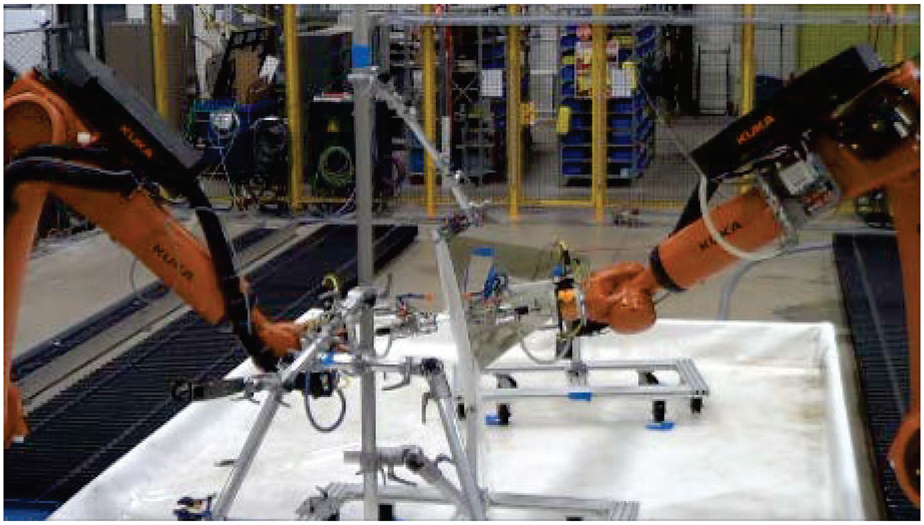

FIGURE 4. Cooperating dual robot example.

PHASED ARRAY APPLICATION

Reverse Phasing Contour Adaptation (RPCA)

Reverse Phasing Contour Adaptation is an ultrasonic technique using linear phased array probes that adapts the PE ultrasonic sound field to the geometry being inspected. The technique is especially useful in two instances. The first instance, Parallel B-Scan, is used when the phased array probe or embedded flaw is not oriented parallel to the surface of the inspected part. In this case all elements of the phased array probe are fired in parallel and the received signals are digitized and displayed as a B-Scan where the surface axis is equivalent to each of the individual elements fired across the probe face and the depth is the time of flight of the received signal. The advantage of this method is that flaws in non-parallel orientations can be more accurately interpreted and sized.

The second use for RPCA is in following the surface and adjusting the sound field of a radius with its scan axis aligned perpendicular to the face of a phased array probe as depicted in Fig. 5. In this method the phased array probe is fired and the times of flight of the individual front surface (interface) reflections are measured and used to modify the next phased array shot sequence to ensure that each phased array shot arrives normal to the parts surface. The technique effectively flattens out the received response providing a more accurate representation of the ultrasonic scan. When properly applied, RPCA has proven to be able to inspect radii varying 6mm to 25mm with the same mechanical setup in a single scan pass.

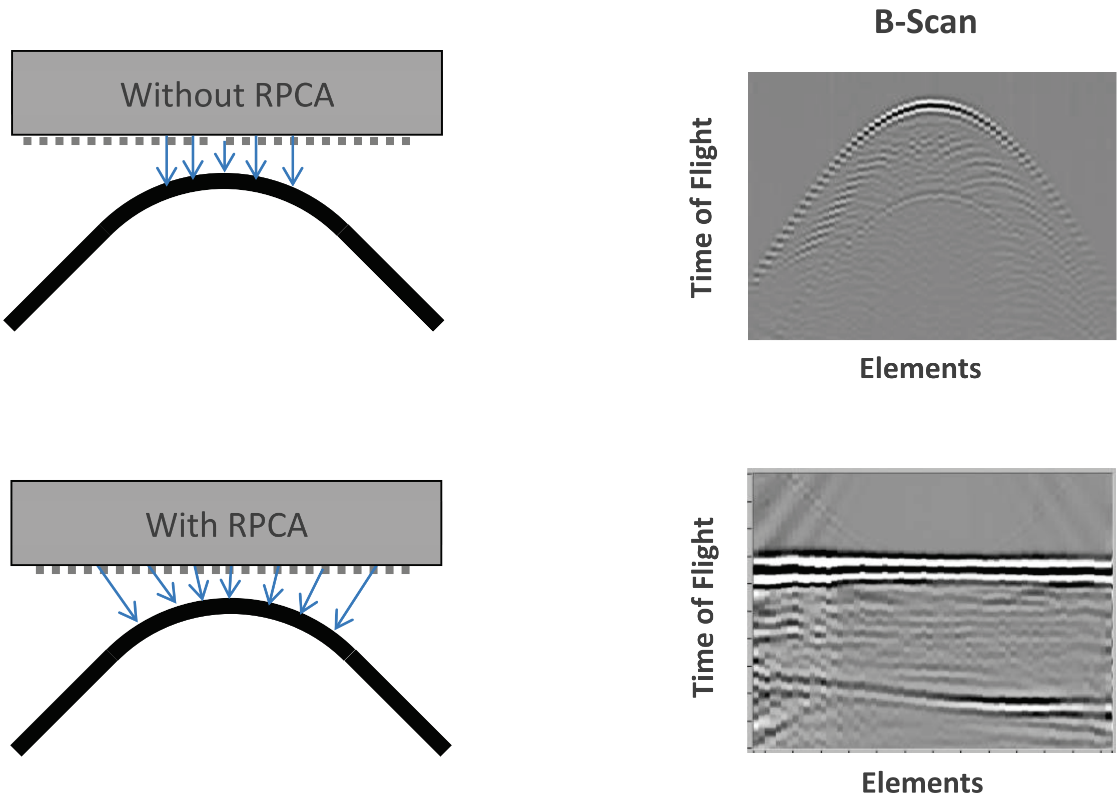

FIGURE 5. RPCA applied to radius inspection.

Application Tools Enabled by Phased Array Ultrasound

The following tools are currently being applied in industry to inspect aerospace composite structures with robotic based automation.

Wide Area Phased Array Squirter Tool

The Wide Area Phased Array Squirter Tool (WAPA) as described in US 2009/0126496A1 [3] is used primarily for high production TTU scanning of laminate composite parts. This tool consists of a phased array probe mounted in a housing containing an elongated couplant flow nozzle that transmits the ultrasonic energy from the phased array probe through a water stream to the surface of the inspected part. Figure 6 displays the actual tool in use inspecting a composite part with both laminate and honeycomb reinforcement. Compared with conventional ultrasonic squirter technologies, WAPA provides up to eight times the throughput for a given scan speed.

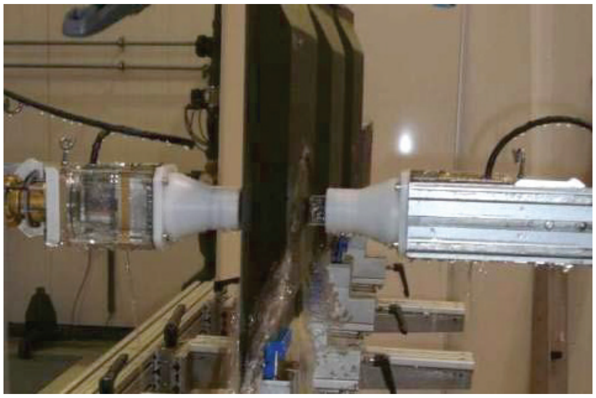

FIGURE 6. Wide area phased array.

Skin Bubbler Phased Array Tool

The Skin Bubbler Phased Array Tool provides PE inspection of relatively flat composite surfaces with up to a 38mm track width in a single scan. The tool's shoe rides on the surface of the part in a gimbaled holder maintaining precise alignment of the ultrasonic probe to the surface reducing the automation challenge of sound beam to surface normality as described above. This tool provides the ability to scan to the edge of a part without losing resolution. The Skin Bubbler Phased Array Tool typically employs a 128 element linear array probe that can also be fired with the RPCA logic to inspect sweeping radii found in larger composite structures. The Skin Bubbler Phased Array Tool, shown in Fig. 7, provides nearly forty times the surface area inspection productivity at a given scan velocity versus a conventional, single element bubbler probe.

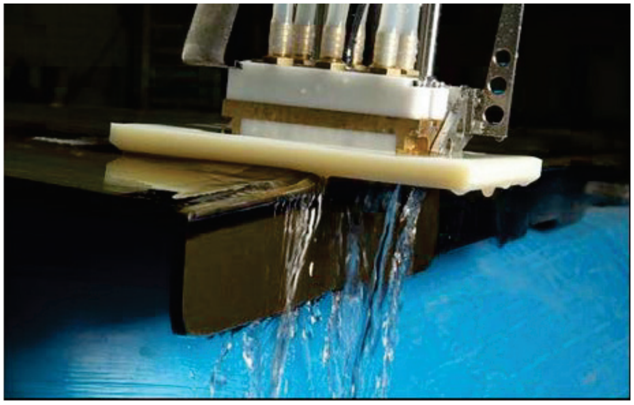

FIGURE 7. Skin bubbler phased array tool.

Phased Array Stringer Inspection Tool

The Phased Array Stringer Inspection Tool is used to inspect T-shaped reinforcement stringers on composite assemblies. The tool includes a 128 element phased array probe mounted in a fixture that clamps onto the stringer providing PE inspection of the T section typically in a single pass. As with the Skin Bubbler Phased Array Tool, this tool provides a degree of self-registration to the part minimizing any issues associated with the automation challenge of sound beam to part surface normality. Figure 8 shows this tool in its application.

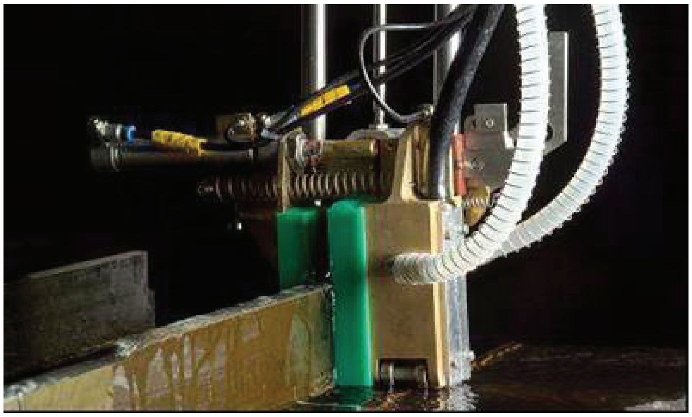

FIGURE 8. Phased array stringer inspection tool.

Inside Radius Tool

The Inside Radius Tool consists of a convex shaped ultrasonic phased array probe mounted in an angle specific holder. The robot positions the tool between to flanges and the tool self-aligns to inspect the radius between the two flanges in a single scan pass. Implementing the RPCA technique allows a single mechanical setup to track radius changes throughout the scan and adapt the sound field to maximizing inspection results. Tests have shown that gradual radius changes from 6mm to 25mm are accurately tracked and scanned in a single pass with this method. Figure 9 shows the general configuration of this tool.

FIGURE 9. Inside radius tool.

Outside Radius Tool

The Outside Radius Tool is similar in application to the Inside Radius Tool but is designed to track and inspect the linear outside radius of an essentially “bent” cross-section. This tool also employs a convex shaped linear phased array probe mounted in a spring loaded gimbaled fixture that mechanically tracks the outside surface of the part inspecting the entire radius in a single scan pass. Like the Inside Radius Tool, the RPCA technique can also be used with this application to allow the system to adjust the ultrasonic sound field to maximize part inspection results. Figure 10 shows the general construction of such a tool.

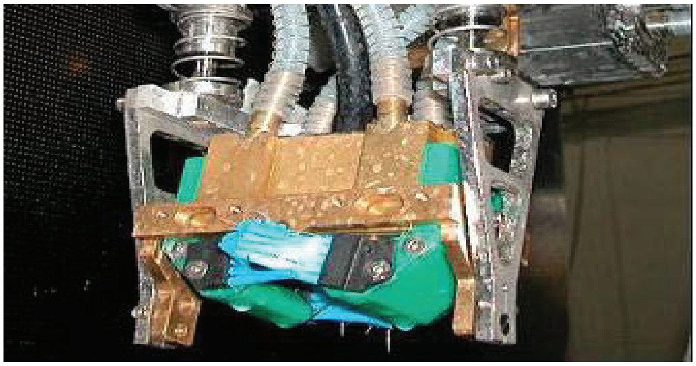

FIGURE 10. Outside radius tool.

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