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Mathematical modelling of ultrasonic testing of components with defects close to a non-planar surface

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SSM perspective

Background

During the last two decades, SSM has supported research to develop a model for the non-destructive test situation based on an ultrasonic technique. This kind of model is important in many ways, for example to complement and plan experimental studies and to perform parametric studies in qualification situations. Modelling can be a useful tool when the inspection system is to be technically justified. Many functions have been added to the model UTDefect and, in this step, modelling of defects close to a non-planar surface is studied.

Objectives

Pipes and components in nuclear power plants often have non-parallel surfaces. When examining this kind of components using ultrasound, there can be complex signal responses when there is a defect close to the surface. The objective of this project was to develop a model and to be able to model ultrasonic examination of defects close to a non-planar surface.

Results

The report describes work that has been performed in order to model ultrasonic testing of components that contain a defect close to a non-planar surface. The studies have been performed in both 2D and 3D, and in 2D in both the anti-plane (SH) and the in-plane (P-SV).

The results show that the presence of a non-planar back wall can reduce the detectability of defects close to the surface.

The results show that the corrugated interface can have important, and in some cases, major effects on the signal response. The results depend crucially on the parameters chosen for the corrugation also the material properties can affect the results.

Need for further research

There is a need for further work within ultrasonic modelling research to be able to develop and assess the reliability of non-destructive inspection systems capability to detect, characterise and size defects in components at nuclear power plants.

Project information

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Contents

Summary

Nondestructive testing with ultrasound is a standard procedure in the nuclear power industry. To develop and qualify the methods extensive experimental work with test blocks is usually required. This can be very time-consuming and costly and it also requires a good physical intuition of the situation. A reliable mathematical model of the testing situation can, therefore, be very valuable and cost-effective as it can reduce experimental work significantly. A good mathematical model enhances the physical intuition and is very useful for parametric studies, as a pedagogical tool, and for the qualification of procedures and personnel.

The aim of the present report is to describe work that has been performed to model ultrasonic testing of components that contain a defect close to a nonplanar surface. For nuclear power applications this may be a crack or other defect on the inside of a pipe with a diameter change or connection. This is an extension of the computer program UTDefect, which previously only admits a planar back surface (which is often applicable also to pipes if the pipe diameter is large enough).

The problems are investigated in both 2D and 3D, and in 2D both the simpler anti-plane (SH) and the in-plane (P-SV) problem are studied. The 2D investigations are primarily solved to get a 'feeling' for the solution procedure, the discretizations, etc. In all cases an integral equation approach with a Green's function in the kernel is taken. The nonplanar surface is treated by the boundary element method (BEM) where a division of the surface is made in small elements. The defects are mainly cracks, strip-like (in 2D) or rectangular (in 3D), and these are treated with more analytical methods. In 2D also more general defects are treated with the help of their transition (T) matrix. As in other parts of UTDefect the ultrasonic probes in transmission and reception are included in the model. In 3D normalization by a side-drilled hole is possible.

Some numerical results are given for all cases both in the form of C scans (line scans in 2D) and A scans. In the examples the nonplanar surface is taken in the shape of a smooth transition (a sine function) between two different thicknesses or a localized bump (only in 3D). As a comparison also a planar back surface is used. The defects are located close to these nonplanar parts of the back surface. The results show that the presence of the nonplanar parts may greatly reduce the capability to detect the defects.

Sammanfattning

Oförstörande provning med ultraljud tillämpas industriellt i kärnkraftsbranchen vid sökandet efter defekter. För att utveckla och verifiera testprocedurer behövs normalt omfattande experimentellt arbete med testblock. Detta kan ta mycket tid och bli dyrbart och det kräver också en god fysikalisk intuition. En pålitlig matematisk modell av provningssituationen kan därför vara mycket värdefull och kostnadseffektiv eftersom den kan reducera experimentellt arbete avsevärt. En bra modell stärker den fysikaliska intuitionen och är mycket användbar för parameterstudier, som ett pedagogiskt hjälpmedel samt vid kvalificeringen av procedurer och personal.

Föreliggande projekt har behandlat modelleringen av defekter i komponenter som har en icke-plan bakyta. I kärnkraftssammanhang kan detta vara en spricka eller annan defekt som ligger på insidan av ett rör med en diameterförändring eller anslutning. Detta är en utvidgning av datorprogrammet UTDefect som tidigare bara tillåtit en plan bakyta (som ofta kan vara giltigt för rör, bara diametern är stor nog relativt våglängden).

Problemen löses både i 2D och 3D, och i 2D studeras både det enklare antiplana (SH) och in-plana (P-SV) problemet. 2D-problemen studeras främst för att få en ”känsla” för lösningsproceduren, diskretiseringarna, etc. I alla fall används en integralekvationsmetod med en Greenfunktion. Den ickeplana ytan behandlas med en randintegralmetod (Boundary Element Method, BEM) där bakytan delas in i små element. Defekterna är framför allt sprickor, remslika i 2D och rektangulära i 3D och dessa behandlas med mer analytiska metoder. I 2D behandlas också mer allmänna defekter med hjälp av sin övergångsmatris (T-matris). Som i andra delar av UTDefect ingår modeller för ultraljudssökare, både som sändare och mottagare. I 3D kan kalibrering mot ett sidoborrat hål göras.

Några numeriska exempel ges för alla fall både i form av C-scan (linjescan i 2D) och A-scan. I exemplen är den icke-plana bakytan plan så när som på en mjuk övergång (en sinusfunktion) mellan två olika tjocklekar eller en begränsad inbuktning (bara i 3D). Som jämförelse studeras också en plan bakyta. Defekterna ligger nära dessa icke-plana delar av bakytan. Resultaten visar att närvaron av icke-plana delar kan avsevärt försvåra förmågan att detektera defekter.

1. Introduction

Nondestructive testing with ultrasound is a standard procedure in the nuclear power industry. To develop and qualify the methods extensive experimental work with test blocks is usually required. This can be very time-consuming and costly and it also requires a good physical intuition of the situation. A reliable mathematical model of the testing situation can, therefore, be very valuable and cost-effective as it can reduce experimental work significantly. A good mathematical model enhances the physical intuition and is very useful for parametric studies, as a pedagogical tool, and for the qualification of procedures and personnel.

The aim of the present report is to describe work that has been performed to model ultrasonic testing of components that contain a defect close to a non-planar surface. For nuclear power applications this may be a crack or other defect on the inside of a pipe with a diameter change or connection. This is an extension of the computer program UTDefect, which previously only admits a planar back surface (which is often applicable also to pipes if the pipe diameter is large enough).

The computer program UTDefect has been developed for more than a decade at Chalmers University of Technology, presently at the Department of Applied Mechanics. The progress has been reported in a number of SKI reports (Boström, 1995, 1997, 2000, 2001, 2002, 2004, Boström and Jansson 1997, 2000, 2010, Boström and Zagbai, 2006) and also in papers in scientific journals and at conferences, and in PhD theses. The program models the ultrasonic testing of a single defect in a component. The defect may be located close to a planar back surface, but not too close to the scanning surface. The defects should be of simple shape, like side-drilled hole, spherical or spheroidal pores, circular, strip-like and rectangular cracks. Also a strip-like surface-breaking crack is possible. Some of the cracks may be rough or partly closed due to a compressive stress. In most cases the component is assumed to be isotropic, but for strip-like and rectangular cracks it is also possible with an anisotropic component, and also to have the crack in an anisotropic cladding with a wavy interface to the base material. In all cases the component is assumed homogenous, but can have damping in the form of viscoelastic losses (which could model, e.g., grain scattering effects). The ultrasonic probes are of standard type, primarily contact probes of any type, angle, frequency, and with elliptic or rectangular effective contact area. Immersion testing is possible and the probes may also be focussing. The scanning is assumed to take place in a rectangular mesh on the surface of the component (or in the fluid in case of immersion testing). Results can be obtained in the form of A, B, and C scans, and it is also possible to obtain frequency data.

The methods used in UTDefect to solve the ultrasonic propagation and scattering problems are various types of integral and integral equation techniques. For side-drilled holes and spheres standard separation of variables is employed. A transmitting probe is modelled by the effective traction it exerts on the component, this is usually taken as a constant except for a phase determining the angle of the probe (usually called the piston model in the literature). The receiving probe is modelled by an elegant reciprocity argument due to Auld (1979). This is strictly valid only in lossless media, so when small viscoelastic losses are included in the model the argument is not strictly valid. It is noted that all methods used in UTDefect are in a sense "exact" in that they can, in principle, give solutions with arbitrarily high accuracy (by taking sufficient number of terms in series, computing integrals sufficiently accurately, etc.). It should remembered, however, that this is within the framework of linear elasticity, only viscoelastic losses, perfect geometry, like infinitely thin cracks, piston model for probes, etc. Still, in many cases the results should be more reliable than solutions depending on the common high frequency approximations like ray theory, Kirchhoff theory, or diffraction theory. For such methods it may be difficult to ascertain the range of validity in frequency, although the methods often work surprisingly well even at relatively low frequency (meaning that the size of typical defects has a diameter of about one wavelength). UTDefect works in the frequency domain and time domain results are synthesized at the end by a discrete Fourier transform. However, when C scans are generated it is often enough to use only the centre frequency. This significantly reduces the computational times as typically 100 frequencies are used to synthesize pulses in the time domain.

An important issue when models and computer programs are developed is of course the validation. For a program like UTDefect this can be done by comparisons with other modelling programs and/or by comparisons with experiments. Through the years some parts (but not all) of UTDefect have been compared in this way (Boström, 1995, Eriksson, et al.,1997, Pecorari 2002, Niklasson, et al., 2006, Jansson and Boström 2009, 2010). In general the agreement is good or fair, typical deviations are in most cases less than 2 dB. In some situations with real fatigue cracks in the near field (Eriksson et al., 1997) the deviations are larger, but this can be attributed both to limitations of UTDefect at that time and to the fact that real fatigue cracks were used and these can be both slightly rough and maybe not quite straight or vertical. It is more surprising that comparisons for a spherical void (Niklasson et al., 2006) show such large discrepancies, about 3-5 dB.

To solve the problem with a nonplanar back surface, other methods than used previously in UTDefect are needed. As boundary integral techniques are already used in UTDefect it is natural to look at extending these. The natural method is then the boundary element method (BEM), and this is the route followed. This method starts from boundary integral representations with a Green's tensor, exactly as other methods in UTDefect, but to solve these a subdivision of the boundary into small elements is performed, much as in the finite element method (FEM). For the nonplanar surface standard BEM is employed, but a crack close to the nonplanar surface is treated in the same way as an isolated crack in UTDefect, i.e. with a hypersingular integral equation which is solved by an expansion in global (on the crack) expansion functions (often Chebyshev functions). The method can be called a hybrid method between BEM and the hypersingular integral equation approach.

All the work reported here is more fully described in a Ph.D. thesis (Westlund 2011b) and in journal articles (Westlund 2009, 2011a, Westlund and Boström 2011) and in conference proceedings (Westlund 2009, Westlund and Boström 2010).

2. Theoretical considerations

The methods used to investigate the scattering problems for a defect, in particular a crack, in a component with a nonplanar back surface are now very shortly described. No formulas are given as all mathematical expressions are given by Westlund (2011b). Here the intention is only to give an overall impression of the methods.

The three-dimensional scattering geometry is shown in Fig. 1. The scanning surface with the two ultrasonic probes, one transmitter and one receiver, is supposed to be located sufficiently far away from the back surface and the defect so that all multiple scattering effects can be neglected. In practice this means that this distance should be at least a few wavelengths, a criterion that is usually met. The back surface may be of, in principle, arbitrary shape (in the figure it is planar except for a smooth transition between two different depths). However, it is assumed that the back surface is smooth in the sense that its normal is continuously varying, thus no cusps or edges are allowed. Different types of defects are treated in the project, either rectangular cracks or more arbitrary defects, characterized by their so-called T matrix (see further below). In the figure four coordinate systems are introduced, one at the defect, one at the back surface, and one at each probe. The distances between these systems are also introduced. The defect system may be rotated arbitrarily with respect to the other systems (which are all collinear). This rotation is parametrized by three Euler angles. The material of the component is assumed to be homogeneous and isotropic. Losses can be included in the form of viscoelastic losses, which in the time domain are modelled by complex stiffness constants. These are chosen to be frequency independent, but an arbitrary dependence on frequency could in fact be used.

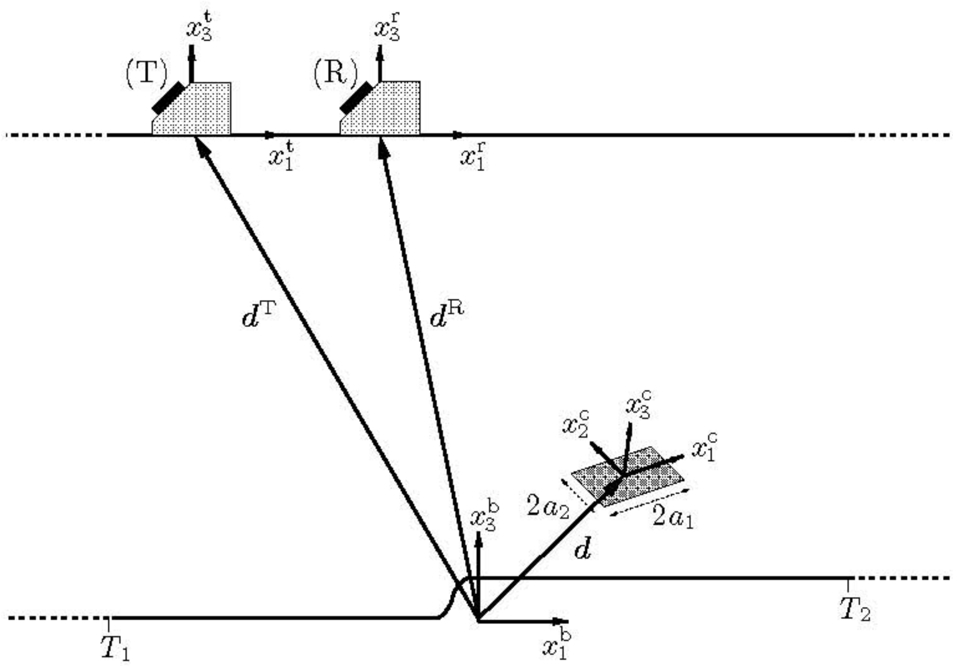

Figure 1: The scattering geometry of a defect (crack) close to a nonplanar back surface.

To solve the full problem with the generation of ultrasonic waves at the transmitting probe, propagation to the defect and back surface, scattering (including multiple effects) by the defect and the nonplanar back surface, propagation back to the receiving probe, and conversion to an electrical signal that is measured, an approach in a number of steps is taken. The treatment of the transmitting and receiving probes is performed in the same way as in other parts of UTDefect. Thus, a piston model is used for the probes and the radiation from the probe is solved for by Fourier transform techniques. The electrical output from the receiving probe is obtained by Auld's (1979) reciprocity argument, which only requires a knowledge of the scattered fields at the surface of the defect and the nonplanar back surface.

The scattering by the nonplanar back surface and the defect is the most challenging part. As in other parts of UTDefect the starting point is an integral representation with the Green's function. This thus involves integrals over the defect and the back surface, and letting the field point approach these two surfaces a set of coupled surface integral equations are obtained. Similar equations in other parts of UTDefect are solved by appropriate sets of expansion functions that are global on the surfaces. For the defect this route is still followed when the defect is a rectangular crack, but for the nonplanar back surface this approach is no longer possible. Instead the back surface is divided into a large number of small elements (less than half a wavelength), and on each element an expansion in quadratic functions is employed. This is a standard boundary element (BEM) approach, but here this approach is coupled to the more analytical treatment of the crack. As the multiple scattering between the defect and the back surface is included, there appear corresponding coupling terms in the discretized integral equations.

There are a number of issues to carefully investigate in the approach, such as the convergence of all involved integrals and the number of elements. A crucial point is the truncation of the infinite back surface; to get good accuracy a relatively large part of the back surface must be retained, but in 3D this results in very many elements and corresponding large computer times and memory demands. This has been alleviated by putting small elements in the system matrix to zero and using a sparse solver for the matrix inverse. Still, computations in 3D are quite demanding, and it has been necessary to use a (small) computer cluster to obtain reasonable computing times (10 hours or so).

In the project also the corresponding 2D problems have been investigated, primarily to investigate the feasibility of the approach. Both the in-plane problem with coupled P and SV waves and the simpler anti-plane problem with SH waves are solved. The method is essentially the same, but the computing times become much smaller. For the P and SV waves also another approach is employed, where the T matrix of the defect is used instead of the integral equation for the crack. A T (transition) matrix for a defect is a matrix relating the expansion coefficients for the scattered field to those of the incoming one. Such a matrix can be computed in some ways and are used in other places in UTDefect. Here only the T matrix for a circular cavity, corresponding to a side-drilled hole in 3D, has been used. The T matrix is used in the Green's function in the integral equation, and in this way only the scattering by the nonplanar back surface remains in the integral equation which is again solved by BEM.

3. Numerical results

In this section some numerical examples showing C and A scans are given to illustrate the effects of the nonplanar surface. Both 2D and 3D examples are given. No systematic parametric studies have been performed; the examples are just to illustrate the type of results that it is possible to obtain.

Only a single probe in pulse-echo is used which performs a line scan in 2D cases and a rectangular scan in 3D cases. Both C scans and A scans (time traces) are given. The material of the component are in all cases assumed to be steel.

3.1 2D SH results

In the 2D antiplane case only shear waves with horizontal polarization exist. These waves are difficult to excite in practice. With a contact probe the couplant must transmit shear stresses and this is difficult in practice. An EMAT has the possibility to excite these waves.

The exact geometry is given in Fig.2, which shows the nonplanar back surface, the vertical crack and the probe positions indicated by the dotted line. The vertical distance from the probe to the crack centre is 20 mm. The crack has a height of 5 mm. The nonplanar back surface has a height difference of 2 mm with a smooth sinusoidal transition during 6 mm. As a comparison a planar back surface is also considered. The probe has length 8 mm and is angled 30 degrees to the right. Its centre frequency is 2 MHz and its 6 dB bandwidth is 1 MHz. The frequency spectrum is a Hanning window.

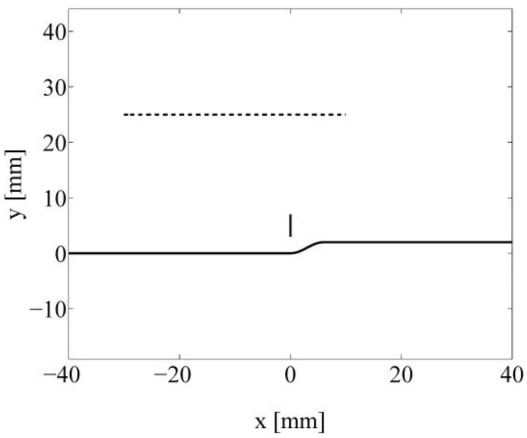

Figure 2: The geometry with the nonplanar back surface, the vertical crack, and the probe positions.

Figures 3 and 4 show line scans for the crack and the planar or nonplanar back surface, respectively. In the figures the full-drawn curves show results with the crack present and the dotted curves show the response from the back surface in the absence of the crack. For detection of the crack it is really the difference between the two curves that is of interest as this is the extra contribution due to the crack. From Fig 3 it is seen that the crack gives a strong corner echo, but from Fig 4 it is apparent that the nonplanar surface gives an even stronger, by about 15 dB, response that may actually mask the response from the crack.

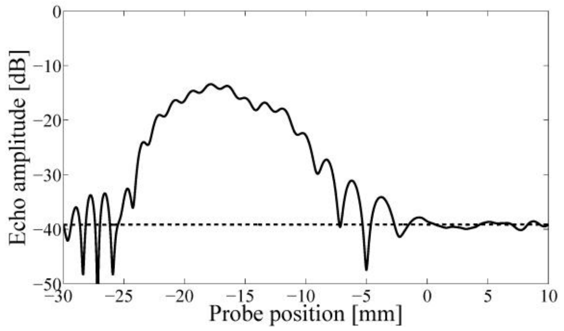

Figure 3: Signal response for a planar back surface as a function of probe position; solid curve with crack, dotted curve without crack.

Turning to time traces Figs. 5 and 6 show A scans for the crack and the planar and nonplanar back surface, respectively. The probe is situated 12 mm to the left of the crack, a position where the response is strong, see Figs. 3 and 4. The time traces also give a check on the results, since the different contributions to the signal response can be identified in these plots. The first arrival for the planar back surface in Fig. 5 around time t =15.6 μs is the weak reflection by the back surface going vertically up and down. The dominating pulse around t =17.4 μs is the corner echo from the crack and back surface. Also the diffraction from the upper crack tip after reflection by the back surface around t =21.4 μs is clearly visible. The diffraction from the lower crack tip has arrival time t = 13.5 μs but is not visible in Fig. 5, but can be identified on a magnified plot. Other tip diffraction contributions coincide with other pulses and cannot be identified. For the nonplanar back surface in Fig. 6 the same pulses can be identified, in this case the corner echo is mixed with direct reflections by the back surface. The tip diffraction around t =21.4 μs is now mixed with other multiple reflections and these also give rise to later pulses.

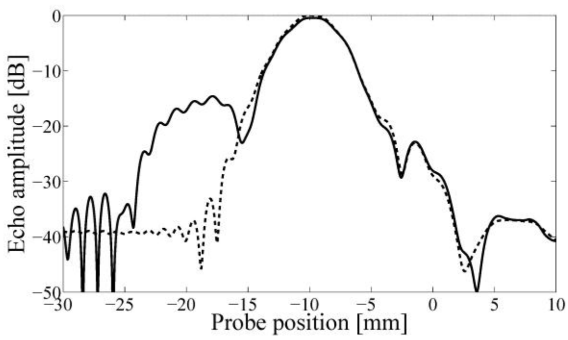

Figure 4: Signal response for a nonplanar back surface as a function of probe position; solid curve with crack, dotted curve without crack.

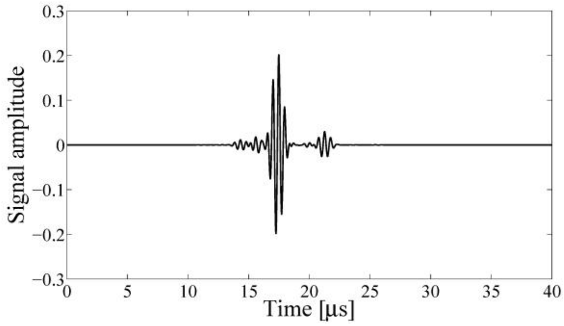

Figure 5: The signal response as a function of time for a vertical crack and a planar back surface.

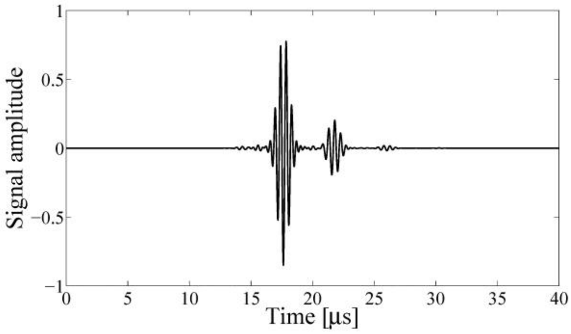

Figure 6: The signal response as a function of time for a vertical crack and a nonplanar back surface.

3.2 2D P-SV results

For in-plane P-SV waves the geometry is chosen very similar to the SH case. The nonplanar back surface has a height difference 7.5 mm on a smooth sinusoidal transition during 7.5 mm. The crack is still vertical and 5 mm. The probe is of SV type, angled 45 degrees to the right, and of length 10 mm. The vertical distance between the scanning surface and the lower part of the back surface is 20 mm. Damping is included with a 1% imaginary part in the stiffness constants.

Figure 7 and 8 show line scans for the crack and the planar or nonplanar back surface, respectively. In the figures the full-drawn curves show results with the crack present and the dotted curves show the response from the back surface in the absence of the crack. These results are computed with the single frequency 2 MHz, for C scans this gives results that are accurate enough. In Fig. 7 the planar back surface gives a very weak constant response, whereas the crack gives a strong corner echo around -20 mm. The nonplanar back surface in Fig. 8 gives a very strong response whether the crack is present or not. In this case the presence of the crack would be difficult to detect from the line scan.

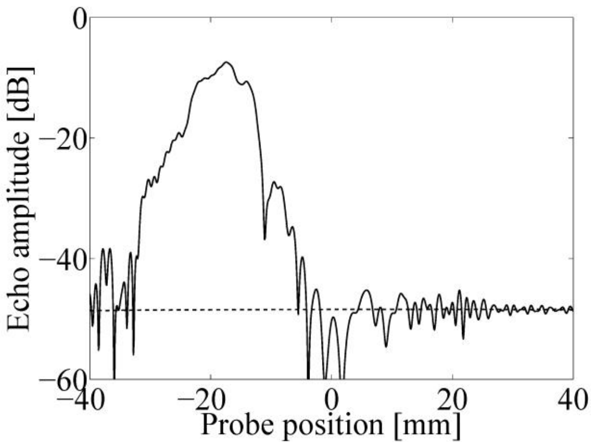

Figure 7: Signal response for a planar back surface as a function of probe position; solid curve with crack, dotted curve without crack.

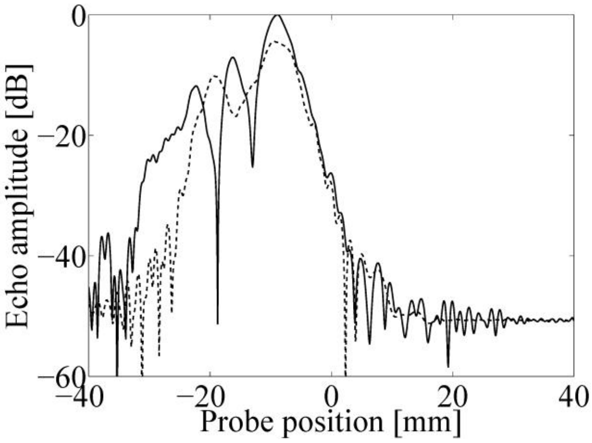

Figure 8: Signal response for a nonplanar back surface as a function of probe position; solid curve with crack, dotted curve without crack.

Turning to time traces, Figs. 9 and 10 show A scans for the crack and the planar or nonplanar back surfaces, respectively. The probe is situated 20 mm to the left of the crack, a position where the response is strong, see Figs. 7 and 8. The centre frequency is 2 MHz and the bandwidth is 1 MHz. In both figures the strongest response around t =17.9 μs is the corner echo for a wave travelling all the way as an SV wave. The pulse around t =14 μs is also a corner echo, but where parts of the way have been a P wave, therefore the earlier arrival time. If the plot is magnified a number of other pulses can be identified, as pulses reflected directly from the planar back surface and tip diffractions. In Fig 10 the situation is similar, and comparing Figs. 9 and 10 it is again noted that it would be difficult to detect the presence of the defect with the nonplanar back surface present.

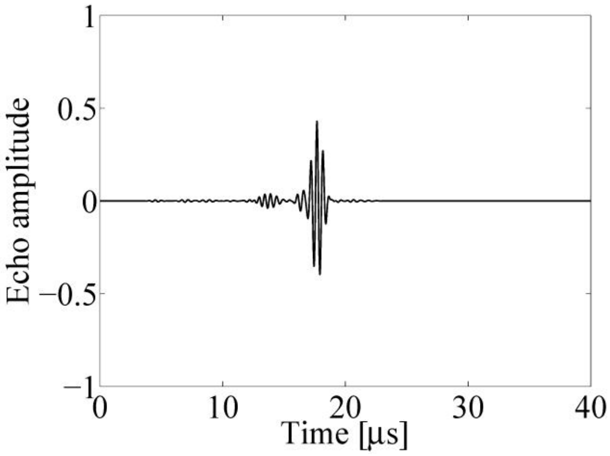

Figure 9: The signal response as a function of time for a vertical crack and a planar back surface.

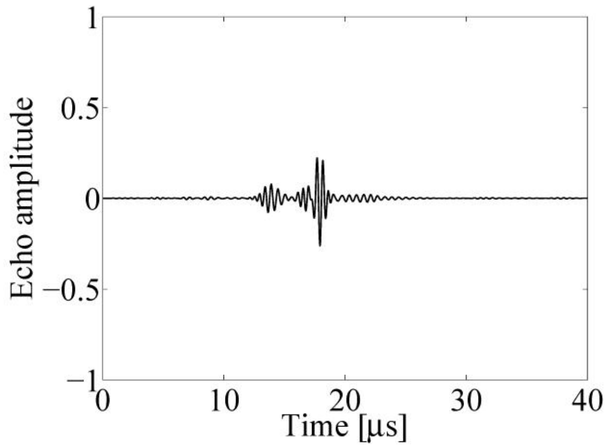

Figure 10: The signal response as a function of time for a vertical crack and a nonplanar back surface.

For 2D P-SV waves the scattering problems have also been solved with the help of the T matrix as described earlier. As an illustration a side-drilled hole (a defect whose T matrix is easily calculated) is considered. The geometry is otherwise similar as before, see Figure 2. The side-drilled hole has diameter 4 mm and is located 6 mm above the lower part of the back surface just where the transition begins. The transition is still sinusoidal but with amplitude 4 mm over a horizontal distance 10 mm. The probe has length 12 mm and a frequency of 1 MHz and 0.5 MHz bandwidth. Figures 11 and 12 show the response for the angle 45 degrees to the right and left, respectively. In the figures the full-drawn curves show results with the crack present and the dotted curves show the response from the back surface in the absence of the crack. In Fig. 11 the nonplanar back surface gives a very strong response and the presence of the side-drilled hole could easily be over-looked. In contrast, in Fig. 12 the reflection by the nonplanar back surface is much weaker and the scattering by the side-drilled hole is dominating.

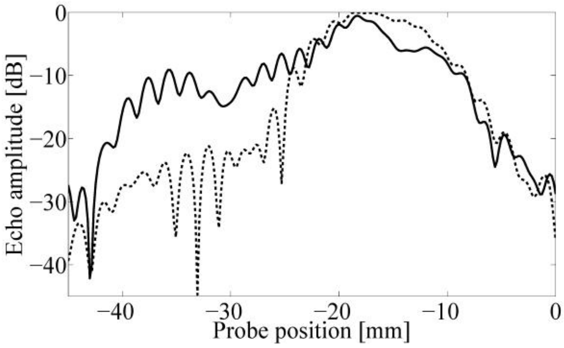

Figure 11: Signal response for a nonplanar back surface as a function of probe position with probe angle +45 degrees; solid curve with side-drilled hole, dotted curve without side-drilled hole.

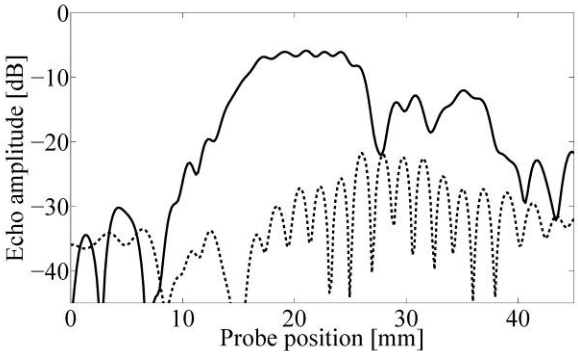

Figure 12: Signal response for a nonplanar back surface as a function of probe position with probe angle -45 degrees; solid curve with side-drilled hole, dotted curve without side-drilled hole.

3.3 3D results

Results in 3D are of course those of most interest and therefore the ultimate goal of the project. The computations become quite demanding and only relatively simple examples are therefore presented.

The back surface can be quite arbitrary; here two simple examples are used. One that is similar to those in 2D, namely a smooth transition with a height difference of 1.5 mm over a length of 5 mm with or without a vertical rectangular crack of height 3 mm and length 2 mm with the crack centre 5 mm above the start of the transition. The other back surface is a smooth local bump which is a product of two sine functions (over half a period) of height 1.5 mm and sides 5 and 6 mm with or without the same vertical rectangular crack with the crack centre 4.5 mm to the left of the middle of the bump. In both cases the largest thickness of the component is 20 mm. The probe is a 45 degree SV probe angled to the right so that the crack partly shadows the transition or bump. The probe is square with side 10 mm and operates at 1 MHz and has bandwidth 0.5 MHz. However, the C scans are computed with a single frequency as this is much more effective. The results are calibrated with a side-drilled hole of diameter 2 mm and centre depth 20 mm.

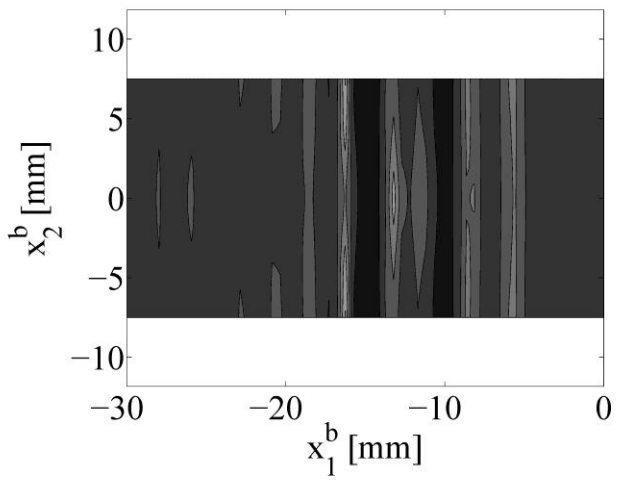

Figure 13: C scan for a back surface with a transition and a vertical crack.

Figures 13 and 14 show C scans for the two cases with a transition and a local bump, respective. In both cases the crack is also present. The grey scale in the figures is in dB with black 8 dB above the calibration level and white 32 dB below the calibration level. There are seven colours in between so the step is in 5 dB. In Fig. 13 the back surface of course gives a response that is independent of the vertical direction, so the variations in this direction are thus wholly dependent on the crack. In this figure it is thus reasonably simple to detect the presence of the crack. In Fig. 14, on the other hand, this is not so as both the bump and the crack give a local response.

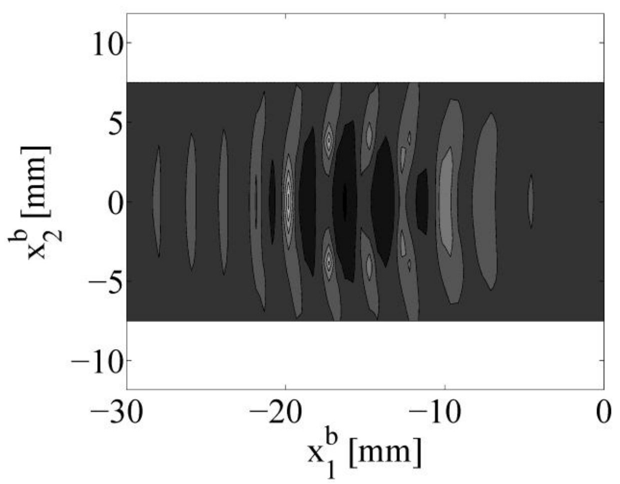

Figure 14: C scan for a back surface with a local bump and a vertical crack.

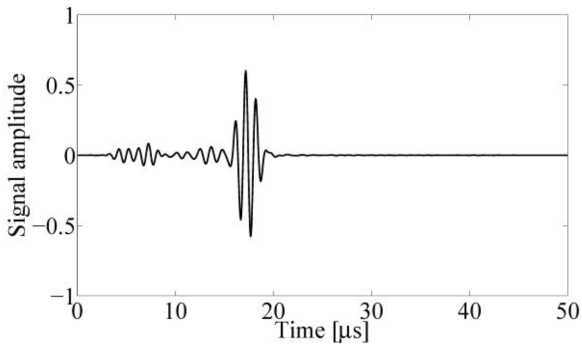

Figure 15: Signal response for a back surface with a transition and without any crack.

Figures 15 and 16 show time traces for the back surface with a transition and with or without the crack, respectively. In these figures the probe is situated 15 mm to the left of the crack, so the main beam from the probe hits the crack, and also the transition behind the crack. The first pulses in the figures in the time interval 7 – 13 μs are from waves travelling from the probe vertically and reflecting in the back surface (which is here planar). The strongest pulse in Fig. 15 around t =18 μs is the reflection from the transition. In Fig. 16 this pulse is smaller, so the crack has "shadowed" the transition, and this pulse also contains the corner reflection. There are also later arrivals stemming from multiple reflections between the crack and the back surface. From these time traces it seems difficult to detect the presence of the crack, although the smaller amplitude might possibly be useful.

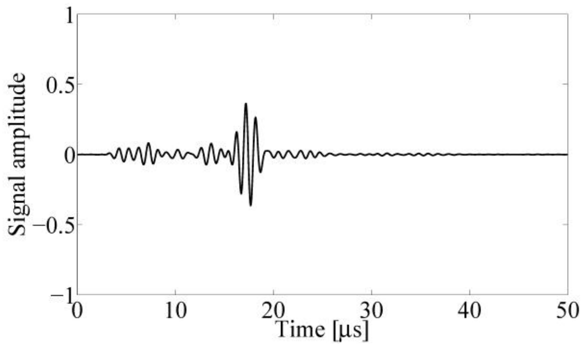

Figure 16: Signal response for a back surface with a transition and a crack.

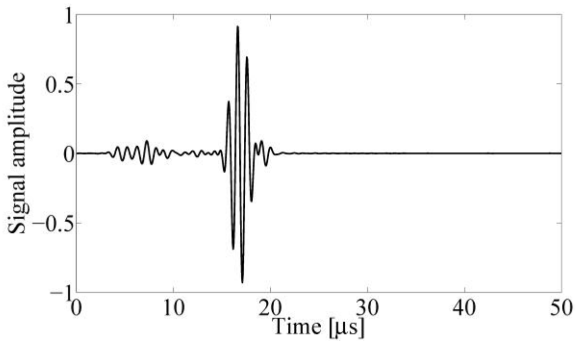

Figure 17: Signal response for a back surface with a local bump and without any crack.

Figures 17 and 18 show similar time traces, with the same probe location, but for the bump instead of the transition. The first part in the traces coming from vertical waves is of course the same as in Figs. 15 and 16. In this case the bump gives a stronger reflection than the transition, but it is also seen that the presence of the crack has a very small influence, it primarily gives some weak and late (due to multiple scattering) response.

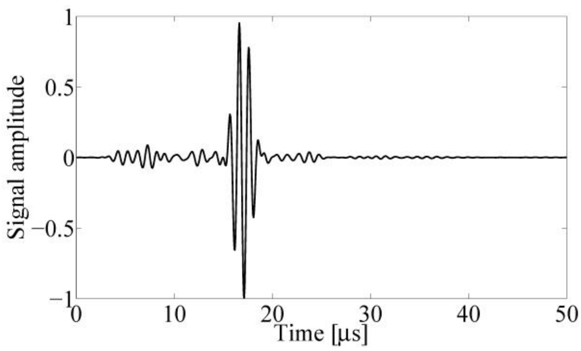

Figure 18: Signal response for a back surface with a local bump and a crack.

4. Conclusions

The present report describes work that has been performed to model the scattering by a nonplanar surface and a defect, mostly cracks. Work is performed in both 2D and 3D. In all cases a boundary integral equation approach is used in conjunction with a boundary element approach for the nonplanar surface. Models of ultrasonic probes are incorporated and in 3D calibration by a side-drilled hole is possible.

The main conclusion that can be drawn from the project is that the nonplanar surface may have a very large impact on the signal response. In some cases the signal due to the nonplanar surface may more or less completely mask the signal due to the defect. A possible use of the present results is thus to perform parametric studies to investigate the best probe to use in specific cases where defects close to a nonplanar surface are of interest.

References

Auld, B.A., 1979, "General electromechanical reciprocity relations applied to the calculation of elastic wave coefficients", *Wave Motion* **1**, 3-10.

Boström, A., 1995, *UTDefect – a computer program modelling ultrasonic NDT of cracks and other defects*, SKI Report 95:53, Swedish Nuclear Power Inspectorate, Stockholm.

Boström, A.,1997, *Ultrasonic probe radiation and crack scattering in anisotropic media*, SKI Report 1997:27, Swedish Nuclear Power Inspectorate, Stockholm.

Boström, A., 2000, *User guide to UTDefect, version 3: a computer program modelling ultrasonic non-destructive testing of a defect in an isotropic component*, SKI Report 00:44, Swedish Nuclear Power Inspectorate, Stockholm.

Boström, A., 2001, *Modelling of ultrasonic non-destructive testing in anisotropic materials – rectangular crack*, SKI Report 01:51, Swedish Nuclear Power Inspectorate, Stockholm.

Boström, A., 2002, *User guide to UTDefect, version 4: a computer program modelling ultrasonic non-destructive testing of a defect in an isotropic or anisotropic component*, SKI Report 02:26, Swedish Nuclear Power Inspectorate, Stockholm.

Boström, A., 2004, *Propagation of ultrasound in claddings*, SKI Report 2004:19, Swedish Nuclear Power Inspectorate, Stockholm.

Boström, A., and Jansson, P.-Å., 1997, *Developments of UTDefect: rough cracks and probe arrays*, SKI Report 97:28, Swedish Nuclear Power Inspectorate, Stockholm.

Boström, A., and Jansson, P.-Å., 2000, *Developments of UTDefect: rough rectangualr cracks, anisotropy, etc*, SKI Report 00:43, Swedish Nuclear Power Inspectorate, Stockholm.

Boström, A., Jansson, P.-Å., 2011, Modelling of ultrasonic testing of cracks in claddings, SSM Report 11:16, Swedish Radiation Safety Authority, Stockholm.

Boström, A., and Zagbai, T., 2006, *Modelling of ultrasonic non-destructive testing of cracks in claddings*, SKI Report 06:25, Swedish Nuclear Power Inspectorate, Stockholm.

Eriksson, A.S., Boström, A., and Wirdelius, H., 1997, *Experimental validation of UTDefect*, SKI Report 97:3, Swedish Nuclear Power Inspectorate, Stockholm.

Halkjaer, S., 2000, *Elastic wave propagation in anisotropic, inhomogeneous materials – application to ultrasonic NDT,* Ph.D. thesis, Department of mathematical modelling, Technical University of Denmark, Lyngby, Denmark.

Hannemann, R., 2001, *Modeling and imaging of elastodynamic wave fields in inhomogeneous anisotropic media – an object-oriented approach*, Ph.D. thesis, Department of electrical engineering, University of Kassel, Kassel, Germany.

Jansson, P.-Å., and Boström, A., 2009, Simulation of the 2008 ultrasonic benchmarking problems using UTDefect, *Rev. Progress Quant. Nondestr. Eval.* Vol. 28B, pp. 1968-1972, eds Thompson, D.O., and Chimenti, D.E., Am. Inst. Phys., Melville, N.Y.

Jansson, P.-Å., and Boström, A., 2010, Ultrasonic benchmarking with UTDefect, *Rev. Progress Quant. Nondestr. Eval.* Vol. 29B, pp. 2149-2156, eds Thompson, D.O., and Chimenti, D.E., Am. Inst. Phys., Melville, N.Y.

Niklasson, J., Boström, A., and Wirdelius, H., 2006, *Benchmarking – a validation of UTDefect*, SKI Report 06:30, Swedish Nuclear Power Inspectorate, Stockholm.

Westlund, J., 2009a, 2D SH modeling of ultrasonic testing for cracks near a non-planar surface, *AIP Conference Proceedings*, 1096, pp. 81-88.

Westlund, J., 2009b, 2D SH modelling of ultrasonic testing for cracks near a non-planar surface, *Eng. Anal. Boundary Elem.* **33**, 1103-1112.

Westlund, J., 2011a, Elastic wave scattering by a rectangular crack near a non-planar back surface, submitted.

Westlund, J., 2011b *On the modelling of ultrasonic testing using boundary integral equation methods*, Ph.D. thesis, Department of applied mechanics, Chalmers university of technology, Göteborg, Sweden.

Westlund, J., Boström, A., 2010a, A 2D model of ultrasonic testing for cracks near a non-planar surface, *Wave Motion* **47**, 383-394.

Westlund, J., Boström, A., 2010b A 2D model of ultrasonic testing for cracks near a nonplanar surface, *AIP Conference Proceedings*, 1211 pp. 89-96.

Westlund, J., Boström, A., 2011, A hybrid T matrix/boundary element method for elastic wave scattering from defects near a non-planar surface, submitted.

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