Adaptive technologies in ultrasound testing

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Abstract
The industry is continuously increasing the complexity of material geometries as a natural outcome of innovation. This trend has been accompanied by the development of adaptive inspection technologies that can overcome the inspection of irregular shapes. Latest advances in electronic and software technologies have introduced a new paradigm in the Ultrasound Testing (UT) method, going from a beamforming approach by mechanical and electronic means (conventional UT and Phased-Array UT, respectively) to the generation of high-resolution ultrasonic images in real-time by the so-called Full Matrix Capture (FMC) process and its derived methods. This article focuses on the fundamentals of one of them, called Adaptive Total Focusing Method (ATFM), used to solve the “last mile” in terms of ultrasonic coupling and image quality in front of uncontrolled and complex surface variations.

Introduction
Ultrasound testing (UT) is a noninvasive, accurate, and efficient method for inspection of materials in a variety of industries, including aerospace, automotive, nuclear, and petrochemical. It involves the use of high-frequency sound waves to detect defects or changes in density, structure, or geometry, taking advantage of different wave propagation phenomena as reflection, absorption, dispersion, or diffraction.

Typically, ultrasonic waves are created and detected by means of piezoelectric probes which convert electrical signals into mechanical waves and vice versa. Effective coupling between the probe and the material under test is essential for accurate results, so that the transmission and reception of ultrasonic waves across its exposed surface be facilitated.

Unfortunately, the same ability of the UT method to detect small changes within the material volume (e.g., cracks or porosity), can become a coupling issue in those surfaces with a complex and/or unknown geometry, or when the surface location is unknown or inaccurate respecting the probe position, provoking undesirable and unpredictable reflections and attenuations of the ultrasonic waves.

Overall, the industry is continuously increasing the complexity of material geometries as a natural outcome of innovation. For instance, note the last advances in manufacturing technologies (e.g., 3D printing) that allow for the creation of complex geometries and materials, previously difficult or impossible to produce.

This trend has been accompanied by the development of adaptive inspection technologies that can overcome the challenges associated with complex geometries, such as variable thickness,
curvature, or irregular shape. By adjusting the inspection parameters in real-time, adaptive UT can provide more accurate and reliable inspection results, while also reducing the need for reinspection and easing the analysis of results.

A typical application for adaptive ultrasonic coupling is found in the aerospace production of carbon fiber reinforced polymers (CFRP) components, frequently designed with radial geometries which are prone to small dimensional deviations in the manufacturing phase (see Figure 1), normally not relevant for their structural mission, but very significant in the ultrasonic coupling, provoking uncontrolled attenuations that could be confused with false porosity indications or even make the own UT inspection unfeasible.

**Figure 1. Typical radius deviations found in CFRP aerospace components.**

Various methods for UT adaptive coupling can be found in the industry, primarily:

1) Flexible probes.
2) Profile following by robotic means.
3) Adaptive Phased Array UT (APAUT).
4) Adaptive Total Focusing Method (ATFM) and related technologies.

This blog post focuses on the ATFM approach and its comparison to APAUT.

**PAUT technologies**

Phased Array Ultrasound Testing (PAUT) uses multiple small transducer elements arranged in an array to generate and receive ultrasonic waves. These elements are electronically controlled to create ultrasonic beams with different directions and focalizations.

The set of electronic delays that are applied to the different elements, both in emission and reception, is called focal law, and the set of focal laws processed, either sequentially or in parallel, is known as electronic scan (in contraposition to the so-called mechanical scan).

The most common electronic scans generated with PAUT instrumentation are:

- **Linear scan**: a fixed focal law is shifted across the elements of an array probe, emulating the linear movement of a conventional probe, and covering in this way a larger area with a single probe and without mechanical action.
- **Sectorial scan**: using fixed elements of an array probe, different focal laws are processed to generate beams focused on different angles, emulating the tilt of a conventional probe, and covering in this way a wider range of angles with a single probe and without mechanical action.
Adaptive PAUT technologies
Adaptive PhasedArray UT (APAUT) is an evolution of PAUT, leveraging the own array probe to learn the surface profile of the material while it is being inspected. APAUT is generally combined with linear scans and involves the emission and reception of dedicated ultrasonic waves aimed to determine the surface profile, dynamically interlaced within the own sequence of focal laws. In this way, variations in the surface-probe alignment can be detected in real time and used to steer the beams, in such a way that they become normal to the material surface, optimizing ultrasonic coupling (see Figure 2).

**Figure 2. Beam steering in APAUT to approach a normal direction to the surface of the material under test. Focalization area is highlighted in yellow.**

In comparison to PAUT, APAUT limits the maximum speed to some extent due to the time needed by the “learning” ultrasonic waves to travel to the surface and return to the probe. Actually, this learning process is usually iterated from 2 to 5 times to converge and result in a stable and accurate steering of the beams, mainly due to acoustic edge effects and the nonevident task of determining the surface profile for standard PAUT instrumentation.

TFM technologies
Total Focusing Method (TFM) is an advanced ultrasonic inspection technique that uses array probes to create high-resolution images of the internal volume of materials. TFM is based in the Full Matrix Capture (FMC) process, which consists in collecting the digitized signals from all probe elements, while they are triggered in a specific sequence (e.g., element by element).

The full set of FMC data is further processed mathematically to generate a high-resolution image of the material’s volume with the best possible focalization in all its extension, as compared to traditional ultrasonic inspection techniques (UT or PAUT), where the focusing area is optimized in limited areas.
Indeed, FMC/TFM methods have introduced a new paradigm in the UT method. Whereas traditional technologies deal with the control of ultrasonic beams by mechanical (UT) or electronic (PAUT) means, FMC/TFM technologies pursue the generation of the best possible ultrasonic images by processing as many data as possible in the smartest and fastest possible way.

The modern FMC/TFM instrumentation has benefitted from the exponential evolution of Graphical Processing Units (GPUs), high-speed data links (e.g., 10 Gigabit Ethernet), and parallel computing software technologies, that has opened a new and broad space in UT imaging. FMC/TFM instrumentation are also built on top of diverse analog and digital electronic technologies as Field Programmable Gate Arrays (FPGAs) that have made possible the development of cost-effective and compact PAUT instrumentation, many of them driven by the medical and consumer electronics sectors (see Figure 3).

![Graph showing the evolution of UT instrumentation](image)

**Figure 3.** Incremental evolution of UT instrumentation, built on top of different technological leaps (e.g., analog and digital electronics as FPGAs, GPUs, high-speed data links, and imaging software technologies).

Different variations of TFM can be obtained depending on the emission pattern of the array elements and the imaging algorithm used. For instance, in Plane Wave Imaging (PWI) all elements are emitted jointly to generate plane waves, as compared to the element-by-element emission in standard TFM (see Figure 4).
Figure 4. Comparison of different UT techniques. Aluminum block with artificial notches created at different angles (left, bottom), and the corresponding B-scan images at the right.

PWI can provide image qualities comparable to those of TFM, and higher inspection speeds than TFM or even PAUT, as the number of ultrasonic waves emitted can be drastically reduced (typically from 1 to 10 plane waves in PWI versus 32 to 128 spherical/cylindrical waves in TFM, or 10 to 100 beams in PAUT). However, in some cases, PWI could worsen near-surface resolution because of the excessive energy of plane waves, as compared to cylindrical/spherical waves in TFM.

TFM/PWI imaging and its derived methods as Phase-Coherence Imaging (PCI) are being increasingly adopted by a variety of industries for its improved resolution and ease of data analysis over PAUT.

**Adaptive TFM technologies**

Adaptive TFM (ATFM) is an advanced version of TFM, introducing the measurement of the surface profile (obtained from the own FMC dataset) into the image computation.

As FMC/TFM is based on quasi-omnidirectional waves (spherical or cylindrical, for square or rectangular array elements, respectively), ATFM is especially indicated in those applications where large variations in the surface geometry are expected (see Figure 5).
Figure 5. Omnidirectionality of spherical/cylindrical waves in ATFM favors the learning of complex surfaces. The yellow dotted pattern represents the optimized area for focalization.

One of the main advantages of ATFM over APAUT is how the images are processed. In APAUT, the obtained images (B-scans) show a flattened surface profile because the beam steering process ends up emulating a probe parallel to the surface. Hence, the surface profile becomes flattened in the resulting B-scan. In contrast, ATFM provides a real view of the material surface and volume (as it is measured), so any unexpected and/or unacceptable anomaly in the material surface would show up in the B-scan image and could be further analyzed (see Figure 6).

Figure 6. Demonstration of how ATFM preserves the surface profile and provides high-resolution images. A standard TFM image (right) is shown for reference.

In contrast to APAUT, the ATFM method makes unnecessary the need for additional ultrasonic waves to learn the surface profile, so the inspection speed is not physically reduced as compared to standard TFM. Nevertheless, adaptive algorithms demand higher computational efforts, so they could limit to some extent the inspection speed depending on the performance of the GPU employed.
Adaptive imaging can be done either in real time, offline (if FMC dataset is stored), or both, and can be applied to the different variations and combinations of TFM, including PCI and PWI (see Figure 7).

Figure 7. Application of Adaptive PWI (APWI) to the detection of inclusions from the top side of a complex geometry weld, using a flexible wedge for absorbing the surface irregularities.

Finally, it is worth mentioning that correction of probe-to-surface misalignments in manual, semiautomatic, and automatic inspections (profile-following) is one the main application fields for ATFM, solving the “last mile” in terms of ultrasonic coupling, even for flat components (see Figure 8).
Conclusions
Diverse adaptive UT techniques have evolved as a reaction to overcome the growing production of complex-geometry materials.

Thanks to numerous advances in electronic and software technologies, ATFM has been proved as an efficient method for generating high-resolution real-time images of complex-geometry components and correcting probe-to-surface misalignments, preserving the measured surface profile, and with no physical overhead in the acquisition process. Equivalent adaptive methods can be derived from other versions of TFM, including PWI and PCI.

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