SIMULATION OF THE 2008 ULTRASONIC BENCHMARK PROBLEMS USING UTDefect

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ABSTRACT. The computer program UTDefect is used to solve some of the 2008 ultrasonic benchmark problems. UTDefect is a program for simulation of ultrasonic testing with applications within the nuclear industry in mind. Scattering from various types of defects, like a side-drilled hole and a flat-bottom hole, is modelled using solutions that are essentially exact. For the benchmark problems the results obtained from UTDefect are in fairly good agreement with the experimental data from CEA.

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INTRODUCTION

Simulation of ultrasonic testing is an important tool for a number of reasons. A good mathematical model can, for instance, be useful for parametric studies, in planning experiments, and in interpreting results. However, to be reliable every model needs verification, typically by comparing with experimental results.

For a number of years the World Federation of NDE Centers has proposed benchmark problems to be used for comparison with ultrasonic models. In the 2008 problems pulse-echo responses from side-drilled and flat-bottom holes are studied. The experiments were carried out by the Commissariat à l'énergie atomique (CEA) in France. The aim of this study is to compare results obtained by the program UTDefect with the experimental results.

THE PROGRAM UTDefect

UTDefect is a program for modelling ultrasonic testing, that has been developed continuously since the early 90's at Chalmers University of Technology with applications within the nuclear industry in mind. The aim of the program is to simulate the entire ultrasonic testing process of a thick-walled component, including transducers, scattering from various types of defects, and calibration.

The material of the component is assumed to be homogeneous. Isotropic as well as transversely isotropic and orthotropic materials are incorporated in the program. It is also possible to include attenuation.

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The basic idea behind UTDefect is to exploit analytical solutions to idealized scattering problems, i.e, approximate methods like GTD or Kirchhoff theory are not utilized, neither are purely numerical methods like FEM. The analytical techniques used include separation of variables, the null field approach, and integral equation mehods. As a consequence only defects of simple shape can be handled. Typical examples are spherical and cylindrical cavities, spherical elastic inclusions, penny-shaped cracks (open or partly closed), and rectangular or strip-like cracks. Most defects may be located in a half-space or close to a planar back surface. The strip-like crack may also be surface-breaking.

Ordinary contact transducers, planar or focused, are modelled by prescribing the traction at the contact surface. Immersion testing is also included, more about that in the following. To model the resulting wave propagation in the component Fourier transform techniques are used. The receiver is modeled using Auld's reciprocity argument [1].

Basically, UTDefect works in the frequency domain, but it is also possible to obtain results in the time domain using a Fourier transform. Hence, results may be obtained as ordinary A-, B- or C-scans.

The basic advantage of UTDefect is that exact, fully three-dimensional solutions are used, meaning that it is never necessary to rely on approximate methods like Kirchhoff theory. In general, the solutions used are efficient from a computational point of view. Purely numerical methods, like finite element methods and finite volume methods are in most cases more computationally intensive and were virtually impossible to use for fully three-dimensional problems at the time when the development of UTDefect started. The main limitation of UTDefect is that only homogeneous components with planar boundaries are included, and that all defects are of simple shape.

The continuous development of UTDefect has been published in a number of papers and reports from the former Swedish Nuclear Power Inspectorate, today part of the Swedish Radiation Safety Authority, [2]-[4].

The development of UTDefect is ongoing. Future versions will employ the boundary element method to model testing of components with a nonplanar back surface. Scattering from a crack in a cladding will also be incorporated in the near future. This a rather challenging analytical problem, since the interface between the main component and the cladding is not planar, but rather corrugated.

THE 2008 ULTRASONIC BENCHMARK PROBLEM

The 2008 ultrasonic benchmark problem consists of two parts. In the first part pulse-echo immersion responses from flat-bottom holes through curved surfaces are considered. The second component of the problem is a study of ultrasonic response from side-drilled holes at various depths. The experimental data for both components have been provided by the Commissariat à l'énergie atomique (CEA) in France.

In both cases a spherically focused transducer was used. An effective diameter of $12,47$ mm and an effective geometrical focal length of 172.9 mm were suggested for transducer modelling. A center frequency of 4.8 MHz and a bandwidth of 6 dB have been used throughout. For all studies the transducer was oriented to produce 0° refracted P waves in each block. The water path length was 75 mm, and the longitudinal wave speed was chosen as 1486 m/s.

Scattering from flat-bottom holes at the following depths were studied: 6.35 mm, 12.7 mm, 19.05 mm, 25.4 mm, 38.1 mm, 50.8 mm, and 76.2 mm. The diameter of each hole was 0.8 mm. Five different aluminum blocks were used, two blocks with concave surfaces, two with convex surfaces, and one with a planar surface. In this paper only the case with a planar surface has been modeled. The density was chosen as $2700\,\mathrm{kg/m^3}$, and the logitudinal and transverse wave speeds as 6381.2 m/s and 3000 m/s, respectively.

In the second part of the study ultrasonic responses from side-drilled holes at different depths in a steel block were studied. All holes had a diameter of 2 mm and a length of 50 mm. The axis was oriented parallel to the surface of the block. The depth varied from 4 to 60 mm in steps of 4 mm, and the horizontal spacing between the holes was 15 mm. The density of steel was taken as $7800\,\mathrm{kg/m^3}$. The longitudinal and transverse wave speeds were 5900 m/s and 3230 m/s, respectively.

IMMERSION TRANSDUCER MODELING

The model of the spherically focused immersion transducer was developed by Niklasson et al. [5]. The basic idea is to model the spherical surface as a number of concentric circular rings. On each ring a harmonically varying pressure with a phase lag is prescribed. The corresponding field in the fluid is matched with the field in the component, modeled as an elastic half-space, so that displacement and traction are continous at the interface. The receiver is modeled using the reciprocity relation by Auld [1].

THE FLAT-BOTTOM HOLE

The flat-bottom hole (FBH) is modeled by a penny-shaped crack parallel to the surface. This should be a good approximation as long as the diameter of the hole is not too small compared with the wavelength, as is the case in this benchmark problem.

To solve the scattering problem an integral equation method originally developed by Krenk and Schmidt [6] is used. The basic idea is to derive an integral equation for the crack opening displacement (COD), and to solve the equation by expanding the COD in suitable functions that have the correct square root behavior at the edge of the crack. In UTDefect the T matrix of the penny-shaped crack is employed. A detailed derivation of the T matrix was given by Boström and Eriksson [7].

As mentioned previously, UTDefect works in the frequency domain. In order to obtain results in the time domain a Fourier transform is used. In this specific case responses at 50 different frequencies with a squared cosine spectrum, i.e. a Hanning window, have been used to determine the response. The frequency spectrum differs somewhat from the experimental conditions, but we do not believe that this should be of any significant importance. The results of the modeling are compared with the experimental results in Table 1, which gives the relative amplitudes in dB with the response from the 12.7 mm FBH as reference value. With one exception all values differ by less than 1 dB. There does not seem to be any systematic deviation from the experimental values.

THE SIDE-DRILLED HOLE

The side-drilled hole is modeled by an infinitely long cylindrical cavity, and the exact solution [8] obtained by separation of variables is used. Even if each hole has a finite length (50 mm), it is reasonable to believe that the error introduced by considering a hole of infinite length is negligible. It is also assumed that multiple scattering between the holes is of minor

TABLE 1. Response from flat-bottom holes at different depths under a planar surface.

Depth of the FBH (mm)	6.35	12.7	19.05	25.4	38.1	50.8	76.2
Experimental	1.3	0	–2.3	–4.9	–11	–14.5	–22.4
Simulation	2.2	0	–2.7	–5.4	–10.1	–14.1	–20.0

TABLE 2. Response from side-drilled holes at different depths.

Depth of the SDH (mm)	Experimental	Simulation (6 dB bandwidth)	Simulation (single frequency)
4	–0.7	–0.9	–0.6
8	0	0	0
12	–0.3	–0.1	–0.7
16	–1.4	–0.9	–1.0
20	–2.4	–1.6	–2.1
24	–3.8	–2.7	–3.3
28	–4.6	–3.6	–4.0
32	–5.8	–4.7	–5.0
36	–7.2	–5.5	–6.2
40	–8.1	–6.4	–6.8
44	–9.0	–7.4	–7.7
48	–10.1	–8.2	–8.7
52	–11.1	–9.0	–9.4
56	–11.8	–9.8	–10.2
60	–12.7	–10.4	–11.1

importance, i.e., the scattering from each hole can be calculated separately.

In Table 2 the results from UTDefect are compared with the experimental results. The relative amplitudes in dB are given with the response from the hole at 8 mm depth as reference value. In this case 80 frequencies at a minimum have been used to reconstruct the signal in the time domain. For comparison we have included results obtained for a single frequency, the center frequency 4.8 MHz. The difference between the simulation and the experimental results are in most cases less than 2 dB. In this case there is a systematic deviation. For the case of a frequency spectrum with 6 dB bandwidth the calcuated responses from holes deeper than 8 mm are generally too strong, while the reponse from the 4 mm hole is somewhat weaker than the experimental value. This indicates that adding some attenuation to the model should improve the agreement. From experience it is well-known that the response for a fixed frequency often gives a reasonably good prediction, which is strongly supported by this simulation. In fact, the results obtained for a single frequency are even in better agreement with the experimental results in this case. Considering the difference in computation time this may be worth bearing in mind.

In Figure 1 the ultrasonic response as a function of the position of the transducer is depicted for the experimental data and for a simulation for a fixed frequency, 4.8 MHz. Once again, it can be noted that the results obtained for a single frequency are in remarkably good agreement with the experiments.

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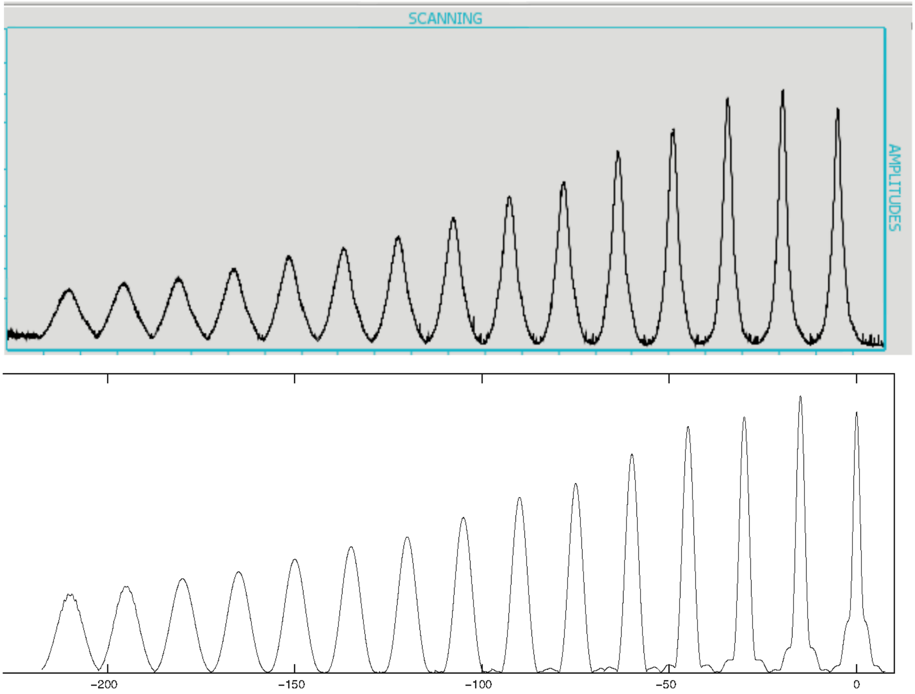

FIGURE 1. The response from the side-drilled holes as a function of the position of the transducer, experimental (top) and simulation (bottom).

REFERENCES

1. B. A. Auld, *Wave Motion* **1**, 3-10 (1979).
2. A. Boström, ”UTDefect – a computer program modelling ultrasonic NDT of cracks and other defects”, SKI Report 95:53, Swedish Nuclear Power Inspectorate, 1995.
3. A. S. Eriksson, A.Boström and H. Wirdelius, ”Experimental validification of UTDefect”, SKI Report 97:3, Swedish Nuclear Power Inspectorate, 1997.
4. A. Boström, ”User guide to UTDefect version 4: a computer program modelling ultrasonic nondestructive testing of a defect in an isotropic or anisotropic component”, SKI Report 02:26, Swedish Nuclear Power Inspectorate, 2002.
5. J. Niklasson, A. Boström and H.Wirdelius, ” Benchmarking – a validation of UTDefect”, SKI Report 2006:30, Swedish Nuclear Power Inspectorate, 2006.
6. S. Krenk and H. Schmidt, *Philos. Trans. R. Soc. London* A **308**, 167-198 (1982).
7. A. Boström and A. S. Eriksson, *Proc. R. Soc. London* A **443**, 183-201 (1993).
8. A. Boström and P. Bövik, *Int. J. Solids Struct.* **40**, 3493-3505 (2003).