Experimental verification of phased array annular probe in ultrasonic immersion setting

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Abstract

With the ongoing development of materials and manufacturing techniques, new product design opportunities manifest themselves. However, care must be taken when applying techniques and material where there is less inherent knowledge about different parameters’ effect on the integrity of the final component. In conjunction with destructive testing of components, non-destructive evaluation (NDE) provides valuable insight into the manufacturing process reliability, as well as the possibility for subsequent future in-service inspection. Phased array ultrasonic testing (PAUT) facilitates the inspection of complex geometries on a wide set of material. Mathematical modelling of ultrasonic signal facilitates the optimization of inspection procedures by e.g., maximizing the probability of detection (POD) of specific defect types. In this paper, the response from an immersion annular phased array probe is experimentally validated to the output of the simulation software simSUNDT. In order to only validate the probe model (as both transmitter and receiver) a set of well-defined defects are used. The validity of the simulated amplitude response from side-drilled holes at a depth range of 20-115 mm is investigated. A total of 14 SDH holes in one test piece of is used as cases for validation. The results show a good correspondence between simulated and experimental data for the case where the probe is normal to the component surface.

KEYWORDS: Experimental Verification; MAPOD; Sensitivity Analysis; Ultrasonic Inspection

1. Introduction

For any product, each subcomponent needs to be designed and dimensioned in such a way that it does not fail prior to the designed lifespan. This can often be ensured by applying simple mathematical models, followed by applying a healthy safety margin. For weight critical application it is important to minimize the need for this safety margin. Reducing the size of this safety margin increases the sensitivity to variation in the manufacturing process; any variation from the expected strength of material can cause a failure of component. New alloys and manufacturing techniques facilitates new design opportunities. However, care must be taken when applying techniques and
material where there is less inherent knowledge about different parameters’ effect on the integrity of the final component.

Non-Destructive Evaluation (NDE) is a process of finding flaws in materials and components without affecting the integrity of the material. NDE gives the freedom to design without unnecessary amount of mass by verifying there are no defects of critical size and characteristics in the component.

Ultrasonic Testing (UT) is a well-established method to locate and evaluate internal defects. UT works on most materials and has a high degree of sensitivity [1]. These characteristics contribute to the fact that the method is used extensively in several industries, including aerospace. To increase the sensitivity of the inspection (the ability to detect small defects), a focused beam probe is often used. A focused beam concentrates the ultrasonic wave front to a specific depth-range which increases the amount of energy reflected by any potential indication. Consequently, constraining the energy focus to a certain depth limits the amount of volume inspected for a given time unit. Phased Array (PA) can steer an effective wavefront by applying delay laws to a series of ultrasonic elements shown in Fig. 1b.

The refraction of the beams as they enter the component is calculated according to Snell’s Law [2].

Figure 1. General configuration and application of annular array probe. (a) shows the configuration of the individual piezoelectrical elements (not all elements are rendered in image). (b) illustrating the focusing effect, where the red bars represent time delay, and the blue line the effective beam propagation direction.

Annular PA probes are probes that have the elements configured in a circular configuration (Fig. 1a) as such applying delay laws does not allow for beam steering away from the normal of the probe surface but does facilitate adjustable focus distance in a symmetrical fashion compared to a 1-dimensional linear PA probe. As such an annular probe can focus the beam energy in a similar way to a conventional ultrasonic probe, but with a flexible focus depth. This solid state based focusing method can switch in milliseconds, allowing for multiple focus depth to be captured continuously during probe scanning. This means for practical applications that a component can be scanned on a single pass compared to a conventional setup where a series of conventional focused probes would be required to focus on the entire depth.

Inspection procedures for critical components needs to be qualified. There needs to be statistical data providing some degree of confidence in that defects that could affect the performance of a component will be identified reliably. Traditionally, these qualifications are performed by having sufficient number of physical specimens with real or artificially created flaws. The testing procedure can then be qualified by applying it to these samples and evaluating the degree to which the flaws were detected. By
applying statistical methods to the acquired results, a Probability Of Detection (POD) indicator value can be calculated.

POD is a well-established method to measure reliability in NDT and is often acquired using well defined procedures, e.g. [3]. However, this approach is expensive, especially when the testing procedure heavily relies on operator input, which tends to introduce more variability to the system and a greater sample size is required.

Model Aided Probability Of Detection (MAPOD) has gained more interest in recent years. MAPOD utilizes simulated data, potentially supplemented with physical experimental data, to calculate a POD value for a specific test case. By simulating the entire test setup, including the defect characteristics and probe-parameters, the number of samples can be made vastly greater than what would be feasible for strictly physical experimental data.

To simulate the propagation of ultrasonic signals within materials there are two main mathematical methods, analytical or numerical. UTDefect [4] uses analytical methods and solves the elastodynamic wave equation. The models are applicable to homogenous materials only, however the material can be isotropic or anisotropic. UTDefect has previously been validated for both contact phased array [5], as well as immersion testing with non-focused and focused conventional probes [6] [7]. There is however a gap in validation for immersion phased array probes.

In this paper, the implemented mathematical models of UTDefect are experimentally verified in an immersion setting using phased array technology with well-defined 3 mm Side-Drilled Hole (SDH) as reference defects in a homogenous noise free component. 3 mm SDH is the reference indicator used in ISO standard for weld inspection [8] which makes it a reasonable choice for the validation. The validation of simulated amplitude response is limited to a specific case with few parameter variations:

- Angle of incidence
  - 0°
  - 5°
- Frequency distribution of simulated wave-front.
  - Monochromatic
  - Cosine square distributed.

simSUNDT/UTDefect can either simulate the wave propagation in a single frequency (monochromatic), or as a spectrum. When a cosine square distribution is chosen and a bandwidth is specified, the software automatically discretizes the signal into a number of independent sub-signals of different frequencies, with the highest energy content at the selected frequency. This is a reasonable model of an actual ultrasonic transducer.

The amplitude difference will be presented in dB which is a logarithmic measurement and defined according to (1)

\[
dB = 20 \cdot \log_{10} \frac{signal A}{signal B}
\]

where signal A and signal B are two signals in any linear measurement system [3].

2. Method

The work consists of comparing the data from physical experiments and simulated experiments. The method of collection of the two datasets are presented in the following two sub-chapters.
2.1 Experimental approach

![Figure 2. (a) 5° calibration block and (b) showing components of the test-bench setup. X and Y axes are mechanized while Z, φ and ψ are manually adjustable.](image)

The experiments were performed with the probe indicated in Table 1. The probe was driven by the TOPAZ64 portable Ultrasonic Testing system, and the data was transferred to a PC for analysis via Ethernet. The tests were all performed by positioning the probes using a mechanized gantry system, Fig 2b. The gantry consists of two mechanized axes (X and Y), allowing for planar scanning of surfaces, as well as three manually actuated axes. The Z-axis as well as the rotational axes for two probe Euler angle adjustment (φ and ψ) are manually actuated. For the 0° incidence test the Euler angles were adjusted manually until the response of the surface echo was maximized to ensure a normal incidence to the surface. For the 5° incidence test a calibration block was manufactured (Fig. 2a) with one surface tilted 5° and the amplitude response from that surface was maximized in a similar fashion.

All tests were performed in a 70-litre water-tank. The water was tap-water and was allowed to de-air and reach room temperature (~21 degrees Celsius) before experiments were performed.

<table>
<thead>
<tr>
<th>Probe</th>
<th>Frequency (MHz)</th>
<th>Number of Elements</th>
<th>Diameter (mm)</th>
<th>Minimum operating distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMASONIC</td>
<td>10</td>
<td>32</td>
<td>45</td>
<td>50</td>
</tr>
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</table>

2.2 Simulated experiment

To perform the simulation the software simSUNDT was used. simSUNDT is acting a pre- and post-processor for the mathematical solver UTDefect. The focusing distance of the probe was consistently set to maximize the amplitude response. This distance was found by iterative approach near the theoretical optimal value. In a similar fashion the probe position was determined to maximize the amplitude response. This was also based roughly on mathematical calculation derived from Snell’s law, and fine tuned with an iterative approach.
The focusing distance in simSUNDT is expressed as a primary focusing distance, that is for an immersion setting the distance to the focusing point if the beam was not refracted along its path. To account for the refraction when the sound wave enters the component a MATLAB script was created to calculate the desired primary focusing distance from the actual “refracted focusing distance”. simSUNDT was set to run with an accuracy index of 3, which defines the step length of the integral solver.

3. Results

Fig. 3 shows the amplitude for tests at different defect depth with simulated and experimental data. The amplitude response for both sets of data has been normalized to the respective SDH at 50 mm. For the simplest case with an incidence angle of 0°, Fig. 3a, the greatest discrepancy between simulation and experimental data is less than 1 dB. This can be put into some context by looking at the ISO standard for acceptance level of evaluation of welds [8] which defines a difference between a reference level (based on a 3 mm SDH) and acceptance level 2 at (-6) dB for short (0.5-1 mm) indications. The result from the normal incidence test with a cosine square distributed frequency is not presented here but is near identical (the greatest difference in normalized amplitude between two simulations at equal depth is 0.32 dB). Similar results have been presented previously, e.g., in [9].

Fig. 3b shows the difference between experimental and simulated data with a probe incident angle. The greatest normalized difference is for the hole at 85 mm depth, where there is an amplitude discrepancy of 2.97 dB.

4. Discussion

The discrepancy between simulated and experimental response can likely partially be explained by how UTDefect defines the surface pressure boundary condition. In the current implementation the pressure zone on the top surface of the component is necessarily modelled as a circle with constant pressure (piston-like model). In reality for an immersion setting with the probe offset from the surface normal, a non-circular pressure zone will be introduced onto the top surface.
Future work should involve re-writing the algorithms to model the pressure boundary condition in a more realistic fashion.

5. Conclusion

This paper investigated to what degree the ultrasonic amplitude response in simulated test cases corresponds to experimental tests. It was concluded that for the most used case, i.e., with a $0^\circ$ incidence angle of the probe the correlation is in the same approximate range from what has been concluded from earlier studies for different test configurations. Whether or not the correlation is sufficient for any application needs to be determined on a case-to-case basis. It should be noted that the domain of the validation is limited and deviation in the simulated test configuration could alter the correlation in a non-linear fashion. The results from the tests with the angled probe revealed possible shortcoming of the current implementation and should be considered carefully before applying the model to cases where they might be relevant.

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References


