Weld Defect Imaging and Characterization Using PAUT and TFM Ultrasonic NDT

Fast and reliable, PAUT technique has dramatically improved the probability of detection of defects inside a weld and became over the years a code compliant replacement solution to the radiographic testing. Nowadays, FMC-TFM technologies can improve even further defects characterisation when used in conjunction with code compliant PAUT solutions.

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Ultrasonic Testing (UT) methodology has been used as a proven non-destructive technology to assess the volumetric integrity of welded material for decades. UT technology has evolved since and new developments like the Phased Array ultrasonic testing (PAUT) technology offers many advantages compared to the conventional UT technique:

- large coverage
- high resolution
- good sensitivity
- fast processing
- repeatable and reliable
- traceable data (encoding)

Those advantages dramatically improved the probability of detection (POD) of defects in welds, making the PAUT a very efficient and applicable solution that has been approved by standards to replace the classic radiographic testing (RT) methodology. While it took time to catch up in the field, the PAUT solutions are now widely considered as the go-to technique for advanced inspections. It is widely accepted by quality managers working in a manufacturing environment and by integrity engineers that want to maintain production workflow and extend equipment useful life within a safe environment.

With increased computing power and better capability to manage large data set of new generation ultrasonic equipment, advanced ultrasonic technologies like the Full Matrix Capture (FMC) and Total Focusing Method (TFM) are now available. Even if standards do not yet recognise these techniques for weld inspection, they can be a big help in certain conditions to improve defects characterisation when used in conjunction with approved methods, like the PAUT one.

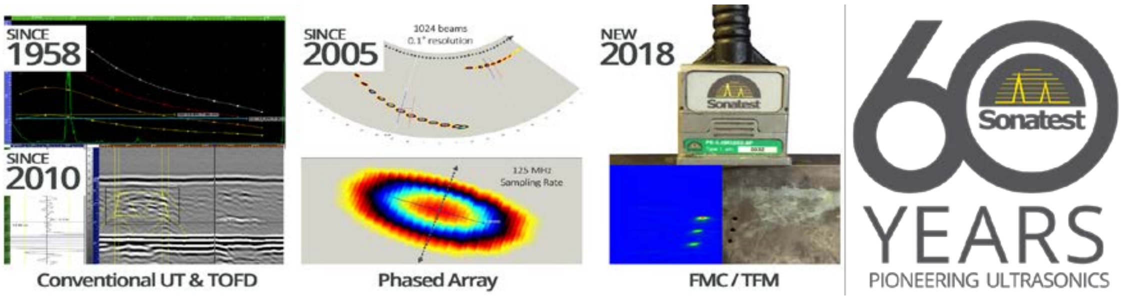


Figure 1: Ultrasonic NDT Technologies

1 Basic Principles

PAUT technique has been a major step ahead of conventional UT technique because of improved scanning coverage (PA steering), resolution (PA focusing), defect characterisation, probability of detection and overall inspection procedure efficiency with traceability. For two years, the TFM imaging technique is a buzz as it can definitely help in some applications and POD. However, from the energy and physics of ultrasonic NDT point of view: if a defect is not detectable using an optimised conventional UT solution, it is unlikely that PAUT or the TFM technology will make a major difference.

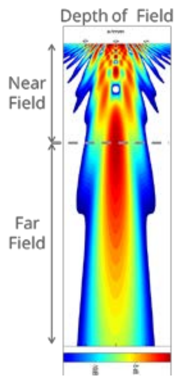


Figure 2: Depth of field

1.1 Phased Array

Phased array ultrasonic is based on real A-scans; the amplitude along the propagating beam is predictable according to the laws of physics. The ray tracing area is simple but usually part of a mandatory inspection plan. The UT data recorded will remain the same unless the inspector changes the gain or some other filtering effects. Once a beam inside a phased array scan is generated, this A-scan is defined by the same properties (aperture, frequency, and focal distance) as conventional UT. The criteria of calibration and rejection of this technique are more or less an adaptation of the conventional UT. It is now widespread across the NDT world as the go-to ultrasound technique for advanced inspections.

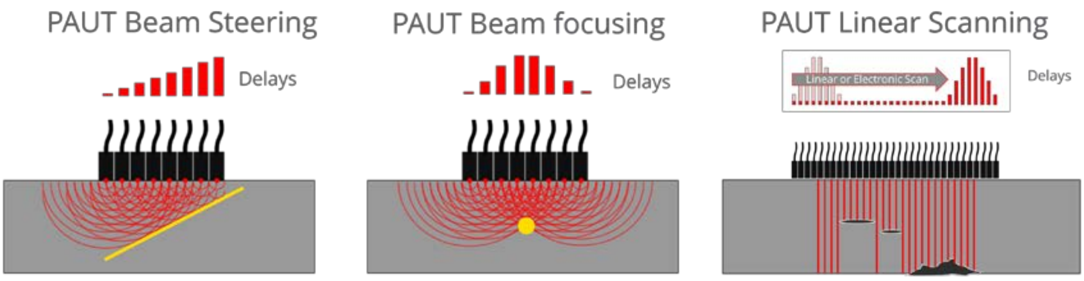


Figure 3: Phased-Array technology

Beam steering is the ability to control the angle at which beams are fired. Using delays, the phased array probe generates a front wave toward the desired angle.

Beam focusing uses the delays between phased array elements to focus energy into a specific point into space. Focusing can be used conjointly with beam steering for weld inspection.

Beam linear scanning uses a virtual aperture of the probe and then it shifts over a series of typically 32 or 64 elements. The result is a high-resolution scan covering a large area.

1.2 FMC / TFM

As explained by the British Institute of Non-Destructive Testing (BINDT), the Full Matrix Capture (FMC) is a technique for capturing all possible ultrasonic data from a phased array probe and the Total Focusing Method (TFM) is a technique using the data from this FMC to produce an image which is focused at every specified point in the image.

The **FMC** is an acquisition technique where every element of a phased array probe is individually pulsed to generate sound that is received on every element including the transmitter. All the A-scan are collected from every combination of transmitting and receiving elements across a specified range, generating relatively large data files that can be recorded or not.

The **TFM** is an imaging technique applied to the FMC dataset. This imaging algorithm, done after the data acquisition or in post-processing, uses the A-scan data from all elements to make a virtual focusing on every point. Ultimately, it creates a set of pixel values computed by the algorithms and aligned on a grid.

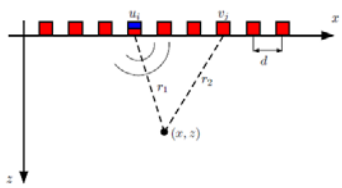


Figure 4: FMC representation of the A-scan acquisition

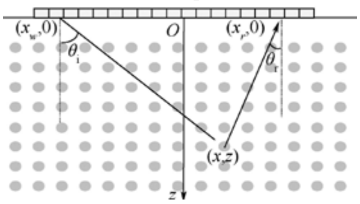


Figure 5: TFM post-processing image representation

What is a TFM image? The result of a TFM image is not necessarily predictable according to the conventional ultrasonic physics. By itself, it does not have the signal information once generated. However, different image outputs could be extracted from the FMC depending on the chosen analysis mode: longitudinal to longitudinal waves (L-L), longitudinal to transversal waves (L-T), longitudinal to transversal to transversal waves (L-T-T) or simply a suite of transversal waves (T-T and T-T-T). The amplitude and delay of the A-scans are summed, on an X-Y coordinate (with a given resolution), and the colour signature indicates a “presence” regardless of its direction or amplitude. Also, the extracted image would be focused on every point, and because of that, the sizing accuracy should be better for a large volume compared to a single PAUT focused beam. While calibration and rejection criteria are not yet defined by standards for these techniques, being able to stock all the FMC A-scans during the acquisition should allow the TFM image to be analysed on different modes. For example, one of the main advantages of stocking this raw FMC information is that a TFM image can be altered afterwards using different processing tools while the FMC information remains unchanged.

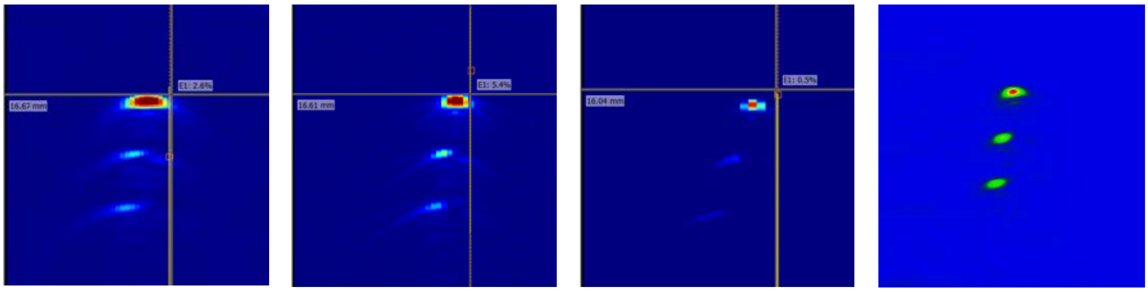
2 Phased Array UT & TFM parameters comparison

For this section, the phased array linear scan data has been recorded at the same time as the FMC data using the multiscan function of the Sonatest Veo+ instrument. All the phased array linear and TFM imaging data analysis have been performed using Sonatest UTstudio+ software (TFM images are computed over 32x32 and 64x64 FMC apertures).

Figure 6: Sonatest FMC/TFM, Phased-Array, TOFD and conventional UT solutions

2.1 Sizing Capabilities

Because of the total focusing advantage, the TFM shows an advantage that can be used to help size critical indications. The AWS resolution block has been selected for the next demonstration because it has three Side Drilled Holes (SDH) close to one another. The diameter of the SDH is 1.5 mm, and the distance between each of them is 4 mm. Figure 4 compares the linear scan phased array and TFM techniques from the same probe position and SDHs:

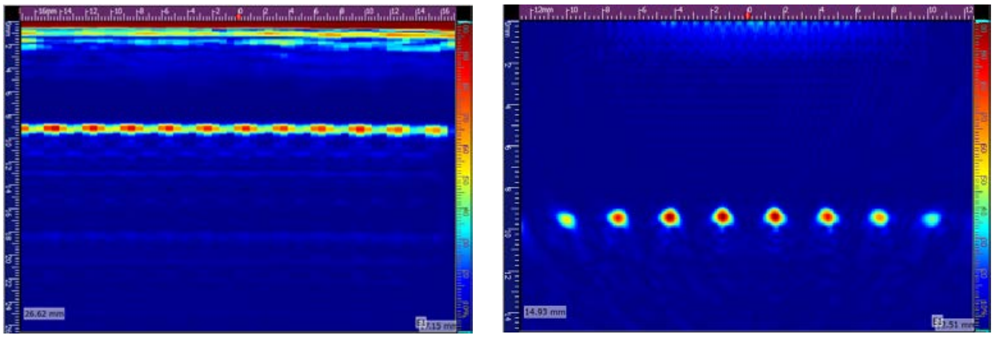


8E. L-scan 16E. L-scan 32E. L-scan TFM image

Figure 4: AWS resolution block with three SDH vertically aligned

For the linear scan, the focal distance was set on the first SDH, and the results show the presence of the three SDHs but the first hole is getting smaller and the beam divergence after the focal point increases as the number of active elements increases. Indeed, the 32 elements aperture (0.8 mm pitch) configuration, hardly shows the last SDH because of that phenomenon but the SDHs can be detected via the other more common linear scanning configurations (16E and 8E). From those results, it is however observed that properties like the number of elements per focal law and the focusing depth, if not properly understood by the user, can affect sizing capabilities of the second and third SDHs. With the FMC acquisition and subsequent TFM imaging, one can successfully size all three SDHs with more precision, even if the amplitude is also lower on second and third SDHs (there is no TCG option in TFM imaging). It also shows that this technique is again less dependent on the scan or probe properties.

2.2 Probe Resolution Parameters



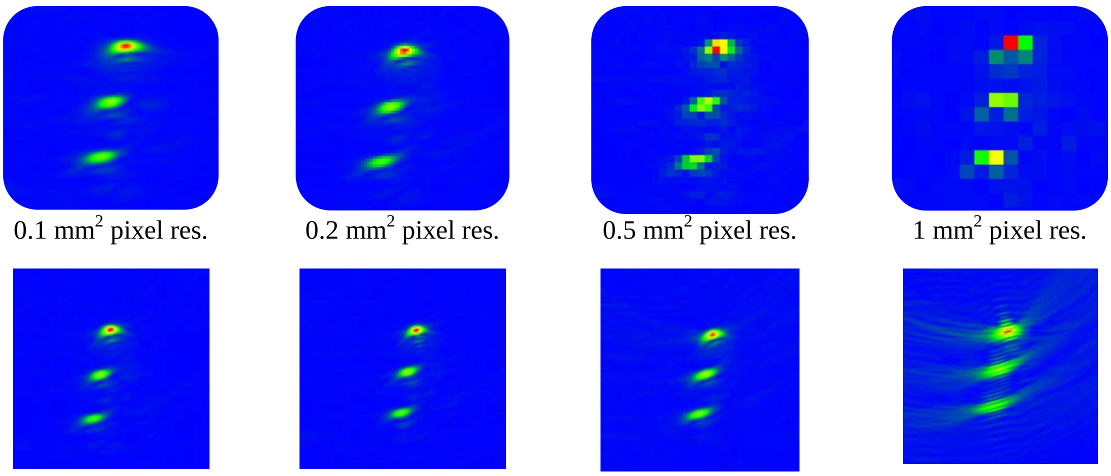
(a) Linear scan (b) TFM image

Figure 5: Lateral resolution

The spatial resolution in the probe axis (lateral resolution) can be considerably improved by recording the FMC and subsequently computing TFM images as well. Figure 5 presents the results of both techniques on a standard test block having diameter 1 mm SDHs with 3 mm between each of them. In Figure 5a, we can see that the linear scan will detect the presence of these SDHs properly, but will hardly distinguish the size of these individual SDHs because the amplitude drop between each SDH is less than 6 dB (A-scan amplitude is comprised between 50% and 80% FSH in the holes region). In the case of the FMC acquisition and TFM imaging, the algorithm triangulates the position of all beams which has the effect of improving the lateral resolution limitation from the physical size of the probe elements to the wavelength of the ultrasound beam. We can see in Figure 5b that the TFM image can size the SDHs properly, with a clear amplitude drop between each of them. The focusing ability of this imaging technique proves again that when required, it can become a real improvement to a standard linear scanning solution where resolution is critical.

2.3 Signal Processing Resolution Parameters

The resolution chosen in the TFM algorithm is a critical parameter which can create errors on the output images. Starting from a matrix that has 1024 A-scans (32x32 FMC); you can extract an image of 256 by 256 pixels. Using a resolution of 0.1 mm^2 represents a region of 25 x 25 mm. increasing to a 4096 A-scans matrix (64x64 FMC) will simply increase the region of interest, not the resolution. On the other hand, decreasing the pixel resolution does not change the centre position, but the software gain needs to be increased to achieve the same result. We can see in Figure 6 that both detection and sizing are not affected if the resolution is increased from 0.1 mm^2 to 0.2 mm^2. The wavelength in this setup being 1.2 mm, a 0.3mm^2 resolution could be used without affecting the amplitude too much, as predicted by the Nyquist theorem. However, as presented in Figure 6, going over that threshold of 0.3mm^2 resolution affects the TFM sizing capabilities. Having access to such resolution software tools is important for precise TFM image analysis.



0.1 mm^2 pixel res. 0.2 mm^2 pixel res. 0.5 mm^2 pixel res. 1 mm^2 pixel res.

1:1 sub-samp. 1:2 sub-samp. 1:8 sub-samp. 1:16 sub-samp.

Figure 6: Pixel resolution and sub-sampling the A-scan comparison

A similar comparison can be made by removing samples directly from the raw A-scans. In the next example, the size of a frame could be cut in half to save memory space, without affecting the result. We can see in Figure 6 that the amplitude is not so different from the first subsampling 1:1 compared to the 1:2 but the image is considerably altered for the 1:16 subsampling.

3 Practical comparison – PAUT and TFM and crack orientation

We can now compare a fairly optimised linear scan to an FMC scan on a real defect. Both techniques use an encoder with a 1mm step resolution to record the data sets. In Figures 7, the PAUT linear scan uses an 8 element aperture, and TFM images are computed in L-L mode algorithm. While the PAUT method is used to scan 100% of the T-Joint, the FMC scan (and computed TFM images) is used not to detect the defects, but to help characterise the defect that was caught by the PAUT method.

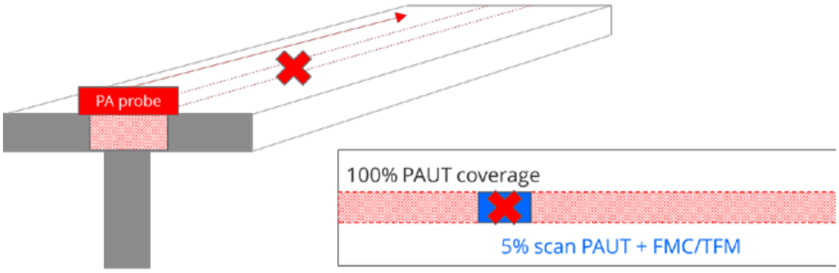
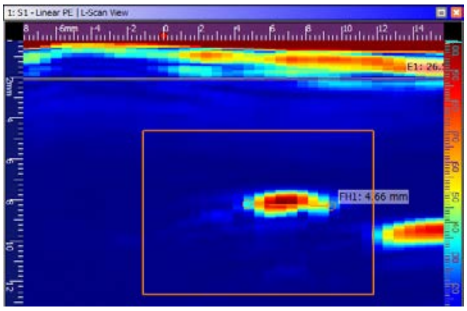
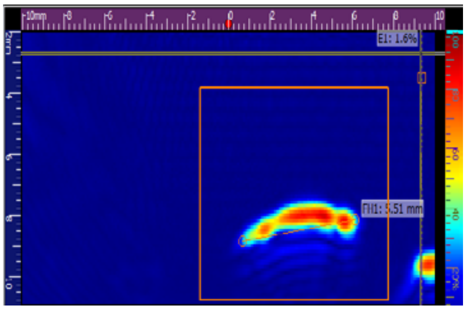


Figure 7: Representation of a T weld acquisition using FMC/PA solutions

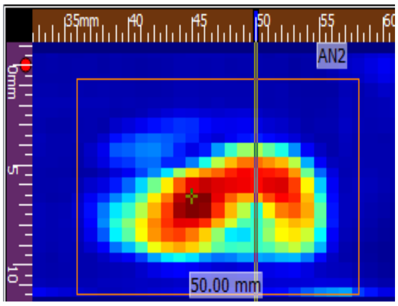
As expected, both techniques detect the crack and can fairly characterise it. However, the convex shape of the defect is not showing up in the linear scan view and, consequently, seems to appear smaller in Figure 8 (a) and (b). In Figure 8 (c) and (d), the left portion of the crack is better represented as the crack orientation respond at different angles which are caught by the TFM algorithm. The analysis through time is a critical action where the growth rate is a major threshold parameter for repair. The absolute measurements, such as flaw length, are almost the same since the passive aperture is identical but the projected top view does not render the same dynamic profile. The defect zone measurement at the -6 dB amplitude is 33 mm^2 for the TFM and 37 mm^2 for the linear scan. The information regarding the crack orientation is useful information that can be leveraged from the TFM image in this case.



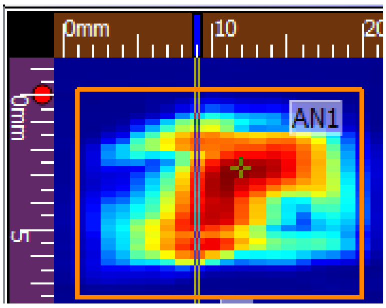
(a) Linear scan - 4.66 mm long



(c) TFM L-L image - 5.51 mm long



(b) Linear scan – encoded top view



(d) TFM L-L image – encoded top view

Figure 8: Linear scan (8 Element) and TFM L-L imaging comparison

4 Practical results – PAUT and TFM porosity and crack sizing

In this second practical comparison, we compare a fairly optimised sectorial scan to an FMC scan to characterise a porosity and a crown crack made in a flat plate welded sample. Both techniques use an encoder with a 1mm step resolution to record the data sets. In Figure 9, the PAUT sectorial scan using a 55º shear wave wedge and a phased array sectorial scan of 32 elements apertures. Simultaneously, the instrument was recording a 64x64 FMC data set. Figure 10 presents resulting sectorial scan and high-resolution 0.1mm² TFM images. While the PAUT method is used to scan 100% of the weld, the FMC scan (and computed TFM images) is used not to detect the defects, but to help characterise the defects that were caught by the PAUT method.

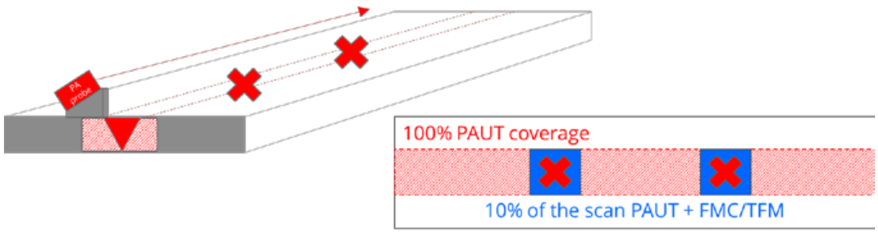
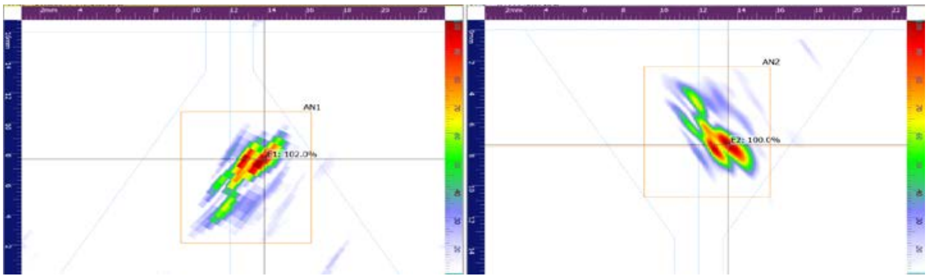


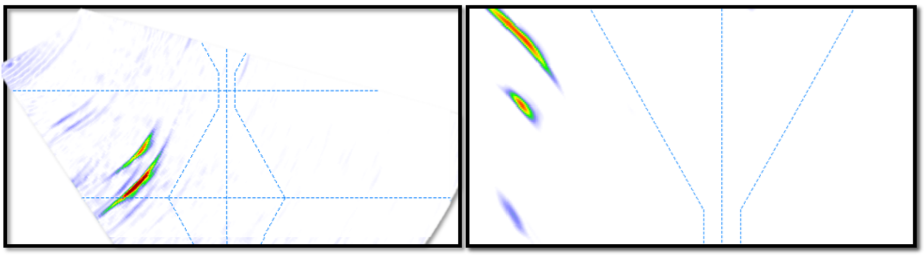
Figure 9: Representation of a butt weld acquisition using FMC/PA solutions

Again, it can be seen that the sectorial scan caught both defects accurately as per the depth and sizing because scan has been done using high energy and precise 32 element aperture focused in the defect area. The TMF imaging technique shows only minor improvements in the sizing capability over the PAUT in this case; however, it offers better imaging and resolution.



(a) Sectorial scan
Porosity depth at 4.13mm and 20.3mm²

(b) TFM TTTT image
Porosity depth at 4.17mm and 20.1mm²



(c) Sectorial scan
Crown Crack depth at 10mm

(d) TFM TTTT image
Crown Crack depth at 8mm

Figure 10: Sectorial scan (32 Element) and TFM imaging comparisons

It is interesting to explain that multiple trials with different TFM algorithms have been tested before generating these images. Ten propagation modes have been tested using the raw FMC data set in the Sonatest UTstudio+ analysis software, and the TTTT showed the best results. For weld inspection, when using transversal waves, mode conversion is an important factor to consider. Because of the different defect orientation and geometry characteristics, some TFM algorithms (modes) are more suitable than others.

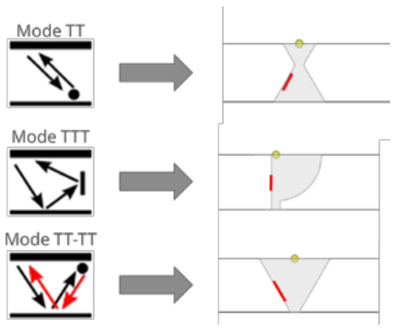


Figure 11 Suggested mode algorithms for specific flaws orientation

5 Conclusion

Fast, reliable and with higher resolution; PAUT technique offers many advantages compared to conventional, is a very powerful NDT solution to detect and size defects in many different weld applications and is now widely accepted in codes and standards. The results shown in this article show that the TFM imaging technique can sometime bring valuable sizing benefits to complement or assist PAUT inspection technique. For example, better geometry details can help to understand the potential behaviour of the defect.

Being an efficient and code compliant NDT inspection technique, the use of PAUT solution should continue to be used as a primary technique for detection and defect sizing. Using FMC recording and TFM imaging over critical defective zones represents a value-added solution that can be used to improve the reporting accuracy. As explained in this article, a recommended approach is to scan with confidence using PAUT technique (1) and then if the user detects the presence of a defect in a critical zone and he thinks TFM imaging could bring some value; then, he can perform an FMC scan (2) and generate TFM images (3) to make the call with confidence.

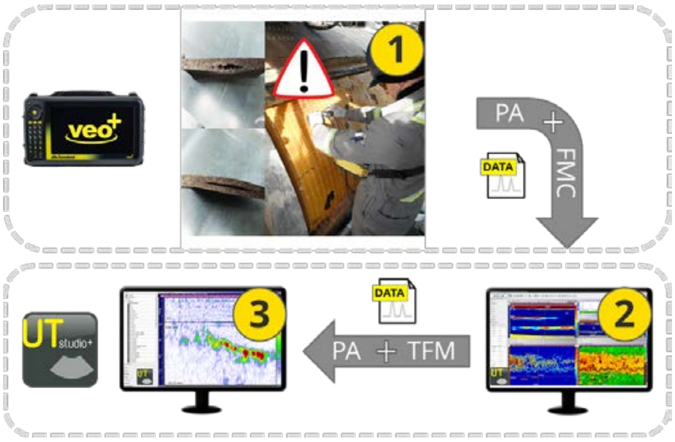


Figure 12: Sonatest veo+ workflow solution