Importance of simulations for Nuclear and Aeronautical inspections with Ultrasonic and Eddy Current Testing

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Abstract

Nowadays the industry is not only demanding quality and accuracy in the global process of the NDE inspections, but also saving time and money.

When a new inspection is going to be developed, after knowing the characteristics of the component to be inspected (material and geometry) and the postulated defects (location and dimensions), one of the first steps is to specify the probes. When mock-ups with realistic defects are available, different probes can be tested to define finally the set of final probes.

This process is not always completely efficient. Sometimes it is not possible to have mock-ups for all the types, dimensions and positions of the postulated defects. Selecting the more suitable probe could require testing a lot of probes, which is expensive and time consuming. Sometimes, it is also difficult to analyse the impact of the geometry in the detection and sizing of defects, and to assess the influence of parameters such as the dimensions, location, skew and tilt of the defects, or the limited access of the beam to the inspection volume.

These preliminary to the inspection preparations are increased when phased arrays probes are used, because new parameters like focal laws, orientations and focalizations of the beams should be taken into account.

Simulation is a powerful tool to complement the results obtained on mock-ups. It can help to select and verify different probes and to define the characteristics of the defects that could be included in the mock-ups. When simulation is used properly, the process of preparing NDE inspections is less expensive and time consuming.

This paper describes some examples about how simulation has been used in different applications on nuclear and aeronautical inspections.

Keywords: Simulation, Ultrasonics, Eddy Current, nuclear, aeronautic, welding, aerospace, carbon fibre composite

1. Introduction

This paper describes several examples of how Ultrasonic and Eddy Current simulations have been used by Tecnatom in some practical cases to solve some issues on the aeronautical and nuclear inspections.

The first task is to define properly the parameters, which are going to be used by the simulation software. Component, probes, inspection and array settings parameters need to be taken into account, since the more accurately a simulation is defined, the more accurate the results will be. That is why is very important to know exactly parameters like material attenuation, internal material configuration, access to the area to be inspected, and other characteristics of the inspection, actual probe parameters like frequency, damping, wedge dimensions and of course all defect parameters like dimensions, material and position.

When a new inspection technique is required, for one reason or another, a report is prepared with all the information concerning the component; this includes material, geometry, access to the control area, postulated defects, their dimensions and locations, and description of the technique that is being used for similar inspections, and their limitations. New probes can be designed in order to access to limited areas, and to have enough energy for detecting defects in the depth where they are postulated. Ultrasonic simulation is usually divided in two stages: the first stage is to know how is going to be the ultrasonic beam in the inspection area, and
the second stage is determining if the postulated defects can be detected and dimensioned according with the Codes.

2. When the goal is probe specification

One of the main advantages of simulation is to test different features of the probes before purchasing them. This helps to specify the most accurate probe for the requirements of the inspection. By using simulations, several parameters can be tested, such as frequency, elements dimensions, focal laws (Linear Scanning, Steering, Single Point Focusing, Dynamic focusing...) and wedge dimensions, so that the different results with these parameters can be compared. This permits to select the combination of parameters, which give the probe more adequate to detect the postulated defects.

Two cases are going to be presented, which have the common objective of probe specification.

2.1. Nuclear inspection in austenitic steel

Objective: Definition of a probe for detection of both open surface and embedded defects in a thickness of 70mm in austenitic steel. Longitudinal and shear waves with different focus beams and refracted angles were configured.

Simulation development: By using ray tracing simulation program, geometrical needs can be known, but it is also necessary to know if ultrasonic beams have enough energy in the depth where the defects are postulated. The first step is to simulate beam profile of the focal laws being used at different thicknesses that is why two different simulations were used: longitudinal and perpendicular to the beam. Different probes configurations were simulated: matrix, dual matrix probes with different number of elements.

In Figure 1 simulations results of beam computation are shown, also preliminary geometrical studies to the simulation are included. With beam profile results, it is possible to evaluate energy distribution in the thickness but also spot distribution, in order to control its symmetry.

![Figure 1. Beam profile.](image-url)
In Figure 2 energy and spot distribution are shown for longitudinal and shear waves of different focal laws configurations.

**Shear waves. Longitudinal waves.**

Shear waves. Beam Profile at 20mm depth. Longitudinal waves. Beam Profile at 7mm depth.

**Figure 2.** Beam profiles for different focal laws

**Conclusions:** Dual Matrix probe, using longitudinal and shear waves, was defined for this inspection. This probe was validated in a mock up with realistic defects at different depths and with different dimensions, with very good results.

**2.2. Aeronautical inspection: Inner and Outer radius.**

**Objective:** To specify the probe to be used in the inspection of CFRP radius, from the inner and outer side.

**Simulation development:** For these simulations several conditions were taken into account: limitation concerning pitch and spacing in the probe elements, geometrical limitation due to that high radius or frequency can affect to lateral grating lobes. All these parameters were calculated with formulas in order to reduce the number of simulations. Different focal laws configuration and focalizations were simulated, first in order to figure out how the beam profile was (Figure 3), and then to know the interaction of that beam with defects (Figure 4).
OUTER RADIUS: BEAM PROFILE

64 elements probe. Sequences of 9 elements. 3.5MHz.

INNER RADIUS: BEAM PROFILE

64 elements probe. Sequences of 9 elements. 5MHz.

Figure 3. Beam profile for outer and inner radius.

OUTER RADIUS

64 elements probe. Sequences of 9 elements. 5MHz. 2mm defect.

INNER RADIUS

64 elements probe. Sequences of 16 elements. 5MHz. 64 elements probe. Sequences of 9 elements. 5MHz.

Figure 4. Beam interaction with defects for outer and inner radius.
Conclusions: The final probes were validated in actual inspection detecting defects at different depths according to one of the most restrictive codes in aeronautical industry. Nowadays the probes are still working with the same configuration after 3 years.

3. When the goal is technical specification: Defect detection.

Technical justification plays an important role in the qualification of non destructive examinations.

The different types of technical justifications and their contents have been described in the ENIQ Methodology and recommended practices. [1]

ENIQ methodology document defines a technical justification as “a collection of all the information that provides evidence about the reliability of an NDT technique as applied to a specific component” [1].

The three most common applications of technical justifications are to justify the use of: inspection procedures, test pieces and defect populations, and inspection equipment. However, there are cases where it is desired to extend an existing qualification to a new situation, for example from one component geometry to another or from one component material to another material structure [2].

The purpose of the technical justification is:

- To overcome the limitations of the limited number of test pieces that can be used by citing all the evidence which support an assessment of the capability of the NDT system to perform to the required level and hence provide a better defined confidence in the inspection.
- To complement and to generalize any practical trials by demonstrating that the results obtained on the specific defects in the test pieces would equally well have been obtained for any other of the possible defects.
- To provide a technical basis for designing efficient test piece trials.
- To provide a technical basis for the selection of the essential parameters of the NDT system and their valid range.

3.1. Nuclear inspection: Defects in a complicated geometry I.

Objective: To guarantee that the postulated defects are detected by the probe (frequency, number and dimensions of elements, etc) and the defined configuration (orientation of the probe, focal laws, and so on). First, it is verified that the configured ultrasonic beams are covering the area of interest.

Simulation development: In Figure 5 are shown the results from simulations of six different angles: From 55° up to 70° with 3° step. Transversal waves.
Defect Response: Six different defects were postulated with different dimensions and different positions in the volume of interest. (Figure 6).

Conclusions: With these results, the conclusion was to evaluate different wedges in order to improve the results in the volume of interest, because a lack of coupling was detected. Once optimal wedges had been manufactures, they were validated in actual inspection with the optimized focal laws.

Ultrasonic modeling contributes to reduce the costs of the experimental part and increase the reliability of the obtained results.
3.2. Nuclear inspection: Defects in a complicated geometry II. Nozzles.

Objective: To compare actual results with the results coming from simulations. Other example of the benefits of simulations for ensuring defect detection is when not only there is a complicated geometry but even it is very tedious to generate the defects where they are supposed to appear.

Simulation development: Eight different probes were considered in this study of austenitic steel inspection, from 2 up to 5MHz, with different angles from 0° up to 70°. Different simulations were developed, with two different beam orientations: X+/X- (circumferential) and Y+/Y- (axial).

In the Y+/Y- inspections defects E2, E3 and E4 described in Figure 7 are intended to be detected. E2 and E3 are 6mm depth and E4 is 4.7mm depth.

![Figure 7. Postulated defects in Y+/Y- inspections.](image)

In X+/X- inspections, E5 defect with 12.5mm depth was intended to detect. (See Figure 8).

![Figure 8. Postulated defect in X+/X- inspections.](image)

Figure 9 shows simulation results from postulated defects in Y+/Y- inspections.
Figure 9. Simulations results.

Conclusions: Amplitude signal results from simulations were compared with actual inspections obtaining that it was necessary to take into account the material attenuation, since the same deviation was observed for all the defects in the same depth.

3.3 Nuclear inspection: Defect detection in pieces with cladding.

Objective: To study the cladding – base material interface signal, to characterize the effect of cladding on the ultrasonic signals that are relevant to the applied examination techniques. The final purpose of the simulations was to compare the results from simulations with the experimental data obtained with the probes used in actual mock ups. Also defect detection had to be demonstrated.

Development: Three different probes from 2.5MHz up to 3MHz were used in order to demonstrate that the defects were being detecting with the defined probes, and with the postulated locations and dimensions of the defects.

<table>
<thead>
<tr>
<th>CASE</th>
<th>PARAMETERS</th>
<th>SKETCH</th>
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| 1    | • Three (3) probes.  
      • x = 2.5mm (A), 4mm (B) and 6.4mm (C). | ![Sketch 1] |
| 2    | • Two (2) probes.  
      • x = 2.5mm (A), 4mm (B) and 6.4mm (C).  
      • y = 5.3 mm | ![Sketch 2] |
| 3    | • One (1) probe.  
      • x = 4mm (A) and 6.4mm (B).  
      • y = 5 mm  
      • l = -5mm (A), 0mm (B), 3mm (C) and 6mm (D). | ![Sketch 3] |

REMARKS  

x: defect depth (out of cladding)  
y: cladding thickness  
l: defect ligament

Simulation results: See Figure 10.
Case 1, probe 1, depth A
Case 1, probe 1, depth B
Case 1, probe 1, depth C
Case 1, probe 2, depth A
Case 1, probe 2, depth B
Case 1, probe 2, depth C
Case 1, probe 3, depth A
Case 1, probe 3, depth B
Case 1 – probe 3 – depth C
Case 2 – probe 1 – depth A
Case 2 – probe 1 – depth B
Case 2 – probe 1 – depth C
Case 2, probe 2, depth A
Case 2, probe 2, depth B
Case 2, probe 2, depth C
Case 2 – probe 1 – depth C
Case 2, probe 2, depth A
Case 2, probe 2, depth B
Case 2, probe 2, depth C
Case 3, probe 1, depth A,
ligament A
Case 3, probe 1, depth A,
ligament B
Case 3, probe 1, depth A,
ligament C
Case 3, probe 1, depth A,
ligament D
Case 3, probe 1, depth B,
ligament A
Case 3, probe 1, depth B,
ligament B
Case 3, probe 1, depth B,
ligament C
Case 3, probe 1, depth B,
ligament D
Case 3, probe 1, depth B,
ligament A
Case 3, probe 1, depth B,
ligament B
Case 3, probe 1, depth B,
ligament C
Case 3, probe 1, depth B,
ligament D

Figure 10. Different simulated cases.
In Figure 11 is shown another example where cladding is affecting to defect detection. In this case it was necessary to introduce a reference defect (DR) in order to be able to compare amplitude signals with the ones coming from D1, D2, D3 and D4.

Several simulated signals have been verified on pieces without and with cladding.

In Figure 12 (a) could be shown the response of a 6mm depth surface breaking defect in a test block without cladding with a probe of 2.25MHz, 45°; its expected response by modeling is shown in Figure 12 (b).

Accordingly, in Figure 13 (a) is presented the B-scan of a surface breaking defect in a test block with cladding and in Figure 13 (b) the modeled B-scan; the defect is 11mm depth, the cladding thickness is 5mm and the probe equal to the one in previous example.

Figure 11. Detection of defects using a reference defect.

Figure 12. B-scan of a surface breaking defect of 6mm depth in a test block without cladding; (a) actual data, (b) simulated data.
Figure 13. B-scan of a surface breaking defect of 11mm depth in a test block with 5mm cladding: (a) actual data, (b) simulated data

Conclusions: Technical justification plays an important role in the qualification of non-destructive examinations. By means of using theoretical assessment such as prediction by modeling, coverage analyses, and parametric studies, a new technical justification has been elaborated without the need of making use of new and expensive test mock-ups.

These studies contribute to reduce the costs of the experimental part and increase the reliability of the obtained results.

The results indicate that the modeling helps to understand and generalize the test data. These results together with the previous finding allow us to elaborate the new Technical Justifications of nozzles group with cladding based on these studies and without the need of making use of test mock-up with cladding.
4. Eddy current

On the Eddy Current Testing field, simulations also play a very important role. While facing up a particular inspection, an analysis of the different parameters imposed has to be done (material properties and defect characteristics), in order to define the correct inspection parameters: architecture chosen, number of elements and its disposition, probe’s trajectory, coil’s dimensions, number of turns, ferrite core, drive current and test frequencies.

Some examples have been included to show how simulations have made this analysis easier:

4.1 Specifications of an eddy current array probe for steam generator tube’s inspection.

Simulations have been used on the design of an eddy current probe array for steam generator tube’s inspection in order to help in defect characterization.

Once the architecture has been chosen (8 x 2 array in this particular case) and depending on the tube’s dimensions, the simulation program is very useful for the configurations of the coil’s parameters (dimensions, number of turns, etc…), and the inspection parameters (test frequency, drive current or probe displacement). It’s possible to analyze the impedance changes due to the interaction between the eddy currents and the defect.

In this case it was very important to compare the different results obtained when changing the characteristics of each coil, and to analyze the effect of different sources of error like cross-talk effect, or low sensitivity.

![Configuration of the probe (left) and signal due to a defect with two different test frequencies (right).](image)

Figure 14. Configuration of the probe (left) and signal due to a defect with two different test frequencies (right).
4.2 Eddy current probe for deep defect’s detection.

Computer simulations have also been used for the specification of an eddy current probe for deep defect’s detection.

It was very important to assure that the eddy current components generated by the emitter could reach the desired depth, so an analysis of the current density levels flowing through the material under test has been made by computer simulations. Those current levels depend directly on the coil’s dimensions, the drive current, the test frequency, number of turns and the use of ferrite core.

With the results obtained on the first simulations a first approach of the emitter could be built, and having into account that some of the coil’s parameters are linked together, (for example, a minimum wire size is needed for a particular drive current, and at the same time, the wire size will determine the coil’s dimensions for a certain number of turns), by real tests in addition with more simulations it is possible to obtain better results.
5. Conclusion

Importance of simulation to optimize the quality of some inspections have been described through different examples, since it provide a means to analyze and improve the characteristics of the probes, to optimize the ultrasound beam characteristics and to understand the physical phenomena that occur during the detection and sizing of defects.

The simulation is a complement to the development of inspection techniques, which must be confirmed and validated by data acquisitions performed on mock-ups with realistic defects.

6. References


