Automated Ultrasonic Testing During Production: Avoiding Bottlenecks and Increasing Throughput

Valery F. GODÍNEZ-AZCUAGA1, Mark F. CARLOS1, Jeff DONAHUE1

1 Mistras Group Inc; Princeton Junction, NJ, United States

Phone: +01 609 716 4000, Fax: +01 609 716 4057; e-mail: valery.godinez@mistrasgroup.com, mark.carlos@mistrasgroup.com, jeff.donahue@mistrasgroup.com

Abstract
The dramatic increase in the use of composite materials experienced in aerospace industry, in the last 10 years, has been driven by a constant demand for higher performance and better fuel economy in modern commercial and military aircraft. A clear example of this phenomenon is the increase in the percentage by structural weight in different modern aircraft both commercial and military. This extensive use of composites poses a challenge for nondestructive inspection for detection and evaluation of defects in those materials, and it has become a critical step in the assessment of the overall structural integrity of modern aircraft. Automatic Nondestructive Inspection (ANDI) is commonly used for the inspection of high performance aerospace composites. Perhaps the technique most used is Ultrasonics coupled with large robotic systems. The use of ANDI allows inspecting large composite components at high spatial resolutions and relatively fast scanning speeds. It is not only used in flat components but also in components showing complex geometries. Inspection of composites using ANDI has become an integral part of the manufacturing process with the obvious benefits of being able to detect Foreign Object Debris (FOD), delaminations, cracking, porosity, etc. However, if the implementation of ANDI is not well planned it could potentially create bottlenecks in the manufacturing process, which can slow down production. This paper discusses the implementation of ANDI and different strategies to avoid bottlenecks and increase throughput in the production.

Keywords: Automated Ultrasonics, robotic systems, aerospace, composite materials

1. Introduction

The use of composite materials is nowadays very common in the manufacturing of modern aircraft both civilian and military, as a way to reduce weight and improve performance as well as fuel efficiency. It is well known that composites offer important benefits to aerospace manufactures like high stiffness-to-weight ratios, better fatigue performance, and corrosion resistance characteristics. These benefits are the cause of the dramatic increase in the use of composite materials experienced in aerospace industry in recent years, as shown by the graphic in Figure 1 [1, 2, 3]. A clear example of this tendency is the percentage of composites by structural weight in different modern aircraft military and civilian: from 39% in the F-35 JSF and 40% in the Eurofighter to 50% in the 787 Dreamliner to 53% in the A350 XWB. This tendency to increase the use of composite materials in aircraft is only accelerating with the introduction of new aircraft technologies such as Unmanned Aerial Vehicles (UAVs) in which, because of scaling factor limiting fuel carrying abilities, weight reduction becomes even more critical specially if payloads such as cameras or weapons are added in [4].

2. The challenge for Non-Destructive Inspection during manufacturing

The detection and evaluation of fabrication defects such as fiber misalignment, inappropriate fiber volume fraction, overlaps or gaps between fiber bundles, Foreign Object Debris (FOD) contamination, excessive porosity, poor wet-out and/or dry spots, delamination, wrinkles, matrix cracking, etc. creates new challenges for component inspection during manufacturing. In addition, manufacturers currently face increasing production volumes as the production rates of new aircraft ramp up, therefore the question is not whether to automated the inspection process, but rather how and when automation should be incorporated [5].
Several NDI methods, automated or semi-automated, have been used in inspection of composite components; Ultrasonics, Radiography, Thermography and Laser Shearography among them. However manufacturers have relied heavily upon Automated Ultrasonic Test (AUT) for NDI during manufacturing.

3. Automated ultrasonic systems

Among the so called Automated Ultrasonic Systems (AUT), there is a large variety of systems ranging from immersion systems equipped with ultrasonic phase arrays, to contour following gantry systems operating with water column coupling, through robotic arms equipped with laser ultrasonic pulsers and receivers. Regardless of the combination of motion and ultrasonic systems, any AUT system has three main subsystems: (1) mechanical sensor positioning subsystem, (2) ultrasonic signal generation/recording subsystem and (3) imaging and analysis subsystem.

3.1 Sensor and Part Positioning.

The AUT systems used for NDI/NDE in the aerospace industry must be capable of positioning an ultrasonic probe at any point along a preprogrammed scanning path with high accuracy and repeatability, typically within 0.005” (0.127mm). These types of systems have at least five degrees of freedom: X, Y, Z and gimbal and swivel angles. This is the minimum number of degrees of freedom necessary to follow a non-planar surface during the inspection system. The spatial resolution of the mechanical subsystems is typically 0.01” (0.25mm) or better.

Most of the AUT systems found in the industry are gantry types equipped with two independent columns with Z-axis and gimbal/swivel angles, which allow one inspection on through-transmission or two independent inspections in pulse-echo mode. One of these
systems is shown in Figure 2(a). Typically, gantry systems are equipped with ultrasonic sensors using water as the coupling medium between the sensor and the part under inspection. This is achieved by mounting the sensors inside squirtsers capable of producing stable water jets that act as waveguides for the ultrasonic beams to travel back and forth between the sensor and the part under inspection. However, there are Ultrasonic techniques that do not require liquid couplant between the sensors and the part as in the case of laser and airborne automated ultrasonic systems shown in Figures 2(b) and 2(c).

![Gantry system](image1)

![Laser AUT system](image2)

![Rotational Airborne AUT system](image3)

![Robotic arm system](image4)

Figure 2: Different AUT systems, (a) Gantry system, (b) Laser AUT system (c) Rotational Airborne AUT system, (d) Robotic arm system.

Gantry systems require the part under inspection to be located inside the envelope of the system in a pre-established position in relation to the defined home position of the system and the geometry of the part to be loaded into the system positioning software. In some cases, the geometry can be “taught” to the system, using a series of training points, so it can be “followed” during the inspection. Typical inspection speeds are in the range of 5 to 20 in/sec (127 to 508 mm/sec) depending on the complexity of the surface of the part under inspection and the length of the scanning line; flat surfaces and long strokes allow higher inspection speeds and curved surfaces with short strokes force the systems to move at slow speeds. The system shown in Figure 2(b) does not need to slow down when inspecting highly curved surfaces, since it uses laser Ultrasonics which does not require normal incidence on the part.
detection subsystem as traditional piezoelectric sensors. Figure 2(c) shows an AUT system in which the part under inspection is rotated at the same time the sensors are moved in only one direction along the main geometrical feature of the part. Figure 2(d) shows a system based on an articulated industrial robot that moves the part between the sensors while these are fixed inside a bath of water. The accuracy in moving and positioning the part, scanning resolution and inspection speed for these systems are similar to those of the gantry systems and are typically used in pulse-echo inspections. The inspection envelope for the robotic arm systems is smaller than for the gantry systems, but offer larger flexibility for parts with complex geometries.

3.2 Ultrasonic Signal Generation/Recording

AUT systems integrate powerful ultrasonic instrumentation to send and receive the ultrasonic signals through the part under inspection. When using traditional piezoelectric sensors, typical excitation voltages are between 300 and 400 volts to produce signals with frequencies ranging from 1 to 15 MHZ. These signals can penetrate laminate composites up to 0.5” (12.7mm) in pulse-echo configuration or up to 1.5” (38mm) when the inspection is through-transmission mode. The signals received are digitized at sampling frequencies in the range of 100MHz and above and if so specified by the inspection procedure, the full RF waveform can be stored for post-processing.

An alternative to traditional piezoelectric sensors is the use of pulsed lasers (CO\textsubscript{2}) to produce ultrasonic signals by thermal expansion in the composite part, as in the system shown in Figure 2(b) [6]. A second laser coupled to an interferometer detects the ultrasonic signals coming from the composite part. Once the signal has been demodulated, it can be recorded and processed in the same way as signal produced by piezoelectric sensors.

The ultrasonic signal received by the sensor, contains information relevant to the part under inspection. If the inspection is carried out in pulse-echo mode, the signal may contain several peaks corresponding to echoes caused by the front and back surface of the piece, and any interfaces in between them, that may represent a discontinuity inside the structure of the composite such a defect, a change in material properties, an insert, etc. By measuring the relative amplitudes and position of these peaks, one can determine whether the composite at that point is in good condition or not. The measurement of the relative amplitude and position of a particular echo, in general identified in the Ultrasonics lingo as Amplitude (AMP) and Time of Flight (TOF), are achieved by measuring gates positioned at the point of interest in the waveform. In general the systems have at least two of these measuring gates. Figure 3(a) shows a typical fully rectified signal in which three measuring gates are set to monitor front- and back-wall echoes and the space between. In this signal, one clearly identifies the front wall echo, an echo produced by an adhesive layer, and an echo produced by a defect located below the adhesive layer. Usually, the height of a peak (AMP) is associated with the size/severity of a defect and/or the difference in acoustic properties between the composite material and the defect. The TOF is associated with the position of the defect along the thickness of the part. Furthermore, if the velocity of the propagating acoustic signal is known, the depth of the defect can be calculated.

3.3 Signal Analysis and Imaging

One of the main features of AUT systems is that the data collected can be displayed in different presentation making their interpretation relatively straightforward. The simplest presentation is that of the signal displayed in Figure 3(a), which is known as an A-scan. The
A-scan display is limited since it shows the condition of only one point of the part. However, a more meaningful display of the data can be created by stacking consecutive A-scans along a scanning line. The display formed in that way is known as a B-scan and it represents geometrical features of a cross section of the part. Figure 3(b) shows a B-scan of the section of a composite part from which the A-scan of Figure 3(a) was recorded.

Figure 3: (a) Typical rectified acoustic signal showing several echoes produced by the composite front-wall, and adhesive layer and a defect below it, A-Scan,(b) B-scan of a composite part showing front wall, an adhesive layer, two defects below it and back wall echo.

The B-scan display is very useful for the visualization of the internal structure of a composite part. However, the true power of the AUT technique is the capability of generating 2-Dimensional (2D) maps of the component under inspection, in which any defects, internal structure, thickness, etc. can be shown. This type of map is known as a C-scan and is built by taking the AMP and TOF values extracted from every point measurement (A-scan) in the scanned area and associating them to the X-Y coordinates of the corresponding point in the scan. The values of AMP and TOF are then plotted in a 2-D color map representing the scanned area. Figures 4(a) and 4(b) present C-scan maps of a composite part with inserts simulating defects.

The AMP C-scan in Figure 4(a) shows several reflectors of maximum amplitude (0 dB) corresponding to square inserts of 0.25" by 0.25" (6mm by 6mm) simulating FOD, over a blue and yellow background (-15 to -25 dB reduction) that results from the area of the part with no defect. In fact, the orientation of the yellow stripes reflects the different fiber orientation in the composite. The rectangular patch in the upper left corner correspond to the adhesive patch with simulated defects below it, as it was observed in the A-scan of Figure 4. The TOF C-scan in Figure 4(b) shows the areas of the part with different thickness, ranging from 0.125" (3mm) to 0.325 (8.25mm). The simulated defects are also observed in this C-scan in the same position as in the AMP C-scan. C-scans produced by AUT systems can be stitched together to visualize a large complete part, even if that part was inspected in several C-scans performed in small sections, with very different topologies. As an example, Figures 5(a) and 5(b) show C-scans formed by small sectional C-scans.
4. Avoiding Bottlenecks and Increasing Throughput

As mentioned in section 2, the increasing demand for production of composite components for modern aircraft makes automated NDI a necessary part of the
manufacturing process. Therefore decisions have to be made regarding the type of inspection automation that better suits a particular component production process. In making this choice, two important aspects have to be taken into account:

- The geometrical characteristics of the composite part under inspection. The components are not limited anymore to reasonable-size parts with flat surfaces; they can vary from high-volume small brackets with intricate shapes to wing skin sections with soft curves and intricate pocket sections, all the way to very large barrel-shaped fuselage sections.

- Large production volume together with high spatial resolution of the inspection process generate lots of data that need to be evaluated by certified Level II and Level III NDI inspectors.

Each one of these aspects is a potential bottleneck point in the manufacturing process. The characteristics of the inspection system need be addressed at the very early planning stages, when the decision has been made to automate the inspection process.

4.1 Mechanical Considerations

4.1.1 Gantry systems
As general rule, large gantry systems with traditional piezoelectric sensors coupled via water columns are better suited to inspect large area components with smooth contours and very large radii of curvature. This geometry permits high inspection speeds since the sensors do not have to be reoriented at every single point during the inspection. When high inspection speed is needed and the part has complex curvatures such as deep pockets and medium curvature radius, gantry laser ultrasonic systems are preferred because laser UT can tolerate incidence angles up to several degrees. Inspection of axisymmetric components, such as cylinders or cones, is better achieved by systems that combine rotation of the component around its axis and movement of sensors along the same axis.

4.1.2 Robotic arm systems
When small complex parts are considered it is preferred to use a robotic arm that moves the part in front of the sensor, or between the sensors if through-transmission mode is used. There are other cases when the component has one dominant dimension, such as beams, in which 2-D scanning with a single transducer will require extremely long time. In these cases, a linear array transducer, which covers the whole area of interest, is used to eliminate scanning in one direction. In this way, the whole inspection process is reduced to scanning and contour following, if required, in one direction, while the scanning in the second dimension is achieved by electronically scanning with the linear array transducer.

In all these cases, the inspection throughput could be further optimized by incorporating CAD input capabilities to reduce training time for contour following. Also, accurate and repeatable part positioning improves throughput.

4.2 Automated AUT Data Analysis

After the inspection process, C-scans similar to those presented in Figure 4 and 5 are analysed by level II and level III inspectors. For this process to be effective, the data analysis software
package in the AUT systems must include utilities that can automatically identify image features created by stringers, bonding lines, etc. that could otherwise be interpreted as defects. Also, it must include utilities that automatically identify rejectable indications based on pass/fail criteria determined by the end user of the part. It is expected that in the near future expert systems, which include knowledge base and decision processes for automatic detection of defects, will be designed and incorporated in the AUT to automatically identify signatures from critical defects [7].

5. CONCLUSIONS

The use of AUT in today’s systems is a common practice in the inspection of composite aerospace materials and components. Current systems provide results in the form of AMP and TOF C-scans images that allow the inspectors to visualize defects and areas of concern.

The use of AUT will increase as the use of composites in military and civilian aircraft will only grow in the immediate future. This trend is reinforced as the use of UAVs for military and commercial purposes increases.

As the demand for composite material increases, the need to avoid bottlenecks in the production of composite parts will become critical. Thus better and more automated data analysis algorithms that can be incorporated into AUT systems to identify quickly and effectively defects will become critical.

References


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