RECONSTRUCTION OF PHASED ARRAY TECHNIQUES FROM THE FULL MATRIX CAPTURE DATA SET

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The Full Matrix Capture (FMC) ultrasonic data acquisition method is a powerful technique. Combining Total Focus Method (TFM) analysis and FMC can provide results beyond the capabilities of standard UT inspection methods. Moreover, the FMC data set can be analyzed by a range of algorithms to obtain different beam forming results. This paper discusses the development and implementation of Phased Array methods reconstructed from FMC data sets. Results are provided for a sample series of Electro Discharge Machining (EDM) notches in both conventional weld geometries and fitting to bend welds (arbitrary surfaces).

Keywords: Phased Array, Full Matrix Capture, Reconstruction

Introduction

The FMC ultrasonic data acquisition technique generates the complete data set that may be obtained for a given array transducer with a specified orientation over an inspection surface [1]. FMC data sets can be analyzed using a number of post processing beam forming techniques such as Wavenumber Method [2], Back Propagation Technique and the Total Focus Method (TFM) [3][4].

When FMC is combined with TFM the result is a very powerful method for imaging the weld volume of complex inspection geometries [5].

In addition to the above beam formers, other conventional UT techniques may be reconstructed during the process of offline analysis. For example Phased Array techniques may be derived from the conventional time domain signal [6]. This approach emulates dynamic surface adaptation phased array techniques. The Phased Array result may be further enhanced via substitution of the time domain signal with the analytic signal series when performing element summation.

Reconstruction of Phased Array addresses several specific requirements. Firstly this process establishes a relationship between Phased Array and the FMC data set. It also serves as a useful platform to progress users from the familiar Phased Array representation to the output of other beamforming methods. It offers the user the ability to isolate and examine regions of interest within a defined range of angles. This is helpful when testing for weld discontinuities with specific orientations. Finally it provides the possibility to derive a code compliant inspection on an otherwise intractable geometry.

Background and PA reconstruction requirements

The Inspection and Maintenance Services Division of Ontario Power Generation developed and implemented an inspection system combining the FMC data acquisition technique with the TFM beam former. The combination of the two technologies was called the Matrix Inspection Technique (MIT) [5]. The system was developed to address the inspection of complex geometries for Flow Assisted Corrosion (FAC) damage (see Figure 1 and Figure 2). The inspection geometries under consideration are: fitting to Grayloc, fitting to fitting and fitting to pipe welds.
The MIT system has been deployed on several inspection campaigns following the completion of its development in 2010. The results obtained significantly exceeded the ability of the previous UT inspection methods. The system is capable of resolving the exterior and interior profiles of the region inspected. Figure 3 shows the MIT intensity map of a weld cross section congruent with ex-service fitting-to-fitting sample (Figure 4). In the intensity map, both the outer surface (the upper curve in Figure 3) and the root are detected accurately.

Figure 3: Intensity map of weld cross sections.

Figure 4: Weld cross sections (Congruent with ex-service fitting to fitting samples).

Figure 5: Lab specimen - abrupt cross section changes through weld region.

Figure 5 shows the intensity map of abrupt X-Section changes through the weld region. The inner surface (the lower curve) is detected successfully.
When the individual surface profiles are assembled, a 3D rendering of the inspection configuration is produced (see Figure 6(R) and Figure 7). The precision and coverage of the MIT system is such that photo realistic results of the inspection geometry are obtained.

Following the development of the MIT inspection system, the addition of other beam former methods was initiated, specifically phased array beam formers. The re-construction of phased array techniques is motivated by the desire to access several perceived benefits:

- Managing the transition from traditional phased array inspection methods to other beam formers, both from the perspective of personnel training and inspection technology continuity
- Pursue the potential of obtaining a code compliant inspection on complex surfaces
- Provide additional supporting evidence for Inspection Qualification of the MIT system

**FMC data set**

The Full Matrix Capture data acquisition strategy is implemented on a linear array transducer by transmitting on one element and receiving on all elements in the array. The next element then transmits and again, all elements in the array receive. The process is repeated until every element in the array has transmitted with all receiving, resulting in a 128 by 128 data matrix, see Figure 8.

The FMC data acquisition process does not introduce focal laws, i.e., no separate transmission or reception delays. A key attribute of FMC is that all phase relationships between transmitter and receiver are retained. This feature permits the post-acquisition application of a range of beam forming analysis strategies. Via the FMC method all waveforms are recorded regardless of mode, source or path. This is an essential attribute when inspecting complex or rapidly varying geometries.

The fundamental limitation of an FMC based inspection is the ability to deliver sound into, and receive sound back from the inspection volume. The FMC data collection process does yield exceptionally large data files and is consequently slower compared to other data acquisition methods. One proposed solution to address the file size and data collection speed is to perform half matrix capture. This strategy takes advantage of the symmetrical property of the matrix about the main diagonal, that is: \( t_{ij} r_{ij} = t_{ji} r_{ij} \). Beam formers that are not sensitive to phase can utilize this approach however in practice we find that \( t_{ij} r_{ij} \approx t_{ji} r_{ij} \). Slight variations exist from element to element, and channel to channel, in addition to noise contributions that are in turn manifested in beam forming strategies sensitive to signal phase.

**Phased Array Beam Formers**

UT phased array inspection technology is both well understood and widely adopted by the NDE community. Simply described; phased array is realized by applying the appropriate time delays to achieve superposition of individual wave sources for the transmission of a UT wave front in a specific direction to a predetermined location in the inspection volume. Typically the same delays are used for reception of the returned response from the same location in the inspection volume. The individual element contributions are then summed into a single A scan representation for the focal law in under consideration. The A scans from multiple focal laws are plotted together in a common representation; for example, a sectorial scan.
Given a linear array operating in the FMC data collection mode, we may define a sub-aperture denoted as the aperture matrix (Figure 8). Phased array focal laws can be implemented on the aperture matrix by applying appropriate delays to the individual A scan members and then performing summation see Figure 9. Note that it is necessary to up sample the constituent A scan signals to a higher effective digitization rate such that the appropriate delay may be applied. The principal contributors to the resultant A scan are found along the main diagonal and the adjacent parallel diagonals of the aperture matrix. The extent of offset distance from the main diagonal is a function of a number of parameters. The main parameters include; element pitch, frequency, velocity, required steering angle and scattering function of the target reflector. The reader will recognize the same parameters are key inputs to the calculation of focal laws and hence intuitively appreciate that a linkage between the FMC data array and phased array exists.

Recall that in the time domain, signals will constructively interfere within a window of $\pm P/4$ where $P$ is the nominal period of the wave pulse. Should the individual waves superimpose in a time increment greater than $P/4$, destructive interference predominates. Given a transducer with a centre frequency of 7.8 MHz, a pitch of 0.27 mm, the interval over which constructive interference occurs is approximately 65 ns. As an illustrative example, a focal law has been applied to create a longitudinal refracted wave in steel of 50 degrees. Isochronal arcs have been plotted for the centre element of the aperture as well as a series of adjacent transmit-receive combinations at an arbitrary distance in the inspection volume, (see Figure 9). The extent over which the members of the adjacent diagonals of the aperture matrix interact is apparent. Further work will derive the empirical formula describing focal law characteristics expressed in terms of the FMC data array.

The application of focussing delays has the effect of incorporating elements further away from the main diagonal. Introduction of these elements into the A scan summation restricts the inspection volume in which constructive and destructive interference occurs thus enhancing resolution and signal to noise ratio (SNR) within this region (Figure 10). Beyond this volume, the resolution and SNR begin to deteriorate. These areas can be addressed by re-calculating the delays and performing the summation again. In this manner several focal regions can be defined and the results merged into one plot. This feature essentially emulates the dynamic depth focussing capability in conventional phased array systems. Performing focussing on the post-acquisition FMC data set permits the user to define an arbitrary series of focal regions, such as the fusion line along a weld preparation for example.
The scattering function of the target reflector is also influential in defining the region in the aperture matrix from which the contributions are obtained. Volumetric reflectors such as slag and porosity will reflect across a wider range of angles. This stands in contrast to smooth planar reflectors e.g., side wall lack of fusion that return sound in a narrower range to fewer elements.

**Implementation**

During the development portion of this effort, the code was written using MATLAB 2012 development tools. MATLAB is a powerful, well-established package that permits rapid development of code. However the plotting capabilities in MATLAB provided a limited range of avenues in which the user can effectively interact with the output. The plots presented in the next section are based on the MATLAB version of phased array software. Following the initial development of phased array capability, the next step in the effort will be to convert the MATLAB code into equivalent C# code for implementation within the OPG Neovision® software. A user interface feature will be created along with the conventional A, B, D and sectorial scan representations. A variety of tools will also be provided to expand the user’s ability to interact with the phased array results. The initial development efforts were directed at obtaining phased array sectorial scans from rudimentary geometries such as linear surfaces with side drilled hole (SDH) targets. The rationale behind this approach was to establish the correct methodology on a commonly used and easily verified geometry then progress to successively more complicated configurations.

**Experiments with flat surface**

- IOW block (side drilled holes)

Figure 11 and Figure 12 depict an immersion L-wave sectorial scan on an IOW block applying a twenty element aperture in a B scan fashion. The results obtained were confirmed with an equivalent set-up using a conventional phased array instrument. The main diagonal image of the FMC data set for this scan is found in Figure 13.
To test performance with planar reflectors, a 1mm EDM notch in a 5mm specimen was introduced in another experiment. The main diagonal for this FMC data set is shown in Figure 14.

Figure 15 and Figure 16 are the results from L-wave and S-wave respectively. The notch can be observed from both sides so both L-wave result and S-wave result are symmetric to the notch position.
- 1mm EDM notch in 5mm specimen

Following examination of the flat surface parallel to the transducer, an angled step wedge with 1mm notch was tested. The surface of the step wedge has a 15 degree angle to the transducer (its FMC main diagonal data are shown in Figure 17). Because of the angle between the sample surface and the transducer, the notch can be seen only from one side (the red rectangle in Figure 17). Its S-wave result is shown in Figure 18.

![Figure 17: FMC main diagonal data for an angled step wedge with 1mm notch.](image1.png)

![Figure 18: Result of S-wave.](image2.png)

### Experiments with arbitrary surface

The approach adopted when addressing surfaces that are not accurately represented by a linear geometry is a hybrid of TFM and phased array. In this method, the Canny edge detector is applied to the TFM image to derive the coordinates of the interface surface. The user provides additional input parameters such as the index point on the interface, desired aperture, range of angles to plot, and focal point, if any. The appropriate delays are calculated through the interface solving the beam paths back to the individual elements at the transducer using the Fermat principle. The method has been tested on a limited range of convex and concave geometries however the results have yet to be verified against the equivalent implementation on conventional phased array instrumentation. This approach is adequate for the first half skip however may be sensitive to variations of the interior surface on the reflected second half skip.

- Arbitrary Geometries 1 – Heat Affected Zone (HAZ) crack in feeder pipe

![Figure 19: HAZ crack design.](image3.png)

![Figure 20: FMC main diagonal for HAZ crack.](image4.png)
Because of the complication of the feeder pipe geometry and position of transducer, the distance and the angle between the transducer and specimen’s surface cannot be pre-determined. The only solution is to treat the specimen’s outer surface as an arbitrary curve. The design of specimen is shown in Figure 19 and its main diagonal data are shown in Figure 20. The crack is detected using S-wave (Figure 22).

Figure 21: S-wave result for region containing Figure 22: S-wave result for region adjacent to HAZ crack.

As depicted in Figure 19, the crack has a limited circumferential extent along the weld HAZ. To further verify the accuracy of the inspection, the region adjacent the HAZ crack was evaluated. The indication noted in Figure 21 is absent in Figure 22.

Figure 23: Flaw sample 005 result for different index points.

Figure 24: Flaw sample 005 result for different index points.
Another experiment was to generate a series of sectorial scans for the crack at discrete circumferential intervals (frames). These multiple frames were tested with the same series of aperture positions (with all the other parameters remaining constant). The crack is observed in this series of frames. In a single frame, when the index point moves right along the surface, the crack position moves accordingly (closer to its index point). These experiments confirmed the validity of the algorithm for phased array beam forming.

- **Arbitrary Geometries 2 – Crack & excess pen. at root**

  In this experiment, the crack (flaw 1 in Figure 25) is at the same position as the flaw 2 at the weld root. Its main diagonal FMC data are shown in Figure 26.

![Figure 25: Crack & excess pen., at weld root.](image)
![Figure 26: FMC main diagonal for crack & excess pen at weld root.](image)

![Figure 27: S-wave result for crack & excess pen. at weld root. (L) Sectorial scan. (R) Enlarged area of interest.](image)

The left image in Figure 27 is the sectorial result. The right image in Figure 27 is the enlarged part to illustrate the 2 flaws clearly. The results of this experiment are also verified through multiple frames and multiple aperture positions in a single frame.
Conclusions

This paper presents a method to reconstruct phased array techniques from the FMC data set as a post acquisition beam forming process. The ability to re-construct phased array techniques from the FMC data set post acquisition has been demonstrated with both simple geometric samples and arbitrary surface samples. The method is verified through with a variety of samples containing manufactured discontinuities.

By successful reconstruction of Phased Array, a relationship between Phased Array and the FMC data set is established. The technique can serve as a useful platform to progress users from the familiar Phased Array representation to the output of other beam forming methods.

References