Abstract

Over the last 15 years, phased array technology has completely changed the face of ultrasonic non-destructive testing. This now mature and widely adopted technology allows highly efficient inspections to be carried out on critical components in aerospace, oil & gas, heavy industry and power generating plants. The Iterative Time Reversal technique is a promising application of phased array technology. It consists of a real-time adaptation of the beam forming parameters, to compensate for varying probe-to-component misalignment conditions. This is particularly useful during inspections of CFRP components after manufacturing.

This paper will illustrate how state-of-the art phased array units controlled by UltraVision® can be used to apply the Iterative Time Reversal technique in order to improve coverage and detection capability of ultrasonic beams for various CFRP geometries. Examples will compare the performance of Iterative Time Reversal with traditional beam forming, and demonstrate the improved behavior towards geometry variations and positioning tolerances.
Introduction

With the recent evolutions in composite material technologies, aircraft composition has started to change. The commercial aircraft industry now incorporates an increasing amount of composite materials (e.g. CFRP) in their structures (Figure 1). CFRP components have the advantage being light and robust. These composite structures are typically shaped in complex and variable geometries.

The various shapes and the complex geometry create a challenge for the NDT inspection of the CFRP components. The preferred NDT technology in the current case is phased array UT. To be fast and reliable, phased array UT (PA UT) requires a combination of dedicated probe configurations, a high performance PA UT system and advanced software that includes specific tools and algorithms.

![Figure 1. Example of aircraft composition](image)

Standard phased array UT inspection requires precise alignment between the probe and the specimen. In the case of complex geometries, this typically involves complex and therefore expensive mechanical systems, and an exact knowledge of the specimen geometry.

Recently, Zetec has implemented the Time Reversal technique, a real-time adaptive process, allowing for rapid and reliable phased array UT inspections on such complex geometries. This paper will illustrate how state-of-the art phased array units controlled by UltraVision® 3 can be used to apply the Iterative Time Reversal technique to improve coverage and detection capability of ultrasonic beams for various CFRP geometries.
Challenges

An increasing quantity of composite structures are used in the aircraft industry. These structures include the fuselage and different parts of the wings; the skin, stringers and spars. All these components have different shapes, most of which are complex geometries. The examination method must be able to adapt to those challenging conditions.

The manufacturing process of the composite materials can generate different types of defects. The inspection after manufacturing must be able to detect porosities, foreign bodies and delaminations present in the CFRP structures (Figure 2).

Another challenging aspect of the inspection of aerospace components is the inspection speed. The large manufacturing volumes demand high inspection speed in order to reduce cost.

![Figure 2. Examples of components and potential defects](image)

Detection of laminations in composite stringers  Detection of laminations in composite spars

Solution

In order to overcome the challenges listed above, Zetec offers an efficient solution for composite material inspection. This solution is based on dedicated 1D linear array PA UT probes, advanced PA UT hardware, and a complete inspection software package including innovative features. The Zetec solution can be integrated to the customer’s manipulator.

Phased Array UT Probes

To optimize the detection capability, the probe selection must be made carefully and according to the specimen geometry. Most inspections are performed essentially at normal incidence with the component surface. For the typical composite shapes, this typically requires a combination of two types of probes.

A linear 1D phased array probe is used to inspect flat surfaces, as shown in Figure 3. These probes typically have 32, 64 or 128 elements.
For curved sections, arc-shaped 1D probes are used, with typically 32 or 64 elements (Figure 4).

**UltraVision Software**

The UltraVision - Classic software manages inspection technique development, UT data acquisition, displays real-time images of the data and provides advanced data analysis and reporting tools. It handles a multitude of phased array UT applications for various industries.

Recently, the Iterative Time Reversal technique has been added to the toolkit offered in UltraVision.

**Time Reversal Concept**

Time Reversal is a real-time adaptive UT inspection technique meant to eliminate the effects of misalignment between the probe and the specimen. This is achieved by using “surface profiling”; this process uses the time of flight from individual elements of the probe to characterize the surface of the inspected specimen. Once the “surface profiling” is complete, a compensation delay is applied to the individual elements of the probe, and essentially normal incidence of the beam on the surface is achieved.
This is a two-step process. The first step is “surface profiling”. During this step, a plane wave is generated by firing all elements simultaneously. When the wave meets the specimen, it is reflected back to the probe where it is received. The reflected wave is no longer a plane wave, it is affected by the shape of the inspected component. The variation in the wave shape translates into a different time of flight for the response on each individual element $i$ (see Figure 5).

Using the different time of flights measured in the initial firing, the software calculates the delay for every individual element $i$ that will compensate the differences introduced by the surface profile. Equations (1) and (2) show how the corresponding emission and reception delays are calculated.

\[
E_i = \frac{1}{2} \left[ Max (t_i) - t_i \right] \tag{1}
\]

\[
R_i = \left[ Max (E_i) - E_i \right] \tag{2}
\]

Where $t_i$ is the time of flight for the wave received by element $i$. This process can be repeated several times, until the wave reflected from the surface back to the probe is a plane wave (see Figure 6).
The second step of the Time Reversal technique is to record data using the delays obtained during the profiling phase. Data acquisition is performed using electronic linear scanning with a limited active aperture (e.g. 8 elements). Figure 7 shows the principle (left) and shows real inspection data (right).

At each scan position, both steps are performed real-time to maintain valid examination accurate data, even on a varying surface geometry.

![Figure 7. Data recording using compensated delays](image)

It is important to mention that this complete process is performed real-time and allows scanning speeds similar to standard phased array UT when using similar focal law groups and equivalent UT settings.

**Advanced PA UT System**

Zetec offers various phased array UT systems supporting the Iterative Time Reversal technique; ZIRCON®, QuartZ® and TOPAZ32®. All systems are battery operated, and are 32/128 configurations. The active aperture of up to 32 elements, and the possibility to connect up to 128 probe elements allow the system to adapt to various inspection conditions. In addition, multiple units can be connected to the same computer to control the complete set of probes from a single station (Figure 8).
Case Study

In order to demonstrate the capabilities of the Time Reversal technique, a case study on a representative sample specimen was performed. A CFRP sample was manufactured for this purpose by an industrial composite provider (see Figure 9). It has typical composite material attenuation and contains multiple artificial brass inserts to simulate typical defects. The inserts are 3 x 10 mm and 30 x 10 mm, and are located at various locations and depths throughout the sample.
This type of geometry can be inspected in three scan lines and will require two different probes. The flat sections are examined using linear 1D probes, and the curved section is inspected using an arc-shaped 1D probe. All inspections are performed in complete immersion.

**Flat Section**

For the flat sections, an LM 5MHz probe was used. It has 64 elements, a pitch of 0.6 mm and a width of 10.0 mm. An aperture of 8 elements was used.

In this case, scanning was performed manually, while attempting to maintain optimal probe alignment and orientation. So in theory, there should be no major difference between the Time Reversal data and the standard phased array UT data. However, different results are shown on the amplitude C-Scans of Figure 10: even when the operator tries to maintain optimal conditions, the backwall amplitude on the standard PA UT data is very sensitive; indeed, a slight misalignment or variation in the water column can cause a loss of backwall amplitude. A constant backwall amplitude is important for porosity detection. On the other hand, the Time Reversal data shows a constant backwall amplitude over the full extent of the specimen.

![Figure 10. Amplitude C-Scan of the flat section: Time Reversal (left); Standard PA (right)](image)

**Curved Section**

The curved section of the specimen was inspected with an arc-shaped 1D probe, at 3.5 MHz, with 64 elements. The probe has a pitch of 0.65 mm and its width is 8.0 mm. Again, an active aperture of 8 elements was used.

At first, the probe was installed on a two-axis mechanical system to ensure optimal orientation and alignment. The probe was then intentionally moved by approximately 3 mm, to demonstrate the capability of the Time Reversal technique to compensate for the misalignment (Figure 11).
Figure 11. Probe misalignment

Figure 12 shows that the Time Reversal data display excellent detection capability throughout the entire scan line, all nine defects appear clearly on the C-Scan. The standard PA UT data do not allow for adequate detection of all flaws in the sample.

Figure 12. Amplitude C-Scan and End View for misaligned arc-shaped 1D probe
Time Reversal data (left); Standard PA UT data (right)

For the second experiment, the probe was aligned correctly with the specimen, and then the incidence angle of the probe was modified by rotating the probe holder.
With the orientation of the probe modified, the standard PA UT data becomes completely useless: the UT data of Figure 14 (right) show that no valid signals are received by the probe. In similar conditions, and during the same inspection sequence, the Time Reversal technique has compensated for the misorientation, and has generated data shown on Figure 14 (left) that allow for adequate detection of the defects.

![Figure 14. Amplitude C-Scan and End View for misoriented arc-shaped 1D probe Time Reversal data (left), Standard PA data (right)](image-url)
Conclusions

From the work presented in this paper, the following conclusions can be drawn about the main benefits of the Time Reversal technique for composite structures inspection:

1. The Time Reversal technique is able to compensate for probe misalignment and misorientation in real time without slowing down the scanning speed significantly.

2. The Time Reversal technique enhances the flaw detection capability, and improves porosity assessment by stabilizing the amplitude of the back wall.

3. By mitigating the need for exact alignment and orientation, the proposed Time Reversal solution reduces the cost of the required mechanical scanning systems, thus bringing additional value (cost savings) for the end customer.

4. The Time Reversal technique is available as an option with Zetec’s standard PA UT hardware (ZIRCON®, QuartZ®, and TOPAZ32®) driven by the UltraVision® software; multiple hardware units can be connected and driven from a single PC; this allows for parallel firing of multiple probes, thus offering the potential for a substantial increase of the scanning speed.

References


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