Fast Scanning and Adaptive Beamforming: two innovative algorithms to improve ultrasonic inspections

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Abstract

Some of the current limitations for Non Destructive Testing of Carbon Fibre Reinforced Polymer (CFRP) Composites are inspection time and probe holder high complexity. The latter is required to follow the wide variety of increasingly complex geometries of the parts being inspected. To overcome these limits, different beam emission strategies followed by specific signal processing have been tried. These techniques have different and complementary goals, such as quality image improvement, inspection time reduction and electronic adaptation to the part geometry. In this context, two new techniques will be presented: Fast Scanning, focused on inspection time reduction, and Adaptive Beamforming, to deal with complex or variable part geometries.

Keywords: Phased Array, algorithms, aerospace, carbon fibre reinforced polymer (CFRP)

1. Introduction

Inspection of large, complex CFRP components is challenging due to both, the part geometry and the time required for scanning to get reliable data. State-of-the-art CFRP manufacturing processes produce parts with non-uniform surfaces and curved regions.

In this context, the main goals for new UT inspection machines for the CFRP component manufacturing industry are the following ones:

- Increase inspection speed
- Flexible systems, adaptable to different component geometries
- Reduced mechanical and transducer sub-systems complexity
- Decrease the number of trajectories required for scanning
- Produce systems less sensitive to mechanical misalignments
- Get flaw detection with increased robustness.

2. Adaptive Beamforming

The Adaptive Beamforming technique proposed in this work addresses the problems associated with complex part geometries. The objective is to build a system that adapts to probe-part geometric changes during the scanning, by computing the adapted focal laws to keep always the image well focused.

Besides, the approach tries to simplify the probe-holders design and transducer arrangements in order to be used in a variety of component configurations. In general, with the Adaptive Beamforming approach, a small set of linear array probes will be enough to inspect a diversity of component shapes.
2.1 Principles

The component to be inspected is defined by a set of parameters (group of curved and straight regions, with their corresponding nominal values). These parameters can be changed to describe the geometry of a different component.

On the other hand, another set of parameters define the probes to be used (shape, number and spacing of elements, central frequency, etc.). These can be also modified to deal with different applications.

Both sets define the nominal part-probe geometry to carry out the inspection. Under a working scenario, the array probe arrangement and the number of active elements are determined to achieve the required resolution, avoid grating lobes and keep high element sensitivity. Software packages have been developed to this purpose at the design stage.

Once the parameters have been defined, the Adaptive Beamforming algorithm is able to self-adapt to variations in the nominal geometry, caused by slight probe misalignments, changes in the component shape or random deviations from nominal values.

Besides, it is important to optimize size and number of probes in order to reduce mechanical complexity of the system, while keeping the required resolution for flaw detection with a high degree of robustness. Cost is also another point to consider in the inspection design stage.

![Fig. 1. A straightforward approach with a single linear array probe](image)

A straightforward approach such as shown in Fig. 1 for an example stringer component, although theoretically possible, will not fit these criteria. First, for 2 mm resolution, a large number of active array elements (~800) would be necessary to cover the whole part with normal incidence. Second, the high steering angle required for normal incidence on the slant faces may be difficult to achieve with conventional probes. Furthermore, high grating lobe levels and low angular sensitivity can be expected, unless the inter-element pitch is kept below half a wavelength (λ/2), which will further increase the number of elements.

Using the developed design tools we found, for the stringer geometry above, that a 3-probe array arrangement fulfils the requirements (Fig. 2). Some other arrangements are also possible using more probes or curved probes, but this is considered the most cost-effective.

First, element number and beam steering angles are kept within reasonable values for standard, commercially available array probes. Second, since steering angles are rather low, grating lobes are easily controlled. Third, since the number of array elements is limited, the cost of probes and electronics is reduced.
2.2 Application of the proposed approach

Fig. 3 shows a lab prototype to perform tests on a Ω-shaped stringer (top) and some results (bottom). In this case, a single probe tilted 30º is used to inspect half of the stringer, including the top, bottom and slanted planes and both curved regions with nominal parameter values.

The B-Scan image shown at the left (distorted) was obtained with the array slightly misaligned. From this image, new focal laws were computed and programmed, obtaining the image shown at the right, where these misalignments have been corrected.
This procedure is used to automatically correct deviations from the nominal probe-part geometry, due to variations in their alignment, part shape or others. Each image is used to compute the new focal laws for the next one, continuously adapting the beamforming process to the “current” geometry (in reality, to the geometry found in the immediately preceding acquisition).

Algorithms to perform this process were developed in MATLAB, controlling the electronics in real-time. Fig. 4 shows the graphic user interface to set inspection parameters and the nominal focal laws computed for normal incidence at a spatial resolution of 2 mm for different array probe arrangements.

![GUI](image1.png)

![Graphs](image2.png)

**Fig. 4.** Top: GUI to control the acquisition. Bottom: partial beams for different array arrangements using nominal geometry parameters.
Figure 5 shows graphically the adaptive beamforming process. Starting with focal laws for the nominal geometry (Top-Center), a B-Scan image is taken. From this image the actual interface geometry is estimated by least squares. Adapted focal laws are computed for the new geometry to finally obtain the corrected image (Top-Left).

Fig. 5- Process of adaptive beamforming beginning from top center (nominal focal laws). An image is obtained, which determines geometric deviations, adjusts the actual interface and computes the adapted focal laws to obtain the corrected image (top left).

Fig. 6.- C-scan of a stringer with several defects. All are detected with the specified resolution (2 mm) in spite of the misalignment of the array probe with the part.

Figure 6 shows C-scan images of this component with several artificial flaws. The part is scanned following a trajectory not parallel to its axis, so that continuous correction is required to detect all the flaws along the component length (~300 mm). Also, the part includes a shape
variation near the centre. Both cause deviations from the nominal geometry, although their effects are not noticeable due to the adaptive beamforming algorithm.

Figure 7 shows another example of a 90° elbow of CFRP, with several artificial flaws that are also detected along the whole scan length in spite of the probe-part misalignments.

![Fig. 7- Inspection results of a CFRP 90° elbow with adaptive beamforming.](image)

### 2.3 Advantages

The proposed adaptive beamforming technique has several advantages, being the most important the automatic correction of unexpected misalignments between probe and part or small changes in the part shape along the scan. The latter eases the definition of the scan, since only a single set of initial nominal focal laws is required and the adaptive beamforming will correct them when the shape changes.

Another advantage is the simplification of the probes, which can be chosen as standard linear or curved arrays. These can be mechanically adapted to different component configurations, not requiring different arrays for flat or curved regions.

Most important, the technique provides a superior robustness with regard to conventional methods, where focal laws are fixed and defined for the nominal part geometry only, so that slight deviations produce erroneous images. On the other hand, known geometric changes require programming different sets of focal laws linked to the scan position, which usually slows down the inspection process.

### 2. Fast Scanning

Fast Scanning is a complementary technique with the objective of reducing inspection time. The inspection speed can be limited by several factors: the ultrasound two-way time-of-flight; the electronics maximum pulse repetition frequency or prf; the time required to compute/load new focal laws following the changes in the probe-part geometry; as well as the data transmission throughput.

With linear scan, a number $N_A$ of elements are chosen as the active aperture. It is shifted along the $N$-elements and, at every position, is used in emission and in reception to build a single line. A set of $L$ active apertures is defined to build the $L$ lines that form the image.

The minimum time $T_I$ required to get an image is the product of the ultrasound two-way time-of-flight $T_U$ (including the transit time through coupling medium) by the number of scan lines $L$, that is: $T_{Image} = L \cdot T_{Line}$, where $T_{Line} = \max (T_U, T_{PRF})$ and $T_{PRF}$ is the inverse of the maximum pulse repetition frequency supported by the electronics (Fig. 8).
To get a spatial resolution $\Delta y$, the maximum scanning speed should be $v_{max} = (1/T_s)\Delta y$. For example, in the best case, where $T_{Line}=1/\text{max. prf}$, being 25 kHz the maximum prf (quite common in commercial equipments), $L = 120$ lines and $\Delta y = 1$ mm, the maximum scanning speed is $v_{max} = 208$ mm/s. It is obvious from this example that the sequential nature of phased array linear scan is the main cause of this rather low scanning speed.

For each image line, the process is:

1. Emission with a subaperture of $M$ elements.
2. Reception with the same $M$ elements
3. A-Scan beamforming (delay & sum)
4. Processing time/line: $T_{line}=\max(T_U, T_{PRF})$

Repeated for every one of $L$ image lines.

Time to get a full image:

$$T_{Image} = L \cdot T_{Line}$$

**2.1 Principle of Fast Scanning**

To overcome this problem Fast Scanning builds several image lines with a single trigger shot. In practice, the full image is obtained with a single simultaneous shot of all the array elements (Fig. 9), which produces a plane wave. In reception, the $L$ scan lines are individually and simultaneously beamformed with single focus by parallel hardware. Every scan line is composed from the echo signals received by a user-defined active aperture of $N_d$ receiving elements, equivalent to that used in conventional linear scan. This approach requires to hardware implement $N_d$ beamformers in parallel.

A dramatic improvement on scanning speed is achieved, in principle by a factor $L$. However, Fast Scanning uses some processing time to share the information recorded by individual elements among system processors. But, since acquisition time is low (typically below 0.1 ms) and processing is carried out by specific hardware in FPGAs, the maximum acquisition + processing time is well below 1 ms, which allows for scanning speeds above 1 m/s with a spatial resolution of 1 mm (that is, at a frame rate above 1000 images/s). The main drawback of Fast Scanning is related to the emission of a plane instead of a focused wave front. This may lead to a loss in lateral resolution and an increase of side lobe levels and, also, to an
increase of signal amplitude of the beamformed A-Scans due to a larger contribution of emitting elements, as presented next.

Fig. 9 - Principles of Fast Scanning

2.2 Validation

These shortcomings have been evaluated by comparison of the conventional Phased Array and Fast Scanning images on the same CFRP component with an artificial delamination (Fig. 10). Both images are nearly equivalent, although looking to the lateral profile of the detected flaw, slightly higher amplitude (13%) and beam width (0.5 mm) are found (Fig. 11). Side lobe levels are also somewhat higher with Fast Scanning, although they do not modify substantially the image.

As a conclusion, the Fast Scanning technique provides a significant increase on the inspection speed at the cost of slight losses in lateral resolution and increase of the side lobe level. Furthermore, it has some other advantages. To achieve the maximum scanning speed with conventional Phased Array techniques, the electronics must be operated near its maximum pulse repetition rate specification (line rate). With Fast Scanning, the pulse rate is limited to the frame rate, not the line rate, a figure about two orders of magnitude lower. This helps to
preserve the integrity of the electronics as well as the transducer, and to avoid sound reverberations.

Fig. 10- Comparison conventional Phased Array (left) and Fast Scanning (right) images

Fig. 11- Profile of the detected flaw with Phased Array (blue) and Fast Scanning (green)

2.3. Extra: simultaneous focal law correction

Fast Scanning is especially adequate to inspect planar components, where the main subject to keep the probe-part geometry is parallel loss between their surfaces. This opens the possibility of on-process focal law correction simultaneously with parallel beamforming. Fig. 12 shows the image obtained with a conventional Phased Array when the probe and part surface are tilted 0º (ideal case), 2º and 4º.

Fig. 12- Effects of slight probe-part misalignments on the image and flaw detection (0º, 2º and 4º from left to right).

With Fast Scanning, as it was done in adaptive beamforming, each image is used to find the steering angle of the next trigger event to produce a plane wave with normal incidence on the component surface. Simultaneously, the corresponding receiving focal laws are computed for the tilted surface and loaded in the focusing circuits.
Figure 13 shows the effect of this hardware-implemented steering and focal law correction. At the left, the ideal image acquired with 0º incidence and, at the right, the image obtained after automatic correction of a 4º misalignment (see Fig. 12-right for the uncorrected image). Although there are small differences with the ideal image, the corrected one still allows detection and evaluation of the flaw and bottom echo.

2.4 Advantages

Reducing the number of trigger and acquisition events by a factor $L (= \text{number of image lines})$ achieves a significant improvement of the scanning speed. Furthermore, the real-time automatic focal law correction for planar surface components improves the flaw-detection robustness. For a typical case of electronic scanning with active apertures of 6 elements and arrays of 128 elements, using a 32/128 multiplexed equipment the inspection speed has been estimated to improve by a factor of 11 with regard to that achieved by the conventional linear scan of Phased Array.

3. Conclusions

Adaptive beamforming together with Fast Scanning provide new possibilities to reduce costs in the manufacturing processes of CFRP components. Increased robustness and reduced inspection time are achieved by keeping controlled the focal laws and simultaneous beamforming of all the image lines. In the case of Fast Scanning, this is gained at expenses of a slight loss in lateral resolution and an increase of the side lobe levels that can be accepted in most applications.

The algorithms have been developed on Matlab, and have being tested with a phased array equipment. The obtained results encourage continuing the yet required hardware developments.

References

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