Imaging the Weld Volume Via the Total Focus Method

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ABSTRACT

The problem of inspection of complex geometries is a challenge many nuclear utilities are compelled to address. Conventionally, inspection of complex geometries can be solved by drawing upon detailed a priori knowledge of the object and then conducting an extensive development programme of an application specific technique. Another approach is to perform on the fly adaptation to the inspection surface either by mechanical means or rapid analysis and compensation of the interface surface irregularity. A method developed at Ontario Power Generation relies on neither of these approaches. OPG’s solution to the inspection of complex configurations instead utilizes a combination of the Full Matrix Capture (FMC) data acquisition method with a post acquisition beam forming technique known as the Total Focus Method (TFM).

Under the current approach, TFM is applied to form an image of the exterior surface. The coordinates of the surface are defined using edge detection techniques. A second iteration of the TFM algorithm is applied to form the image of the weld volume and interior surface. Edge detection is performed again to define the interior surface. The combinations of interface and interior surface are then assembled into a full 3D rendering of the object inspected. This inspection strategy was successfully deployed at OPG’s Pickering NGS Unit 4 campaign in 2011. The inspection yielded highly detailed results with excellent coverage and marked the first successful application of this technology. OPG will continue to use the technology and is actively seeking to expand its application to other inspection problems.

KEYWORDS

Total Focus Method, 3D Imaging, Automated Analysis, Ultrasonic Testing

INTRODUCTION

The CANDU nuclear units at Ontario Power Generation (OPG) are equipped with components that supply heavy water to and from the individual fuel channels. These components are known as feeder pipes. Hundreds of feeders converge in a relatively small zone at the reactor face. To accommodate the routing of the feeders, a wide range of piping configurations are used comprised of various orientations, pipe diameters, bend radii, bend sweep angles and twist angles. Permutations of these factors give rise to what is effectively a complex geometry at the fitting to bend or fitting to fitting joints. When coupled with manufacturing and assembly tolerances, and in light of the requirement of the Inspection Specification, each of these joints represents a unique configuration.

Flow Assisted Corrosion (FAC) has been identified as a degradation mechanism in the outlet feeders of OPG’s units. The FAC thinning has been widely distributed throughout the first metre of piping run adjacent the Fuel Channels. However highly localized FAC thinning has been identified at and adjacent the weld root of joints in the piping run. The thinning creates abrupt changes in profile and can be randomly distributed around the joint circumference. The feeder welds have been left in the ‘as fabricated’ condition. Fitness For Service assessments take the weld cap reinforcement into account, thus grinding or smoothing of the weld cap to aid inspection is not permissible.
The inspection of complex geometries is an issue that many utilities and service providers are obligated to address at some point in the plant lifecycle. Solutions to this problem vary widely but typically involve reverse engineering or modelling the inspection geometry. A technique is then proposed and evaluated on models and purpose built mock-ups. Once the technique is fully developed, inspection personnel are then trained and deployed to the inspection campaign. This approach is rigorous and produces the desired results but is both costly and time consuming.

A different approach to this inspection problem was adopted at OPG. Recognizing that knowledge of the feeder joint geometry was incomplete and uncertain OPG chose not to use methods that require \textit{a priori} information of the inspection target. That choice lead to the selection of the Full Matrix Capture technique as data acquisition method.

**FULL MATRIX CAPTURE (FMC)**

FMC is a relatively new and underutilized ultrasonic data acquisition method. Contributing to the lack of use is the fact that only two vendors currently market commercial systems capable of performing FMC. The FMC technique does have distinct advantages over other ultrasonic inspection modes. FMC, unlike phased array methods, does not use a transmit aperture nor focal laws. FMC operates by transmitting on a single element at a time and receives on all elements in the array creating an n by n array of A scans where n is the number of elements in the transducer. The individual contributions are not summed but rather retained as individual A scan traces. The fundamental limitation of the FMC technique is the ability to transmit sound into, and receive sound from the inspection volume.

The strengths of the FMC technique are:

- For a given transducer positioned over a target – FMC acquires the maximum possible data in one acquisition cycle
- All possible focal laws that can be executed for a given transducer are a subset of, and contained within the FMC data set
- Ideally suited to post processing and automated analysis techniques
Challenges to the FMC technique are the relatively low rate of data acquisition compared to other methods, as well as the exceptionally large resultant data files.

**TOTAL FOCUS METHOD (TFM)**

TFM was selected as the data analysis and imaging method for this application. This method is effectively a triangulation technique wherein the A scans of the various transmitter-receiver combinations are summed into the appropriate points in a image grid associated with a specific flight time. In preparation to perform TFM, the FMC dataset is converted from a scalar time series into a vector time series. This is accomplished by applying a Hilbert transform to a copy of the A scan signal and assigning the result into the imaginary plane. Where the original A scan represents amplitude, the new signal can be thought of as representing phase. The new signal is then added to the original to form signal in the complex plane. The advantage of using vectors rather than scalars is summation with vectors provides superior discrimination than can be achieved with scalars.

Total Focus method is performed by first establishing an image search grid in the area of interest. The granularity of the grid is set to optimize computation speed with respect to the need for spatial resolution of the interface surface. The transit time from each element to each point in the grid is calculated. The image is formed by summing the vectors corresponding to the appropriate total transit time. Where valid surfaces exist at point P, the vectors will constructively add, where no surface exists the vectors interfere resulting in a low baseline value. Once the image is formed, edge detection methods are applied to the leading edge of the image to identify the coordinates of the interface. It should be noted that side lobe and grating lobe effects can be imaged in the image search grid. Limiting the transmitter-receiver aperture with respect to the transducer element directivity is helpful in mitigating these effects.

The image of the inspection volume beyond the interface is treated in essentially the same manner as with the interface surface with the exception of forming the transit time matrix. In this case, the transit time from transmitter m to point P through the interface is solved at discrete increments along the interface. Applying the Fermat principle, the path with the least transit time through the interface is the appropriate one, see Figure 3. The necessity of iteratively solving the path through the interface to adds significantly to the computational burden of the TFM.

![Figure 3 Solving flight time through an interface applying the Fermat Principle.](image)

**ANALYSIS SYSTEM**

Data from the field is uploaded to a gateway server, the server then sends notification to the analyst that a new job is available. The analyst retrieves the raw data and begins evaluating the raw data for the purpose of monitoring data quality and processing parameter adjustment. Once the processing parameters have been adjusted the job is submitted to the gateway server that then divides the job among the blade
servers, shown in Figure 4, using a distributed grid computing strategy. The results are compiled by the gateway server and upon completion transferred to the analysis technician for review and evaluation.

**Figure 4** Analysis computer incorporating both Gateway and Blade servers.

The Neovision™ analysis software contains two modules. One module facilitates analysis parameter modifications while the second module provides the results review facility. Results are plotted as OD/ID image and contour pairs, see Figure 5, as well as 3D plots colour coded for thickness or rendered as solids. Results may be exported in tabular form or in a stereo lithography (STL) compatible format.

**Figure 5** Neovision™ user interface developed for Results output.
The development of this technology began at the concept stage without the benefit of prior efforts from which to draw upon. It was understood that further work would likely be required to address emergent issues in order to provide a robust, optimal configuration. Inspection Qualification work was deferred until such time as the desired changes to the toolset were fully implemented.

RESULTS

Results presented here have been compiled from several stages of progress during the system development. The image of the surface in Figure 7 illustrates the ability to resolve small scale surface variation down to better than 0.01 mm in water. Estimates of the system accuracy and precision are derived based on repeat measurements of the Reference block sample. The Reference block is presented in Figure 8. Accuracy the measurement is estimated to be 0.022 mm. The precision of the measurement is estimated to be 0.002 mm.

Figure 6  3 mm pitch ripple plate and result depicting ripples 0.03 mm and 0.01 mm high.

Figure 7  Example of Reference block used for calibration.

Figure 8 presents the result for the 5 mm step and the angled step wedge in the Reference block. The 5 mm step has a 1 mm by 5 mm EDM notch. Observable in the image is the direct reflection from the top of the notch as well as the symmetrical arcs of the L wave and S wave response. If the analysis software was modified to account for second reflections, these artefacts would be plotted in the position of the normal beam response. The measurements produced by TFM of the steps under the angled surface
correspond to the measurements provided by metrology. This agreement provides evidence of linearity of the measurement in both axial and depth directions.

Figure 9 and Figure 10 illustrate the ability to clearly image the abrupt changes in interior surface profile through curved geometries including the weld cap. The profile obtained from field inspection exhibits similar steps as found in ex-service feeders. See Figure 10.

Figure 11 presents the images for the 1.5 mm diameter sensitivity hole in an IIW block and the resolution series in an IOW block. These were obtained in immersion mode, solving for the interface surface prior to imaging in the material. This illustration is evidence of the ability to resolve isolated reflectors in the material volume. In Figure 12, a series of adjacent TFM images of a weld joint from the P1141 inspection campaign is presented. A minor LOF indication, under the weld cap, is identified in several consecutive frames. This is evidence of the ability to image internal weld discontinuities in a real application.

Figure 8  5 mm step with EDM notch left, and angled step wedge feature right, in Reference block.

Figure 9  Image and profile pair at the intrados of a Grayloc to fitting weld depicting abrupt changes in profile.

Figure 10  Step profile under weld cap (left) resembling that of an ex-service feeder (right).
Figure 11  Side Drilled Hole in IIW block left, diameter measured as 1.2 mm and resolution series in IOW block right.

Figure 12  Mid-wall inclusion identified in consecutive frames.

Evidence of the ability to image surface features such as weld pool ripples, coarse and smooth texture is found in Figure 13 and Figure 14. In Figure 13, the fine weld pool ripple is evident along with the pebbled texture of the fitting and the punch mark in the fitting surface. Figure 14 illustrates the coarse texture of the fitting on the right portion of the photo and image as well as the smooth texture on the left of both photo and image. The peaks and troughs of the weld ripples are identified. This ability can be exploited to ‘fingerprint’ the weld and used as registration points to facilitate year over year comparison of inspection results.
Figure 13  Surface texture and punch mark image (left) with photo of weld sample (right).

Figure 14  Surface image of fitting to pipe weld (left) depicting weld ripples and pebbled texture with photo of sample (right).

Figure 15 illustrates the inspection result for a segment of a feeder removed from service. Highly localized FAC thinning was found in a region confined under the weld cap. A photograph of a rubber replica of the same defect is given in the right side of the figure. In this case the measurement of the minimum thickness agreed with the metrology value to within 0.02 mm.

Figure 15  Localized FAC identified under weld cap (left) with rubber replica of same flaw (right).

Figure 16 and Figure 17 depict the 3D views of welds from data obtained during the P1141 inspection campaign. These views are comprised of the edge pairs of the individual TFM frames. In Figure 16, the
two results are colour coded for thickness variation. Both images are renderings of the fitting to Grayloc weld joints and are typical of the results obtained. Excellent inspection coverage of the target region is evident from these images. Note that in all cases, changes in the OD and ID surfaces are uniquely identified. Illustrated in Figure 17 is another fitting to Grayloc joint however this is rendered in gray with lighting applied to highlight the surface texture and features. This is compared to a photo, taken in the hotlab of a similar type of joint. The similarity between these two images is quite striking and underscores the capabilities of the TFM technique.

Figure 16  3D views of exterior and interior of fitting to Grayloc weld colour coded to represent thickness.

Figure 17  3D solid of TFM result (field inspection, left) with photo of a typical Grayloc to fitting weld (hotlab sample, right).
CONCLUSIONS

The ability to image an irregular surface located behind a complex geometry inclusive of a weld cap with weld pool ripple has been demonstrated.

The combination of FMC and TFM provide contour coverage through welds of complex joints to better than 95 percent coverage.

Variations in contour and cross section are attributed to the appropriate surface rather than lumped into one thickness value.

Surface detail such as texture and weld pool ripples are imaged with this method and may be used as benchmarks for year over year comparison of results.

Linearity of the measurement in depth and length has been demonstrated. The accuracy and precision of the technique exceed that of the Inspection Specification requirements.

Minor mid wall inclusions have been identified in scans, and the technique has potential to identify surface breaking defects.

Improvements to the surface detection strategy will yield even greater capability.

REFERENCES


