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Novel imaging techniques for defects characterisation in Phased Array inspection

Nowe techniki obrazowania dla charakteryzacji wad w badaniach Phased Array

ABSTRACT

Phased Array ultrasonic testing has demonstrated over the years that it has many advantages compared to conventional techniques: fast, reliable, with higher resolution and sensitivity. While it took time to catch up in the field, it is now widely considered as the go-to technique for complex inspections. At the same time, technology has continued to evolve, thus increasing the possibilities of ultrasonic NDT techniques. Due to increased computing power and better capability to manage large data sets of the new generation ultrasonic equipment, advanced imaging techniques like TFM are now available. Unfortunately, these techniques are not yet recognized by standards and can't be used alone during the critical inspection. On the other hand, they can be a big help in improving defects characterisation when used in conjunction with standards-approved methods. In this paper, we will demonstrate that the combination of Phased Array inspection with advanced imaging techniques, can enhance the defects characterisation process for common applications of ultrasonic testing.

Keywords: *ultrasound testing (UT); phased array (PA); sizing; full matrix capture (FMC); Total Focusing Method (TFM)*

STRESZCZENIE

Badania ultradźwiękowe Phased Array wykazały się przez lata wieloma zaletami w porównaniu do konwencjonalnych technik w tym: szybkością, niezawodnością, wyższą rozdzielczością i czułością. O ile zajęło to trochę czasu, aby stała się metodą adekwatną do badań prowadzonych w terenie, obecnie jest powszechnie uważana za technikę kompleksowych inspekcji. W tym samym czasie technologia ta nadal była rozwijana, skutkując zwiększeniem możliwości ultradźwiękowych technik NDT. Zwiększona moc obliczeniowa i lepsze możliwości zarządzania dużymi zbiorami danych uzyskanymi za pomocą urządzeń ultradźwiękowych nowej generacji wpłynęły na udostępnienie zaawansowanych technik obrazowania, takich jak TFM. Niestety, techniki te nie są jeszcze rozpoznawane przez normy i nie mogą być używane samodzielnie podczas krytycznych inspekcji. Z drugiej strony mogą być bardzo pomocne w poprawie charakterystyki wskazań w połączeniu z metodami zatwierdzonymi przez normy. W tym artykule pokażemy, że połączenie kontroli Phased Array z zaawansowanymi technikami obrazowania może poprawić charakterystykę wskazań dla typowych zastosowań badań ultradźwiękowych.

Słowa kluczowe: *badanie ultradźwiękowe (UT); phased array (PA); wymiarowanie; pełne przechwytywanie macierzy (FMC); metoda pełnego ogniskowania (TFM)*

1. Introduction

While the phased array ultrasonic equipment has not changed a lot in the past few years, the software advances on signal processing have had breakthroughs. One of the last improvements in the NDT world is the full matrix capture (FMC) and total focusing method (TFM). A new generation of portable devices equipped with these features has followed the industrial systems.

The FMC is the ultrasonic acquisition of the area and the TFM applies an algorithm on this acquisition to create an image, where each pixel is a sum of the resulting delays at every coordinate. With this technique, the ultrasonic emission only requires one element, but all elements contribute to the reception. This enhances the focusing capability and the extracted images can show different travel paths and velocities. These transmitted and received patterns are referred to as modes.

The NDT community is currently trying to standardise this new approach which has advantages and disadvantages compared to phased array.

This paper compares the two techniques and shows how they can become complementary to enhance inspection results where applicable.

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2. Basic Principles

2.1 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 complex inspections.

2.2 FMC / TFM

For the full matrix capture (FMC) technique, the raw A-scan data is collected by using a single element as transmitter and all elements as receivers [1]. The TFM imagery is based on coloured pixel representations of a specific area inside the part [2]. This image is based on huge matrices of ultrasonic A-scan obtained through the FMC acquisition process. The TFM result is an image that is not necessarily predictable according to conventional ultrasonic physics. By itself, it does not have the signal information once generated.

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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 in every point, and because of that, the sizing accuracy should be better compared to a single focusing point, while using the same phased array transducer. 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 analyzed 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.

The first section of the paper shows the results comparing a standard linear scan at a 0 degree longitudinal wave (L-wave) with an FMC where L-L TFM images are computed. The second section of the paper shows the results comparing a standard sectorial scan transversal wave (S-wave) with an FMC where T-T-T-T TFM images are computed.

3. Results – Phased Array Linear Scan & TFM

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 32 x 32 and 64 x 64 FMC apertures).

3.1 Instrument Sensitivity

To begin with, Figure 1 shows amplitude measurements of A-scans extracted from a linear pulse echo (PE) phased array setup (L-scan) and TFM images. The extracted A-scans from the phased array setup have been generated using active apertures of 1, 8, and 16 elements. Six reference holes have been used for the measurement. Diameters are ranging from 2.38 mm SDH at 80% FSH to 0.4 mm SDH. For every acquisition, the signal from the reflector was brought to 80% FSH. For the FMC acquisition, the TFM image is from an L-L mode algorithm, and the amplitude value was taken from the binary digital pixel value, which was converted into the full digital scale of the 16-bit ADC (analogue digital converter) of the equipment and then normalised to 80% FSH.

Figure 1 illustrates four necessary gains in dB: three PE phased array data sets (1, 8, and 16 active elements) and a TFM image, to bring the corresponding SDH to 80% FSH. As one could have expected, the TFM image requires higher gain to bring the defects to the desired amplitude. Figure 2 shows results over the 0.4 mm.

Generally speaking, for the phased array images, the more elements used for the acquisition, the less amplification is needed; as the laws of physics would predict. The principal advantage of using an aperture of many elements with phased array is the noise reduction; there is an average improvement of 24 dB using an aperture of 16 instead of 1 elements. This is mainly because the more elements are used, the more energy is transmitted into the part for one acquisition.

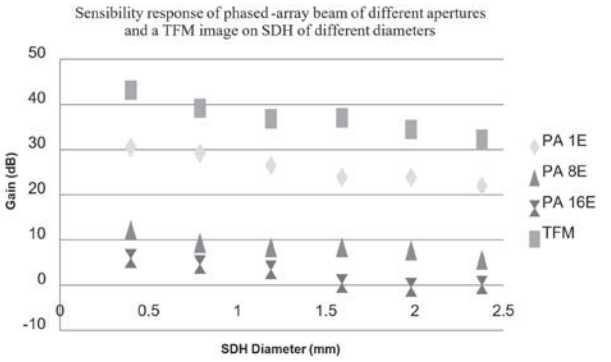


Fig. 1. Necessary gain on ASTM block to get SDH from 0.4 mm to 2.4 mm at 80% FSH.
Rys. 1. Konieczne wzmocnienie na wzorcu ASTM by uzyskać SDH od 0,4 mm do 2,4 mm przy 80% FSH.

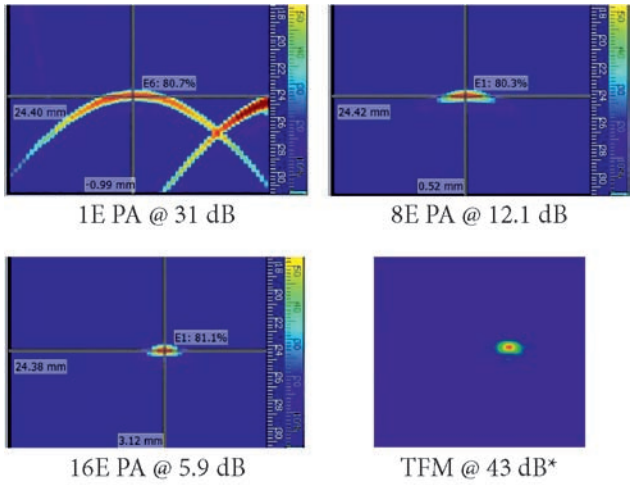


Fig. 2. Sensitivity of a 0.4mm SDH, according to the compared techniques. *Reference to the sampled image peak value then converted into FSH and dB.
Rys. 2. Czułość dla SDH 0,4 mm, zgodnie z porównanymi technikami. * Odniesienie do wartości szczytowej obrazu próbkowanego, następnie przekształcone w FSH i dB

For the TFM image on the right of Figure 2, the FMC acquisition was produced with the same gain as the 1 element phased array scan (31 dB) and an equivalent gain of 43 dB was found. The colour palette of the TFM image is set automatically using an equivalent palette as standard phased array. Interestingly, even if the equivalent gain used for the TFM image is higher (43 dB) compare to PA (31 dB), the signal-to-noise ratio of the TFM image is much better than the 1 element phased array scan. This signal-to-noise ratio enhancement can also be observed besides the SDH compared to other images (8E and 16E phased array) as seen in Figure 2. The total focusing effects of TFM enhance the signal and build the image by positive interference. Since the UT noise is everywhere and random, its contribution is destroyed by the algorithm and significantly reduced in the TFM images.

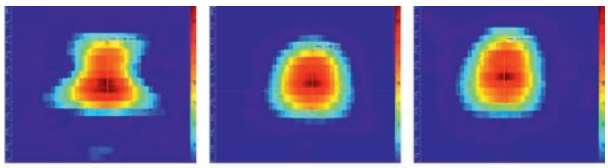


Fig. 3. Sensitivity of a 0.4mm SDH, according to the FMC gain sensitivity.
Rys. 3. Czułość dla SDH 0,4 mm w odniesieniu do czułości wzmocnienia FMC.

Another advantage, derived from the positive interference technique applied in the TFM solution, is that instrument gain applied during the FMC acquisition is far less critical for sizing a defect when compared to phased array. While computing the TFM images over a defective zone, the maximum will be automatically normalised to 100% FSH. Then the user can compensate using software gain with minimal impact on induced noise, regardless of the original instrument gain sensitivity setting. These low noise and high resolution TFM images are possible because the selected instrument, the Sonatest Veo+, records over 16-bit and has a very low noise chain of acquisition. On Figure 3, TFM images of the same SDH have been computed from FMC acquisitions done at three different gain levels to show this behaviour, i.e. that over a 60 dB gain span for FMC acquisition, the same 0.4 mm SDH can be characterised using the TFM algorithm.

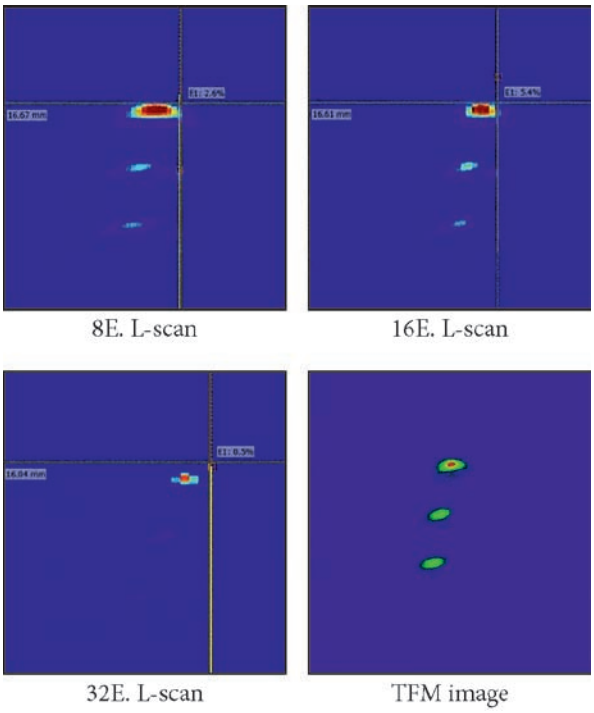


Fig. 4. AWS resolution block with three SDH vertically aligned.
Rys. 4. Wzorzec rozdzielczości AWS z trzema SDH ułożonymi w pionie.

3.2 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 SDHs 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:

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 dependant on the scan or probe properties.

3.3 Probe Resolution Parameters

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 results of both techniques on a standard test block having diameter 1 mm SDHs with 3 mm between each of them.

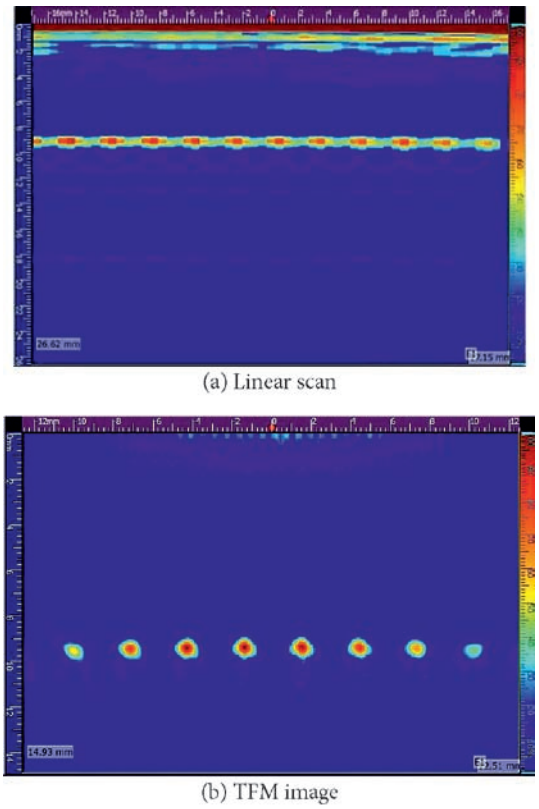


Fig. 5. Lateral resolution.
Rys. 5. Rozdzielczość boczna.

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.

3.4 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 (32 x 32 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 (64 x 64 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.

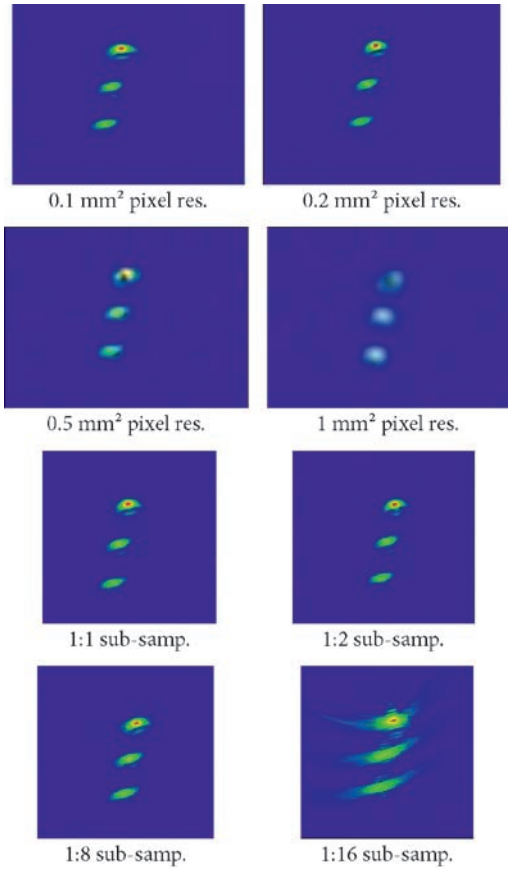
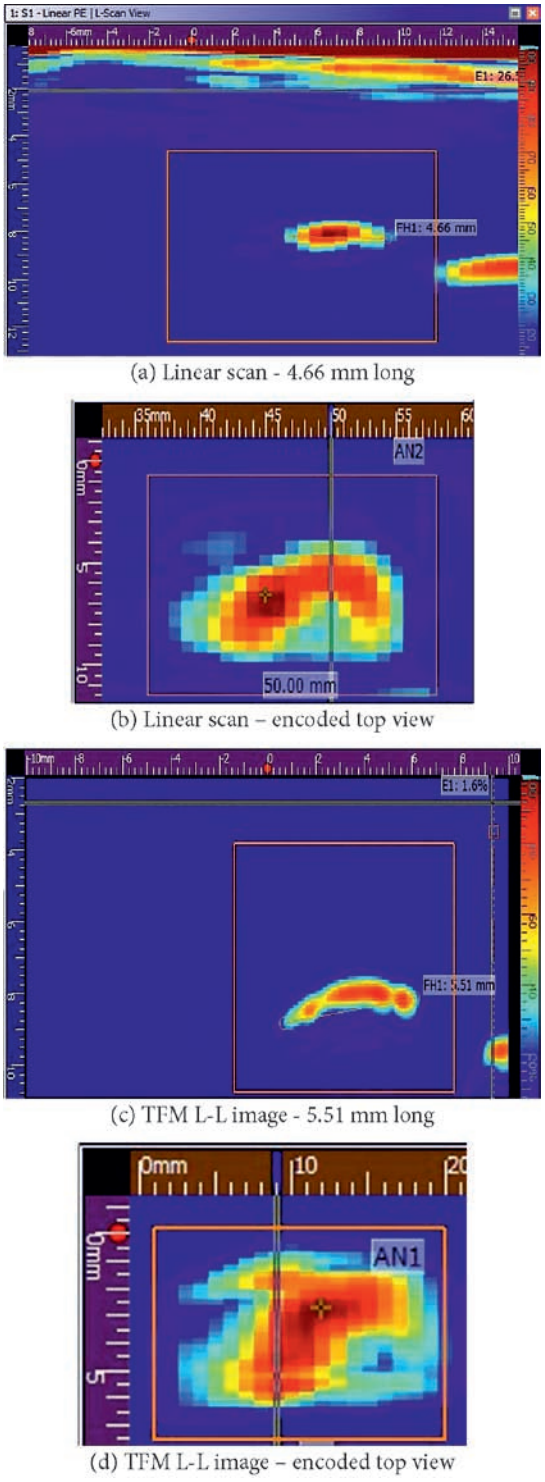


Fig. 6. Pixel resolution and sub-sampling the A-scan comparison.
Rys. 6. Porównanie wyników dla różnych rozdzielczości i dla różnych stopni pod-próbkowania sygnału czasowego typu A.

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 0.3 mm^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.



(a) Linear scan - 4.66 mm long
(b) Linear scan – encoded top view
(c) TFM L-L image - 5.51 mm long
(d) TFM L-L image – encoded top view

Fig. 7. Linear scan (8E) and TFM L-L imaging comparison.
Rys. 7. Porównanie obrazowania liniowego (8E) i TFM L-L.

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. In numbers here, using a subsampling of 1:2 for a 50.8mm range will reduce the sample density from 42 samples/mm to 21 samples/mm. It still respects the 5 to 1 ratio of the acquisition frequency to the probe frequency. This sampling rate has virtually no impact at this wavelength of 1.2 mm. The FMC frame size is smaller by 2 MB (4 to 2 MB). For a 300 mm long encoded scan, this represents 600 MB of memory instead of 1.2 GB, which is not negligible.

3.5 Encoded Real Crack Sizing Comparison

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 over a crack that is 100 mm long. In Figures 7, the linear scan uses an 8 elements aperture, and TFM images are computed in L-L mode algorithm. 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 7 (a) and (b). In Figure 7 (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.

4. Results – Phased Array Sectorial Scan & TFM

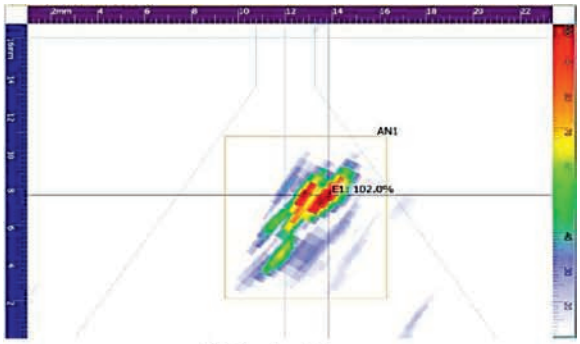
For this section, the phased array sectorial scan data has been recorded at the same time as the FMC data using the multiscan function of the Sonatest Veo+ instrument. All the phased array linear and TFM imaging data analysis have been performed using Sonatest UTstudio+ software (TFM images are computed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

Since conclusions of the sections 3.1 to 3.4 similarly apply to a sectorial scan comparison, the next section will focus on presenting the results of real weld defects characterisation.

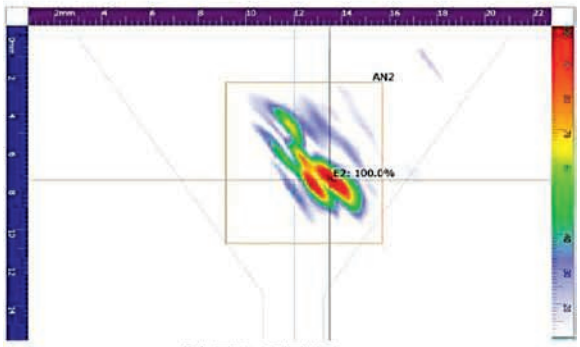
4.1 Real Weld Porosity and Crack Sizing Comparison

Two defects have been scanned using a 55° shear wave wedge and a phased array sectorial scan of 32 elements apertures. Simultaneously, the instrument was recording a 64 x 64 FMC data set. The Figure 8 presents resulting sectorial scan and high-resolution 0.1mm^2 TFM images.

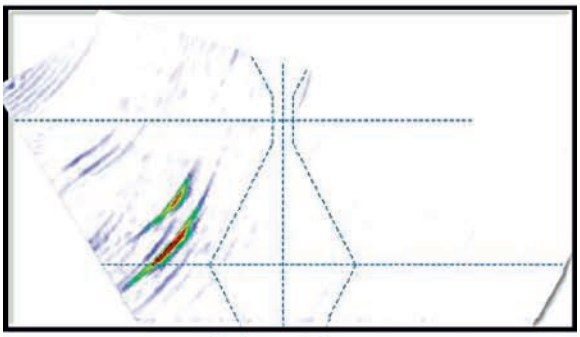
Again, it can be seen that the sectorial scan caught both defects accurately as per the depth and sizing because scan has been done using high energy and precise 32 element aperture focused in the defect area. However, as expected the TMF imaging technique shows some improvements in the sizing capability. TFM is especially good to show the shape of the defects. The signal-to-noise ratio is also a slightly better on the TFM images.



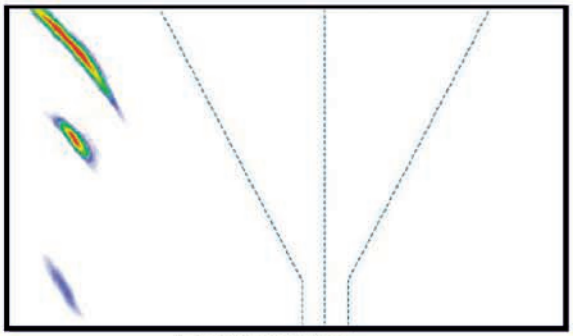
(a) Sectorial scan
Porosity depth at 4.13 mm and 20.3 mm^2



(b) TFM TTTT image
Porosity depth at 4.17 mm and 20.1 mm^2



(c) Sectorial scan
Crown Crack depth at 10 mm



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

Fig. 8. Sectorial scan (32E) and TFM imaging comparisons.
Rys. 8. Porównania obrazowania sektorowego (32E) i TFM.

It is interesting to explain that multiple trials with different TFM algorithms have been tested before generating these images. The LL, LT, TT, LLL, LLT, LTL, LTT, TTT, LLLL and TTTT modes have all 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, the TFM algorithms will generate different results. Longitudinal wave inspection mode is less dependant on this behaviour, and the TMF L-L algorithm is mainly used for this one. Because the instrument was simultaneously recording the full FMC raw data set during the recording, data is available for further analysis anytime. This approach is interesting not only for improving sizing capabilities but also to ensure traceability and monitoring defect propagation over time since a data can be re-open any time after the acquisition.

5. Conclusion

Fast, reliable and with higher resolution and sensitivity; ultrasonic phased array technique offers many advantages compared to conventional ones. Also, being now widely accepted in codes and standards phased array remains a very powerful ultrasonic NDT solution to detect and size defects in many different applications efficiently.

This paper has shown that the TFM imaging technique can bring valuable sizing benefits to complement or assist phased array inspection technique. For example, an improved signal-to-noise ratio can become important to discriminate small indications from the noise, and better geometry details can help understanding the potential behaviour of the defect. Sometime, to achieve similar results using phased array technique, apertures of 32 elements with a focus on the defective zone needs to be implemented. Such technique proved to work on many occasions, but it also puts more pressure on the technician to correctly set the acoustic parameters of his instrument. On the other hand, it has been demonstrated in this paper that recording FMC data presents an inferior risk of error than phased array; moreover, it opens the door to a multitude of TFM analysis options.

In conclusion, the approach proposed in this paper supports the methodology of using ultrasonic phased array technique for detection and sizing of defects as it remains today a very efficient and code compliant NDT inspection technique. Using FMC recording and TFM imaging as a detection and sizing technique would also be compliant, but would generate a large amount of data and this data management is still today a concern in the industry. Since the phased array technology proved to cover detection, sizing and traceability requirements, performing FMC/TFM technique only if required over critical defective zones represents a much more efficient solution. According to this approach, an NDT technician can scan with confidence using an approved phased array technique that generates manageable data sets all day long. Then, if he feels challenged by the presence of a defect in a critical zone of his job task, high resolution (down to 0.1 mm^2) TFM imaging and analysis tools are subject to help making that call with confidence. This being said, it has been observed in this paper that the TFM image resolution processing must respect a certain threshold in order to avoid potential sizing errors. Taking this observation into account, performing a TFM analysis over a set of raw FMC recorded data will ensure the inspection decision can be tracked back for future assessment, as it is required by the traceability concept.

Since the usage of this novel FMC/TFM approach gets more and more mainstream, standard procedures are being reviewed by different NDT committees to help NDT technicians work with this new technology. Finally, it is clear that the trend for innovative NDT ultrasonic manufacturer is to invest in this technology; this shall also contribute to making this technology more accessible to NDT professionals.

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