NDT Modelling in North America

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Abstract:

This paper is a review of recent aspects of "modelling" used in North America. Particular attention is paid to the regulatory aspects that now "stimulate" simulations. Some examples of projects in which modelling has played a part in improving or rationalising the inspection techniques are presented. Examples are taken from Canadian and American experiences in pressure vessel and pipeline venues.

Introduction

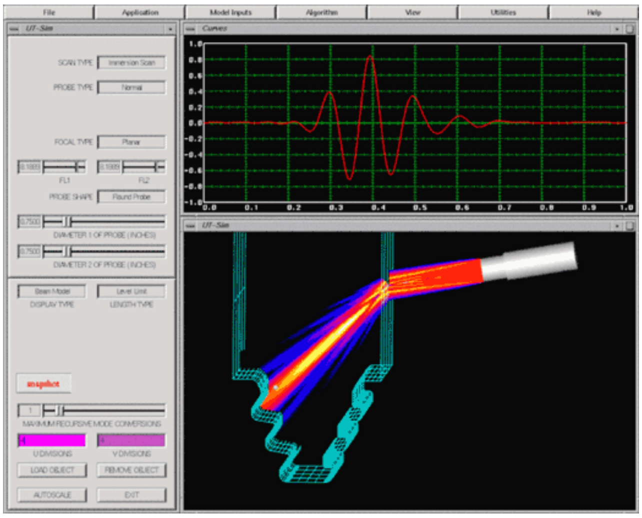
North America has been the origin of several of the developments in NDT modelling. Modelling has been used in North America for training, transducer modelling and simply better understanding of what is happening to the acoustic beam or EM field in a test piece.

There are many aspects of NDT modelling. Wave propagation, field effects, boundary interactions and basic electro-mechanical parameter considerations are all items that are modelled as a part of NDT processes.

Electro-mechanical modelling programmes such as PiezoCAD and PiezoFlex have been used by several of the major transducer manufacturers in designing new transducer lines or custom probes.

Some of the major training facilities such as CNDE in Iowa State University have been using (and developing) in-house software programmes that have been used as training aids. UTSIM, and XRSIM are examples of the training software developed at IOWA State. (Figure 1 illustrates an example of the probe directed at a CAD image and the resultant A-scan using UTSIM).

Figure 1 UTSIM Training Software (CNDE) [1]



Although the academic side of NDT has benefited from modelling, the field-applications of NDT has seen fewer examples of modelling than might be expected considering the size of the market. A few of the exceptions are addressed in this presentation.

Modelling Applications

Some of the areas in which NDT modelling has proven useful in field applications include:

- Aerospace
- Pipeline girth welds
- Vessel and structural welds
- Qualification/verification in the nuclear industry

Most of the examples from the field that are used in this presentation are taken from phased array applications. It is not pre-requisite that all the modelling be done using phased array systems, however, the variety of focusing and angles that can be achieved with phased arrays make them eminently suitable to blend with modelling principles.

Also of note, none of the modelling used in the North American examples has taken advantage of the mathematic modelling options such as FEM (Finite Element Method) or EFIT (Elasto-dynamic Finite Integration Technique). Hopefully this will change in the near future as the advantage of mathematic modelling becomes more evident to the Technical Justification requirements in several regulatory documents.

Aerospace

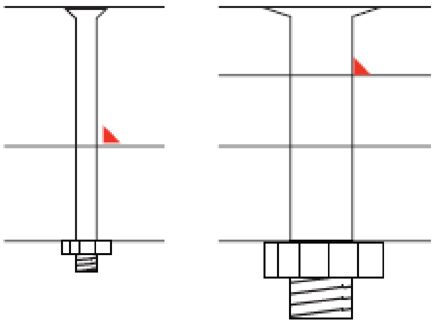
FastFocus [2]

A concern has existed for inspection of fasteners on the skin of military aircraft. The existing technology was imprecise and slow. Goals of the project included:

1. Detecting cracks 0.75 mm in length around faying surface fastener holes
2. Applying the technology to a wide variety of skin thicknesses and fastener hole diameters (see Figure 2)
3. Achieve a scanning time less than 1 minute per fastener
4. Provide the inspection system as a Handheld phased array head
5. Validate the system

Of the various combinations of fasteners and skin thicknesses, the large head fasteners with the thick skin prove to be the most difficult to address.

Figure 2 Aircraft Fasteners



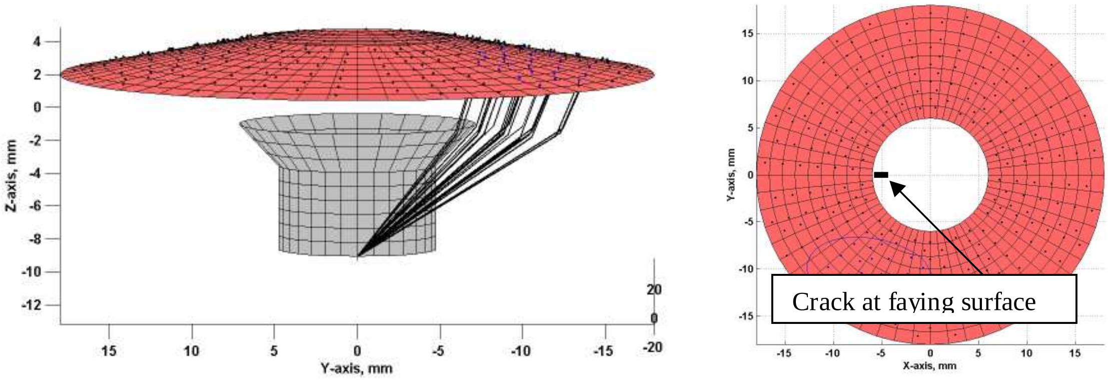
Faying Surface Corner Cracks in Fastener of two sizes: (a) small head/thick skin; (b) large head/thin skin

The engineering design was to be based on phased arrays using a conical array that self-centres. This would result in no moving parts and all scanning would be performed electronically. The concept also proposed that the inspection head be lightweight and hand-held.

The multi-angle, multi-position scanning provided by the phased array head was considered the best option to improve Probability of Detection of the flaws of concern.

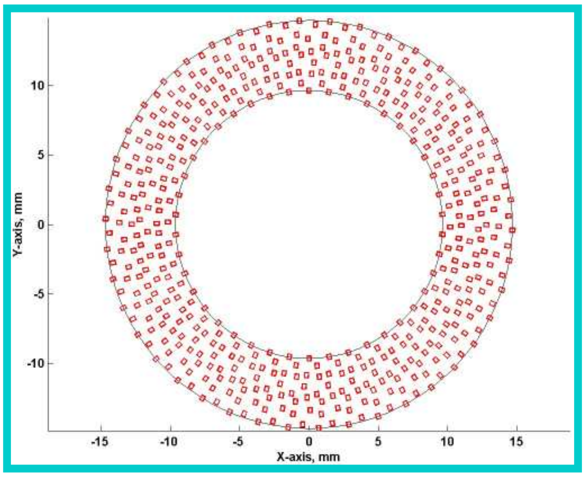
Modelling was carried out on the Probe design and the expected beam characteristics. The array design originally featured a conical matrix with 4,000 elements, each ~0.3×0.4 mm. 4,000 elements proved to be too many (cost and fabrication logistics) so this was reduced to 504 elements. To cover the 360° of the fastener the lower number of elements required a "Sparse" array design to avoid grating lobes. Feasibility modelling minimised grating lobes by using a "quasi-random" array. Figure 3 illustrates the modelled array with Figure 4 indicating the "sparse-array" configuration.

Figure 3 Conical array



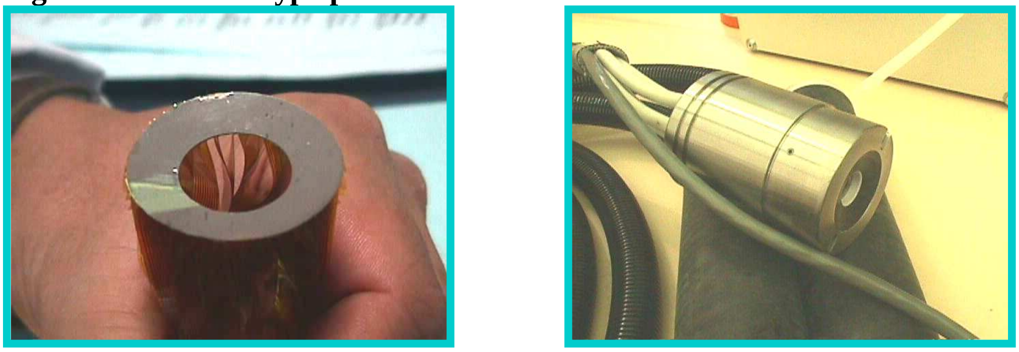
The beam (left image in Figure 3) is designed to be directed tangential to the fastener faying surface so as to strike the potential crack face perpendicularly.

Figure 4 Quasi-random sparse-array pattern



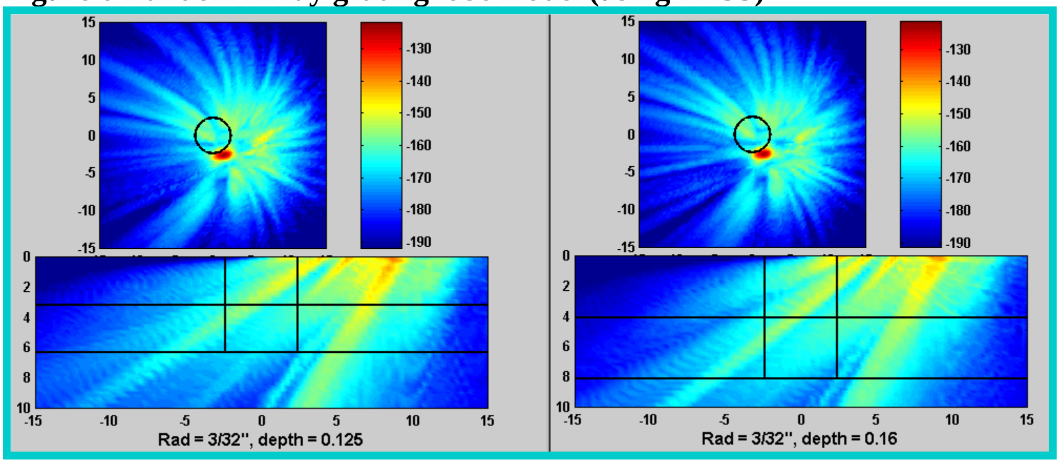
The quasi-random array model was then transferred to the manufacturer of the probe for the prototype fabrication. Figure 5

Figure 5 Prototype probe



The array output was pre-modelled for its beam characteristics using PASS (Phased Array Simulation Software). The results indicated that the randomness was suitable to reduce the grating lobes.

Figure 6 Random Array grating lobe model (using PASS)



3/16-in.-diameter fasteners on 0.125-in. skin (left) and 0.160-in. (right)

The array was eventually put into a housing (Figure 7) and the software equipped with both a centring system based on ultrasonic responses and an inspection sequence that provided 18 "hits" at each location in the modelled grid of the fastener. [1]

[1] All images in this section on the FastFocus were kindly provided by M. Moles of Olympus NDT.

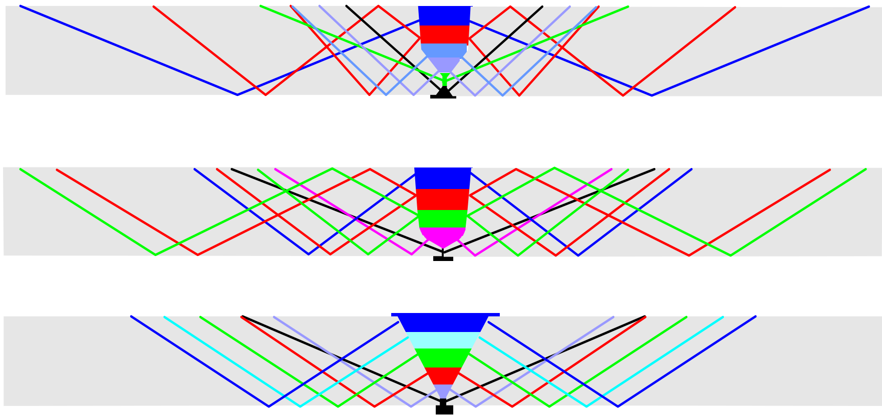
Figure 7 Fast FOCUS in Inspection housing on fastener mockup

Pipeline girth welds

Pipeline girthwelds have been inspected by UT instead of RT since the early 1990s in Canada and now more companies worldwide are finding it feasible to rationalise the change. In 1998 the first prototype unit using phased array system was used on a line in eastern Canada. That unit was built around the basic components of the existing generic phased array technology. After it had proven to perform as well as (or better than) the existing multi-probe systems, a concentrated effort was made to customise the software for the pipeline applications. Pipeline girth weld applications are generally repetitive with only minor variations in the weld bevel preparation and a small range of diameters and thicknesses. Typically diameters range from 24" to 36" (with some projects having smaller or larger diameters) and wall thicknesses from 10-35mm.

The inspection process is simple and fast. The weld is divided into zones typical1y 1-3mm high and beam angles are selected to optimise response off the fusion face of the weld bevel as shown in Figure 8.

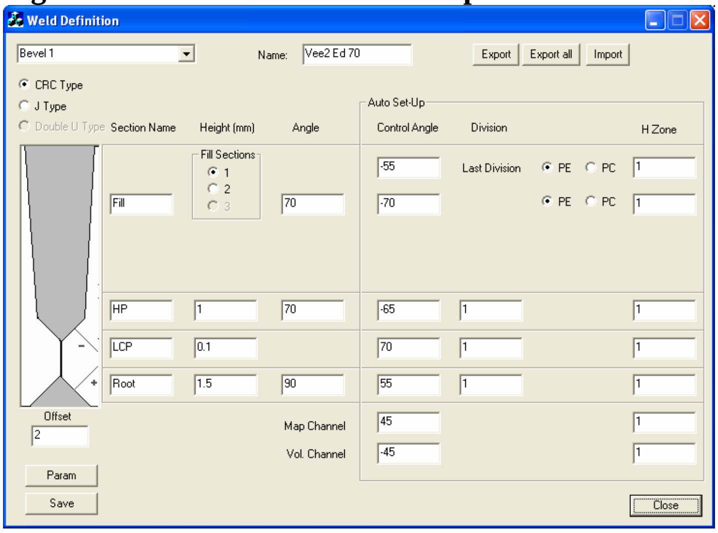
Figure 8 Schematic representation of weld zones and optimised beam paths for three weld bevel shapes commonly found in pipeline girth welds



The original multi-probe systems attempted to select focused probes that would be focused at, or as close as possible to, the fusion face. With the introduction of phased array technology the ability to achieve focus at the fusion line was no longer an approximation and zone discrimination was greatly improved.

In order to streamline the process of zonal discrimination, a modelling tool with a firmware feedback was developed. All phased array focusing is based on the Fermat model whereby a minimum arrival time along a given path is used to calculate the focal law delays. The girth weld inspection software was then designed to allow for the operator to design the weld by entering the appropriate values to define the bevel geometry and this included defining the number of zones desired. See Figure 9.

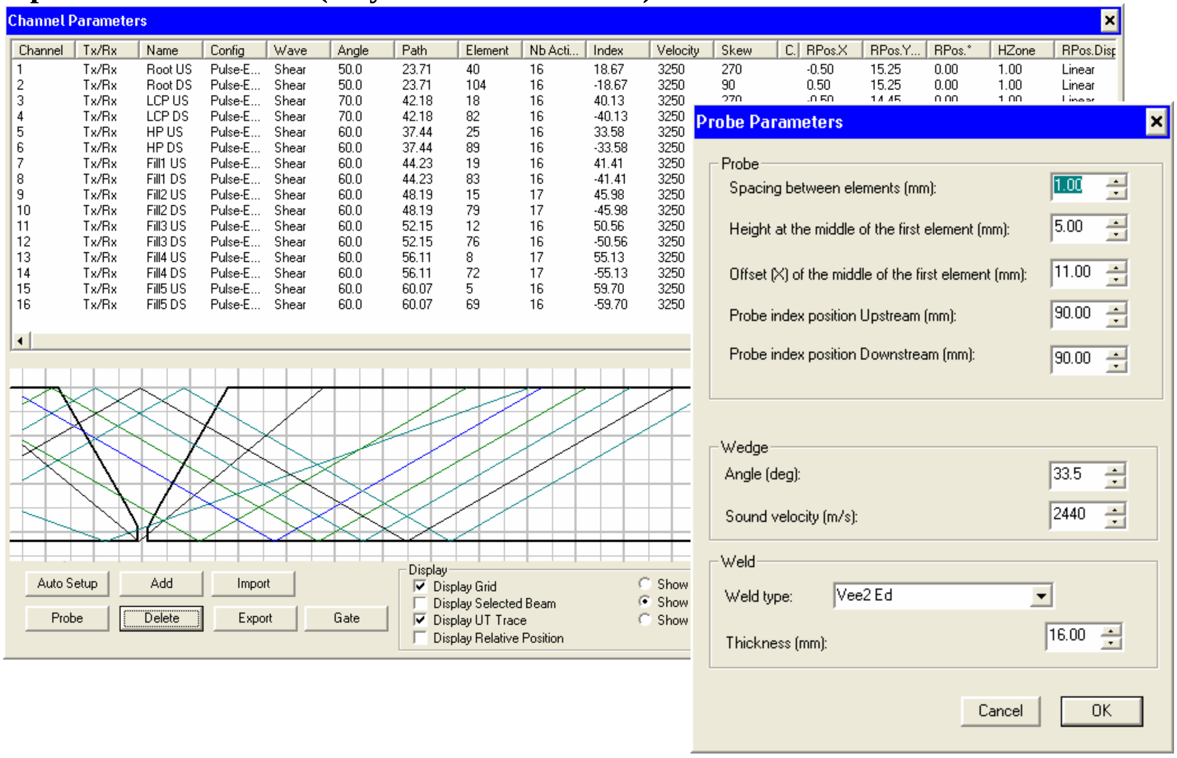
Figure 9 Weld Definition Graphic User Interface



This is used to calculate the positions of the calibration targets centred in each zone. This data is exported as a txt file and then used in the Focal law setup to prepare a set of focal laws that focuses the required beams at the ideal locations for the defined zones. Further information about the probes is entered in a separate GUI and then the weld bevel file is imported and the auto-setup clicked (see Figure 10). This displays a table of focal law parameters and a graphic representation of the centre of beam rays is provided indicating where the beam is directed and focused. In addition to providing a txt file from which the hardware focal laws are set up, the process also lays out the display for the data acquisition and analysis modes. The display is a combination of stripcharts, B-scans and TOFD.

Provided the acoustic velocities are entered correctly for the wedge and each angle in the steel, the operator is generally within one element of the ideal starting element and need only adjust the receiver gain. The modelling is clever enough to identify the optimum number of elements required to effect the focus at the soundpath calculated to each target. These parameters are coordinated with the probe and wedge parameters and a detailed list of the focal law parameters is calculated and displayed (see Figure 10).

Figure 10 Probe parameter GUI and auto-setup focal law generated with Raytrace representation to zones (only one side illustrated).



Prior to this phased array modelling feedback tool, the users of multi-probe systems would use Excel spreadsheets to calculate the "ideal" exit point and then use a ruler to position probes. Then they would still need to use a small hammer and tap the probes forward and back to optimise the signal. The manual multi-probe process could take 10-12 hours (and sometimes more) whereas the modelled phased array positioning reduces the calibration setup time to about 2 hours.

General Component Inspection

When dealing with weld inspections (other than pipeline) it seems that few outside the nuclear industry in North America are using modelling tools to their full potential. One exception is a Canadian company, Eclipse Scientific Products. Much of their work involves "special requests" to automate the UT inspection. This does not always mean "motorise" but it always involves encoding position. Over the past 3-4 years ESP have developed most of their solutions around phased array technology. When applied to irregular or complex geometries it is virtually impossible to design a "typical" inspection technique using the traditional pencil and paper. The variability of refracted angles in an S-scan and the potential for constantly varying test piece geometry makes it much more effectively addressed using CAD linked modelling of the ultrasonic beam. McCarley [11] has described in some detail the CAD process going from a client's product to the finished SLS (Selective Laser Sintering) prototype scanning system.

3D CAD modelling, when linked to ultrasonic modelling, allows a complete mechanised system to be designed on the computer. This avoids having to make several iterative empirical design changes as would be the case for a manual operator trying to locate a target or feature in a test piece and then providing measurements to a design engineer.

The process is usually multi-stepped.

1. A component requiring inspection is presented and then a 3D CAD drawing of it is generated or a client can provide a CAD drawing.
2. The areas of concern and most probable flaw orientations are identified
3. Access surfaces for testing are identified and distances and approach options to the areas of concern are ascertained.
4. Probe parameters for the material, surface access and inspection distance are determined and a probe is selected or designed (initially the probe is virtually designed)
5. The virtual probe is then positioned on a 3D representation of the component using a modelling programme that permits importing of the 3D CAD designed component. This ensures all dimensions (including the probe) are to scale.
6. A scan path or fixed position is then determined that will provide the most probable detection option
7. A specimen calibration piece and scanning rig can then be fabricated for demonstration

As an example, a scanner was required to investigate the flange seal face while the flanges were still bolted in situ. The client supplied details of the flanges and bolting arrangements (in particular the protrusion of the bolts was required to determine the nearest approach of the wedge that was possible from the flange taper. A CAD drawing was made of the flange with provision to adapt to other sizes (using the Standard Pipe Schedule tables).

Next, a dual linear array probe wedge was designed that allowed for the taper and nearest approach possible with the bolts. The Flange and Wedge design were then exported to the raytrace modelling programme and the optimum skew and roof angles were assessed. This was then sent back to the CAD designer who implemented the iteration on the wedge design and then integrated the optimisation into the scanner design. Animation of the motion was possible using the 3D CAD programme to verify that the hold-down mechanisms and probe would not strike any components during the scanning. An SLS prototype of the relevant scanner components was made and mounted on the actual test piece to confirm the final functionality. The main parts of the design process are summarised in the images below. (See Figures 11, 12 & 13)

Figure 11 Flange and Wedge as CAD Solids

Flange Design Wedge Initial design

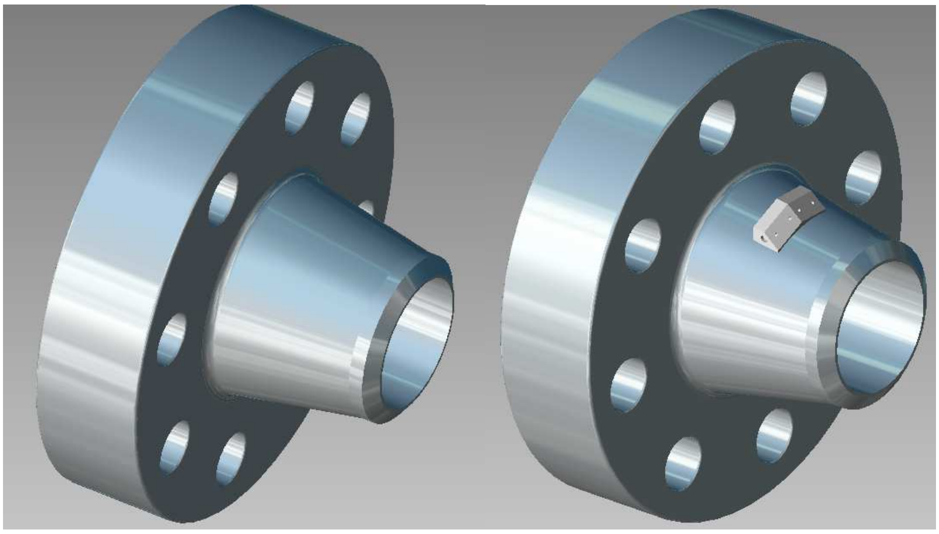


Figure 12 Raytrace optimisation of wedge and placement

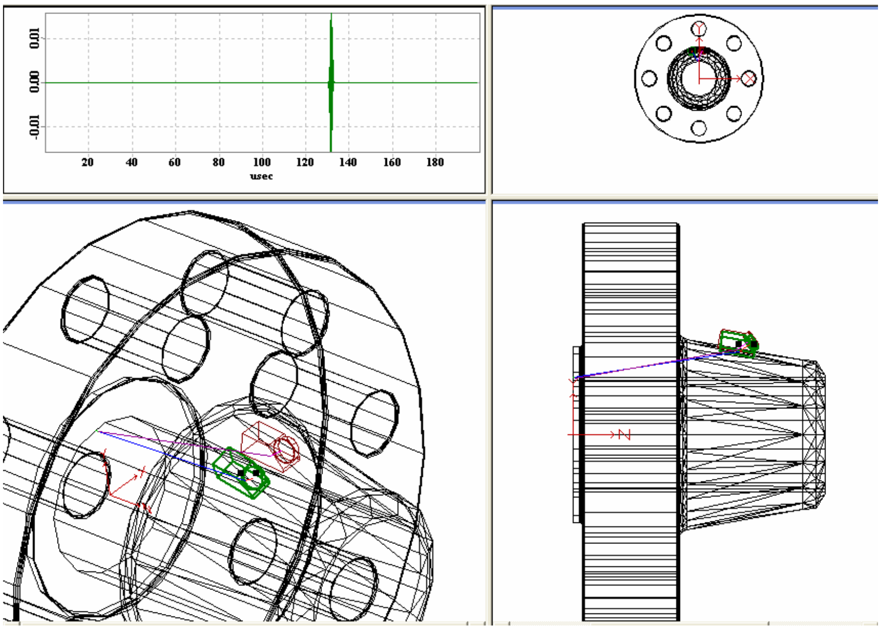
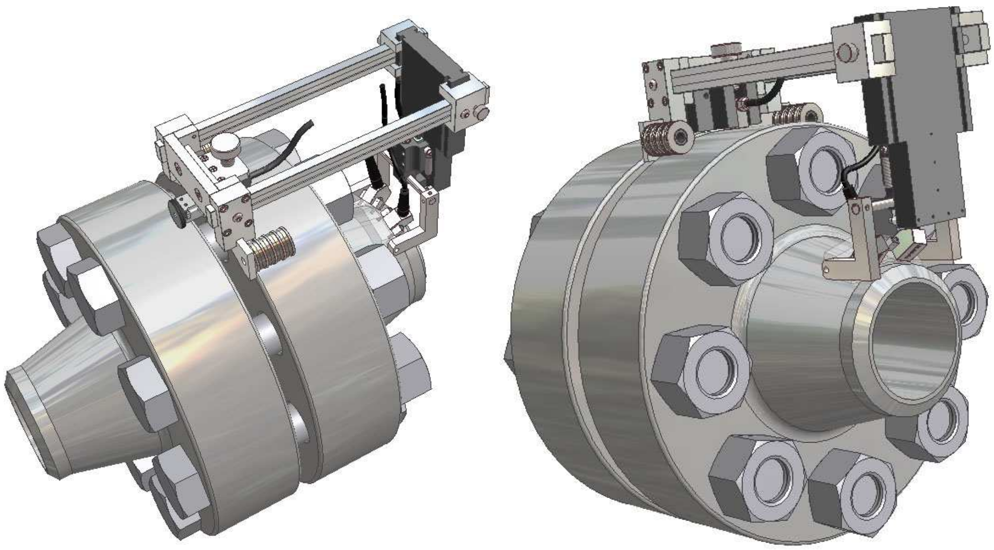


Figure 13 Scanner Assembly with motion options



Phased Array Butt Weld Models

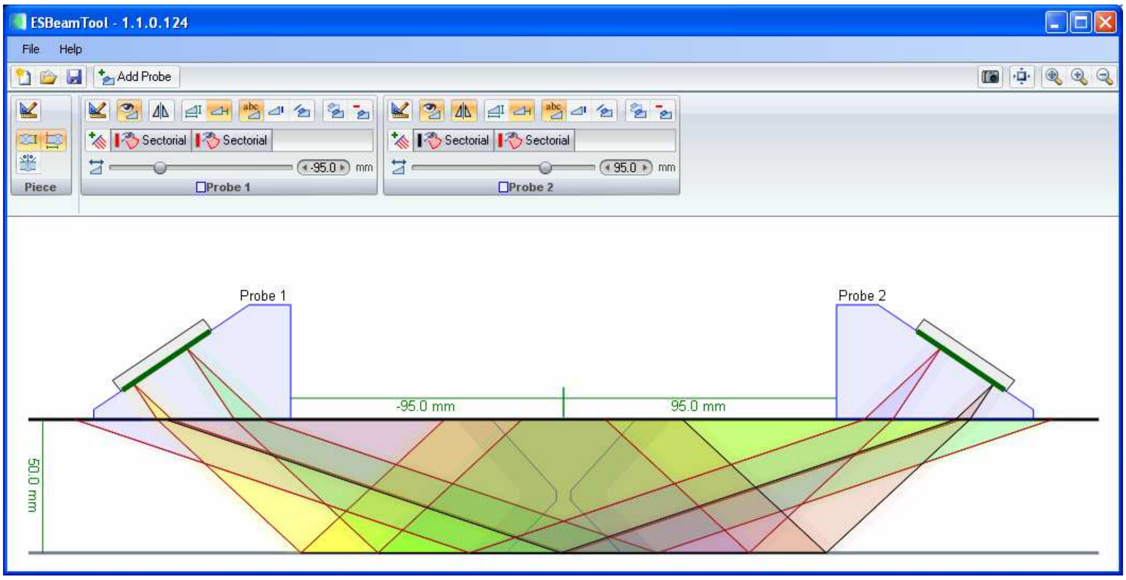
Even simple weld inspections using phased array probes require some planning to ensure adequate coverage when trying to minimise probe movement to a single line scan.

S-scan inspections of simple butt welds can often be done using a single probe standoff. However, this usually requires at least 2 sets of S-scans and a probe with sufficient elements that can provide starting elements in the S scan focal laws that are sufficiently spaced.

Optimisation is made using a very simple raytrace model indicating the weld bevel with weld cap allowance, heat affected zone and probe/wedge dimensions.

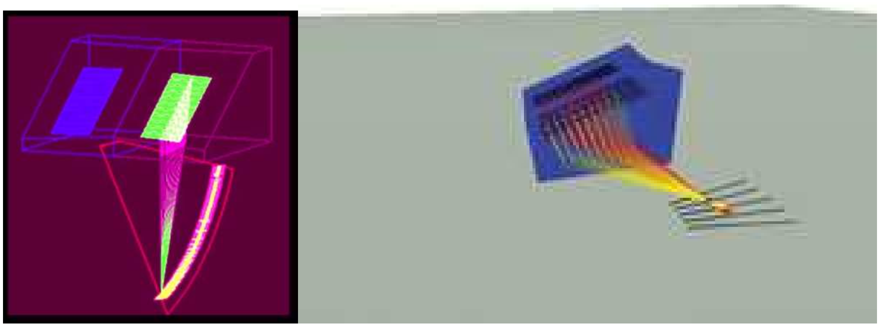
The image indicates a 50mm thick plate with a pair of phased array probes on each side, each with 2 sets of S scans (45°-70°). In Figure 14 coverage from a single S-scan per side is seen to be inadequate to achieve full volume coverage.

Figure 14 S-scan Coverage verifications



More elaborate modelling options linked to the phased array focal law setups are provided by the manufacturers. ONDT (Olympus NDT) has developed the Advanced Focal Law calculator and Harfang Microelectronics provides their Phase FX software for modelling the beamforming delays and resultant focalisation. They are ideal (and absolutely necessary) when the array is a 2D array with steering in more than one plane.

Figure 15 Phased Array Beamforming Models



Phase FX Advanced Focal Law Calculator

Nuclear Applications

This presentation is intended to highlight modelling in North America. Examples provided so far have been used by both Canadian and American companies for applications as varied as pipeline, aerospace, general weld inspection, probe design and even system design. The examples have all been transducer or Raytrace applications.

Unfortunately, until recently in North America, there has been very little opportunity for the more elaborate modelling options available as described by authors such as [3,4,5] who have pointed out the advantages of mathematic modelling. Best hopes for this situation to change lie in the nuclear field.

Background on Differences

This presentation has been portrayed as a "North American Overview" but in the nuclear industry the entire continent cannot be considered in the same light. To understand this will require a short background in the regulatory differences between Canada and the USA.

Ashwin reported on the American approach in a 2001 conference in Seville, Spain. He noted that;

"…the 1989 addenda of the ASME Boiler and Pressure Vessel Code, of Section XI, introduced new requirements for the performance demonstration of ultrasonic procedures, equipment and personnel. Starting in the early 1990's the United States Nuclear Utility industry organized a project aimed at implementing the requirements of ASME Section XI, Appendix VIII on a uniform basis. This project is commonly referred to as the PDI - Performance Demonstration Initiative and includes representatives from all US utilities as well as some foreign organizations that also utilize ASME.

On September 22, 1999, that the US Nuclear Regulatory Commission (NRC) issued their final ruling on the implementation of ASME Section XI, Appendix VIII. Within the NRC ruling a schedule was included for Nuclear Plant licensees to comply with the requirements. Additionally the ruling included supplementary requirements to *those specified by ASME. In anticipation of expanded the requirements PDI has proactively engaged in qualifying NDE procedures and personnel in accordance with a program that complied with the full requirements of the NRC ruling".*

Until 2003, there was no way in which the American users of ASME, attempting to meet the NRC requirements could do other than a performance demonstration of a new examination system. The 2003 revision to the 2001 Edition of ASME Section V added a new Article. Article 14 covers Examination System Qualification. Article 14 specifically states it is for "qualification of systems when specifically invoked by the referencing section". Since Section XI specifically requires NDE examination systems to be qualified this is a much needed clarification for what seemed to be an "unformatted" scenario prior to 2003. The new Article 14 now sets out the guidance and involves the evaluation of general, technical, and performance-based evidence presented within the documented technical justification, and when required, a blind or non-blind performance demonstration.

In the explanation of the Technical Justification requirements the Article 14 describes a list of items that MAY be used:

> The technical justification provides the technical basis and rationale for the qualification, including:
> *(a)* mathematical modelling
> *(b)* field experience
> *(c)* test hierarchy ranking
> *(d)* anticipated degradation mechanism
> *(e)* NDE response by morphology and/or product form

Therefore, as of 2003 users of ASME in the USA may now augment rationale for NDE systems with mathematic modelling. However, as of 2007, none have used this opportunity as part of their qualification process [12].

Canada took a slightly different approach. Much of this has to do with the difference in regulatory hierarchies between Canada and the USA and the fact that there is no "private" ownership of nuclear power generating stations in Canada. In Canada provincial governments own and operate nuclear electric generating stations. The regulating Code for Periodic Inspection of Nuclear components is CSA N-285.4.

The Canadian federal government has set safety requirements for reactor operations in an Act of Parliament (the Nuclear Safety and Control Act) and assigned a crown corporation, the Canadian Nuclear Safety Commission (CNSC) to oversee their enforcement. Design, manufacture, construction, commissioning, operation, inspection, maintenance, and decommissioning of nuclear facilities in Canada are subject to the provisions of the Nuclear Safety and Control Act and Regulations as well as other regulatory documents of the Canadian Nuclear Safety Commission (CNSC). The CNSC may impose requirements additional to those specified in N-285.4.

The standard N-285-4 reflects the common ground of all the concerned parties as representatives from manufacturing, design, operations and regulatory agencies all contribute to the document.

The CSA code points out that periodic inspection is not intended to discover flaws or weaknesses overlooked during the stages before plant start-up, nor should it be implemented as a means of providing additional manufacturing or installation inspection. However, during the operation of a unit there may be processes or conditions that were unforeseen at the design or fabrication stage.

When components or materials are used beyond the original conditions of service these should be added to the periodic inspection programme. The CANDU units have identified several areas where this situation has arisen and the affected components have been specifically added to the scope of the document. Steam generator tubing, fuel channel pressure tubes and fuel channel feeders have been added as appendices to the document.

The requirement to "qualify" a new system as is done for the NRC in the USA has its equivalent in Paragraph 4.2.6 in N-285.4

4.2.6
A procedure that deviates from the above requirements(*) shall be proven capable of yielding results to a sensitivity appropriate to the system/component. The procedure shall be submitted to the regulatory authority and approval should be obtained before inspection commences.

(*) The requirements referenced are the standard examination practices stated in ASME Section V and for ultrasonic examinations it references Article 4.

With the responsibility of the Licensees to "demonstrate" the efficacy of their procedures, Canadian licensees began to consider the method by which this process would fit into the Canadian requirements. The EPRI PDI method was looked at but the concepts they discussed were all concerning weld inspections and the use of ASME "Grading Units" did not fit their requirements. Around the same time the European community was looking at similar qualification requirements and began developing what became the ENIQ programme (European Network for Inspection Qualification) initiated in 1992.
The ENIQ concept is limited to providing general guidelines on how inspection qualification should be carried out. It does not, in itself, constitute a specification for NDT qualification for a specific component but is intended to be used as a basis for development of such specifications. Because of this more flexible aspect and the fact that they would not have to make special "modifications' to an ASME programme that did not allow for the CANDU situation, the Canadian Licensees agreed to adapt to the ENIQ format. This lays out a common approach consisting of required documents that includes a Technical Specification, a proposed Inspection Procedure and the Technical Justification. Several groups within the Canadian nuclear community have taken advantage of modelling to assist in their development programmes [9, 10].

The ENIQ recommended practice for the contents of a Technical Specification [7] allow for modelling to "to help show that the required inspection performance for detection and/or sizing can be achieved". In fact, a separate Recommended Practice [8] augments the ENIQ Procedure collection.

The concepts of this modelling "tool" were added to some of the background information presented as part of the Technical Justification carried out by COG (CANDU Owners Group) in development of the inspection methods used to assess the Fuel Channel feeder tubes.

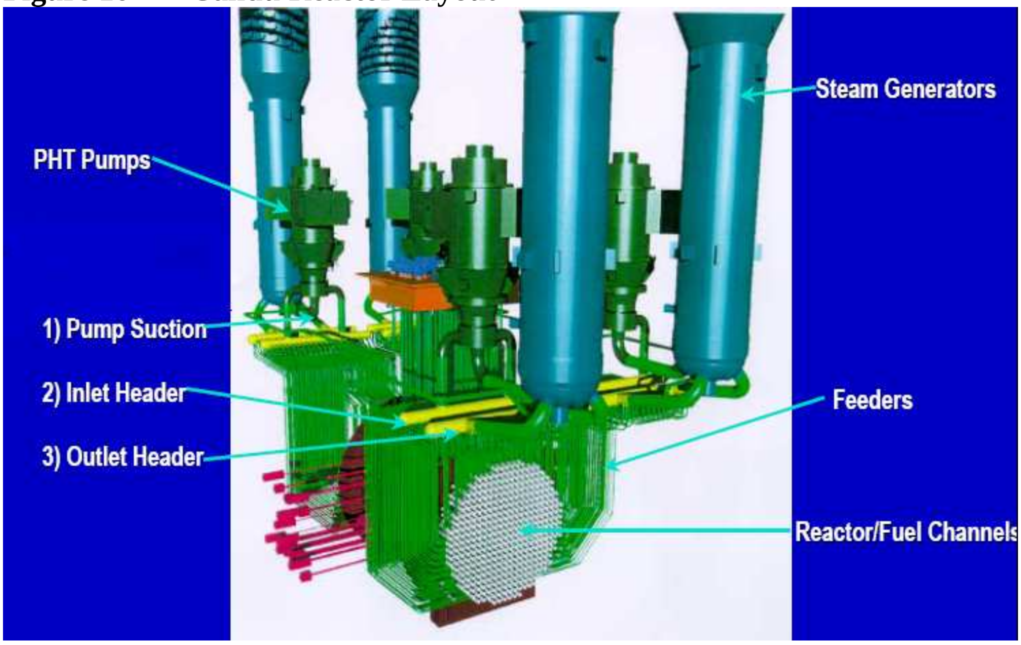
CANDU Fuel Channel Feeder Tube Inspections

There are 18 CANDU reactors in Canada and several others in Korea, Argentina and Romania. Although not exactly identical they share many common aspects of design; in particular the Fuel Channel and on-power fuelling capabilities. This commonality is the foundation of the CANDU Owners Group.

Therefore, when one of these CANDU reactors exhibited a problem with SCC (stress corrosion cracking) in the feeder tube elbows, all similar units shared a concern that it may be a design issue. Therefore a programme to monitor the component was developed by all.

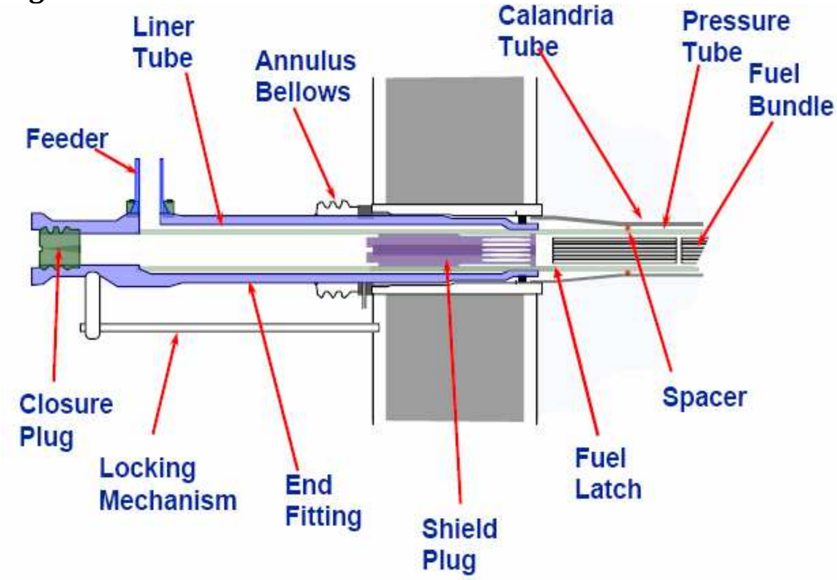
The CANDU reactor is unique amongst reactors in that its fuel is horizontally loaded and can be re-fuelled while the unit is on-line. A pictorial of the reactor is provided in Figure 16.

Figure 16 Candu Reactor Layout



Heavy water is used as both the neutron flux moderator and as the heat transport fluid. The heat transport heavy water is fed into and out of the fuel channels via the Feeders, seen in Figure 17.

Figure 17 Fuel Channel with Feeder connection



The first indication of a problem was seen in Point Lepreau Nuclear Generating Station where a feeder was found to leak in Dec. 1996. The cause of leak was identified as a crack in an outlet feeder. A programme of inspection was initiated using manual UT to determine if this was an isolated event or a systemic problem. Two other "suspect" feeder pipes were identified and subsequent analysis identified the problem to be a form of stress corrosion cracking.

The manual inspection process was daunting. It involved working in a radiation zone with very poor access for probe movement as shown in Figure 18.

Figure 18   Limited access requiring multiple skip technique

The detection method proposed used a multi-skip transverse wave directed around the circumference of the pipe that was intended to detect the inside and outside surface-breaking flaws. The process worked well on EDM notches and the inspection technique was continued as part of the periodic inspection programme.

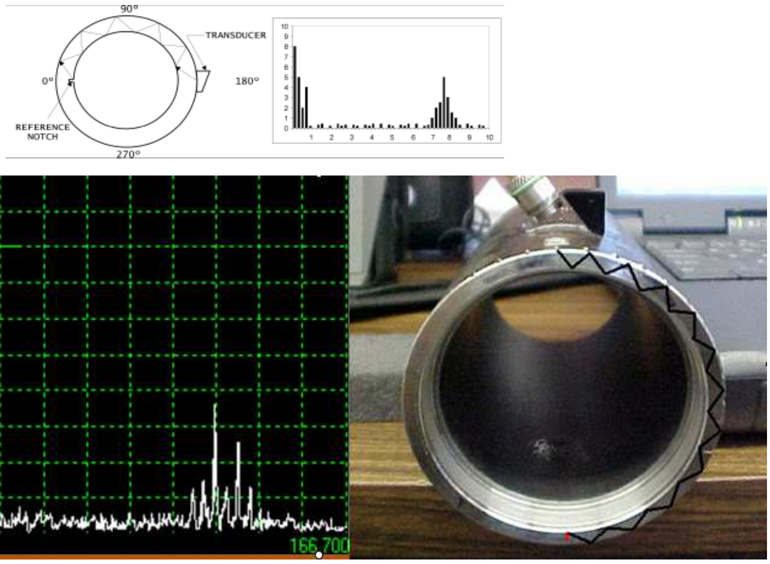
In addition to the periodic programme, a validation process was also put into place to determine the efficacy of the tests. This became a qualification programme that also introduced raytrace modelling, visualisation, and cracked sample mock-ups for reliability POD (Probability of Detection) assessments.

The modelling (raytrace and visualisation) were used as tools to both understand the nature of the signals and to provide a training tool to the technicians.

Inspection Concepts

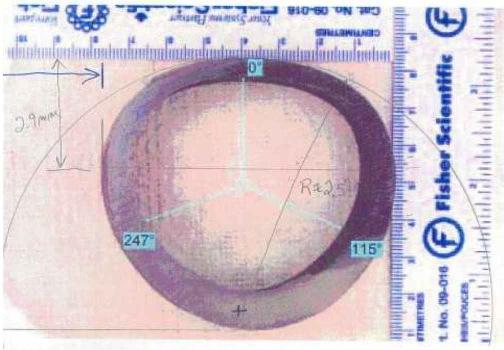
The setup for the Feeder Pipe inspections involves directing a nominal 45° refracted transverse wave around the pipe. This results in detection of the small reference notch, but the signals are not the "normal" sort of signal that an operator expects. Instead of a single response there is a group response with some signals earlier and some later and a poorly defined "peak" signal. The A-scan display of a simple notch is shown in Figure 19.

Figure 19 Multiple response from notch



In addition to this issue, the measurement of signal position as a simple relationship between sound-path and circumference is not possible. The pipes in the area of concern were bent to form elbows. This results in a thinning of wall on the extrados and a thickening of the wall on the intrados. This left an elliptical shape with wall thicknesses varying from 5mm to 9mm. A sectioned piece from a removed sample is presented on a scale in Figure 20.

Figure 20 Sample Cross section of bent Feeder Pipe

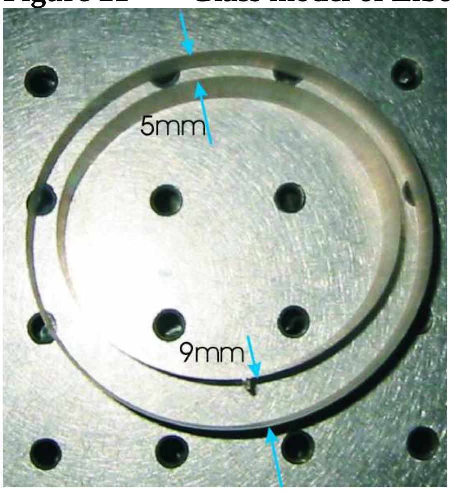


Simple modelling of a pipe with concentric ID and OD and using a single 45° centre of beam ray was therefore not suitable to explain the observed signals.

To provide answers to these questions a pulsed raytracing model and a photoelastic visualisation model were made.

The glass model was made using fused silica 25mm thick and cut to shape using a computer controlled glass cutter. The model is shown in Figure 21 with a notch cut on the ID surface near the thick section.

Figure 21 Glass model of Elbow

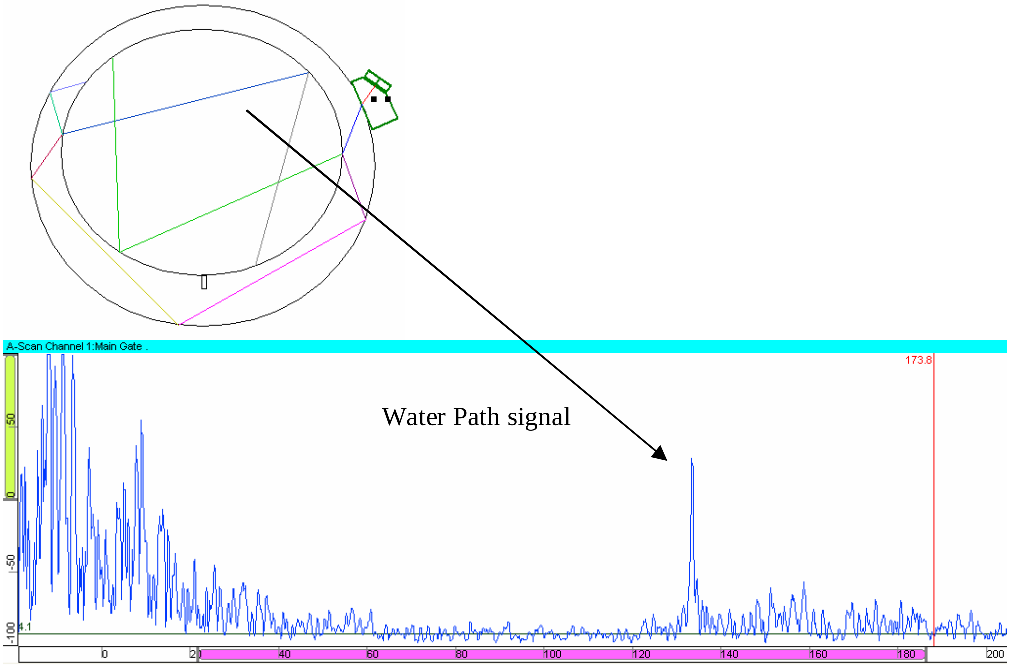


The acoustic velocity of fused silica is 5970m/s in compression mode and 3750m/s in shear mode. Since the shear mode is the "intended" mode for inspection and the glass model is 500m/s higher than the carbon steel, a slight modification to the incident angle had to be made to get a nominal 45° refracted angle.

A similar "model" was made in the Raytrace programme used but this allowed for "adjustment" to match the material parameters. Carbon steel velocities of 5940m/s and shear mode of 3250m/s were used.

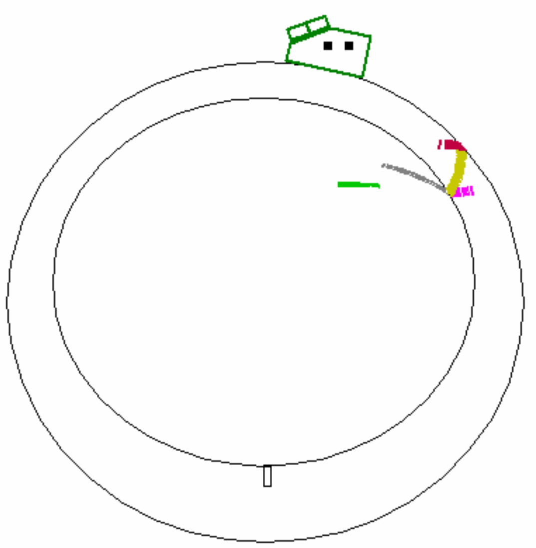
A further adaptation was required to duplicate the physical test conditions. During inspections the pipe is filled with heavy water. Heavy water has an acoustic velocity of 1430m/s compared to light water at 1480m/s. This provided a means of illustrating the odd signal that originated from the compression waves transmitting into the pipe. Raytracing (Figure 22) was capable of illustrating the origin of the waterpath signal seen during the in-service monitoring.

Figure 22 Raytrace modelling to illustrate waterpath signal (lower image is a capture A-scan of the waterpath signal)



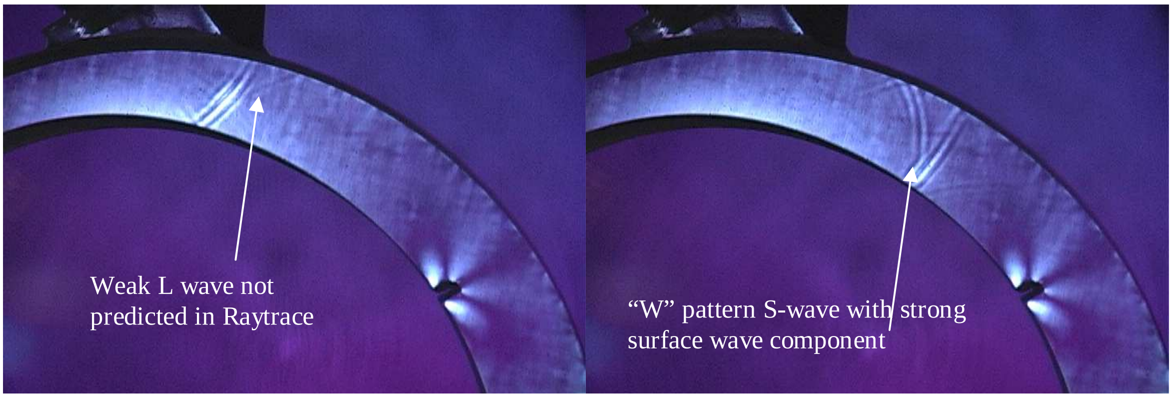
Origin of the multiple arrivals seen at the target notches could be understood once the modelling was used to illustrate the effect of beam divergence. After 2 or 3 skips the divergence provides a "W" shaped pulse moving within the wall. The W shape and the transfer of pulses to the internal water are illustrated in the modelling shown in Figure 23.

Figure 23 "W" shaped pulse modelled by beam divergence



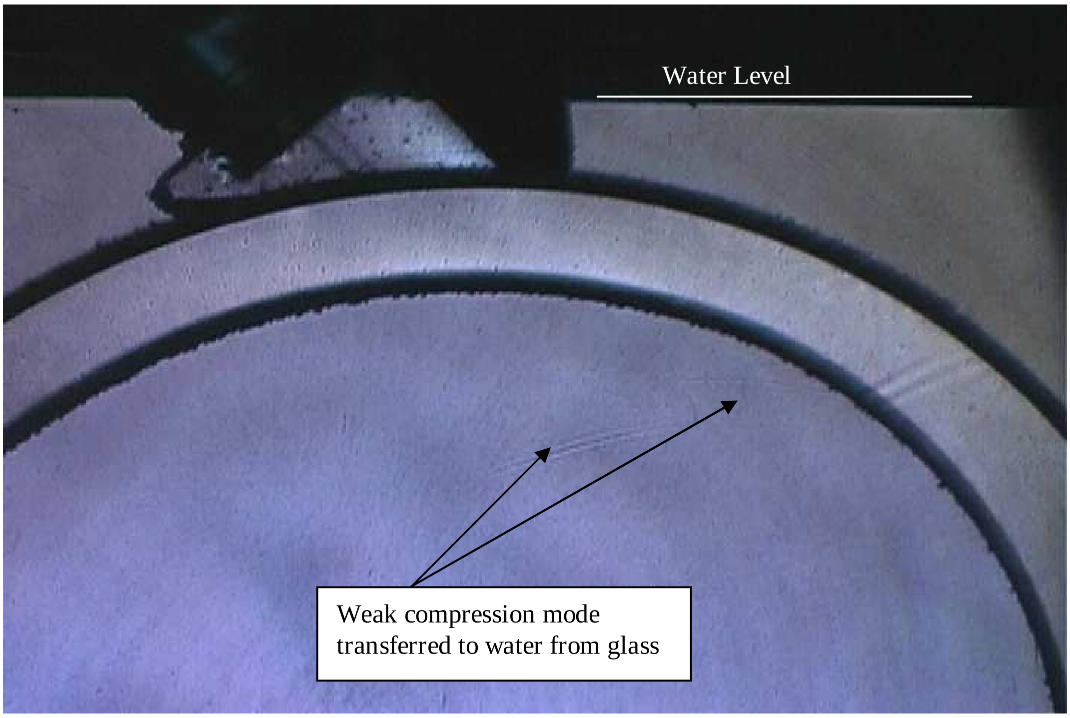
These effects were seen as well on the photoelastic model. The effects predicted in the Raytrace modelling were confirmed when the glass model was used to simulate the conditions using photoelastic visualisation. Phtoelastic visualisation was able to illustrate the presence of weak compression modes that were not predicted by the raytrace model as these were a result of diffraction at the entry surface. See Figure 23.

Figure 23 Confirmation of W shape and discovery of diffraction effets by photoelastic visulaisation



Transmission of the pulse into light water was possible to illustrate with the photoelastic modelling, however, the signals were difficult to see in the water due to a much smaller intensity and shortening of the wavelength. As a result it was not considered useful to further develop the immersion experiment using heavy water. The weak signals from the transmission of pulses from the glass to the light water are seen for two skip points in Figure 24.

Figure 24 Transmission of compression mode to water



The modelled aspects of the project were capable of explaining the nature of the signals received in the real conditions. As such, they were adapted into parts of the training materials used to prepare operators for what to expect when performing data acquisition on the reactor face.

Conclusions

Modelling has been available to a variety of industrial venues in North America. Although some advanced facilities have taken advantage of the modelling tools available, its benefits seem to have been under-utilised in the general NDT service industry.

With the increasing demands for demonstration of performance and it now being mandated as part of the ASME BPV Code, there seems to be some hope for future growth of modelling use in industry.

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