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Research

Propagation of Ultrasound in Claddings

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SKI

SKI perspective

Background

During the last decade, SKI has supported research to develop a model for the non destructive test situation based on ultrasonic technique. Such a model is important in many ways, for example to complement and plan experimental studies in qualification situations or as a tool in technical justifications. During the years, many functions have been added to the model and in this step propagation of ultrasound in cladding is studied.

Purpose of the project

Pipes and components in nuclear power plants are often equipped with a cladding material to prevent material degradation from media influence from the surface. This cladding material, often anisotropic, makes the ultrasonic test situation harder. To better understand the phenomenon and model the propagation of the ultrasonic signal through the material and the cladding this project was set up.

Results

The report describes, in the 2D and 3D case, the propagation of ultrasonic waves in a cladding that is both anisotropic and corrugated in the boundary between ground material and cladding.
The results and numerical examples show that the tilt and skew of the austenitic cladding has strong effects on the transmission of the waves. The results also show that the corrugated surface, in this case approximated as a sinusoidal function, also effects the transmission for certain values. This effect, in this approximation only valid for small corrugated heights, gives us guidance in understanding the complication of propagation through such a boundary.

Project information

Responsible for the project at SKI has been Lars Skånberg and Peter Merck.
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Propagation of Ultrasound in Claddings

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Summary

Nondestructive testing with ultrasound is a standard procedure in the nuclear power industry. To develop and qualify testing procedures extensive experimental work on test blocks is usually required. This can take a lot of time and therefore be quite costly. A good mathematical model of the testing situation is therefore of great value as it can reduce the experimental work to a great extent. A good model can be very useful for parametric studies, as a pedagogical tool, and for the qualification of testing procedures.

In anisotropic materials, e.g. austenitic welds, the propagation of ultrasound becomes much more complicated as compared to isotropic materials. Therefore, modelling is even more useful for anisotropic materials. The present project has been concerned with the propagation of ultrasound in claddings, i.e. a layer of material used for corrosion protection. This is often an austenitic steel that is welded onto the surface to be protected. For modelling purposes it may be a valid assumption to take the cladding as homogeneous but anisotropic. A complicating factor with a cladding is, however, that the interface between the cladding and the interface is often corrugated. This corrugation can have pronounced effects on the transmission of ultrasound through the interface and can thus change the detectability of defects in the cladding.

To model the propagation of ultrasound in claddings the null field approach is adopted. This has the advantage that the problem is reduced to a type of integral equations on the interface, which is further reduced to one period of the interface if it is periodic. The interface has, in fact, been taken as sinusoidal, both because this is reasonably realistic and because it simplifies the computations. Altarnative methods, primarily FEM and EFIT, use volume discretizations and in 3D this often leads to very large problems and excessive execution times.

The modelling is performed both in 2D and 3D, and in addition one part of the project has been concerned with the derivation and evaluation of approximate boundary conditions to simulate the corrugated interface with periodic boundary conditions on a (fictitious) flat interface. This simplifies the computations and could be of particular value when modelling defects in the cladding by integral equation techniques.

Some numerical results are given showing the capabilities of the programs. Only a combination with an isotropic ferritic base material and an anisotropic austenitic cladding is considered, but both the tilt and skew of the austenite and the height of the corrugations are varied. Only a 45° 1 MHz SV probe is used to excite waves in the structure. To get a good overview of the wave propagation field plots of the ultrasound are given. These are given at a fixed frequency and thus show the wavefronts, wavelengths, and direction of propagation. But the travel time information is of course missing. The results show that both the tilt and the skew of the anisotropy have very important effects on the transmission of the ultrasound into the cladding (and thus on the detectability of defects there). The height of the corrugation is also of importance, and the heights that are found in practice will in many cases have strong effects on the transmission of ultrasound into the cladding.

The approximate boundary conditions are evaluated by comparisons with the exact calculations, and the conclusion is that they are useful for small corrugation heights. The

heights that are found in practice will often violate the range of applicability of the approximate boundary conditions.

This project has been supported by the Swedish Nuclear Power Inspectorate (SKI).

Sammanfattning

Oförstörande provning med ultraljud tillämpas industriellt i kärnkraftsindustrin vid sökandet efter defekter. För att utveckla och verifiera testprocedurer behövs normalt omfattande arbete med testblock. Detta kan ta mycket tid och därmed bli dyrbart. En god matematisk model av testsituationen kan därför vara värdefull eftersom den kan reducera det experimentella arbetet avsevärt. En bra modell kan vara mycket användbar vid parameterstudier, som ett pedagogiskt hjälpmedel och vid procedurkvalificering.

I anisotropa material, t.ex. austenitiska svetsar, är utbredningen av ultraljud mycket mer komplicerad än i isotropa material. Därför är modellering ännu mer användbart för anisotropa material. Föreliggande projekt har som syfte att studera utbredningen av ultraljud i pläteringar, dvs. ett lager av ett material som är påsatt som korrosionsskydd. Detta är ofta ett austenitiskt stål som är påsvetsat. För modelleringen kan det vara rimligt att antaga att pläteringen är homogen men anisotrop. En komplikation med en påsvetsad plätering är att gränsytan mellan pläteringen och grundmaterialet ofta är korrugerad. Denna korrugering kan ha stora effekter på transmissionen av ultraljud genom gränsytan och därför på detekterbarheten hos defekter i pläteringen.

För att beräkna ultraljudsutbredningen i en plätering används nollfältsmetoden. Detta har fördelen att problemet reduceras till en typ av integralekvationer på gränsytan, som reduceras vidare till en period av gränsytan om denna är periodisk. Gränsytan har valts som en sinusfunktion, både därför att detta är rätt realistiskt och därför att det förenklar beräkningarna. Alternativa metoder, framför allt FEM och EFIT, använder volymdiskretiseringar, och i 3D leder detta ofta till mycket stora problem med orimliga exekveringstider.

Modelleringen utförs både i 2D och 3D, och dessutom har en del i projektet gått ut på att härleda och verifiera approximativa randvillkor som kan simulera den korrugerade ytan med periodiska randvillkor på en (fiktiv) plan yta. Detta förenklar beräkningarna och kan vara speciellt värdefullt om defekter i pläteringen skall behandlas med integralekvationsmetoder.

För att illustrera möjligheterna ges en del numeriska resultat. Bara en kombination med ett isotropt ferritiskt grundmaterial och en anisotrop austenitisk plätering tas upp, men orienteringen hos anisotropin varieras i två riktningar och även höjden på korrugeringarna varieras. Bara en 45° 1 MHz SV sökare används för att excitera ultraljudet i strukturen. För att ge en bra översikt över ultraljudets utbredning ges gråskaleplottar av fältet. Dessa ges vid fix frekvens, vilket visar vågfronter, våglängder och utbredningsriktningar bra. Däremot finns naturligtvis ingen gångtidsinformation med. Orienteringen hos anisotropin har stora effekter på transmissionen av ultraljud genom gränsytan (och därigenom på detekterbarheten av defekter i pläteringen). Korrugeringshöjden är också viktig och höjder som är vanliga i praktiken har i många fall stor inverkan på transmissionen av ultraljud in i pläteringen.

De approximativa randvillkoren utvärderas genom jämförelse med exakta beräkningar, och slutsatsen är att de är användbara för små korrugeringshöjder. Höjder som förekommer i praktiken är ofta större än de som de approximativa randvillkoren tillåter.

Detta projekt har bekostats av SKI.

1 Introduction

Nondestructive testing with ultrasound is a standard procedure in the nuclear power industry when searching for defects. To develop and qualify testing procedures extensive experimental work on test blocks is usually required. This can take a lot of time and therefore be quite costly. A good mathematical model of the testing situation is therefore of great value as it can reduce the experimental work to a great extent. A good model can be very useful for parametric studies and as a pedagogical tool. A further use of a model is as a tool in the qualification of testing procedures.

The computer program UTDefect and the mathematical model behind it has been developed for a decade. The program models the ultrasonic testing of isotropic and anisotropic thick-walled components with a single defect. Conventional contact and immersion probes can be modelled. The calibration is performed by a side-drilled or flat-bottomed hole. The list of possible defects is rather long and primarily includes some simply shaped cracks, but also a few volumetric defects. Some of the cracks can have rough faces and one can be partly closed due to a compressive stress. The defects can also be located close to a planar back wall of the component and surface-breaking cracks can be modelled. The output from UTDefect is in the form of conventional A-, B- and C-scans. The developments have been documented in a number of reports, see Boström (1995, 1997, 2001, 2002), Boström and Jansson (1997, 2000), and and Eriksson et al. (1997), as well as in many scientific journal publications and doctoral theses.

The modelling of anisotropic components is troublesome in several ways. The model must include all the essential effects of a real component. This in particular includes the anisotropy, but even if the anisotropy is homogeneous it is not a trivial matter to accurately determine all the stiffness constants (five for a transversely isotropic medium, nine for an orthotropic medium). In addition, in nuclear power plant components the anisotropy is often inhomogeneous and this is problematic in two ways. Firstly, the inhomogeneity must be known accurately enough and presently there seems to be no way to do this in a nondestructive way. So on old components it may be a more or less impossible task to determine the inhomogeneous structure, in a weld for instance. Secondly, even if the inhomogeneity is accurately known, it is difficult to model this. Ray tracing is possible (using RAYTRAIM for example) and this gives some insight into the ultrasonic propagation, but it is hard to assess how accurate this method really is. Otherwise one must resort to purely numerical techniques like FEM or EFIT, but these become very computer intensive in three dimensions. See Halkjaer (2000) and Hannemann (2001) for examples of using EFIT in two dimensions for an inhomogeneous and anisotropic weld model.

A common anisotropic part in nuclear power components is a cladding, i.e. a layer of material used for corrosion protection. This is often an austenitic steel that is welded onto the surface to be protected. The handbook by Hudgell (1994) gives a discussion of the problems with this and gives guidelines for the ultrasonic testing of components with claddings. Due to the processing a welded cladding is both anisotropic and also somewhat inhomogeneous, but for modelling purposes it may be a valid assumption to take the material as homogeneous. Another complication is that the surface between the cladding and the base material is corrugated, typically with a wavelength around 5 mm and a peak-to-peak amplitude of 1–2 mm. These properties of claddings can have a large impact on the ultrasonic wave propagation, leading to high noise levels and an increased attenuation. It can also lead to unexpected beam directions and to difficulties to detect and size defects inside the cladding.

The present project is concerned with the modelling of the ultrasonic wave propagation in claddings, taking both the anisotropy and the corrugated interface into account. Both two-dimensional and three-dimensional computations are performed. The cladding is taken to be homogeneous so the anisotropy is constant throughout. The results are presented as field plots so that it is possible to see how the whole ultrasonic field behaves with different kinds of reflections and scattering. However, no defects are included in the computations, this is instead taken up in a just started project. This also means that the present models and computational methods are not integrated into UTDefect as this program is only concerned with the modelling of the recieved signals from defect scattering and does not produce any field plots.

The work presented here is more fully described in three papers, where full mathematical details are given, see Krasnova et al. (2003), Krasnova and Jansson (2004), and Krasnova (2004), and also in the coming thesis of Krasnova (2004).

2 Theoretical considerations

To model the testing situation with a probe transmitting ultrasonic waves into a component with a cladding a geometry as shown in Fig. 1 is appropriate. The component is locally modelled as a thick plate consisting of two different materials, both of which are allowed to be anisotropic. The interface between the materials is assumed to be corrugated. As a special case the interface is instead taken to be flat but with boundary conditions that are periodic so as to try to simulate the corrugations. With the chosen geometry it is possible to model the testing from both sides of a clad component by chosing the material closest to the probe as the base material or the cladding as appropriate.

Both 2D and 3D computations are performed, the 2D case is exactly depicted in Fig. 1. It should be noted that to obtain a really 2D situation the probe must be assumed to be infinitely extended in the third direction. Nevertheless, 2D computations can give a good idea of what is going on. But exact values on amplitudes should not be trusted (there are ways to try to correct the amplitudes), particularly because waves are decaying like the inverse distance in 3D but as the inverse square root of the distance in 2D. When 3D problems are considered, Fig. 1 is still valid with the specification that the interface does not have any variations in the third dimension. But the probe is of course taken to have a finite width in the third direction, and because of this the field distribution is 3D although the geometry is in a sense 2D.

The base material and the cladding can both be anisotropic, either transversely isotropic (five stiffness constants, two angles to specify the symmetry axis) or orthotropic (nine stiffness constants, three angles to specify the orientation). This should cover all materials of interest in the nuclear power industry (the computations are, however, performed with the full stiffness matrix, so it is only to change the input to allow for arbitrary anisotropy). Also damping is included, this is of the viscoelastic type, and in the frequency domain this means that the stiffness constants (and thereby the the wave speeds) are complex with an (usually small) imaginary part representing the damping. For a 2D problem the 2D plane must be a plane of elastic symmetry and this reduces the number of stiffness constants to four for a transversely isotropic material and to six for an orthotropic material. In addition one angle is needed to specify the orientation of the anisotropy. It should be stressed that this is a good reason to perform also 3D computations as the limitation on the orientation

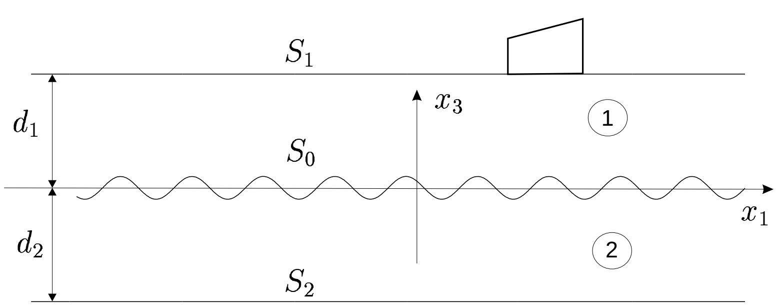

Figure 1: The geometry of a clad component with wavy interface.

of the anisotropy in 2D may be unrealistic in some situations. In the cladding, for example, it is expected that one of the crystal axes is skewed into the plane in Fig. 1 and this gives a truly 3D situation.

Ultrasonic probes have been modelled in previous projects. This is essentially followed here, although the simplest version is chosen. It is easy to change to other probe models should reasons for this appear. As chosen, the model prescribes the pressure on the probe's contact area. This pressure is constant except for a phase that accounts for the angle of the probe (this phase in the frequency domain corresponds to a time lag in the time domain). The probe is thus characterized by the type (P or SV), frequency, angle, and size. The bandwidth is also of importance, but to give a better overview of the fields (and to speed up the computations) all results will be given at a fixed frequency. Frequency results also have the benefit of reducing the number of figures as one figure at the centre frequency corresponds to a number of figures at different times. But the cost for this is of course that the travel time information is lost and that it may be more difficult to identify the different wave types.

To solve the wave propagation problem in the two anisotropic media with the wavy interface the null field approach is adopted. This method starts from surface integral representations including the Green's tensor. After some manipulations this reduces the problem to finding the unknown displacement and stress on the interface. This is effective because it reduces the problem from unknowns in a volume to unknowns on a surface. The corrugated surface is specialized to a sinusoidal one, this seems to be reasonably realistic, see Hudgell (1994), and it leads to great simplifications in the calculations. The periodicity and the particular shape of the surface lead to a reduction to one period of the surface and that all integrals can be computed analytically. The resulting linear system of equations for the expansion coefficients of the surface displacement and stress is rather small and easily solved. Having obtained the surface fields, the fields everywhere can be obtained from the integral representation, this probably being the most heavy part of the computations. However, it is more difficult to obtain the fields inside the grooves of the corrugated interface. This has not been pursued here, so the fields in the grooves are not computed at all and this will be seen in the numerical examples.

The 2D and 3D cases are treated in essentially the same way. The 3D case involves an additional Fourier type integral in the third direction and this leads to much longer execution times (hours).

One part of the project involves the investigation of a simplified type of boundary condition that can be used instead of the exact ones on the corrugated interface. The continuity of dispacement and stress on the corrugated interface is then exchanged to approximate boundary conditions at a fictitious flat interface. This is achieved by Taylor expansions of relevant quantities, assuming that the height of the corrugations is small and that only linear terms in this height need be kept. The boundary conditions look more complicated, but the great advantage is that they are applied on a flat surface. This is useful already for the propagation problems considered here, but it should be even more useful when considering the scattering by a defect in the cladding (at least when integral equation methods are applied). For the approximate boundary condition the solution procedure is straightforward. Upgoing and downgoing waves are assumed in both the base material and the cladding and all expansion coefficients are determined by applying all the boundary conditions. The only complication is that the approximate boundary condition depends on the coordinate along the interface in a periodic manner, but particularly for a sinusoidal interface this is easily coped with.

3 Numerical examples

In this section some numerical examples are given to show a little what type of results that can be obtained. There are then a lot of parameters to vary, so obviously a comprehensive study is not possible and most of the parameters are fixed. The only parameters that will be varied are the tilt (and skew) of the anisotropy and the corrugation period and height of the interface.

The geometry is given in Fig. 1. The upper base material is chosen as an isotropic steel and the lower cladding as an anisotropic austenitic steel (weld material). The thickness of the base material is 15 mm and the thickness of the cladding is 10 mm. Only an SV probe with the fixed angle 45° and frequency 1 MHz is used. The probe is square with side 10 mm (in 2D only the length of the probe is relevant). The near field length of the probe is thus only about 8 mm.

The upper material is chosen as a ferritic steel which is isotropic with Lamé constants $\lambda = 114$ GPa and $\mu = 82.6$ GPa and density $\rho = 8420$ kg/m^3. The lower material is an austenitic steel, with material parameters that correspond to a typical weld material. This material is transversely isotropic with stiffnesses $C_{33} = 216.0$, $C_{11} = C_{22} = 262.7$, $C_{66} = 82.2$, $C_{44} = C_{55} = 129.0$, $C_{13} = C_{23} = 145.0$ and $C_{12} = 98.2$, all measured in GPa, given in the crystal system. As usual in a transversely isotropic material with symmetry axis in the 3-direction $C_{66} = (C_{11} - C_{12})/2$. The density is 8120 kg/m^3. In addition the orientation (of the crystam system) of the material must be specified. In 2D problems only one angle is needed and that is the tilt of the material, which is given counterclockwise relative a vertical 3-direction. In 3D the orientation can be specified by three Euler angles. For a transversely isotropic material only two angles are needed, namely the tilt as in 2D and the skew, which is the rotation around the horizontal axis in Fig. 1.

The slowness surfaces of the austenitic steel are given in Fig. 2 and the corresponding wave surfaces in Fig. 3. Due to the isotropy in the 12-plane, it is sufficient to show the surfaces in the 13-plane. In Fig. 2 three curves are seen, the innermost is the slowness for the qP wave, the middle one is for the SH wave (in a transversely isotropic material a pure SH wave exists) and the outermost nonconvex curve is for the qSV wave. These nonconvexities lead to the wellknown cusps that are seen on the corresponding curve in Fig. 3, where the outermost curve is for the qP wave. The slowness and wave surfaces are very helpful when interpretation of numerical or experimental results are performed. In particular the slowness surfaces show the relation between the phase and group velocities, i.e. between the wave front and energy propagation, as the slowness is the inverse of the phase velocity and the group velocity is normal to the slowness curve. The wave surfaces in Fig. 3 give the group velocities as a function of direction of propagation and it is in particular noted that the cusps give rise to three qSV group velocities in some directions. The wave surfaces can be viewed as the waves due to an impulsive point source.

To illustrate the ultrasonic fields, the absolute value of the real part of the displacement vector is plotted in linear greyscale in the x_1x_3-plane of Fig. 1 (for various reasons these axes have different names in the field plots). Black is the strongest field and white is a practically vanishing field. As the fields are plotted at fixed frequency this gives a good

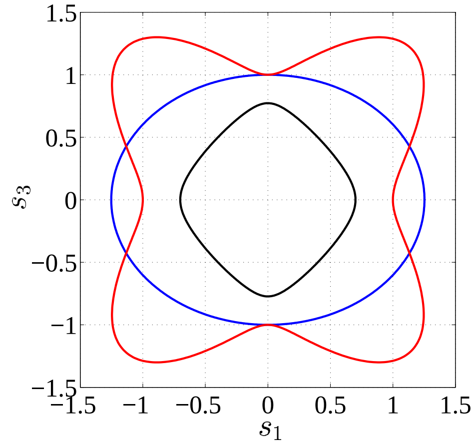

Figure 2: The slowness curves for the austenitic steel.

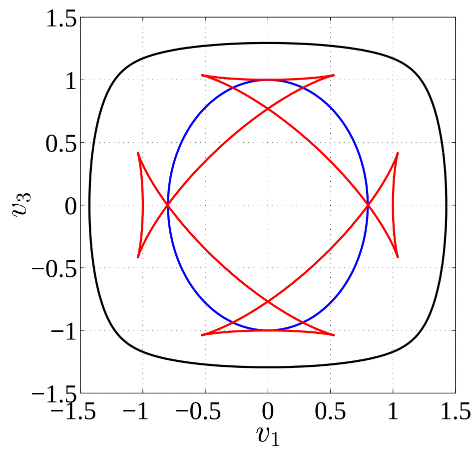

Figure 3: The wave curves for the austenitic steel.

overall picture where the wavefronts, wavelengths, and direction of propagation are directly seen. The only information that is missing is the travel time, and thereby the wave speeds.

Figure 4 shows a field plot for a 2D case with a flat interface. The weld material in the cladding is tilted 45° and this tilt angle is kept the same in the following four figures. In Fig. 4 (and in all the following figures) the probe is situated at the left upper corner, centred around $x_1 = 0$ and with width 10 mm. The direct field from the probe, the transmission into the cladding, and a reflectid field are all easily identified. The energy velocity is almost vertical in the cladding in this case and as the back wall gives a total reflection this results in a standing wave in the cladding. In Figs. 5 and 6 the interface is corrugated with period 5 mm and height 0.3 and 1 mm, respectively, with all other conditions the same as in Fig. 4. The small corrugation height 0.3 mm gives only minor effects on the field, but for the height 1 mm there are clear effects. The reflection is weaker and there is also a clear reflection back towards the probe. In Fig. 6 the part of the materials within the corrugated region is left white. The reason for this was discussed above. However, for

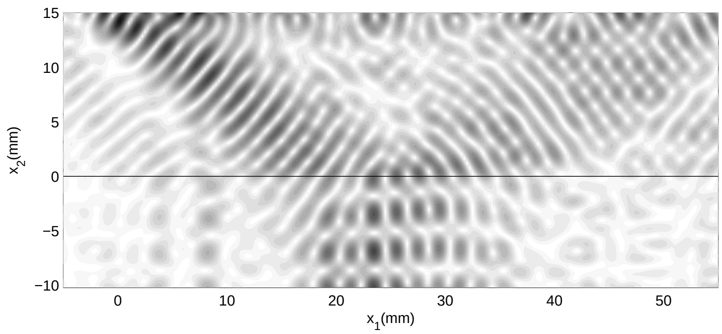

Figure 4: Field plot for flat interface with anisotropy tilted 45° in 2D.

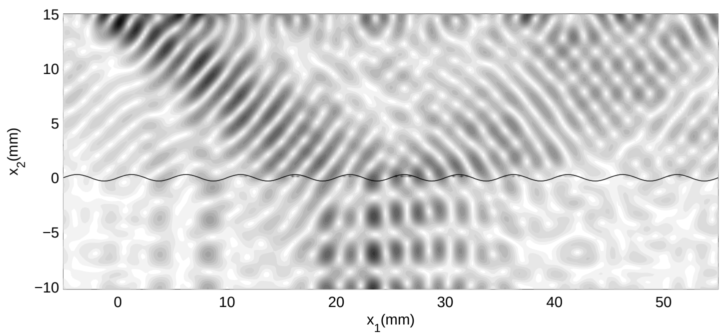

Figure 5: Field plot for corrugated interface with period 5 mm and height 0.3 mm and the anisotropy tilted 45° in 2D.

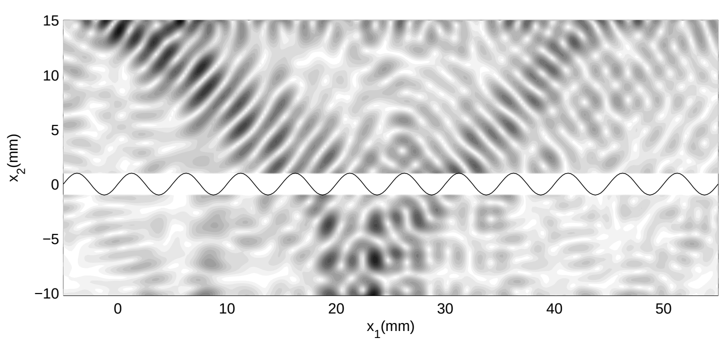

Figure 6: Field plot for corrugated interface with period 5 mm and height 1 mm and the anisotropy tilted 45° in 2D.

small corrugations as in Fig. 5, the field can be directly continued into the grooves and thereby given everywhere.

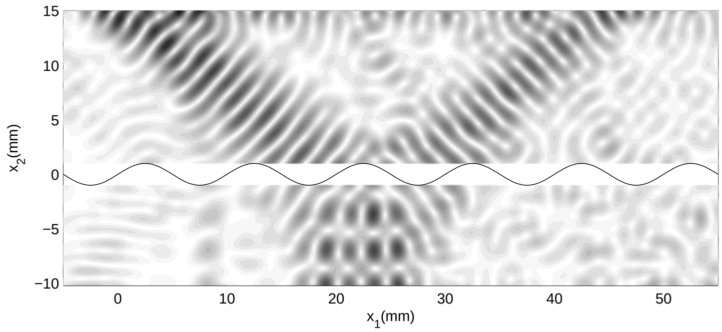

Figure 7: Field plot for corrugated interface with period 10 mm and height 1 mm and the anisotropy tilted 45° in 2D.

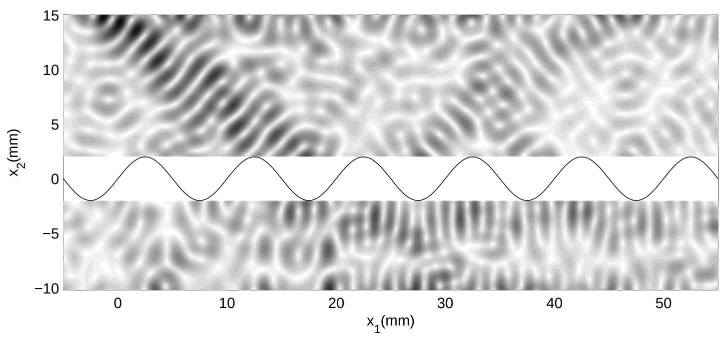

Figure 8: Field plot for corrugated interface with period 10 mm and height 2 mm and the anisotropy tilted 45° in 2D.

In Figs. 7 and 8 the interface is corrugated with period 10 mm and height 1 and 2 mm, respectively. For the height 1 mm the effects are similar to the ones in Fig. 6, which is for the same height but half the period. For the larger height in Fig. 8 the field distribution is much more scattered with only a weak reflection. Is seems like the field in the cladding is more or less propagating sideways. For this combination of interface and probe it would be more or less impossible to detect a defect in the lower material.

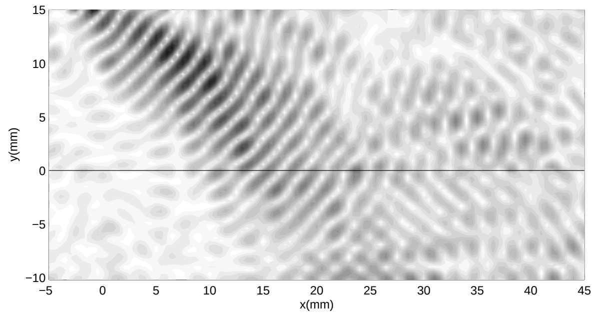

Figure 9: Field plot for flat interface with anisotropy tilted 45° in 3D.

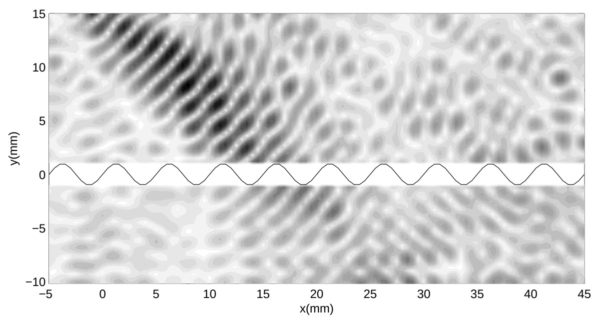

Figure 10: Field plot for corrugated interface with period 5 mm and height 1 mm and the anisotropy tilted 45° in 3D.

Turning to 3D results, Figs. 9 and 10 show field plots for the same cases as in Figs. 4 and 6, respectively, i.e. the anisotropy is tilted 45° and the interface is flat or corrugated with period 5 mm and height 1 mm, respectively. At first glance the differences between 2D and 3D seem to be large. At closer examination, however, it is realised that this is due to the different incoming fields. The 3D field decays faster with distance and it also has stronger sidelobes. The directly reflected wave at the interface in 3D in Figs. 9 and 10 looks very weak, but this is partly an illusion because of the interference with a sidelobe that "hids" this wave. Also the back wall reflection may seem weaker, but this is probably due to the faster decay of the fields with distance. There is of course no common normalization between 2D and 3D so it is only meaningful to compare relative amplitudes.

In a real cladding the tilt of the anisotropy is expected to be more or less small. A number of plots are now shown to illustrate this with tilt and skew 0° and/or 15° and varying corrugation height (but corrugation length fixed to 5 mm). The untilted case with a flat interface is shown in Fig. 11. There is a relatively weak transmission into the cladding in this case. The reflection also looks weak, but this is again an illusion which is due to the interference with a sidelobe. If the corrugation is small, $b = 0.3$ mm, in Fig. 12, the field distribution is only altered a little. For a stronger corrugation, $b = 1$ mm, in Fig. 13, the field distribution is more disturbed with a somewhat stronger transmission into the cladding.

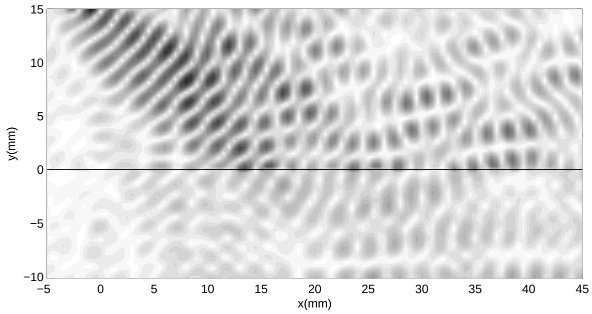

Figure 11: Field plot for flat interface with untilted anisotropy in 3D.

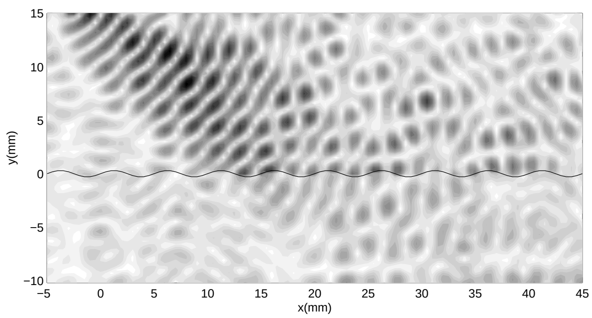

Figure 12: Field plot for corrugated interface with period 5 mm and height 0.3 mm and untilted anisotropy in 3D.

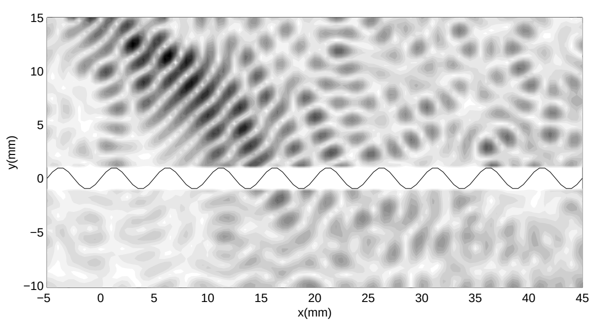

Figure 13: Field plot for corrugated interface with period 5 mm and height 1 mm and untilted anisotropy in 3D.

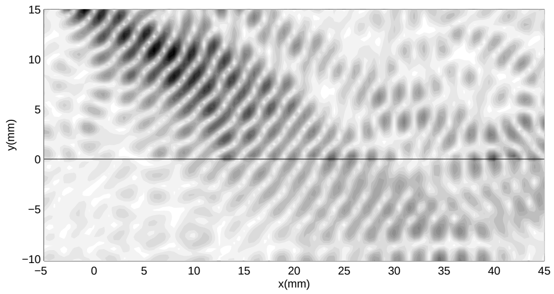

Figure 14: Field plot for flat interface with anisotropy tilted 15° in 3D.

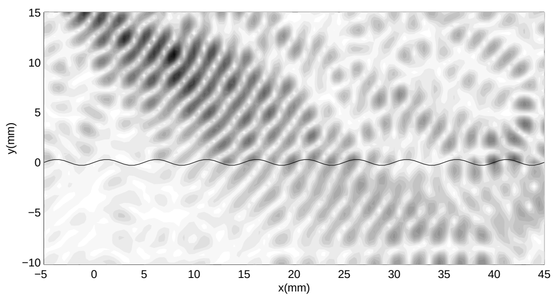

Figure 15: Field plot for corrugated interface with period 5 mm and height 0.3 mm and the anisotropy tilted 15° in 3D.

If the anisotropy is tilted 15° the fields are clearly modified, see Figs. 14–16 for $b = 0$, 0.3, and 1 mm, respectively. For the flat interface in Fig. 14 the field is strongly transmitted through the interface without change in propagation direction and the reflection is correspondingly rather weak.

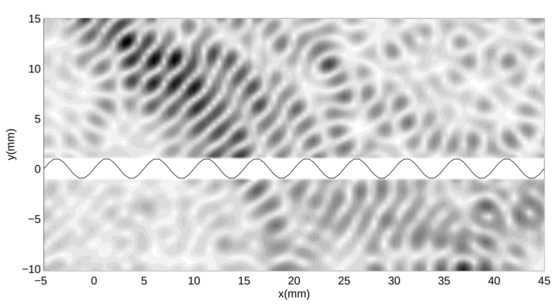

Figure 16: Field plot for corrugated interface with period 5 mm and height 1 mm and the anisotropy tilted 15° in 3D.

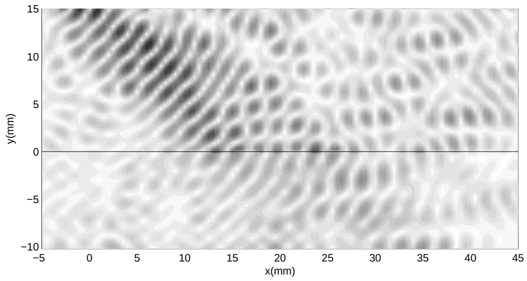

Figure 17: Field plot for flat interface with anisotropy skewed 15° in 3D.

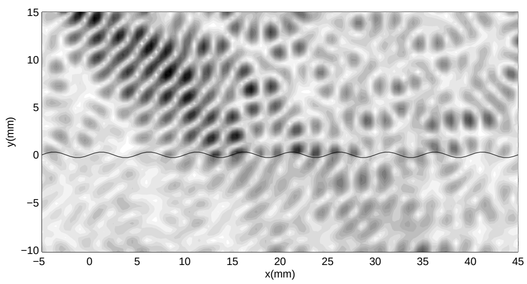

Figure 18: Field plot for corrugated interface with period 5 mm and height 0.3 mm and the anisotropy skewed 15° in 3D.

If the anisotropy is skewed 15° instead of tilted 15° the fields are only somewhat modified, see Figs. 17–19. In general both the reflection and transmission seem to be weaker and more spread out. It should be noted that in the skewed cases in Figs. 17–19 (and in Figs.20–22 below) it is not wholly appropriate to plot the fields only in one plane because the group (energy) velocity in the cladding is not in the plotted plane. Instead the group velocity has a component out of the plane and therefore the transmission into the cladding may look weaker than it really is, although in this case with a rather small skew this effect is not expected to be strong. To fully illustrate this situation where all the group velocities no longer lie in a common plane it is necessary to perform computations in several planes.

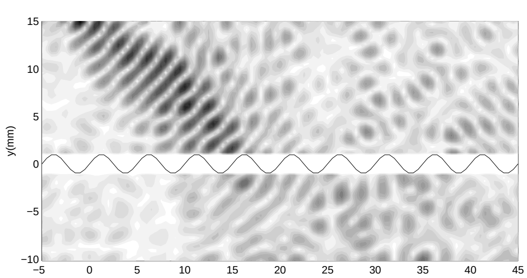

Figure 19: Field plot for corrugated interface with period 5 mm and height 1 mm and the anisotropy skewed 15° in 3D.

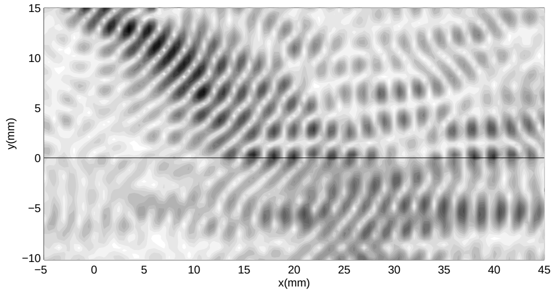

Figure 20: Field plot for flat interface with anisotropy tilted 15° and skewed 15° in 3D.

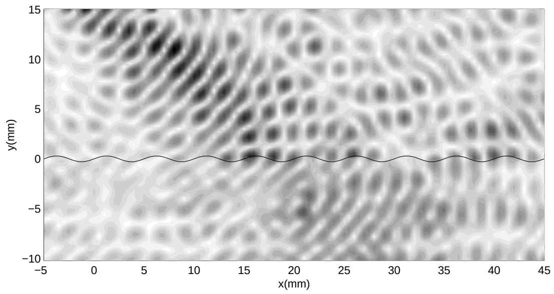

Figure 21: Field plot for corrugated interface with period 5 mm and height 0.3 mm and the anisotropy tilted 15° and skewed 15° in 3D.

The results when the material is both tilted 15° and skewed 15° are shown in Figs. 20–22, again for $b = 0$, 0.3, and 1 mm, respectively. For the flat and almost flat interfaces in Figs. 20 and 21 the transmission into the cladding is strong with the waves travelling more or less horisontally in the cladding. For the stronger corrugation in Fig. 22 the field distribution is more scattered and it is particularly noticed that a rather strong reflection is obtained in the back direction towards the probe.

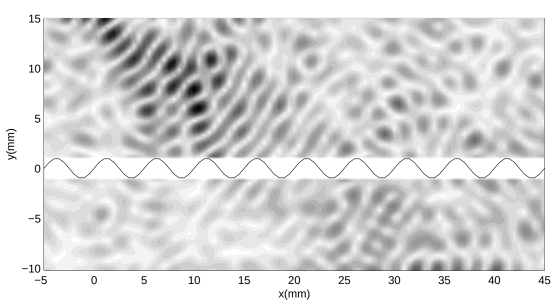

Figure 22: Field plot for corrugated interface with period 5 mm and height 1 mm and the anisotropy tilted 15° and skewed 15° in 3D.

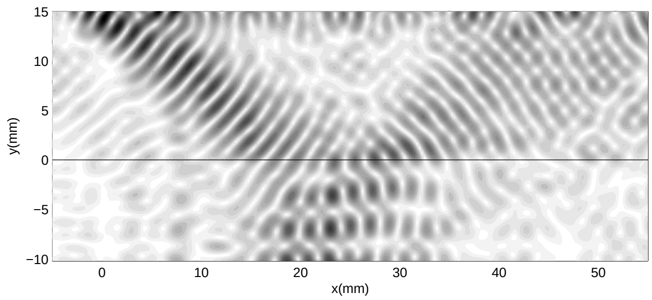

Figure 23: Field plot for flat interface with anisotropy tilted 50° in 2D.

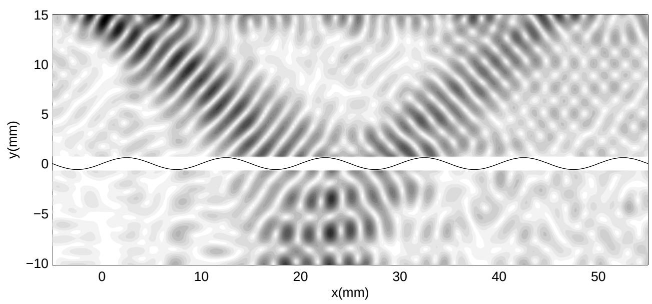

Figure 24: Field plot for corrugated interface with period 10 mm and height 0.6 mm and the anisotropy tilted 50° in 2D, exact solution.

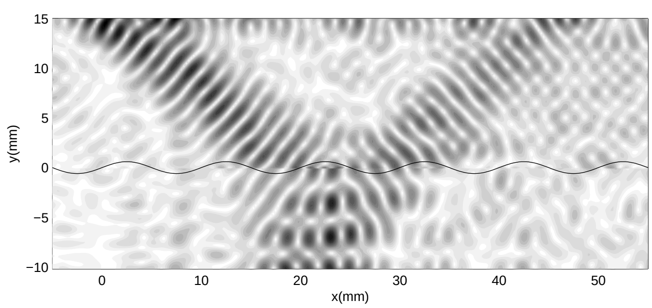

Figure 25: Field plot for corrugated interface with period 10 mm and height 0.6 mm and the anisotropy tilted 50° in 2D, approximate solution.

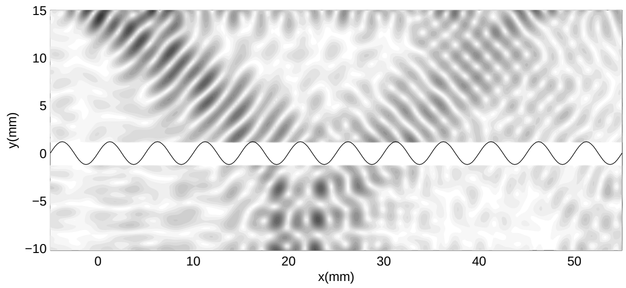

Figure 26: Field plot for corrugated interface with period 5 mm and height 1 mm and the anisotropy tilted 50° in 2D, exact solution.

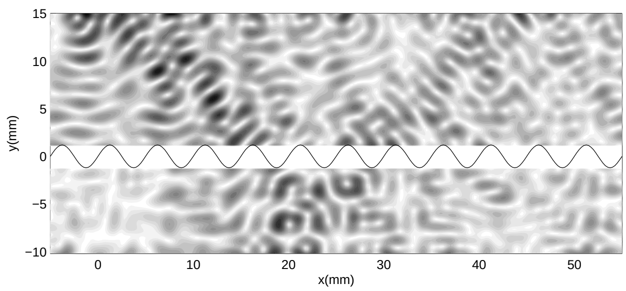

Figure 27: Field plot for corrugated interface with period 5 mm and height 1 mm and the anisotropy tilted 50° in 2D, approximate solution.

Finally, to investigate the approximate boundary conditions described a little in the previous section, Figs. 23–27 give exact and approximate field plots for the anisotropy tilted 50° and varying corrugation height. In Fig. 23 the interface is flat and the exact and approximate boundary conditions of course coincide in this case; this figure is almost identical to Fig. 4, the only difference is the tilt that is 45° or 50°. In Figs. 24 and 25 the corrugation period is 10 mm and the height is 0.3 mm, but the difference between the exact computation in Fig. 24 and the approximate one in Fig. 25 is negligible and the approximate boundary condition thus works well in this case. Still, it should be observed that there are some differences between Fig. 23 on one hand and Figs. 24 and 25 on the other. In particular it can be seen that the reflection from the interface is much wider for the flat case in Fig. 23 compared to the corrugated case in Figs. 24 and 25. In Figs. 26 and 27 the corrugation period is 5 mm and the height is 1 mm and in this case it is clear that the approximate boundary conditions used in Fig. 27 give a completely different and thus useless solution compared to Fig. 26.

4 Conclusions

In this report the propagation of ultrasonic waves in a cladding that is both anisotropic and has a corrugated interface to the base material is considered. Both 2D and 3D cases are treated and in addition an approximation of the corrugated surface is investigated in 2D. The problems are solved using the null field method, this has the virtue of reducing the problem to a type of integral equations on the interface, thus reducing the dimensionality of the problem and giving a relatively effective numerical procedure. In contrast, FEM or EFIT, that discretize directly in 3D, lead to very large problems with time-consuming numerical procedures.

Some numerical results are given showing the capabilities ot the programs. Only a combination with an isotropic ferritic base material and an anisotropic austenitic cladding is considered, but both the tilt and skew of the austenite and the height of the corrugations are varied. The results show that both the tilt and the skew have very important effects on the transmission of the ultrasound into the cladding (and thus on the detectability of defects there). The height of the corrugation also has important effects. The small height 0.3 mm has only minor effects in most cases, but the height 1 mm usually has strong effects. One noteworthy effect is that the ultrasound can be directly back-scattered towards the probe for this corrugation and in a pulse-echo setup this can of course lead to complications such as false events.

The approximate boundary conditions are evaluated by comparisons with the exact calculations in 2D, and the conclusion is that they are useful for small corrugation heights. The validity of the approximate boundary conditions should depend on both the height of the corrugations relative the ultrasonic wavelength and the slope (a dimensionless quantity) of the corrugations. Both these quantities must be small, typically in the range 0.1–0.3. The heights that are of practical interest often violate these restrictions.

The interest in ultrasound propagation in claddings of course emanates from the need of nondestructive testing of claddings, typically to detect defects in the cladding. The results of the present project can be directly useful in this respect as they show when the transmission into the cladding is weak or when other complications occur. But the results can also be used as the starting point for the modelling of the whole ultrasonic testing situation with a defect in the cladding. A project with this goal has recently been started.

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