Application of Ultrasonic Simulation Technology in Technical Justification of In-Service Inspection of Nuclear Power Plant

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Abstract:

Ultrasonic modelling and simulation are widely used in inspection qualification by industrial non-destructive test. Due to limitation of inspection conditions and radiation environment inside the nuclear power plant, it is useful to study the application of ultrasonic simulation technology to in-service inspection in nuclear power plant. Simulation can be used to demonstrate the inspection capability and determine the inspection scope and inaccessible area. Meanwhile for the in-service inspection of nuclear power plant, application of ultrasonic simulation technology can enhance the effectiveness while site inspection and reduce the cost associated with inspector training.

This paper firstly reviews the application of ultrasonic modelling in inspection qualification in the world. Then according to the actual dimensions of nozzle to shell weld of one reactor pressure vessel, simulation is used to help determine the inspection parameter. Another example is for dissimilar metal weld in nuclear plant, the coarse grain of material and energy loss as sound transmits across different material interface result in lower signal-to-noise rate; the simulation technology is utilized to compare the inspection validity and limit of different probe. Both simulation results indicate that ultrasonic simulation is useful for inspection parameters and technical justification for in-service inspection, especially for extension of applicability to more complex configurations and to enhance its reliability.

Keywords: Ultrasonic simulation, technical justification, in-service inspection, dissimilar metal weld

1. Introduction

With rapid development of nuclear power plant (NPP) in China, non-destructive test (NDT) makes a vital contribution to nuclear power plants, helping us to guarantee the reliability of key components before they enter service to ensure that no manufacturing flaws are present, and during periodic plant outages to make sure no damage has taken place during operation. These delicate tests are performed on some of the most sensitive components in the plant, reactor pressure vessel, steam generator, coolant piping system, and et al, to prove their fitness for purpose.

However the ultrasound wave propagation through complex geometry component or anisotropic materials is not straightforward due to the skewing of energy flow direction with respect to the direction of phase velocity. For instance ultrasonic inspection of dissimilar welds is still a challenge due to the different acoustic impedances across the interfaces between parent metals, welded, butter or cladding regions. Typically parent metals are fine grained carbon/ferrite/steel, which show isotropic character. Whereas weld/buttering/cladding metals are inconel/ austenitic steel, which exhibit anisotropic character, attributed to their columnar grained texture resulting from the high thermal inputs during welding process.

Nowadays numerical simulations play a role in an increasing range of NDT applications. The objectives pursued by the NDT operator using simulation are very different. Simulation is commonly used to conceive methods and demonstrate their performances at a low cost [1-2].

2. Simulation in Ultrasonic NDT

A mathematical model of NDT may be defined as any theoretical algorithm or method which generates quantitative predictions about some aspect of inspection performance. Usually the algorithm is implemented as a computer code, although some models may be amenable to hand calculation using simple mathematical formulae or implementation in spreadsheets. A wide range of models has been developed to satisfy different inspection requirements. For example, in ultrasonic, models have been developed which provide the following application [3]:

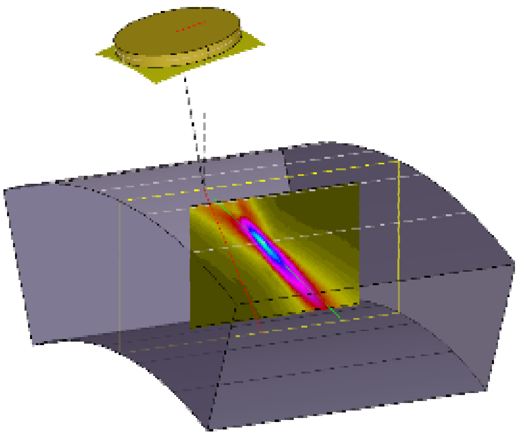
- calculations of ultrasonic beam paths or wave fields in components of complex geometry, possibly including reflections off postulated defects;
- predicted echo amplitudes from postulated defects as a function of probe position;
- predicted beam paths or wave fields in anisotropic and possibly inhomogeneous material such as an austenitic weld, possibly including reflections off postulated defects

Mathematical modelling of the ultrasonic NDT situation has become an emerging discipline with a broadening industrial interest in the recent decade. New and stronger demands on reliability of used procedures and methods applied in e.g. nuclear and pressure vessel industries have enforced this fact. To qualify the procedures, extensive experimental work on test blocks is normally required. A thorough validated model has the ability to be an alternative and a complement to the experimental work in order to reduce the extensive cost that is associated with the previous procedure. The most significant advantage of a computational fast and against experiments validated and verified model is its capacity in parametric studies and in the development of new testing procedures.

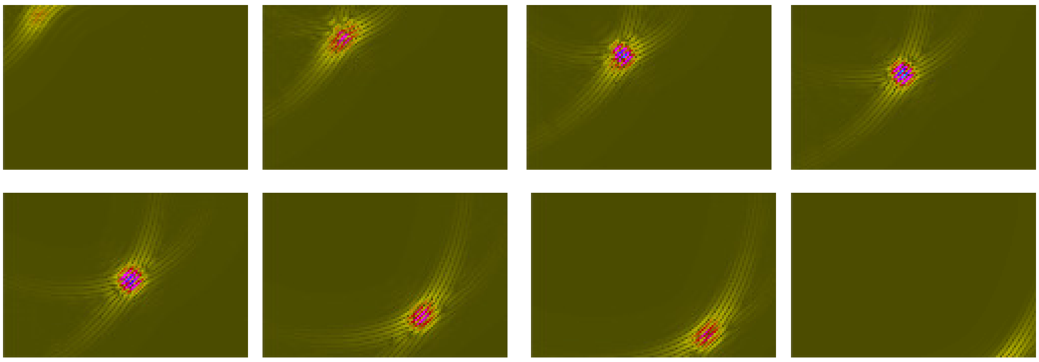
Computer models have been used for many years to simulate inspections, aid interpretation of complex data and defect characterisation, examine parametric effects, optimise the planning and procedures for an inspection, aid validation or provide input to safety cases. To date a couple of models have been developed that cover the whole testing procedure, i.e. they include the modelling of transmitting and receiving probes, the scattering by defects and the calibration. These can vary from simple physical models to proper simulation models [4], to sophisticated simulators linked into CAD design packages such as AEA Technology's MUSE or CEA's CIVA model which can display real and simulated NDT data. Such models may simulate the inspection process and data and allow geometric effects, probe angle and location and coverage to be optimised or the signal be calculated. Chapman [5-6] employs geometrical theory of diffraction for some simple crack shapes and Schmitz et al develops a type of finite integration technique for a two-dimensional treatment of various defect types. These models are compared with experiments within the PISC project by Lakestani. Overviews of the modelling of ultrasonic NDT are given by Gray et al and Achenbach [7].

2.1 Beam field of probe in carbon steel

The CIVA software is an expertise platform dedicated to non-destructive test. It is composed of simulation, imaging and analysis modules, which allows to conceive or to optimize inspection techniques and to predict their performances upon realistic NDT configurations. CIVA could deal with in terms of wave propagation and echo formation simulations; allow both to optimize and to predict performances of phased array techniques. Figure 1 show the beam transmission in one sequence time when the 2MHz frequency transducer with 40 mm diameter element emit sound wave in carbon steel block. Each map of Figure 1(b) show different transient time of one sound pulse.



(a) Beam field of an immersion probe in block.



(b) Series beam transmission with continuous moment time.

Figure 1 Beam field of probe in carbon steel

The simulation tools have been used to illustrate the ability to predict and to compensate beam distortions or deviations which may occur through a complex shaped specimen.

2.2 Simulation inspection of a piece with complex surface

To predict results obtained with the defect response module for a piece with a complex surface, where there is a significant beam width irregularities, Figure 2 demonstrate the influence of complex surface geometry to predict the beam echo reflected from the defect. Three notches are placed each with 5mm height, 0.2mm length and 45° tilt angle, which located separately below the flat surface and complex surface as shown in Figure (a). The incident beam is computed in real-time beam computation module. The simulation B-scan image with online beam computation is shown in Figure 2(b). Superpose the echo dynamic curves of above two modes simulation results, as in Figure (c). It can be seen clearly that complex geometry influence beam interaction with defect compared with the flat surface.

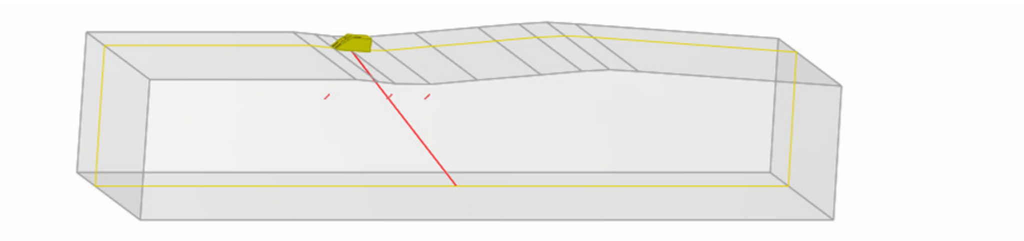


Figure (a) Complex surface piece with three notches

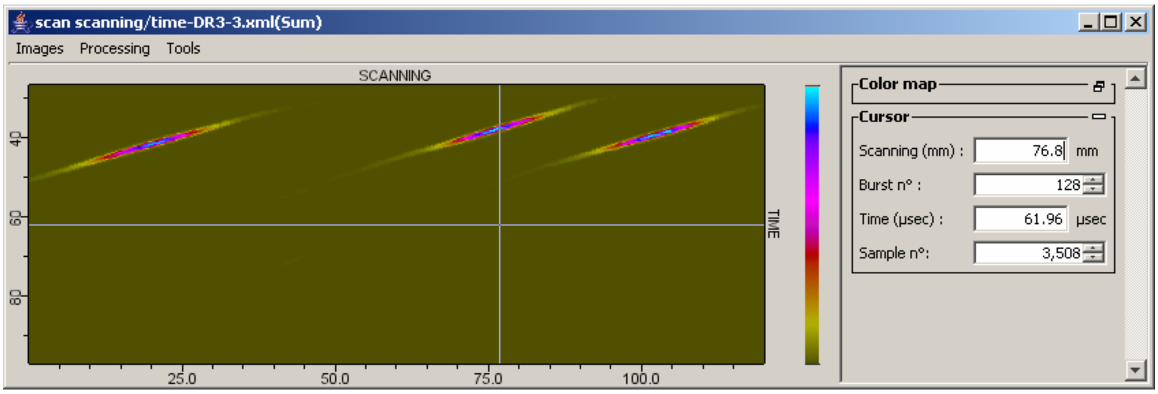


Figure (b) Simulation of inspection with real-time bean interaction with defect

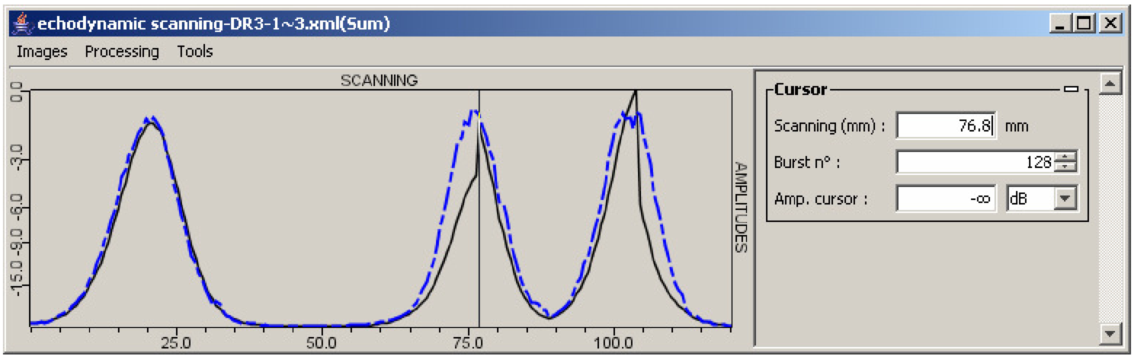


Figure (c) Comparison of curved between stored beam (solid line) and real-time beam (dotted line)

Figure 2 Beam interactions with defect under complex surface geometry

3. Ultrasonic simulation in the technical justification process

In order to ensure the safety and integrity of nuclear power plant components, extensive qualification efforts are achieved to reach the highest level and provide the best guarantees. Taking into account the American and European demonstration methodology standards ASME and ENIQ [8], it defines the settings and operating rules of in-service inspection and describes the methodology used to demonstrate the performances of NDT techniques. As new tools and innovative technologies expand, the use of modeling becomes of more and more value to help in the qualification procedure. By ultrasonic simulation software, given a component and an ultrasonic transducer, echoes arising from defects and component geometry are interactively and automatically computed, stored, displayed as ultrasonic images and can be analyzed and compared with experimental acquisitions.

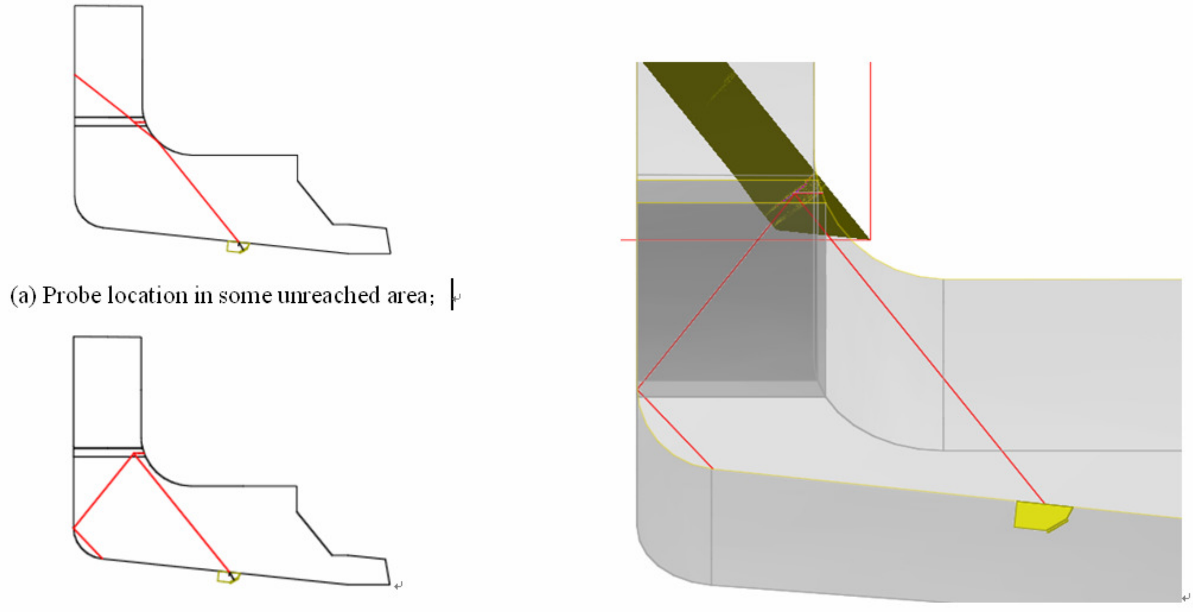
According to the rule for in-service inspection, a technical qualification is associated with each area. It consists in assessing the whole NDT system (equipment, procedure and operators) to ensure it meets the required performances in in-service inspection conditions. According that an indication has been detected and that it may have safety and integrity consequences, different classes of qualifications are applied in RSEM (Rules for in-service inspection of nuclear power plant mechanical equipment): conventional, general or specific qualification[2, 9]. For very specific cases, an inspection can lead to an expertise. All qualifications are based on:

- Experiment assessment (test on mock-up or block contained artificial real defect)
- Technical justification: It involves application feed-back, available documentation about the technique, laboratory studies, state of the art defined in codes and standards, and modelling.

The combination of these information sources depends on each application but from a technical and economic point of view, the use of simulation is obviously of the high interest. Nowadays, models as those developed in simulation software can deal with increasingly complex examination configurations, thus most of the NDT configurations encountered can now be simulated. The flexible models make it possible to identify the influential parameters of a configuration. A quantitative estimation of the effects of any variation of one or several parameters in the configuration can be performed.

3.1 Nozzle to shell weld inspection parameter

For nozzle to shell weld in reactor pressure vessel a pilot study was made by simulation for determining appropriate inspection parameter. Figure3 shows the geometry and probe location. The probe is with 1.5MHz frequency, 45 degree shear wave refraction angle in workpiece and element size is 25mm x 23mm. The notch is located in weld near outside surface with 30mm width and length. From the simulation result, owing to the geometry influence to sound beam path, the 45 degree probe is of some difficulty in detecting the defect near shell outside surface, although it can detect more or less, but considering that loss some reflection echo maybe result wrong evaluation. It's suggested that the refraction angle should be adjusted to cover the whole scope, e.g., 35degree refraction angle in workpiece.



(a) Probe location in some unreached area;

(b) Ultrasonic tip diffraction of defect near outside surface

c) Simulation result of beam interaction with defect

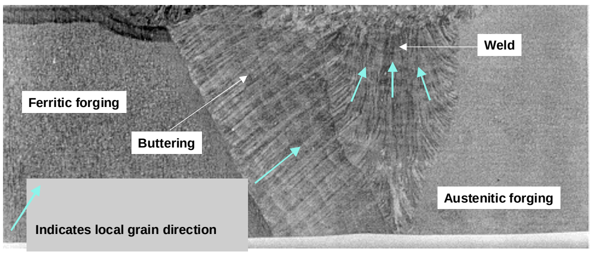
Figure 3 Nozzle to shell weld inspection parameter justification

3.2. Safe end inspection technical justification

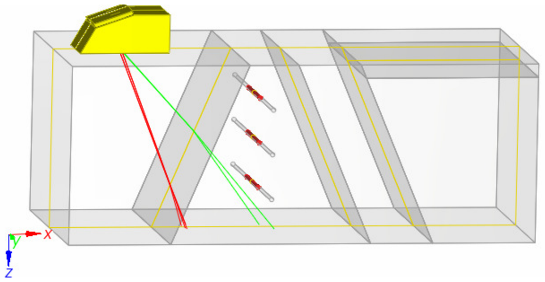
Ultrasonic examination of dissimilar metal welds (DMW) remains a challenge due to the anisotropic nature of the austenitic weld metal and the complexity of joint configurations, as shown in Figure4 (a), exhibiting different acoustic impedances across the interface between parent metals, welded, buttering or cladding regions. The primary application of dissimilar metal welds in nuclear plants is at weld joints that connect the reactor pressure vessel nozzles to selected piping systems. Because the nozzles are low alloy carbon steel and the piping is typically an austenitic material, a dissimilar metal weld must be used to join the two materials. Ultrasonically, this presents a significant challenge for detecting flaws. In addition, discrimination between flaws and geometric or metallurgical reflections is known to be difficult [10].

During the practice of Ultrasonic inspection for the dissimilar metal weld, many problems maybe appear, e.g., terrible signal-to-noise rate, too higher interface reflection echo signal and badly bent transmission sound angle[11], all these kinds of problems make examination of DMW quite difficult to be accurate. Even skilled dissimilar metal weld examiners generally require additional skills and understanding to address variables such as cracking in austenitic weld, metallurgical interface reflections, weldment geometry, and discrimination of fabrication-induced weld flaws.

Three side drilled hole (SDH) was marker as the flaw. Figure 4 (b) shows the geometry of piece. The inspection simulation of DMW was carried out using three transducers with 37°, 45° and 70° respective refraction angle. The simulation was implemented in both positive direction and negative direction.



(a) DMW microstructure



(b) Geometry of DMW piece with three SDH

Figure 4 Typical dissimilar metal weld microstructure and simulation block with holes

According to respective simulation experiments, the following results could be obtained:

(1) There is an obvious influence on simulation result due to the cladding interface and buttering interface, in addition to the anisotropic character, which attributed to their columnar grained texture.

(2) The probes with 37° and 45° refraction angle can detect all side drilled holes with different depth of 20mm, 40mm and 60mm, whatever scanning either in positive direction (stainless steel side) or in negative direction (carbon steel side).

(3) Nevertheless as for 37° refraction angle probe, there is an obvious split and discontinuity in the result when the emitting centre of probe passes across the both interfaces of weld.

(4) The probe with 70° refraction angle can detect successfully low depth SDH of 20mm in stainless steel side and in carbon steel side, as for SDH of 40mm depth in stainless steel side it get weak response as a result of large refraction angle. Whereas from carbon steel side, it can attempt to detect the hole but gets nothing for large depth holes. The reason should attribute to large refraction angle and strong reflection in several interfaces in carbon steel side.

4. Conclusion

Application of ultrasonic simulation platform can enhance the effectiveness while site inspection and reduce the cost associated with inspector training and assessment. Meanwhile inspection parametric could be validated by simulation technology. Moreover it is necessary to study the application of technical justification of inspection procedure by ultrasonic simulation technology which to be used effectively in-service inspection in nuclear power plant. Simulation also allows investigating and assessing the validity domain of an inspection procedure as it can produce results for a very wide parameters range. Two simulation practices for ISI technology demonstrate the use and effective of ultrasonic simulation.

Acknowledge

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