The Implementation and Validation of a Phased Array Probe Model into the simSUNDT Software
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Abstract
Ultrasonic phased array technique has gone from being a unique technique with few and very specific purposes into being an established tool and replacing conventional contact technique in a broad field of applications. Even though the far-field behaviour is more or less identical to single crystal techniques the knowledge in e.g. how it differentiates in interaction with defects and geometry closer to the probe is rather limited. A thorough validated mathematical model based on the physics has the ability to overcome this lack of understanding and is the only realistic alternative in the development of new procedures based on this technique. The simSUNDT software consists of a Windows®-based preprocessor and postprocessor together with a mathematical kernel (UTDefect), dealing with the actual mathematical modelling. The model employs various integral transforms and integral equation and enables simulations of the entire ultrasonic testing situation. In the latest released version (2.0) a model of phased array probe has been incorporated. Each of its elements is in the model represented by the boundary conditions that generate a plane wave, at a certain angle, in the far field. These boundary conditions (i.e. the pressure on the surface under the element) are then translated into the main coordinate system and after superposition they built up a phased array wave front (constructive phase interference) with prescribed nominal angle. Modelling has been identified as an effective tool and in a previous work the developed methodology based on simulations of a well defined procedure was validated. In this paper a new model of phased array technique is implemented in the simSUNDT software and thoroughly validated.

1. Introduction

Stronger demands on reliability of used non-destructive methods and procedures (NDT/NDE) have enforced different strategies to quantify the inspection capability. The European nuclear industry decided in the middle 1990’s to develop an industry specific methodology in order to assess the NDT capacity, not only in detection but also as a tool of sizing and characterization. The ENIQ approach (European network of inspection qualification) is characterised by what is known as the Technical Justification. This is a document that gathers evidence (experimental data, physical reasoning or by modelling) of the system capacity.

The most dominant and frequently used method within the aero industry is the probability of detection (POD) methodology. The intention is that these POD curves should provide with a statistically sound measurement of a method’s capacity to detect a defect as function of its size. These POD curves can then be used to find the optimal NDT technique in aspect of a specific object, material, defect size and other defect characteristics.

Traditionally all qualification methodologies have been empirically based with extensive experimental work on test pieces. An infinite number of variables and possibilities then have to be reduced into a limited group of statistically relevant NDT situations. Besides the problem of reconstructing the geometry and material, the fabricated defects also have to be introduced with a verified prescription of their sizes and NDT characteristics. In the recent decade a number of mathematical models have been developed and used as tools within parts of these qualification processes. A thorough validated model has the ability to be an alternative or a complement to the experimental work in order to reduce the extensive cost that is associated with the previous procedures.

A number of ongoing projects [1-3] address the possibility to enable simulated data to be used within the development of POD curves. One possible approach is then to have an
optimized experimental phase (representative samples, but easy to manufacture) combined
with much more efficiently retrieved simulated data. This paper describes the implementation
and validation of a model of phased array technique into the simSUNDT software (version
2.0). In the continuation the intention is to use this model in order to generate POD curves
and compare with conventional technique used in a specific procedure [4].

2. The simSUNDT software

Figure 1. An overview of the pre- and postprocessor simSUNDT.

The simSUNDT program is a Windows®-based preprocessor and postprocessor together with
a mathematical kernel (UTDefect, [5-9]) dealing with the actual mathematical modelling. The
UTDefect computer code has been developed at the Dept. of Mechanics at Chalmers
University of Technology and has been experimentally validated and verified [4, 7-10]. The
model employs various integral transforms and integral equation techniques to model probes
and the scattering by defects. The software simulates the whole testing procedure with the
contact probes (of arbitrary type, angle and size) acting in pulse-echo or tandem inspection
situations.

The simulated test piece is at the present state restricted to be of a homogeneous and isotropic
material. The model is completely three dimensional though the component is two
dimensional (infinite plate with finite or infinite thickness) bounded by the scanning surface
where one or two probes are scanning the object within a rectangular mesh. It is also possible
to include a planar back surface, which for the strip-like crack may be tilted, but is otherwise
assumed parallel to the scanning surface.

The probe is modelled by an assumed effective area beneath the probe, used as boundary
conditions in a half-space elastodynamic wave propagation problem. This enables an
adaptation to a variety of realistic parameters related to the probe, e.g. wave type, angle,
crystal (i.e. size and shape), focus depth and contact conditions. In order to completely simulate the actual NDT situation, an option of calibration against a reference reflector is included in the software. The calibration procedure with a side-drilled hole is treated exactly, with the use of the cylindrical cavity, while the flat-bottom hole is approximated with an open circular crack.

2.1 The phased array model

The phased array probe has been treated in the same way as previously was done for the conventional contact probe. Each element is then represented by the boundary conditions that generate a plane wave, at a certain angle, in the far field. These boundary conditions (i.e. the pressure on the surface under the element) are then translated into the main coordinate system and after superposition they built up a phased array wave front (constructive phase interference) with prescribed nominal angle. Alteration of the delay of each element also enables a focusing effect. If no wedge is specified (see figure 3) each element is unangled and the angle of the produced front then only is caused by the delay law term. Note though that this is only possible for small angles. It is also possible to specify individual elements as being dead (figure 4). In some applications the contact between wedge and inspected component can be difficult to ensure and the option to specify dead element can then be used in sensitivity studies of the technique.

Figure 2. Geometry and parameters that defines the phased array probe (left), boundary conditions on the surface and far field plane wave (right).
2.2 Validation of the probe model

An ultrasonic benchmark study was initiated by the World Federation of NDE Centers and practically conducted by Commissariat a l’énergie atomique (CEA, France) during the year of 2009 [11]. The experiments included experimentally measured signal responses of side-drilled holes, flat-bottom holes and rectangular surface breaking defects (slots). The intention was to make experimental data available in order to validate the capability of different mathematical models of ultrasonic NDT techniques.
The test specimen was manufactured in stainless steel (density 7950 kg/m$^3$, P-wave speed 5748 m/s and S-wave speed 3157 m/s) with 12 different artificial defects (see figure 5). The surface breaking defects were slots (width of 0.3 mm) in two different lengths (5 and 40 mm) and in four different heights (2, 5, 10 and 20 mm). The flat-bottom hole (3 mm in diameter) was tilted 45 degrees in order to achieve specular reflection using a 45º UT probe. Three side-drilled holes (1, 1.5 and 2 mm in diameter) were machined into the test piece with the largest used as reference defect. The phased array probe used in the experiments was a linear probe with 48 elements (20 active) working on a wedge with 21º incident angle and a delay law specified as providing a longitudinal wave 45º in a ferritic steel component. The center frequency was specified as 5 MHz and the bandwidth as 45% (further details see [11]).

As can be deduced from table 1 above both direct longitudinal and transversal wave contributions corresponds very well between experiments and simulated data when it comes to the well defined side drilled holes and the flat bottom hole. It was actually possible to get the maximum signal response to 2.8 dB, as in the experimental data, either by reducing the diameter of the FBH to 2.6 mm in the simulations or provide the 3 mm FBH with a tilt of 48.5º instead of specified 45º.
The comparison between direct longitudinal, transversal and mode converted corner echo from the slots doesn’t show the same good correlation except for the larger one (10 mm in height). This isn’t that surprising since the slots are compared with mathematical two dimensional surfaces (surface breaking crack) without any width (COD) and the smaller slots in used test piece represents more a volumetric defect than an actual crack.

In order to validate the model of the phased array probe a comparison with the previous simSUNDT model is shown in table 2. The main difference is that no wedge and no delay law is included in the previous version and modelled by subdividing the effective boundary on the surface of the component into identical small probes with identical angles, i.e. if no focus of modelled probe is specified. Note though that the results would be more or less identical if the wedge had been prescribed with an angle of 16º instead of 21º as used in the experimental set-up.

In the benchmark study some A-scans were provided as text files. The position for each a-scan was though not specified but the amplitude was normalized against the largest SDH in the test piece. The result from the simulation based on the smallest SDH is presented in figure 6. Based on the two provided A-scans (maximum L and T signal response) it was concluded that a time delay of 7.9 µs gave a good correlation between the experimental data and made simulations (see figure 7). The difference in time corresponds to time for the wave to propagate from generating element on the wedge to the component times two (transmitter and receiver) since the model only models the boundary condition on the surface.
Figure 6. The result from the simulation when a 1 mm SDH was specified as defect. -2.2 dB lower than the calibration piece (2 mm SDH) represents 100% in the A-scan and 0 dB in the C-scan.

Figure 7. Comparison between experimental A-scans (solid lines) and simulated data (dotted lines). In 7a the longitudinal corner echoes are compared and corresponding transversal corner echoes in 7b.
When the same time delay was used in the comparison between the made simulation (figure 8) and experimental A-scans from the 2 mm slot, the rather large difference found in table 1 was significantly reduced (L corner 8 -> 2 dB, TL corner 12 -> 6 dB). There is also a strong diffracted component present in one of the simulated A-scan (dotted line in figure 9a) that isn’t identifiable in corresponding experimental data (solid line in figure 9a). This confirms above discussion of that the smaller slots represent volumetric defects rather than cracks.

Figure 8. The result from the simulation when a 2 mm surface breaking crack was specified as defect in a 50 mm thick component (same calibration as in figure 6).

Figure 9. Comparison between experimental A-scans (solid lines) and simulated data (dotted lines). In 9a the longitudinal corner echoes are compared, corresponding transversal corner echoes in 9b and in 9c the mode converted corner echoes are compared.
References

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