DEVELOPMENT AND VALIDATION OF A FULL MATRIX CAPTURE SOLUTION

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ABSTRACT
For the last 15 years, phased array has completely changed the face of ultrasonic non-destructive testing. This now-mature and widely adopted technology allows highly efficient inspections to be carried on critical components in aerospace, oil & gas, heavy industry and power generation plants.

The Full Matrix Capture (FMC) technique is an upcoming and promising application of the phased array technology. It consists of capturing and storing all possible time-domain signals (A-Scans) from every transmitter-receiver pair of elements in the array. After recording, all raw information is available to generate the data resulting for any given beam (aperture, refracted/skew angles, focusing position), through off-line processing.

This paper will address the challenges faced in order to achieve an efficient FMC data collection and will show the data processing capabilities that the technique has to offer. Results of a complete validation program will also be presented.

Moreover, various aspects of the hardware and software specification will be addressed, highlighting the potential benefit of enhanced performance on the FMC implementation.

INTRODUCTION
For long mostly used for medical and laboratory applications, the phased array (PA) UT technology has now been embraced by the non-destructive testing industry. Since the early 2000’s, its adoption has been a game-changer for ultrasonic inspections of critical components in aerospace, oil & gas, heavy industry and power generation plants.

A new advanced method for applying PA UT is also currently making the transition from laboratories to industrial applications: the Full Matrix Capture (FMC) technique.

This paper will give a detailed explanation of the principles supporting FMC. It will illustrate the benefits of the FMC technique over standard PA processing, and address the challenges faced in order to achieve an efficient FMC data collection. Results of a complete validation program, including thorough comparisons with standard PA processing, will also be presented.

Moreover, various aspects of the hardware and software specifications will be addressed, highlighting the potential benefit of enhanced performance on the FMC implementation.

STANDARD PHASED ARRAY PROCESS VS FULL MATRIX CAPTURE
In order to introduce the principles of the FMC technique, a short reminder of the standard PA principles is presented. The PA technology uses multiple independent UT transmitting-receiving channels. During the emission process, standard PA systems apply time delays to the individual elements of a PA probe in order to generate a physical ultrasonic beam with specific acoustic characteristics through constructive interference of the individual wavefronts. In reception, these standard systems also apply time delays to the signals received by the individual elements in order to put them in phase for the hardware summation process. The summed and digitized A-Scan signal is then transferred to the computer for display and recording (see Figure 1).
During the standard PA acquisition process, the raw elementary signals are processed at the hardware level and are therefore not available for off-line software processing. In opposition, the Full Matrix Capture (FMC) technique consists of capturing and recording all possible time-domain signals (A-Scans) from every transmitter-receiver pair of elements in the array [1], as shown on Figure 2.

The interest of FMC does not reside in the data acquisition process itself, but in the post-processing possibilities which are offered by the data acquired through FMC. Indeed, with the raw elementary signals stored on drive, it is possible to synthetically generate the data resulting from any given beam (aperture, refracted/skew angles, focusing position), through off-line processing.

Figure 3 illustrates the new possibilities offered by FMC data. A standard PA search unit is placed at a static position on a calibration block with side-drilled holes (SDH). Using a standard PA process, some SDH are detected with an azimuthal (or sectorial) scan from 40° to 70°SW (a). Simultaneously, FMC data are acquired (b). Through offline software summation of the FMC data, an azimuthal scan from 40° to 70°SW is generated and gives results equivalent to the standard PA process (c). Using the same raw FMC data, another azimuthal scan from -10° to 10°LW is generated. SDH located just under the search unit, which were not detected with standard PA, can now be observed (d). This shows that, by acquiring FMC data, the phased array summation can be efficiently optimized offline during analysis. This is a
significant benefit over standard PA process and it might in some cases prevent costly re-scans.

![Figure 3: Example of FMC Data Processing Capabilities](image)

In addition, having access to the raw signal information opens the door to the implementation of advanced processing algorithms. In particular, the Total Focusing Method is drawing a lot of attention [1,2]. Also, FMC is identified as a possible solution for the inspection through complex surfaces [3].

**CHALLENGES OF FMC**

Offering so many benefits over standard PA process obviously comes with some challenges. In order to allow an efficient FMC data collection, several hurdles need to be overcome by the acquisition hardware & software.

**Number of A-Scan Signals**

By definition, for a \( n \)-element probe, FMC captures \( n^2 \) individual A-Scans per acquisition position. The hardware and software used for FMC data acquisition thus need to be able to handle a substantial amount of A-Scans. The equipment used for the validation program is the DYNARAY® high-performance PA system driven by the UltraVision® 3.3 software (see Figure 4). In order to improve the support of FMC, ZETEC is currently working to increase the capability of this equipment, which will be able to handle up to...
32,768 A-Scans per acquisition position. This means that the DYNARAY and UltraVision 3.3 will support FMC with a maximum aperture of 181 elements, or two separate apertures of 128 elements.

**Data Transfer Rate**

Given the amount of data that needs to be transferred from the acquisition system to the remote computer, the data transfer rate is in most cases the limiting factor of the data acquisition speed. Therefore, still looking to better support FMC, ZETEC is currently working to increase the maximum data transfer rate of the DYNARAY system to 30 MB/s. Of course, high-end computers will be required to keep up with such high throughput.

Still, for FMC data acquisition, very low acquisition speed has to be expected. In some cases (many elements, large time base range), it can be lower than 1 Hz.

**Data File Size**

FMC data files can easily reach several GigaBytes. The data acquired using UltraVision 3.3 are directly saved on drive and not in RAM memory, which allows the acquisition and storage of very large FMC data files.

In order to minimize the amount of data generated, the use of Half Matrix Capture (HMC) can be considered. The principle of HMC (see Figure 5) is to eliminate “reciprocities”. When considering a point UT source and a point reflector, pulsing with element \( x \) and receiving with element \( y \) is theoretically identical to pulsing with element \( y \) and receiving with element \( x \). By applying HMC, the amount of A-Scans required drops from \( n^2 \) to \( n(n+1)/2 \). HMC is part of the validation process described in the next section of this document.
Acoustic Energy

As FMC consists of consecutive single-element emissions, very low acoustic energy is produced during FMC data acquisition. Moreover, as it requires very low directivity of the ultrasonic energy, it is better to use small PA probe elements for FMC data acquisition. As a direct consequence, the energy levels of the received signals are also very low. Therefore, in order to make sure the reflected UT signal is not lost in the electronic noise of the acquisition system, high-quality pulser-receiver channels are absolutely required.

VALIDATION PROGRAM

In the framework of our systematic quality assurance program for the UltraVision 3.3 software, ZETEC has performed various comparative tests aiming to validate both the theoretical principles supporting FMC data processing and the implementation of the FMC solution in the ZETEC ecosystem. A series of test configurations, representing typical PA applications, was defined to serve as a common ground for quantitative and qualitative comparison. For each configuration, standard PA data acquisition (hardware summation) was performed simultaneously with FMC or HMC data acquisition. The elementary data was then processed offline (software summation) to synthetically generate the standard PA data and compare both resulting data sets.

1D Probe – Pulse Echo – Side-Drilled Holes

An encoded data acquisition was performed on an aluminum calibration block with several SDHs, using a 5-MHz, 64-element, 0.6-mm pitch 1D PA probe mounted on a 36°-wedge. An azimuthal scan from 40° to 70°SW and a depth scan from 5mm to 45mm true-depth at an angle of 55°SW were acquired in addition to HMC data. Focal laws identical to the two standard PA scans were used for off-line processing of the HMC data (Figure 6).

Results show a very good match between the hardware and software summation processes in terms of indication positioning: the difference in the position of the maximum amplitude is in all cases smaller than 1mm on both the scan and the ultrasound axis. On the other hand, the maximum amplitude of the data summed through software process is between 0.9dB and 2.8dB weaker than the data summed through hardware process. This can be explained by the stronger acoustic energy emitted by standard PA process, which obviously leads to a stronger received acoustic energy. Table 1 shows the quantitative comparison between hardware & software summation processes for this test configuration.
Figure 6: Comparison of Hardware & Software Summation on Calibration Block with SDHs

First Row: Hardware Summation – Azimuthal Scan 40° to 70°SW
Second Row: Software Summation – Azimuthal Scan 40° to 70°SW
Third Row: Hardware Summation – Depth Scan 5mm to 45mm True-Depth
Fourth Row: Software Summation – Depth Scan 5mm to 45mm True-Depth
Table 1: Quantitative Comparison between Hardware & Software Summation Processes on Aluminum Calibration Block with SDHs

1D Probe – Pulse Echo – Flat-Bottom Holes

Encoded data acquisitions were performed on an aluminum calibration block having several FBHs, using a 5-MHz, 64-element, 0.6-mm pitch 1D PA probe mounted on a 0° delay line. Electronic (or linear) scans at 0°LW using an active aperture of 8 elements were acquired in addition to FMC and HMC data. Focal laws identical to the two standard PA scans were used for off-line processing of the FMC and HMC data (Figure 7).

For this configuration, the equivalency of the hardware and software summation processes is nearly perfect. The amplitude difference of the peak signals is negligible (≈ -0.3dB) for both FMC and HMC data, and the positioning of the indications along the scan, index and time axis is accurate to ±1 sampling position. No significant difference was observed between the results of the FMC and HMC data summations in terms of signal quality and signal amplitude.
Figure 7: Comparison of Hardware & Software Summation on Calibration Block with FBHs

Upper Left: Hardware Summation – 0°LW Linear Scan (FMC Data File)
Upper Right: Software Summation – 0°LW Linear Scan (FMC Data File)
Lower Left: Hardware Summation – 0°LW Linear Scan (HMC Data File)
Lower Right: Software Summation – 0°LW Linear Scan (HMC Data File)

2D Probe – TR – Realistic Flaws

Encoded data acquisition was performed on a 12-in. OD stainless-steel pipe specimen containing three realistic flaws, using transmit-receive (TR) configuration with 1.5-MHz, 16x2-element 2D PA probes mounted on a TR wedge assembly. Electronic scans at 0°LW, 45°LW, 60°LW, 70°LW, 45°SW and 60°SW using an active aperture of 8x2 elements were acquired in addition to FMC data. Focal laws identical to the six standard PA scans were used for off-line processing of the FMC data. Figure 8 compares the hardware and software summation results of the 45°SW scan, which is the most relevant as it shows all three flaws.

Again, results are showing a very good match between the hardware and software summation processes. The amplitude difference of the peak signals is small (≈ 1dB) and the positioning of the indications along the scan, index and time axis is accurate to ±1 sampling position. This test configuration also demonstrates that FMC data processing is applicable for 2D matrix probes and TR configurations.
CONCLUSIONS
From the work presented in this paper, the following conclusions can be drawn:
1. An internal test program has demonstrated the validity of FMC data collection and processing. In all test configurations, the results obtained by software summation of the FMC data provide equivalent results to standard PA processing, when using identical focal laws. The observations are valid for artificial reflectors (SDH & FBH) as well as realistic flaws.
2. Post-processing of FMC data can provide much more information than standard PA processing; focusing depths and beam angles can be optimized after the inspection, to better characterize detected indications.
3. For all test configurations, HMC data processing has been found equivalent to FMC data processing.
4. In order to conduct efficient FMC data collection, the equipment used requires the following characteristics:
   • Support high number of A-Scans per acquisition point
   • Provide a very high data transfer rate
   • Handle very large data files (several GigaBytes)
   • Provide very high signal quality (low electronic noise)
5. ZETEC has developed and validated an efficient and user-friendly solution for FMC data acquisition and processing, using commercially-available high-performance PA hardware and software.

REFERENCES