Fast Scanning: achieving high scanning velocities in the phased array inspection of aeronautic components

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Abstract
This work proposes a fast inspection method for large planar and soft curved aeronautic components, named Fast Scanning, able to obtain more than 1000 images per second in continuous operation. Using arrays, this method is based on composing every B-scan image in real time with a single trigger event, which reduces the acquisition time by the amount of image lines. Differently from other approaches, Fast Scanning performs real-time parallel beamforming of all the A-scan lines that compose the image with an adaptive control of focal laws. The former provides well focused images, while the latter keeps the optimal focal laws under probe-part geometry variations. Experimental results show that phased array imaging and Fast Scanning yield similar image quality with regard to resolution, sensitivity and signal-to-noise ratio. However, Fast Scanning provides one to two orders of magnitude higher frame rates, opening an opportunity to significantly reduce the inspection time of large aircraft components without compromising the image quality.

Keywords: phased array, parallel beamforming, aerospace, carbon fiber composite

1. Introduction

Inspection time is an important parameter for efficient handling and cost reduction in the aeronautic industry, specifically in the manufacturing process of composites. Automatic phased array imaging improves inspection time and reliability by providing B and C-scan images of the tested part covering the full extent of the transducer array, wider than conventional mono-element based inspections. Furthermore, its beam focusing capabilities yields higher image quality.

However, conventional phased array images are obtained in a line per line basis, usually following a linear scan strategy. This requires multiple trigger events to get the whole set of lines that compose the image. Since the ultrasound transit time is bounded by different parameters, the frame rate becomes limited up to some tens of images per second, which yields a moderate scanning speed (typically bellow 300 mm/s).

Several efforts have been performed to overcome this limitation. The so named Paintbrush technique [1] simultaneously excites all the array elements and registers the A-Scans received with each one of them. The B-Scan image is directly formed with these A-Scans, which yields relatively low resolution and signal-to-noise ratio. Some quality improvement techniques have been proposed, but they require the use of parallel processor units (GPUs) for their real time realization.

Another interesting approach is the SAUL technique, which performs between 2 and 4 excitation events to iteratively adapt the generated wave-front to the shape of the part, ensuring normal incidence at all surface points. Although it is an excellent technique for the inspection for complex shape components [2], achievable scanning speed is moderate. For example, when acquiring a B-Scan image every 2 mm and using 4 iterations, reported scanning speed is about 100 mm/s [3].
This work proposes an alternative method, named Fast Scanning, able to obtain over 1000 images per second in large and soft curved aeronautic components. It is based on composing every B-scan image in real time with a single trigger event, which reduces the acquisition time by the amount of A-scan lines in the image. For a typical automated inspection with index resolution of 2 mm, scanning speeds above 3 m/s are estimated to be achieved.

Differently from other approaches, Fast Scanning performs real-time parallel beamforming of all the A-scan lines that compose the image with an adaptive control of focal laws. The former provides well focused images, while the latter keeps the optimal focal laws under probe-part geometry variations. Image formation is achieved by switching the acquired data to multiple beamformers, each one with an active aperture up to 16 elements (limited by hardware resources) and their own focal laws. This way, all the image lines are beamformed in parallel. Simultaneously, the ultrasound hardware computes the focal laws for the next acquisition from the acquired data, thus performing adaptive beamforming for planar and soft-curved surfaces.

Experiments were performed to compare the performance of Fast Scanning and conventional phased array imaging. Both yield similar image quality with regard to resolution, sensitivity and signal-to-noise ratio. However, Fast Scanning provides one to two orders of magnitude higher frame rates, opening an opportunity to significantly reduce the inspection time of large aircraft components without compromising the image quality.

2. Fundamentals

Figure 1 shows a schematic representation of a typical phased-array linear scan process. A sub-set of $M$ elements (active aperture) is excited with some emission delays to generate a focused beam into the material. Echoes are registered by the same $M$ elements and individual signals are combined in a reception beamforming process, usually involving apodization, delay and sum operations. The obtained raw A-Scan is usually further processed with band-pass filters, envelope detection algorithms and peak detections gates, to finally get a single image line. The whole process is repeated moving the active aperture between emissions, thus generating a B-Scan image.

In this scenario, scanning speed is limited by image formation time, which is physically limited by the ultrasound time-of-flight (TOF) to the bottom of the component. But besides this upper limit, there are some other technological factors like maximum pulse repetition frequency (PRF), beamforming and digital processing (DSP) time or data transfer rate that usually further reduce inspection speed.

Lets consider a case study of a CFRP component with thickness $E = 40$ mm and speed of sound $c_P = 3000$ m/s. An $f_R = 5$ MHz array with $N=128$ elements and pitch $d=1$mm is used to perform a linear scan with $M = 6$ active elements, resulting in $L=123$ image lines. Scanning resolution in the movement direction (index resolution) is $dy = 2$ mm and signal sampling frequency is $f_s = 20$ MHz. A water column of $H = 30$mm is assumed between the array and the component surface.

With these numbers, the ultrasound time-of-flight to the back-wall is ($c_W = 1500$ m/s):

$$T_V = 2E/c_P + 2H/c_W \approx 67 \mu s$$ (1)
For each image line, the process is:

1. Emission with a sub-aperture of $M$ elements.
2. Reception with the same $M$ elements
3. A-Scan beamforming (delay & sum)
4. Digital processing (Filter, Envelope, gate, etc)

Processing time/line: $T_{\text{line}} = \max(T_U, T_{\text{PRF}})$

Repeated for every one of $L$ image lines to get a full image:

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

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<thead>
<tr>
<th>Image</th>
<th>Description</th>
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<tr>
<td><img src="image1.png" alt="Image" /></td>
<td>For each image line, the process is:</td>
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<tr>
<td><img src="image2.png" alt="Image" /></td>
<td>1. Emission with a sub-aperture of $M$ elements.</td>
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<td><img src="image3.png" alt="Image" /></td>
<td>2. Reception with the same $M$ elements</td>
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<td><img src="image4.png" alt="Image" /></td>
<td>3. A-Scan beamforming (delay &amp; sum)</td>
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<td><img src="image5.png" alt="Image" /></td>
<td>4. Digital processing (Filter, Envelope, gate, etc)</td>
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<td><img src="image6.png" alt="Image" /></td>
<td>Processing time/line: $T_{\text{line}} = \max(T_U, T_{\text{PRF}})$</td>
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<td><img src="image7.png" alt="Image" /></td>
<td>Repeated for every one of $L$ image lines to get a full image:</td>
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<td><img src="image8.png" alt="Image" /></td>
<td>$T_{\text{Image}} = L \cdot T_{\text{Line}}$</td>
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Figure 1 – Schematic representation of the conventional linear scan process.

With conventional phased-array technique, the minimum acquisition time for each B-Scan is (assuming null beamforming and digital processing times)

$$T_{\text{ACQ}} = L \cdot T_V = 8.2 \text{ ms}$$ (2)

If data transfer time is neglected, the maximum achievable frame rate is

$$\text{FPS} = 1/T_{\text{ADQ}} \approx 120 \text{ images/s}$$ (3)

and the maximum scanning speed is

$$v = \text{FPS} \cdot \Delta y = 240 \text{ mm/s}$$ (4)

The required system PRF to obtain this inspection speed is

$$\text{PRF} = L \cdot \text{FPS} = 15 \text{ kHz}$$ (5)

Finally, the required data communication bandwidth between the acquisition system and the evaluation computer for sustained operation is about 16 MB/s, if only the samples inside the component are registered and transferred (540 samples per A-Scan). This throughput can be
achieved with conventional links like USB 2.0, but there are other limiting factors like beamforming time, operative system latencies, etc, that usually reduce inspection speed typically below 300 mm/s.

The goal of the Fast Scanning method [4] is to increase this figure an order of magnitude, above 2 m/s. If it could be achieved, scanning speed will not be limited by the ultrasound inspection process. Instead, limitations will arrive from mechanical movement and restrictions related with operation safety.

Figure 2 depicts the overall process. After emission of a plane wave with all array elements, individual signals are registered. If the B-Scan image were formed directly from these signals like in the *Paintbrush* method, a low resolution and SNR signal would be obtained (Figure 2.top-right). Instead, in the Fast Scanning method, a set of L hardware implemented beamformers are used to generate L focused scan lines with higher resolution and SNR. Depending of the processing power of the target hardware, this process could be realized in strict real time (same output and input throughput) or with some overhead time for internal signal transfer and processing.

For each B-Scan, the process is:

1. Emission with all array elements.
2. Reception with all elements
3. Parallel hardware beamforming and signal processing of all A-Scans beamforming

Processing time/image : \( T_{\text{Image}} = T_{\text{Line}} \)

![Figure 2 – Schematic representation of the Fast-Scanning method](image)
Besides increasing resolution and contrast, the beamforming process allows to correct probe-part misalignments by electronic beam steering. Signal loss because of array misalignment is a quite severe problem in this kind of inspections, mainly because of the high directivity of the generated beams. A slight inclination of 3° can produce more than 12 dB of signal loss in the interface echo. Moreover, refraction at the interface because of the large impedance mismatch between water and composite deflects the beam and further reduces defects and back-wall echo amplitudes.

To overcome this limitation, a focal-law correction algorithm was developed. Based on the echo-start information of each acquired image, surface inclination angle is estimated and a new set of emission and reception delays are calculated. This ensures normal incidence for both the emitted plane-wave and generated reception beams. The algorithm was optimized for being implemented in the acquisition hardware. Parallelizing the angle correction and the image formation processes, a negligible overhead is ensured. Moreover, because correction information is obtained directly from each B-Scan data, no extra emission events are required like in other approaches.

Figure 3 – Schematic representation of the Fast Scanning hardware implementation.

Table I summarizes the expectable maximum inspection speed depending of the active aperture size, for a 5 MHz array with 128 elements, pitch 1 mm and a component of 50 mm thickness. Scan resolution is 2 mm in both C-Scan directions, and all frame rate restrictions were considered (TOF, PRF, beamforming time, DSP, etc.). Calculations were performed for the available hardware platform based on Xilinx Spartan 3 FPGAs.

Highlighted in green is a common configuration used in aerospace industry to ensure detection of 6x6 mm defects. In this case, Fast scanning method is 11 times faster than conventional phased-array linear scan, and a theoretical scanning speed of 5.5 m/s could be achieved.
Active elements (M) | Image lines (L) | Inspection speed increase factor (K) | Maximum inspection speed (m/s)
--- | --- | --- | ---
1 | 64 | 13 | 5.5
4 | 60 | 12 | 5.5
6 | 56 | 11 | 5.5
8 | 52 | 10 | 5.5
10 | 48 | 8 | 4.6
12 | 44 | 6 | 3.4
14 | 40 | 4 | 2.7
16 | 36 | 3 | 2.3

Table I – Maximum inspection speed for several active apertures with 2 mm resolution scan

3. Image quality

The proposed method can be valid for industrial applications only if image quality is comparable to that obtained with the conventional phased-array method. Emitting a plane wave with all array elements instead of a narrower beam will produce a broader main lobe and higher side-lobe levels, reducing resolution and contrast. In any case, because of the high directivity of array elements typically used in this kind of inspections (d > 3\( \lambda \)), image quality losses are not expected to be high.

Figure 4 shows a continuous-wave simulation of the two-way lateral beam pattern of an active aperture of 6 elements with 1 mm pitch, at 30 mm away from the probe surface, with phased-array (blue) and fast scanning (red) techniques. Main lobe at -6dB is 25% wider and side lobes about 5 times higher with fast scanning method than with phased-array. Because of the large refraction index of the water-CFRP interface, it is expected that side-lobes level increase have low impact in image quality.

![Figure 4](image.png)

Figure 4 – Simulation of the continuous wave lateral wave pattern of a 6 elements 1 mm pitch aperture with conventional phased-array (blue) and fast scanning method (red).

Figure 5 shows experimental results with a 12 mm thick CFRP with artificial defects at different depths, inspected with a 5 MHz array of 1 mm pitch. On the left column are images obtained with conventional phased-array linear scan, and on the right column the corresponding Fast Scanning images. In all cases images are equivalent, with just a slight
increase in lateral defect size for the Fast Scanning method. Side-lobe level increase of Figure 4 is not noticeable, mainly because continuous-wave simulation is a worst-case scenario when compared with pulse-echo broadband acquisitions.

Figure 5 – Images of defects at different depths obtained with conventional phased-array (left) and with fast scanning method (right). Active aperture of 6 elements and 1 mm scan resolution.

Figure 6 shows the lateral profile at the depth of the shallowest defect \((z = 6 \text{ mm})\) for both methods. Fast Scanning (green) produces 13% more amplitude at the defect because of the emission with a larger number of elements, with the counterpart of increasing the defect size in 1 mm in the lateral direction when measured at -6 dB. This value is bellow the theoretically expected value of 1.5 mm predicted by continuous wave simulation.

Considering that the minimum defect size for aerospace industry is 6x6 mm and that typical inspection step is 2 mm, the increase of 1 mm in defect size will not be noticed in practice because it is below the measurement grid resolution. In any case, if focusing is used, active aperture size could be slightly increased to compensate this lateral resolution loss, ensuring the same detection capabilities than with the phased-array inspection.
4. Experimental results

As a proof of concept, the whole algorithm was software implemented in Matlab, working in real-time with a full parallel 128 channel ultrasound system. A 5 MHz array with 128 elements and 1mm pitch was used to acquire images of a 12 mm thick CFRP with planar surface and several artificial defects. A mechanical device was added to change the angle between the part and the probe to emulate misalignment errors. Figure 7 shows the user interface that allows setting the acquisition and processing parameters.

Figure 8 shows the image obtained with conventional phased-array technique when the probe and part surface are tilted 0º (ideal case), 2º and 4º. As expected, amplitude of the surface echo is significantly reduced even for a low tilt angle, which could easily break in the inspection if the echo-start gate loses its reference. Furthermore, because of large refraction index between water and CFRP, normal incidence is lost into the material, which significantly reduces echo amplitude from delaminations and back-wall.
Figure 8 - Effects of slight probe-part misalignment on the image: 0º, 2º and 4º from left to right. Defect detection degradation is evident.

With Fast Scanning, each image is used to find the steering angle for 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 into the focusing circuits.

Figure 9 shows the effect of this steering and focal law correction algorithm. 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 Figure 8-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.

Figure 9 – Comparison between the original image at 0º (left) and that with the probe tilted 4º and automatic steering correction (right).

5. Conclusions

Main conclusion of this work is that it is possible to inspect planar CFRP components at speeds above 1 m/s without significant losses in resolution and contrast when compared with conventional phased-array linear scan. Developed algorithm, named Fast Scanning, can be implemented in the current hardware platform to obtain more than 2500 images per second, achieving a scanning speed of 5 m/s in a typical configuration of 6 active elements with 2 mm resolution. Furthermore, a full automated tilt angle correction algorithm was developed to minimize the adverse effects of misalignment between the probe and the component surface. Because it can be implemented in the acquisition hardware, it does not degrade inspection speed and it is independent of the evaluation computer.
Algorithms were software implemented and validated by experimental trials with a CFRP planar component with artificial defects. Results were satisfactory and encourage continuing with the hardware implementation process of the technique.

6. Acknowledge

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References

4. J. Camacho, C. Fritsch, J.F. Cruza, 'Documentación de Algoritmos de procesado de señal para la inspección de componentes con curvatura y requisitos HW para su aplicación en tiempo real', Target Project deliverable, June 2013.