Application of a FMC/TFM Ultrasonic System to Inspection of Austenitic Welds

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Abstract. Ontario Power Generation (OPG) has successfully developed and deployed an ultrasonic inspection system based upon the combination of the Full Matrix Capture (FMC) UT acquisition technique with the Total Focusing Method (TFM) beamformer. The system, called Matrix Inspection Technique or MIT, was applied to selected carbon steel components that comprise the Primary Heat Transport System. The purpose of the inspection is the mapping of highly localized Flow Accelerated Corrosion (FAC) occurring at and adjacent the weld root of fitting to fitting welds. The MIT system has yielded outstanding results in multiple field inspection campaigns from 2010 to present. Results from these inspection campaigns also identified welds containing minor welding defects such as; lack of fusion, isolated porosity and slag inclusions. A programme was initiated to advance the capabilities of the MIT system beyond that of carbon steel to stainless steel components. The required changes to the MIT system include a relatively straightforward substitution of the transducer and a significant modification to the TFM beamformer strategy to address the anisotropic nature of the weld material. This paper describes the work conducted in the modification of the MIT beamformer and the results obtained on sections of 304 stainless steel pipe welded with 308L fill material.

1. Introduction

Effective inspection of anisotropic inhomogeneous materials is often a challenge due to the deleterious effects of the material properties on the bulk wave transmission of ultrasound. Reliable inspection capability for these materials must provide high probability of detection whilst minimizing false calls. Upon detection of an indication, the sizing and plotting of the indication within the search volume must be sufficiently accurate to support disposition in accordance with applicable codes. Common metallic members of this group of materials include austenitic stainless steel welds, coarse grain cast stainless steels and dissimilar metal welds. The task of development of inspection capability for this category of materials usually includes many if not all of the following; modelling, simulation, fabrication of mock-ups and samples containing realistic defects, procedure development, validation and subsequent training. Thus development of inspection capacity represents substantial commitments of time, personnel, capital, and other resources.

The FMC data acquisition technique combined with the TFM beamformer offer a new approach to the inspection of anisotropic inhomogeneous materials. The chief advantage
of the FMC technique is that for a given transducer placed at a position and orientation with respect to the search volume, the maximum amount of information is obtained [7]. One advantage of the TFM beamformer is given a suitable model of the search volume, both material anisotropy and inhomogeneity may be addressed.

OPG has developed an inspection system based on FMC data acquisition operated in conjunction with a two stage TFM beamforming strategy, see reference [1] and [2]. This combination is referred to as the Matrix Inspection Technique or MIT. The system was originally developed to address localized FAC at and adjacent weld roots of carbon steel fitting to fitting welds. An example of a weld region profile is found in Figure 1a, a 3D reconstruction of an inspected fitting in Figure 1b. Encouraged by the MIT results, further development was initiated to extend the system capabilities to the inspection of austenitic weld material.

![Figure 1](image)

**Figure 1** a) left - typical profile of a fitting to fitting weld. b) right - 3D reconstruction of a fitting to fitting joint aggregated from multiple profiles.

2. **Proposed Solution**

The solution adopted in this work follows the convention of dividing the problem into two separate issues; one of the inhomogeneous material, the other of the anisotropic characteristic. Widely accepted approaches to the problem of the inhomogeneous characteristic of austenitic welds is addressed either via numerical solution for the grain orientation, or by partitioning the volume into regions that may be approximated as homogeneous. An extensive body of work has been published regarding numerical modelling of austenitic weld structures, see references [3], [4] and [5]. Models exist for configurations including Vee and double Vee welds. Corresponding models for U groove welds have not been developed, in part due to the variability in the design of the weld preparation. In the case of U groove weld, derivation from macrograph is the preferred method for determining the orientation of the face centred cubic grains.

A macrograph of the subject weld was not available from the manufacturer. In lieu, a macrograph of a similar configuration was obtained from published literature found in [6], see Figure 2a. Separate regions in the macrograph were evaluated with respect to grain orientation. Regions were differentiated based upon criteria of an angle range of +/- 4 degrees defining a unique region. Epitaxial grain growth is observed from the fusion line of the weld preparation. Grain growth then turns towards the vertical direction following the path of heat transfer during pool solidification. Symmetry about the weld axis was introduced to simplify coding of the region, see Figure 2b.
Figure 2  a) left - Macrograph of a U groove weld of a similar profile to the inspection sample (from Wirdelius)  b) right - corresponding weld model segregated into regions of homogeneous grain orientations

The anisotropic characteristics of the austenitic weld material are addressed by solving for the directionally dependant velocities of the group and phase components of the wave. While it is beyond the scope of this paper to provide the complete derivation, the velocities of the applicable wave modes with respect to direction may be obtained by solving the Christoffel equation for the corresponding eigenvalues and eigenvectors. The slowness surfaces for the quasi longitudinal, quasi transverse wave modes can be further derived. A plot of the phase slowness surface is found in Figure 3.

Figure 3  Slowness plots generated with elastic constants corresponding to 308L weld material. Quasi-longitudinal wave in blue, quasi-shear wave in red and green.

Within the anisotropic material the phase velocity and group velocity will nominally differ in the direction of the group vector. Recall that when performing signal summation with the TFM beamformer, an analytic representation of the original waveform is employed. The analytical waveform provides greater sensitivity to phase information compared to the time domain waveform. With TFM it is implied that the phase of the analytic waveform remains coherent with the group at all times within the reconstructed volume. In contrast, anisotropic materials with the difference between the phase and group velocity will exhibit a
lack of coherence between the phase and group. The TFM beamformer will perform poorly under these conditions. It is necessary to calculate the displacement of the phase relative to the group for each point within the reconstruction volume. The net phase displacement for a given transmit-receive pair can then be compensated such that the phase is returned to a coherent state relative to the group.

Assumptions were applied in order to simplify the model, aid in code integration into the existing structure, and to reduce unduly long computation intervals. These assumptions included:

- Weld material properties are isotropic in the direction along the axis of the weld.
- Imaging functions are performed in L wave mode thus both $S_H$, $S_V$ waves and mode conversion may be neglected.
- The properties of the parent material are isotropic.
- Weld material modelling is adequately addressed by defining 27 separate regions of uniform orientation with anisotropic properties.
- Solutions resulting in evanescent wave modes may be neglected.
- Elastic constants used to derive the slowness surfaces are appropriate for the weld fill material.

Portions of the existing code related to the imaging and edge detection of the exterior surface were retained without modification. Code segments were added to the interior imaging code. These segments address mapping of the grain orientation model into the interior search region [8], calculation of the Fermat solution for flight time into or transiting through the anisotropic regions and calculation of the phase displacement.

The adaptations to the existing MIT analysis code are summarized as follows:

- Extract corner features from detected exterior surface - define coordinates of weld toe
- Register model to detected corners.
- Map the weld model to interior volume to match weld area thickness as determined via cross correlation.

For every element in the array:

- Solve for flight times to isotropic regions excluding transit through anisotropic regions.
- Solve for flight times into anisotropic regions from anisotropic/isotropic boundary points applying group velocity vector.
- Calculate phase displacement for each point in anisotropic regions using phase velocity in the direction of the group vector.
- Solve for flight times in isotropic regions transiting through anisotropic regions.

The code modification required to address the anisotropic region departs from the conventional approach used in the TFM beamformer. The transit time for incoming ray is solved in sequential steps. Thus for the anisotropic region the process is akin to the methods used for ray tracing.
3. **Code Evaluation Trials**

A series of trials were conducted to evaluate the imaging capabilities of the modified analysis code. Improvement in the imaging of the weld discontinuities is taken as an indication of the validity of the modified analysis code.

3.1. **Sample, Instrumentation and Test Apparatus**

The inspection sample is a 6 inch NPS schedule 80 304 SS pipe segment containing a U groove weld, see Figure 4. The weld was fabricated using 308L fill material. The weld crown has been ground flat, but is not flush with the parent material. The manufacturer performed dimensional checks pre and post fabrication. Significant shrinkage of the sample occurred during fabrication resulting in a change in weld profile. A total of five manufactured defects have been inserted into the sample, three of which are appropriate targets for the goal of the test. The manufactured defects are: side wall lack of fusion, slag inclusion and root crack, see Figure 5.

A Peak NDT, Micropulse FMC operated with OPG’s Neovision software was used for data acquisition. A five axis scanning apparatus was used for the tests, see Figure 4. The apparatus has a configuration of 3 linear axis; X, Y and Z with an independent rotary axis, theta. The fifth axis is typically used for transducer index and was not required for this application. Scanning speeds were set to 1 degree per sec with an acquisition index of 0.67 degrees per frame. Acquisition repetition frequency of 3 Hz is sufficient to minimize motion blur in the FMC frame.

![Figure 4](image1.png)  
*Figure 4* Inspection sample mounted in scanning apparatus - left. 6 inch NPS schedule 80 sample - right.

![Figure 5](image2.png)  
*Figure 5* Sketch of the weld sample; solid - as designed, dashed - as manufactured - left. Lack of fusion, slag inclusion and root crack implanted into sample - right.
3.2. Transducers

Three transducers were utilized for this work. All are 128 element linear arrays. Properties of each transducer are provided in Table 1. The 3, 5 and 7.5 MHz transducer along with the waveform characteristics are found in Figure 6, Figure 7 and Figure 8 respectively.

Table 1 Characteristics of transducers used for application development.

<table>
<thead>
<tr>
<th>Transducer</th>
<th>f_{NOM} (MHz)</th>
<th>f_{ACT} (MHz)</th>
<th>Pitch (mm)</th>
<th>Elevation (mm)</th>
<th>Pulse Duration</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.0</td>
<td>2.9</td>
<td>0.47</td>
<td>8.0</td>
<td>1245 ns</td>
<td>42%</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>5.6</td>
<td>0.30</td>
<td>5.0</td>
<td>445 ns</td>
<td>75%</td>
</tr>
<tr>
<td>C</td>
<td>7.5</td>
<td>7.7</td>
<td>0.27</td>
<td>5.0</td>
<td>320 ns</td>
<td>71%</td>
</tr>
</tbody>
</table>

Figure 6 a) left - 3 MHz, 128 element transducer, b) right - waveform and frequency spectra plots.

Figure 7 a) left - 5 MHz, 128 element transducer, b) right - waveform and frequency spectra plots.

Figure 8 a) left - 7.5 MHz, 128 element transducer, b) right - waveform and frequency spectra plots.
4. Results

The results of the application of the model on scans conducted with the 3, 5 and 7.5 MHz transducers are presented in Figure 9, Figure 10 and Figure 11 respectively. In each figure, the upper row of images are results obtained assuming homogeneous, isotropic material properties while the lower row are the results obtained with the application of the model.

Figure 9  Result obtained with the 3 MHz transducer. Upper row - without code modification, lower row with code modification; a) and d) root crack, b) and e) lack of fusion, c) and f) slag inclusion.

Figure 10  Results obtained with the 5 MHz transducer, upper row without code modification, lower row with code modification; a) and d) root crack, b) and e) lack of fusion, c) and f) slag inclusion. Minimal imaging improvement obtained.
4.1 Discussion

The model is observed to improve the imaging of the implanted defects with data obtained using the 3MHz transducer. In contrast however, the model has a marginal influence on the scans obtained with the 5 MHz transducer and effectively no improvement to the results obtained with the 7.5 MHz transducer. It is speculated the difference in performance related to the relative sensitivity of the transducer frequency with respect to phase error. Additionally, the 7.5 MHz transducer may be inappropriate for this application given the scattering that would occur upon interaction with the coarse grains of the weld fill material.

The process of implanting controlled weld flaws in a sample involves some degree of deviation from the conventional weld procedure depending upon the nature of the defect and the means by which it is introduced. The deviation may be significant enough to invalidate the proposed model of the grain orientation within the weld. In this event, an adaptive approach to the weld model may be appropriate [9]. Further assessment of the modified code is required to determine if the error is a result of deviation between the grain orientation model and the actual sample or incorrect elastic constants used in the determination of the slowness surfaces.

5. Conclusions

A weld model has been developed to separately address the inhomogeneous nature and anisotropic characteristics of the 308L weld material. The model has improved the imaging performance of the 3 MHz array for the three defects implanted in the sample, however the imaging performance of the 5 and 7.5 MHz array did not appreciably improve. Further work is needed to determine which specific aspects of the model depart from the characteristics of the weld sample.
6. Acknowledgements

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7. References