Chapter 8

Conclusions and suggestions for future work

This thesis has been concerned with mathematical modelling of elastic wave propagation in anisotropic and inhomogeneous materials in relation to ultrasonic NDT. This type of materials is the most general and as such the most difficult topic to consider from a modelling point of view. The problem has mainly been investigated using a numerical finite-difference approach (EFIT) which in principle puts no restrictions on the materials considered.

In the following section, conclusions are made based on the activities in the preceding chapters. The following section focuses on the industrial aspects and benefits of relevant conclusions, while the last section makes recommendations for future work on the subject.

8.1 Conclusions

In chapter 3 the analytic solution (Green's function) to the 2D problem of a line source on the free surface of a general anisotropic, homogeneous material was presented and implemented. The aim of this approach was originally twofold. Firstly, besides giving a qualitative insight into the nature of the solution, it was expected that this approach would provide a computationally fast method for computing the sound field from a general transducer in 2D and, after a natural extension of the solution, in 3D in large material domains. Secondly, the analytic solution would be an easy and convenient way of validating the more general numerical approach. Considering the first point, it was found that the analytic solution was much slower than the numerical approach at computing the sound field over a large area (at least for a time horizon relevant for NDT, i.e. microseconds). As a summary, the numerical method was roughly about a factor of five faster for the times considered. It was therefore decided not to pursue analytic 3D modelling of the transducer sound field any further. Secondly, the analytic solution was intended to validate the numerical solution. As for the comparison, it was found that there was an excellent agreement between the analytic and numerical solution inside the material, while there were small discrepancies at the material surface observed at the transverse and Rayleigh waves. As discussed, this might be due to the Rayleigh wave term in the analytic solution which is rather sensitive to the choice of the small imaginary constant.

In Chapter 4 and 5, the numerical solution EFIT was presented together with a description of the various implemented features. In particular, it is possible to include circular and rectangular defects with stress-free surfaces (cracks) in the simulations. A number of simulations are performed for isotropic as well as anisotropic materials and it is demonstrated how plane wave theory qualitatively may be used to interpret the often very nonintuitive behaviour of anisotropic wave propagation. As a simple but computationally efficient model of the piezoelectric transducer signal due to scattering of the sound field from included material defects, surfaces etc. an average over the velocity components normal to the surface of contact was considered. This simple model of the receiver signal was compared with a model based on an adapted version of the electromechanical reciprocity relations, where the transducer only needs to modelled as a transmitter. Good agreement between the two methods is found. The numerical solution with these two methods for calculating the receiver signal has been compared with full analytic 3D solutions (SUNDT) also using the electromechanical reciprocity relations. In general the receiver signals have similar forms, but there is a rather large discrepancy between the amplitudes of the signals. There may be at least two reasons for this. The numerical method is a 2D solution while the considered analytic solutions are 3D as mentioned. For the cases considered this issue is however only relevant for the transducer size modelling, and the types of discrepancies resulting from the different simulations indicate that these may not be explained consistently by this fact. The other reason is the finite widths and the rectangular form of the cracks considered in the numerical simulations, whereas the analytic solutions consider infinitely thin cracks. It is wellknown, that the scattered amplitudes depend to a large degree on size and geometry in this limiting case. This problem being of a more academic nature has not been pursued further in this project, as such perfect mathematical geometries may hardly be found in practical ultrasonic inspections.

Chapter 6 was concerned with the description and adaption of a mathematical model of the anisotropic structure of the austenitic MMA weld to the numerical approach. This type of weld is an important and difficult component within ultrasonic NDT. For each cell in the numerical grid an elastic matrix is assigned according to this anisotropy model, resulting in each grid cell representing a grain. A comparison of the simulated wave propagation through a weld based on this model with an experiment showed reasonably good agreement concerning the path of propagation. The attenuation due to scattering at grain boundaries was however poorly modelled. This is probably due to the fact that each grid cell is acting as a grain in these simulations. With a typical cell length of 0.1 mm and with each cell being of a quadratic geometry (in 2D) this is probably not realistic. The modelling of grain size and geometry is however an extremely difficult topic. Several simulations were performed and in general is was concluded, that SV are the wave type most effected by the weld structure, while the SH and L waves are only weakly distorted. This is in agreement with empirical observations.

Finally, in Chapter 7 a simulation model of a real material component from a power plant containing an austenitic weld as well as a cladding and a buttering is set up. The austenitic weld is described using the anisotropic, inhomogeneous model presented in Chapter 6. An isotropic and homogeneous version of the weld is also considered to study the effect (and it's size) of the weld model on the results. A parameter study involving transducer position for a vertical rectangular crack placed in the weld is carried out. The parameter study serve to demonstrate, how the developed simulation tool may be used in the preparation to an ultrasonic inspection job for optimizing inspection procedures.

8.2 Industrial aspects and benefits of the project

The main conclusions on the activities reported in this thesis have already been mentioned. However, as this project is an industrial research project, at this point it is appropriate to summarize and briefly discuss those conclusions particular relevant from an industrial point of view. In headlines, the most important industrial benefits, mainly illustrated in Chapter 7, are

1. Reduction of number of required test blocks, transducers etc
2. Reduction of qualification time period
3. Focusing the qualification activity
4. Valuable insight into elastic wave propagation in relation to A-scan interpretation

with the first three items being directly related to the qualification of an inspection procedure. In the following, these headlines are briefly discussed.

Concerning 1), the price of a test block can be quite large depending on geometry, material and included defects, but a prize of 100,000 DKr. is not unusual. In a qualification, 2-3 or even more different test blocks may be required, and if already existing test blocks are not suitable for the task, this may be quite expensive. Furthermore, a number of different transducers, in terms of frequency, angle and size are required. The price of a typical transducer is from 5,000 DKr. and up. As to item 2), the manufacturing of a test block, again depending on the complexity, may take from weeks up to a few months. Clearly, the use of mathematical modelling for cutting costs and time of duration in relation to the qualification is very attractive and may offer a competitive advantage. As demonstrated, in a modelling situation it is easy to insert the desired type of defects in an appropriately developed material model. A parameter study of defect parameters such as dimension and orientation or transducer parameters such as frequency, angle, size and the position from the defect may easily be carried out. Based on the results of this modelling activity, the absolute essential test blocks may be pointed out (or the need for them even eliminated altogether). The activity may also pinpoint the worst types of defects to detect for a given procedure and thus determine its scope.

Item 3) may be considered an important (side) result of the two first items. The initial activities as well as superfluous work may be carried out or identified respectively through the modelling activity, thus allowing a focus on the essential problems in the qualification.

The final item describes another important use. As has (hopefully) been demonstrated, the combination of contour plots of the sound field with the corresponding A-scan is extremely valuable for interpretation. The tool may thus serve an educational purpose regarding the inspection personnel at the company.

8.3 Suggestions for further work

Much of the time in this project has been devoted to the development and testing of the numerical method EFIT itself. Just as important a topic is the study and development of inhomogeneous material models. A model of an austenitic MMA weld has been studied and implemented as described in this thesis. However, little attention has been paid to the grain size and geometry. Intensive work on such grain modelling tasks (that is the specification of the elastic matrix and the mass density throughout the medium) as well as on specific inhomogeneous material models in general would be an obvious suggestion, if not the most important, for future work. Such work may involve the study of macrographs as shown in the thesis.

The simulations shown in the thesis has been run on a PII-450MHz pc with a single processor. In order to reduce calculation times, future work may also consider the obvious task of parallelizing the source code for several processors.

A larger repertoire of defect geometries (for example elliptic geometries) with stress-free surfaces would be desirable in the simulation program.

True 3D simulations may also be of great importance. As explained earlier in connection with the austenitic weld description, the restriction to 2D problems, especially for anisotropic materials, may neglect important information due to the presence of all three wave types, i.e. qL, qT1 and qT2. Although 3D volumes would be rather small they could provide such important information as a start. With the speed of development within the electronics industry these issues may receive increasing attention in the future.

Absorbing boundaries is an important alternative to stress-free boundaries. Especially the vertical boundaries may be non-real and in those cases the domain must be chosen large enough to avoid artificial reflections. This often results in large required amounts of memory and increased computational times. Absorbing boundaries may also be of relevance for modelling the transducer as a receiver.

An interesting application of EFIT together with the described receiver model is in connection with Synthetic Aperture Focusing Technique (SAFT) for reconstruction of defect location, size and orientation. SAFT results from scalar inverse scattering theory. This interesting problem has not been addressed in this thesis, instead the reader is referred to [43], which discusses SAFT applied to anisotropic, homogeneous materials, for more information on this topic.

Viscoelastic damping of elastic waves has been neglected in this presentation. This topic may also be taken up in future work, although it is perhaps not as important as the above suggestions.