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A Computer Program Modelling Ultrasonic Nondestructive Testing of a Defect in an Isotropic or Anisotropic Component

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User Guide to UTDefect Version 4:

A Computer Program Modelling Ultrasonic Nondestructive Testing of a Defect in an Isotropic or Anisotropic Component

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Contents

Abstract

This user guide to the computer program UTDefect gives a reasonable overview of the program and its possibilities and limitations and should make it possible to run the program.

UTDefect models the ultrasonic nondestructive testing of some simply shaped defects in an isotropic or anisotropic but homogeneous component. Such a model can be useful for educational purposes, for parametric studies, for the development of testing procedures, for the development of signal processing and data inversion procedures and for the qualification of NDT procedures and personnel.

The theories behind UTDefect are all of the type that can be called "exact", meaning that the full linear elastodynamic wave equations are solved. The basic assumption in UTDefect is that the tested component is homogeneous. However, the component can be isotropic or anisotropic and viscoelastic losses can be included. The ultrasonic probes are modelled by the traction they are exerting on the component. The action of the receiving probe is modelled by a reciprocity argument. The various defects are all idealized with smooth surfaces and sharp crack edges, although a model for rough cracks is also included. The wave propagation and scattering is solved for by Fourier transforms, integral equation techniques, the null field approach and separation-of-variables. The methods are all of the semi-analytical kind and with enough truncations, number of integration points, etc., give very good accuracy. The models are all three-dimensional and give reasonable execution times in most cases. In comparison, the more general volume discretation methods like EFIT and FEM tend to be useful for wave propagation problems mainly in two dimensions.

The probe model in UTDefect admits the usual kind of contact probes with arbitrary type, angle and frequency. The effective contact area can be rectangular or elliptic and the contact lubricated or glued depending on the probe type. Focused probes are also possible. Two simple types of frequency spectra can be chosen. Finally, a model for immersion testing has recently been implemented, but it can not at present be used with all defect types.

The list of defects in isotropic media in UTDefect includes a spherical cavity, a spherical inhomogeneity, a spheroidal cavity, a circular crack, a rectangular crack, a strip-like crack and a side-drilled hole. All but the side-drilled hole may be located close to a planar back surface. The circular crack may be fluid-filled or partly closed due to a compressive stress and the rectangular and strip-like cracks may have rough surfaces (a type of rather smooth roughness with relatively small amplitude).

For an anisotropic component the strip-like and rectangular cracks are the only possible defect types. The cracks may be located close to a back side. The crack, the back side and the anisotropy may be arbitrarily rotated.

The calibration in UTDefect is performed by a side-drilled hole or a flat-bottomed hole, the latter being modelled by a circular crack under normal incidence.

There is a simple preprocessor, UTDpre, to UTDefect. This is run interactively and requires answers for all relevant parameters. Upon completion the input file to UTDefect is created. This file can of course also be edited manually which is useful for parametric studies when only one or two parameters are to be changed.

The output from UTDefect is in the form of conventional A, B or C scans. There is, however, no postprocessor, so some graphical package must be used for plotting the results.

Chapter 1

Introduction

1.1 Purpose

The purpose of the present report is to be a user guide to the computer program UTDefect, version 4. This program models ultrasonic NDT in an isotropic or anisotropic homogeneous component with a single defect of simple shape. The report of course describes the type of input and output to the program. Possibilities and limitations of the program are described and the type of theories that the program builds on are briefly outlined with references given to sources where detailed descriptions can be found. The validations that have been performed by comparisons with experiments and other theories are mentioned by giving references. Some concluding remarks contain some plans for future possible extensions.

UTDefect has been developed for almost a decade. The first version is described in Boström (1995a) and also in a short user guide (Boström (1995b)). The second version is described in Boström and Jansson (1997). In these reports some validation work is also performed and further comparisons with experiments are given in Eriksson et al. (1997). The developments behind the third version is described in Boström and Jansson (2000) and in a user guide (Boström 2000). The present fourth version includes two defect types in an anisotropic component (Boström 2001, Grahn 2002) and some other changes. The computer code has now been changed to FORTRAN 90 from FORTRAN 77. The main advantage with this is that FORTRAN 90 admits dynamic memory allocation. This has been exploited both to save memory and to lift some of the restrictions on the sizes of the defects.

For a user of UTDefect it is of course necessary to have a reasonable background in ultrasonic NDT. Some knowledge of elastic wave propagation in solids is also very useful.

1.2 Usefulness of a model

With the increase in computer capacity and the development of computer software the role of mathematical modelling is steadily increasing. A well tested and validated program can be useful in a number of ways:

1. It is a good educational tool and can help in giving a "feeling" for the ultrasonic wave propagation. One reason for this is that a program gives very "clean" signals: there is no noise and the defects are highly idealized with smooth surfaces and sharp and straight crack edges, etc. Some modelling programs can also give field plots of the ultrasound so that it is possible to identify and follow the various parts of the total field.

2. It is easy to perform parametric studies. In contrast it can be very costly to vary some of the parameters in an experimental study. This is particularly true for the defect where each new position, size and tilt of a crack, for instance, may require an additional test block.

3. Because of the capabilities to perform parametric studies, a model is also well suited for the development of testing procedures.

4. Because a program gives idealized and clean data it is useful when developing signal processing and data inversion procedures. But one must remember that a procedure that works on clean data may run into difficulties with real noisy data.

5. A program can be very helpful when qualifying NDT procedures. According to ENIQ (European Network for Inspection Qualification, 1999), mathematical modelling can be used for that part of a qualification that is called technical motivation (which also includes previous use of the procedure, experimental studies, physical considerations, etc.).

6. A program can be used when qualifying NDT operators.

1.3 Mathematical models

During the last twenty years many mathematical models of ultrasonic NDT have been developed, although not so many include all parts of the testing situation. One way to categorize the methods is to divide them into more or less "exact" theories that solve the elastodynamic wave equation and high frequency approximate theories. The former may be further divided into volume discretization methods, like FEM (Finite Element Method) and EFIT (Elastodynamic Finite Integration Technique) and other methods, mostly various types of integral equation techniques but also analytical methods like separation-of-variables for scattering by a sphere. The high frequency methods may be divided into ray methods, including the geometrical theory of diffraction (GTD), and Kirchhoff theory (also called physical optics). The Born approximation is applicable at all frequencies, but only for weak scattering, and is thus not useful for defect scattering which is the main focus here.

Volume discretization methods like FEM and EFIT can handle more or less arbitrary geometries and materials, like inhomogeneous and anisotropic materials, without any serious approximations. The programs can be hard to run (generating meshes etc.) and the running times can be long. In practice these methods are mainly useful in 2D because the number of unknowns usually becomes excessively large in 3D.

UTDefect is an example of a method that employs integral equation techniques and other analytical methods as further described in chapter 3. The integral equation techniques are of the analytical type, but an alternative is to use a boundary element method (BEM). However, regular BEM seems to run into problems for cracks, due to the hypersingular integral equations that appear.

Among the approximate theories ray methods are attractive because of their simplicity. An example of a commercial software based on ray methods is RAYTRAIM (developed at Harwell Laboratory of AEA Technology), which can handle anisotropic and inhomogeneous materials. Another example is the code PEDGE (developed at Nuclear Electric), which is based on GTD in an isotropic and homogeneous component, and can thus treat crack scattering in a satisfactory way.

Kirchhoff theory is not as simple as ray theory. It generally gives good results at higher frequencies, but in general edge diffractions are not well modelled. An example is PKIRCH (developed at Nuclear Electric) which treats crack scattering close to normal incidence (the code is developed as a complement to PEDGE). In France the software MEPHISTO (developed at EDF) can handle more complex geometries by Kirchhoff theory.

In the US there have of course also been modelling activities, particularly by the groups in Ames, Iowa, but it seems that this has not resulted in any released software. A good way to follow the modelling activities in ultrasonic NDT is by the yearly conferences Review of Quantitative Nondestructive Evaluation (documented by conference proceedings). Other conferences with proceedings include European Conference on NDT and International Conference on NDE in the Nuclear and Presure Vessel Industries.

Chapter 2

Inspection configurations in UTDefect

2.1 The component and scan

The first and most fundamental limitation in UTDefect is that the tested component is homogeneous. The component may be isotropic or anisotropic, although the the list of possible defects is very short for anisotroic components. The assumption of homogeneity of course excludes cases like layered structures or inherently inhomogeneous media like welds.

The anisotropy can be can be transversely anisotropic or orthotropic. These materials are described by five and nine independent stiffness constants, respectively. These are conveniently given in the abbreviated notation with two indices, see e.g. Auld (1990). In addition the orientation of the crystal axis system where the stiffness constants have their simplest values must be given. This orientation is specified with two and three Euler angles for transversely isotropic and orthotropic materials, respectively. In UTDefect any orientation of the crystal axis system is allowed. (It is also worth to mention that internally UTDefect works with arbitrary anisotropy, it is only the input that is restricted, and it would thus be simple to extend the program to any anisotropy.)

Although the material is homogeneous, the latest version of UTDefect admits losses. These are of the viscoelastic type and as UTDefect works in the frequency domain this leads to complex wave speeds. At present the losses are specified by giving the dB drop per wavelength at the probe's centre frequency. Working in the frequency domain it would of course be easy to admit any frequency dependence of the losses.

The probe(s) is assumed to scan over a planar surface of the component in a rectangular raster. Also immersion testing over a planar surface is allowed. The component is assumed to be sufficiently thick-walled so that all multiple scattering between defect and scan surface can be neglected. The multiple scattering between the defect and a planar back surface can be taken into account for all defects except the side-drilled hole. Also a surface-breaking strip-like crack is allowed. For some of the defects the back surface may be tilted.

Multiple scattering between the back surface and the scanning surface is not taken into account. Thus testing with 1, 3/2 or more skips is not directly modelled. This type of testing is usually performed by angled shear wave probes above the critical angle and this essentially only leads to a longer sound path which could be modelled by a deeper lying defect, when needed with a back surface.

As output from UTDefect it is possible to obtain conventional A, B and C scans. These are just given as long lists and must usually be plotted in some way. However, UTDefect contains no plotting facilities so this must be managed in some other way. As UTDefect basically works in the frequency domain it is also possible to get the received (complex valued) signal as a function of frequency instead of time. This can be convenient for signal processing, for instance.

2.2 Probes

The most common type of probe in ultrasonic NDT is probably a contact probe of piezoelectric type. To model such a probe in all its details with a piezoelectric plate, a plastic wedge, backing, housing and electrical connections is a complicated task. For the present purposes this is not necessary as experience says that a reasonably good model is obtained by prescribing the traction vector (often the pressure is enough) on the component's surface beneath the probe. In this way a probe of any type, angle, frequency and shape can in general be modelled. In UTDefect the shape is restricted to be rectangular or elliptic.

Due to edge effects a probe of any type radiates waves of all types. These are included in the model, but as an option it is possible to suppress all waves of the "wrong" type, i.e. for a shear wave probe all pressure waves are suppressed and vice versa. Due to the more complicated wave types in anisotropic media this option is not in effect for anisotropic components.

With the chosen model shear horizontal (SH) probes can also be modelled although these are difficult to realize in practice with a piezoelectric contact probe. SH waves can instead be generated by an EMAT (electromagnetic acoustic transducer). Probably, the model used in UTDefect can also be employed for an EMAT.

More complicated probes can also be employed in UTDefect. The immersion probe has already been mentioned, but also line or point focused probes are admitted. Such a probe is modelled by a subdivision into smaller elements, where each small element can be modelled as before, and an introduction of suitable phase lags between the elements. In this way it is of course also possible to model phased arrays in a straightforward way although at present no such implementations have been performed.

Apart from the centre frequency of the probe, the frequency spectrum must be described in some way. In UTDefect there are two possibilities. In the simplest model only the -6dB bandwidth is specified. The total bandwidth employed is then twice the -6dB bandwidth with a $\cos^2$ curve for the spectrum (Hanning window). In the other model a somewhat more complicated curve can be specified, see further in Sec. 4 where the input is specified. In UTDefect the spectrum is precomputed and stored as an array, so it would be easy to admit any frequency spectrum, even an experimental one. In practice the exact shape of the spectrum often seems to be rather unimportant.

The sending and receiving probes can be chosen individually, but as a special case pulse-echo testing with the same probe acting as both transmitter and receiver is of course possible. With separate probes it is possible to choose between tandem testing with a fixed distance between the probes or a fixed transmitter and a moving receiver.

2.3 Defects

In UTDefect the defect can be chosen from a list of simply shaped defects, both of volumetric type and cracks. All the defects are specified by a few parameters. For all defects the depth to the centre must be given, except for the surface-breaking crack where the depth to the crack mouth specifies the depth. For an anisotropic component the list of defects is much shorter. First, the defect types in an isotropic component are described.

Among the volumetric defects there are three that are cavities, i.e. in practice air. One is a side-drilled hole which is assumed to be parallel with the scanning surface and perpendicular to the main scanning direction. The other two are a sphere and a spheroid (with two equal and one longer (prolate) or one shorter (oblate) axis). The orientation of the spheroid is specified by its tilt and skew. The last volumetric defect is a spherical inomogeneity which is assumed to be of a different elastic material whose density and wave speeds must be given. The spherical and spheroidal defects can lie close to an untilted planar back surface.

The simplest type of crack in UTDefect is the strip-like one, i.e. in practice one that is longer than the main lobe of the ultrasound from the probe. This crack may lie close to a planar back surface and it may also be surface-breaking. Both the crack and the back surface may be independently tilted. As a special option the crack can also have rough surfaces. This roughness can only be relatively small in the sense that the rms height of the roughness must be much smaller than the ultrasonic wavelength and that the correlation length (roughly the distance between two peaks) must be much larger than the rms height. The model of the roughness is rather simple, only the rms height and correlation length are specified. A rough surface is then constructed as a sum of sinusoids with random phases. But it should be stressed that once constructed the defect is treated in a deterministic way (no averages of any kind are taken). However, rerunning the program with identical input will give new sinusoids with random phases and thus a new deterministic surface and a new signal response.

A rectangular crack is a further possibility in UTDefect. This crack has the same options as the strip-like one, i.e. it can be tilted, have a back surface and have rough surfaces.

The last crack type is circular. This crack may have arbitrary tilt and skew and it may lie close to a planar untilted back surface. Apart from being open as the other cracks, this crack has two further options. The crack may be fluid-filled, which is modelled by requiring the normal displacement and stress to be continuous across the crack and the tangential stress to vanish. The last option is that the crack may be partly closed due to a static compressive stress. This is modelled by spring boundary conditions acting across the crack, where the spring constant is determined from the compressive stress and the average diameter of the contact spots.

For an anisotropic component the only possible defects are the strip-like and rectangular cracks. These may also lie close to a planar back side, although they may not be truly surface-breaking (they may be pushed to become almost surface-breaking, but the crack mouth will always remain closed). The cracks can be arbitrarily rotated, except that the strip-like crack may not be cutting through the scan surface. The cracks can not have rough surfaces.

2.4 Calibration

The signal response in UTDefect may be uncalibrated or it may be calibrated by the maximum response from a side-drilled hole (SDH) or a flat-bottomed hole (FBH). The SDH has already been mentioned. To model a FBH a circular crack is employed. This may seem drastic but close to normal incidence the scattering is dominated by the direct reflection for all frequencies except very low ones. To determine the calibration level the probe is allowed to make a line scan in the vicinity of the position where the probe's beam axis hits the SDH axis or the FBH centre normally. This also gives the position and thereby the angle with the maximum response and this gives a "true" probe angle as opposed to the nominal one that is the input.

Chapter 3

Theory

3.1 Introduction

As mentioned, the only part of the ultrasonic testing that is modelled in UTDefect is the mechanical part, i.e. the generation, propagation, scattering and reception of ultrasound in the component. When modelling the receiving probe an electromechanical reciprocity argument is employed, so to a small degree electromagnetics also enters. However, no part of the circuits, amplifiers, etc. is modelled, nor is any signal processing involved.

The ultrasound is assumed to be governed by the linear elastodynamic wave equation. Nonlinear effects are thus neglected, but in ultrasonic NDT the amplitudes are very small so this should be an excellent approximation in almost all cases. The wave equation is assumed to have constant coefficients, i.e. the material is assumed homogeneous. On the other hand, the material can be anisotropic, although most defect types are only possible for an isotropic component. Losses are included and this takes care of the small scattering losses that are present in most grainy materials. However, no noise mechanism is included.

To treat the time dependence a Fourier transform in time is applied and UTDefect thus works in the frequency domain with a final integration over all required frequencies. As an option a single frequency can be used and this is often adequate when computing C scans.

The methods to solve the wave equation in UTDefect can be said to be semianalytical in nature. This involves Fourier transforms, separation-of-variables, Green functions and integral equations. This will be further explained in the following sections for the different parts of UTDefect.

3.2 Volumetric defect in isotropic component

The spherical defects are the simplest to treat. The scattering by a sphere is a classical problem in mathematical physics that is solvable by separation-of-variables. However, the scattering in an elastic medium is considerably more complicated than the corresponding problem in a fluid and a completely satisfactory solution was not given until Waterman (1976) obtained a solution within the framework of the null field approach (often called the T matrix method). This solution is very systematic in that it completely separates the defect scattering from the incident field with the scattering being described by the so called T matrix that is given in a spherical wave basis. The T matrix for a sphere is almost diagonal and is given relatively explicitly in terms of spherical Bessel and Hankel functions. The solution can be regarded as exact and although a larger matrix is needed for increasing frequencies, there is in practice no restrictions on its use.

The spheroidal cavity is also treated by the null field approach although by the variant of Varatharajulu and Pao (1976) and not that of Waterman (1976). The method is much more numerical in character than for a sphere and among other things it involves the inversion of a matrix whose elements are obtained through a numerical quadrature. To obtain a stable method one must restrict the ratio of the larger to the smaller axes of the spheroid to about 5. Due to increasing matrix sizes the method also becomes progressively harder to apply for higher frequencies, although it can with success be applied for a spheroid with diameter at least 10 shear wavelengths.

The scattering by the SDH is also treated by separation-of-variables in a similar way as the sphere, see Boström and Bövik (2002). The solution is complicated by the fact that it involves a Fourier integral in the wavenumber along the SDH axis, but otherwise the remarks for the sphere are valid also for the SDH without any practical restrictions in frequency.

When a spherical or spheroidal defect is located close to a planar back surface the multiple scattering is taken care of by the T matrix method, see Boström (1980). In the implementation used in UTDefect, this method sums a number of the multiple scattering terms employing a spherical wave basis and the T matrix of the defect. The method seems to be useful and stable for all frequencies for which the T matrices can be obtained.

3.3 Crack in isotropic component

The scattering problems for the crack types that are included in UTDefect are all solved by integral equation techniques. These integral equations contain a Green function and the unknown in them is the crack opening displacement (COD). The integral equations are solved by a semi-analytical approach which means that the COD is expanded in a (on the crack) global system and is projected on the same system. As opposed to a boundary element approach, this technique is only applicable to a few very simply shaped cracks, but it leads to an efficient and very stable method.

The method for the strip-like crack is described by Bövik and Boström (1997). The crack can be located close to a planar back surface by using a half-space Green function. One can also try to let the crack become surface-breaking, but this seems questionable as the expansion of the COD does not allow any crack opening at the crack mouth. Boström (1999) has investigated this a little further by changing the COD expansion to one that does allow a crack opening at the mouth, leading to a more complicated procedure. At least for pulse-echo testing, the difference between the two approaches is negligible except for very low frequencies such that the crack height is less than half a wavelength.

To avoid a costly numerical integration (in the wavenumber along the crack axis) a stationary-phase-approximation is performed. The approximated integral contains factors from both the crack and the probe and the approximation is only valid when the distance between crack and probe is larger than the near field length of both the probe and the crack. For the probe this is no problem because when needed the probe can be subdivided into smaller elements each with a shorter near field length (see further below), but for the crack this can be a serious limitation. In the near future it is planned to extend the program and perform a numerical integration in cases when this is needed.

The strip-like crack can have rough surfaces with a relatively small roughness, see Jansson

(1998). The exact shape of the roughness is always unknown in practice, typically only some statistical measures like the rms height and the correlation length of the roughness can be estimated. For that reason and for methodological simplicity a model of the rough surface as a superposition of a few sinusoids has been constructed. The model contains a number of random numbers with only the rms height and the correlation length as input parameters. Once the rough surface has been constructed the method is deterministic, the scattering by *the* particular crack is considered. This is in contrast to most other theories where an ensemble average over a large number of cracks with the same rms height and correlation length is typically calculated. This tells rather little about how a particular crack scatters and for a small roughness the dominating effects due to roughness are averaged out.

To solve for the scattering by the rough crack a perturbation approach with the rms height as the small parameter is employed. Then the same type of integral equation technique as for the smooth crack is used. However, the procedure becomes much more involved and therefore more computer time and storage is needed. For the smooth strip-like crack UTDefect can be used at least to a crack height of 20 shear wavelengths. The rough crack can be used at least to half this value.

The rectangular crack is treated in a manner very similar to the strip-like crack, see Jansson (2000) for the smooth crack. The extra complication with a finite size in one more dimension leads to an extra expansion and dramatically increased matrix sizes. Therefore the smooth and rough rectangular cracks can not be used at so high frequencies as the other defects.

The circular crack is treated by a similar integral equation method as the other cracks, see Boström and Eriksson (1993). However, for this crack type it is convenient to compute its T matrix because then exactly the same coupling to the probe and to a planar back surface can be employed as for the spheres and spheroids which are also described by their T matrices. Apart from being open, the circular crack can be fluid-filled or partly closed due to a compressive stress. The fluid-filled crack is modelled by requiring the normal displacement and stress to be continuous across the crack whereas the tangential stresses vanish. This is very easy to implement and results in that parts of the T matrix is simply set to zero.

For the partly closed crack a spring boundary condition due to Boström and Wickham (1991) is employed. This type of boundary condition relates the stress to the crack opening displacement, with the factor of proportionality being the (distributed) spring constant. The spring constant is essentially proportional to the applied pressure and the radius of the contacts across the crack (this radius is of the order of 10 μm for a crack in steel) and inversely proportional to the flow pressure of the component (the flow pressure is typically about three times the yield strength). It should be mentioned that this spring boundary condition approach involves several approximations, the validities of which are difficult to assess. It is believed, however, that the approach gives reasonable results.

3.4 Crack in anisotropic component

For an anisotropic material the same approach can be used for the strip-like and rectangular cracks as in the isotropic case (Grahn 2002). The procedures of course become more involved and also much less explicit. For example, it is no longer possible to write analytical expressions for wavenumbers, polarization vectors and group velocities. These have to be computed by solving an eigenvalue problem instead. It does not seem to be fruitful to employ the stationary-phase- approximation any longer. Instead a direct integration is performed and this then leads to essentially longer execution times as compared to isotropic components.

The cracks in an anisotropic component can also lie close to a back side, but the cracks can not be truly surface-breaking. Also, they can not have rough surfaces.

3.5 Probes

As mentioned the probe is modelled by the traction vector it is supposed to exert on the component's scanning surface. This is the most common approach also in other theories of ultrasonic testing. The radiated ultrasonic waves due to the applied traction are then solved for by Fourier transform techniques as is more fully described by Boström and Wirdelius (1995). The probe can be rectangular or elliptic and can be of any type and angle.

With the chosen model it is possible to perform the Fourier transform of the applied traction analytically. In this way an exact (within the chosen model) expression of the radiated ultrasound is obtained as a double spatial Fourier representation. When the scattering by the defect is considered it is necessary to perform an integration over the surface of the defect (or the circumscribing sphere for the spheroid or circular crack). This leads to multiple integrals that are rather costly to compute and therefore a two-dimensional stationary-phase-approximation can be performed, leading to a much quicker approach (for cracks in an anisotropic component the option with the stationary-phase-approximation does not exist). However, the approximation is only valid when the distance between the probe and the defect is much larger than the wavelength, the probe diameter and the probe near field length. For the strip-like and rectangular cracks this distance must also be much larger than the defect's near field length (defined in analogy with the probe's near field length). For the near field lengths it seems that "much larger" can be interpreted as "a few times greater than". This restriction can often be violated in practice where it is common to chose a probe with a near field length about equal to the distance between probe and defect. To circumvent this difficulty the probe can be divided into elements where the elements are chosen small enough so that the elemental near field length is much smaller than the distance between the probe and the defect. This, however, does not remove the restriction on the defect near field length. So in many cases it is necessary to perform a direct numerical integration and with the present version 4 of UTDefect this is possible for all defects except the strip-like crack (and the program automatically choses the right alternative). It is planned to implement a direct integration also for the strip-like crack in the future.

The subdivision of the probe into elements has a further benefit and that is that this makes it possible to model line or point focused probes. Also immersion testing is possible in the latest version of UTDefect. This is essentially modelled in the same way as the contact probes, but with an initial step where the pressure on the component due to the waves from the probe is first calculated. At present focused immersion probes are not possible.

The receiving probes in UTDefect can be of exactly the same types as the transmitting ones. An electromechanical reciprocity argument due to Auld (1979) is employed to determine the action of the receiving probe. This in effect means that it is the receiving probe's action as a transmitter and its radiated field at the defect that enter so that a totally symmetric expression between the transmitting and receiving probes results for the signal response, see Boström and Wirdelius (1995). The reciprocity argument is not strictly valid when the component is lossy, but at least for small losses, it is expected that the expressions are still valid with good accuracy. It should also be pointed out that the reciprocity argument only gives that part of the total signal that is due to the presence of the defects. This means that when there is a back surface the direct reflection from this surface is absent.

3.6 Validations

A very important aspect of a modelling program like UTDefect is the validations that have been performed. A validation can be divided into steps regarding the physical model, the numerical methods and program coding. A comparison with another mathematical model will typically only validate the last two aspects whereas a comparison with experiments will validate all three.

In previous reports (particularly Boström and Jansson (1997) and Eriksson et al. (1997)) comparisons between UTDefect and experiments are reported. Some comparisons with other theories via the PISC exersize (Lakestani (1992)) are also given. In general the comparisons fall out favourably; when larger discrepancies show up they can in general be attributed to the problems with the stationary-phase-approximation discussed in the previous subsection. Problems with a great sensitivity for some of the parameters have also occurred in one case, see Boström and Jansson (1997). It should be pointed out that all comparisons have been performed for the strip-like crack, including the surface-breaking one. This of course checks the probe model and the reciprocity argument for the signal response, but it also checks the scattering by the SDH that is used for calibration. The other defect types are, however, not validated in this way. There are some internal methodological checks, in particular on the T matrices for those defects described by such matrices, and some physical checks, like the right wave type appearing at the right time, can be performed, but the other defects are still not fully validated. The easiest and cheapest way to perform further validations would be through comparisons with other models, but this may be difficult due to the lack of accurate three-dimensional models.

Chapter 4

Input to UTDefect

4.1 The preprocessor UTDpre

The input to UTDefect is rather simple and almost all of the parameters have a clear physical meaning. This could be contrasted with the situation when running a FEM program, for instance, where the modelling of the geometry can be quite laborious. However, the appearance and length of the input file can vary somewhat depending on the chosen defect and probe. Therefore a simple interactive preprocessor has been written, which has been named UTDpre. This puts simple questions to the user and after completion constructs the input file to UTDefect. This file lists all the necessary parameters for the chosen configuration and also contains a short descriptor for each parameter. When performing parametric studies it is thus simple to edit this file if the value of one or two parameters is to be changed.

It should here be mentioned that there also exists a Windows-based (for PC) front-end for UTDefect (called SUNDT), see Wirdelius (2000). In SUNDT all the parameters are filled in a few windows and after running UTDefect the results are plotted as A, B and C scans, where the operator can choose what to plot. As mentioned, UTDefect does not contain any postprocessing software. SUNDT is, however, based on version 2 of UTDefect and does not contain the extensions of the present version 4 (but a new version of SUNDT is planned).

In the following subsections the input parameters to UTDefect are defined. It is noted that all lengths are measured in millimetres, times in microseconds, stiffnesses in gigapascal, densities in kilo per litre and angles in degrees. It follows that frequencies are in megahertz and velocities in millimetre per microsecond. The input to both UTDefect and UTDpre is in free format so a real number can be given as 10, 10., or 1.E1, for example.

4.2 The component and scan

To describe the geometry a main coordinate system xyz is introduced, see Fig. 4.1. The x and y axes lie in the planar surface of the component on which the scan is performed. The x axis is the main scanning direction. The z axis is pointing upwards out of the component. The origin is located straight above the centre of the defect except for surface-breaking cracks where it is straight above the crack mouth. The parameters that describe the scan are given in Table 4.1 below. The internal UTDefect name is given, together with the range and a description.

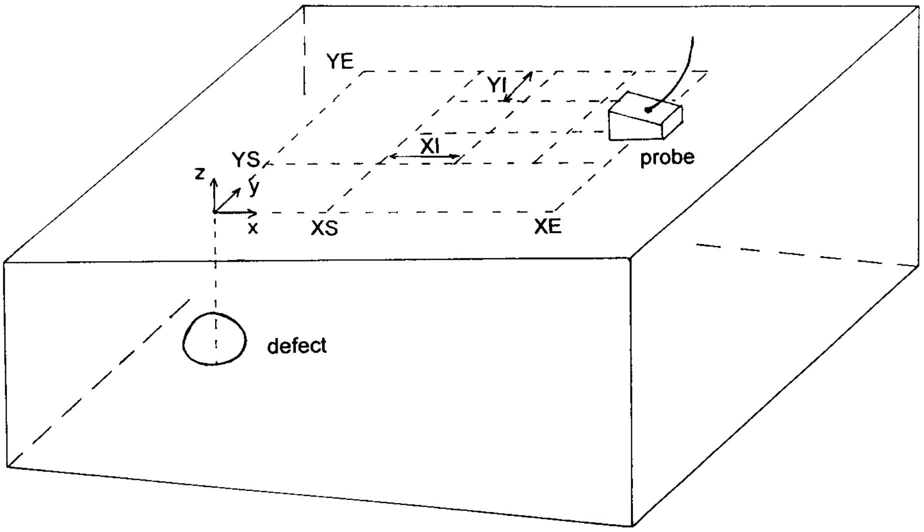

Figure 4.1: *The scan.*

Instead of the parameter LP and LS the output from UTDpre gives the combination LSTY =10*LS + LP.

For an isotropic component it is easy to give the material constants. For UTDefect it is enough to specify the longitudinal (pressure) and transverse (shear) wave speeds and the damping. For an anisotropic component this is a little more complicated. It is best done by first specifying the stiffness constants in the crystal axis system, where the number of such constants is as small as possible (five for a transversely isotropic material and nine for a orthotropic material). Then the orientation of the crystal axis system relative the scanning system must be given. This can be done by Euler angles where in general three angles are needed. For a transversely isotropic component only two angles are needed as the third angle would only rotate the material in the isotropy plane. In Table 4.2 the material parameters are summarised. The Euler angles are specified as (zyz) or (zy), which means that first the crystal axis system is aligned with the scanning system; then a rotation with angle PHI is performed around the z axis (the outward normal to scanning surface), followed by a rotation with angle ETHA around the new y axis and possibly a rotation PSI around the final z axis.

4.3 Probes

In this subsection the parameters of the probes are given. UTDefect can as an option be run at a single frequency and for C scans this can often be adequate. Otherwise there are two types of frequency spectra available. The simplest is a $\cos^2$ curve between two consecutive zeroes, the centre frequency corresponding to the point where $\cos^2$ is equal to unity and the -6dB bandwidth being half of the interval between the zeroes (Hanning window). The other spectrum consists of two $\cos^2$ parts joined by a straight line as shown in Fig. 4.2. It is specified by four frequencies f_1, f_2, f_3, f_4 and the spectrum value at f_2 and f_3. The simpler spectrum is of course a special case with $f_2 = f_3 = (f_1 + f_4)/2$ and with the spectrum values at f_2 and f_3 equal. The following Table 4.3 lists all the probe parameters. The parameters of

Name	Range	Description
LP	0	frequency data (complex signal)
	1	A or B scan (time traces)
	3	C scan (maximum values)
LS	1	pulse-echo (only one probe)
	2	tandem (two probes with fixed separation)
	3	fixed transmitter and moving receiver
XS, YS	real	scan start in x, y (mm)
XE, YE	real	scan end in x, y (mm)
XI, YI	real	scan increment in x, y (mm)
XSEP, YSEP	real	separation between probes for LS = 2; position of fixed transmitter for LS = 3 (mm)
LTTY	1	time window set automatically
	2	time window given by user
	3	time window set to diffraction point
TS, TE, TI	real	time start, end, increment for LTTY = 2 (μs)
XD, YD, ZD	real	x, y, depth of diffraction point for LTTY = 3 (mm)
TS, TI	real	time window, increment around diffraction point for LTTY = 3 (μs)

Table 4.1: *Scan parameters.*

Name	Range	Description
LISO	1	isotropic component
	2	transversely isotropic component
	3	orthotropic component
CP	real	longitudinal wave speed (mm/μs; LISO = 1)
CS	real	transverse wave speed (mm/μs; LISO = 1)
A	real	component's damping (dB/wavelength)
RHO	real	density (kg/dm^3; LISO = 2, 3)
C11, C33, C12, C13, C44	real	stiffness constants (GPa; LISO = 2)
PHI, ETHA	real	(zy) Euler angles of material (degrees; LISO = 2)
C11 ,C22, C33	real	stiffness constants (GPa; LISO = 3)
C12, C13, C23	real	
C44, C55, C66	real	
PHI,ETHA,PSI	real	(zyz) Euler angles of material (degrees; LISO = 3)

Table 4.2: *Material parameters.*

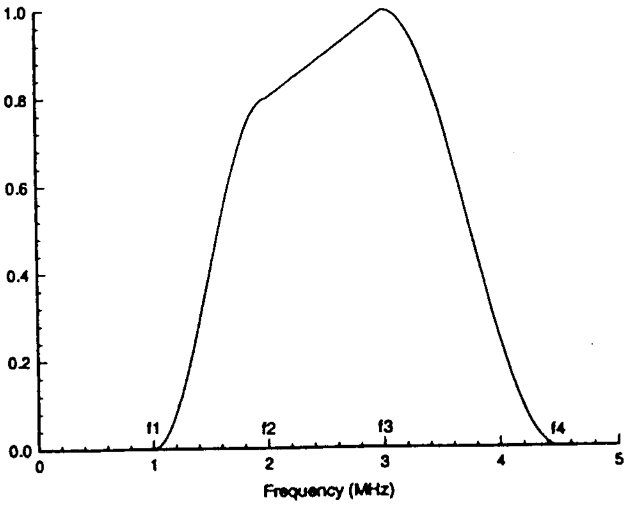

Figure 4.2: *The second frequency spectrum.*

the receiving probe are of course not needed in pulse-echo mode. Probe rotation and probe angle are defined in Fig. 4.3 for contact probes and in Fig. 4.4 for immersion probes.

4.4 Defects

In this subsection all the defect parameters are defined. Tilt and skew of a circular crack or spheroidal cavity are defined in Fig. 4.5 and defect tilt and back-side tilt (when applicable) are defined in Fig. 4.6. Table 4.4 lists all the defect types and all corresponding parameters for isotropic components. Table 4.5 likewise lists all the defect types and parameters for an anisotropic component.

4.5 Calibration

The calibration is performed by a side-drilled hole (SDH) or flat-bottomed hole (FBH) or else the results are left uncalibrated. The calibration scan is performed close to the position where the nominal beam axis of the probe hits the SDH or FBH straight on, see Fig. 4.7. As mentioned the FBH is approximated by a circular crack. When two probes are used the calibration is still performed with the transmitting probe operating in pulse-echo. The parameters needed for calibration are listed in Table 4.6.

4.6 Accuracy

The integral and integral equation methods used in UTDefect lead to numerical computations with integrations and matrix operations. The number of integration points, the sizes of the matrices and some other parameters that control the accuracy of the computations are set automatically. However, there is a parameter controlling these settings. This parameter is called IACC and can attain the values 1, 2, 3, 4 or 5. Usually it will be satisfactory to set IACC $= 3$ which can be used as a default. IACC should be increased when there is any doubt about the accuracy of the results. One can also try to decrease IACC as this can speed up UTDefect considerably.

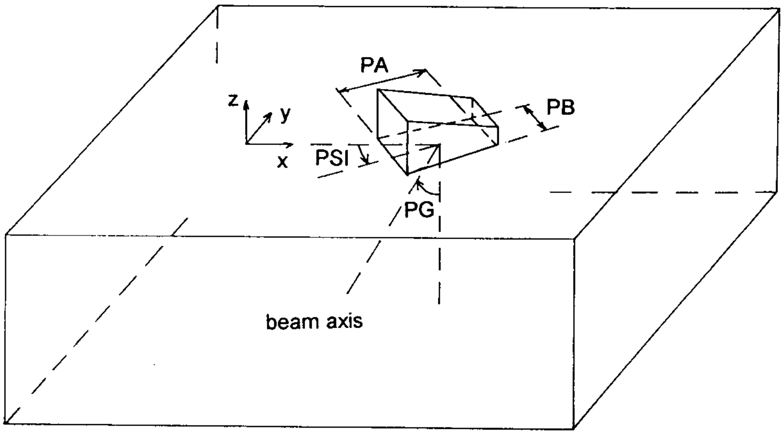

Figure 4.3: *Probe parameters for a contact probe.*

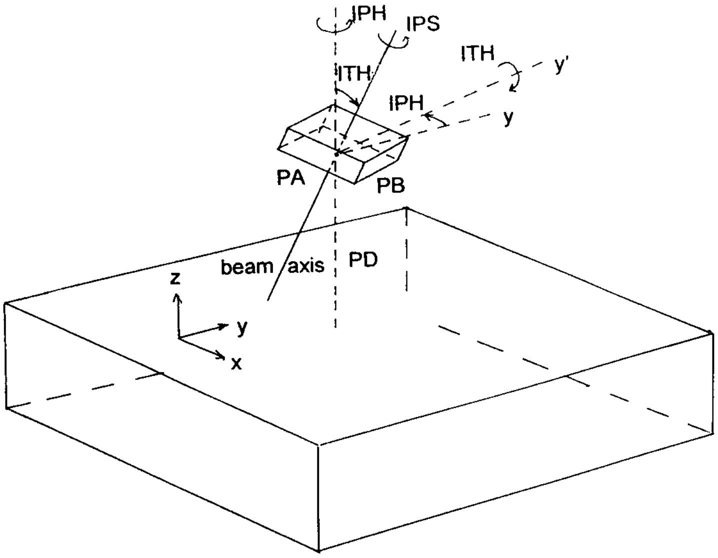

Figure 4.4: *Probe parameters for an immersion probe.*

Name	Range	Description
NFR	1	single frequency
	0	number of frequencies set automatically, compound spectrum
	pos. int.	number of frequencies, compound spectrum
	-1	number of frequencies set automatically, simple spectrum
	neg. int.	number of frequencies, simple spectrum
FREQ	real	centre frequency, simple spectrum (MHz)
BANDW	real	-6 dB bandwidth, simple spectrum (MHz)
F1, F2, F3, F4	real	f_1, f_2, f_3, f_4 of spectrum in Fig. 2 (MHz)
AF, BF	real	heights at f_2 and f_3 of spectrum in Fig. 2
IMODE(1), IMODE(2)	1, 2, 3, 4	SH, SV, P, immersion probe type
	11, 12, 13	SH, SV, P line focussed contact probe type
	21, 22, 23	SH, SV, P point focussed contact probe type
INSTY(1), INSTY(2)	0	suppression of "wrong" wave type
	1	no suppression of "wrong" wave type
PG(1), PG(2)	real	probe angle for contact probes (degrees; see Fig.3)
ISHA(1), ISHA(2)	1	rectangular probe
	2	elliptic probe
PA(1), PA(2)	real	probe length in x direction (mm; see Fig.3)
PB(1), PB(2)	real	probe length in y direction (mm; see Fig.3)
PSI(1), PSI(2)	real	probe rotation for contact probes (degrees; see Fig.3)
FOC(1), FOC(2)	real	focal distance for focussed probes (mm)
PD(1), PD(2)	real	depth to immersion probe (mm)
IPH(1), ITH(1), IPS(1), IPH(2), ITH(2), IPS(2)	real	Euler angles of immersion probe (degrees; see Fig. 4)

Table 4.3: *Probe parameters for transmitting (1) and receiving (2) probes, respectively.*

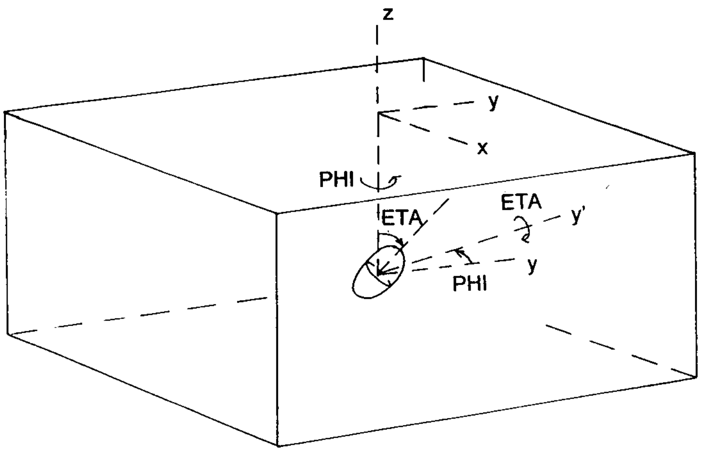

Figure 4.5: *Tilt and skew of spheroidal cavity (or circular crack with crack normal parallel to main axis of spheroid).*

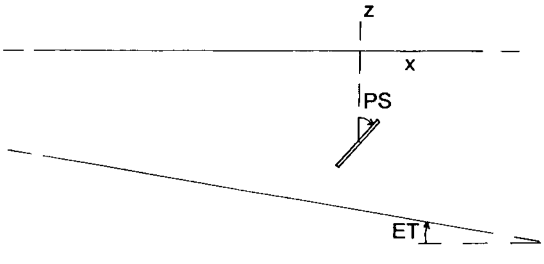

Figure 4.6: *Tilt and back-side tilt of strip-like crack.*

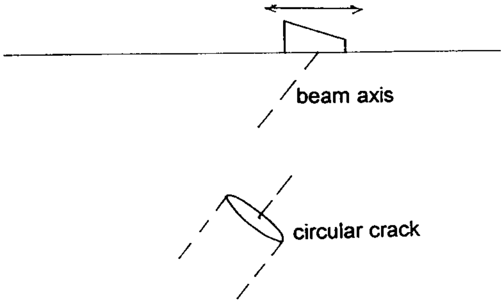

Figure 4.7: *Calibration scan for FBH.*

Name	Range	Description
LDTY	1	spherical cavity
	2	elastic spherical inclusion
	3	circular crack
	4	spheroidal cavity
	5	rectangular crack
	7	strip-like crack
	8	side-drilled hole
	11–17	as 1–7 but with a close planar back-side
	19	surface-breaking strip-like crack
	25,27,35,37	as 5, 7, 15, 17, but with rough crack faces
DZ	real	depth to defect centre (mm)
BZ	real	depth to back-side (mm)
ET	real	tilt of back-side (degrees; see Fig. 6)
DA	real	defect diameter (mm; LDTY = 1, 2, 3, 8, 11, 12, 13)
DRR	real	relative density of inclusion (LDTY = 2)
CPI, CSI	real	longitudinal and transverse wave speeds of inclusion (mm/μs; LDTY = 2)
DBI	real	damping in inclusion (dB/wavelength; LDTY = 2)
ETA, PHI	real	tilt and skew of circular crack or spheroid (degress; see Fig 4.5; LDTY = 3, 4)
LDC	1	open crack type (LDTY = 3)
	2	fluid-filled crack (LDTY = 3)
	3	partly closed due to compressive stress (LDTY = 3)
DC	real	quotient of compressive stress and flow pressure (LDC = 3)
DAC	real	diameter of contacts across crack (μm; LDC = 3)
DB, DC	real	spheroid symmetry axis and other axis with restriction restriction $0.2 \leq$ DB/DC ≤ 5 (mm; LDTY = 4)
DB, DC	real	crack length and height (mm; LDTY = 5, 15, 25, 35)
PS	real	crack tilt from vertical (degrees, see Fig. 4.6; LDTY = 5, 7, 15, 17, 25, 27, 35, 37)
DA	real	crack height (mm; LDTY = 7, 17, 27, 37)
EPSI	real	rms height of rough crack (mm; LDTY = 25, 27, 35, 37)
CLZ	real	correlation length (LDTY = 25, 27, 35, 37)

Table 4.4: *Defect parameters for isotropic component.*

Name	Range	Description
LDTY	5	rectangular crack
	7	strip-like crack
	15, 17	as 5, 7 but with a close planar back-side
CPHI,CTHETA,CPSI	real	Euler angles of crack orientation
DZ	real	depth to defect centre (mm)
BZ	real	distance between back-side and crack (LDTY = 15, 17)
BPHI,BTHETA	real	two Euler angles of back-side (LDTY = 15)
BPHI	real	tilt of crack relative back-side (LDTY = 17)

Table 4.5: *Defect parameters for anisotropic component.*

Name	Range	Description
LCTY	0	no calibration
	1	calibration by SDH
	2	calibration by FBH
CZ	real	depth to SDH axis or FBH centre (mm)
CA	real	diameter of SDH or FBH (mm)

Table 4.6: *Calibration parameters.*

Chapter 5

Output

As already mentioned the output from UTDefect is only in the form of simple lists. There is thus no postprocessor with graphical possibilities. However, all computer systems today include more or less advanced graphical packages so there should be no problems to produce the types of plots that are needed.

In its present form all the output from UTDefect is written on a single file. If desired it is of course simple to change this and write the initial data on one file and the listings on another.

The first part of the output is essentially a listing of all the input parameters. Everything is written out in full so it is clear what all the parameter settings are. A few computed quantities are also given for the probe(s). These include the wavelength and the near field length.

If the results are calibrated the calibration level is given. Furthermore, the location and the corresponding angle of this maximum response is given. This "true" probe angle should be compared with the given nominal angle (which is giving a time delay along the probe corresponding to a wave with the desired angle). Typically the two angles differ by less than 2°, but particularly for small probes the difference may be larger. Sometimes the exact angle can be a critical parameter (see Boström and Jansson (1997) for an example) so it may become necessary to rerun UTDefect with a new nominal angle that gives a better "true" angle.

When the calibration is performed a line scan around the expected (as given by the nominal angle) maximum position is conducted. The length of this scan corresponds to an angular change of about 25° at the probe. If the maximum response appears at one of the endpoints, then clearly the result is not to be trusted and UTDefect signals this by writing a warning. The length of the calibration scan cannot be changed by the user, but a possibility to explore what happens is to run UTDefect with the desired calibrator as the defect and choose a longer scan.

The output list from UTDefect gives the probe position (for tandem testing the transmitting probe is given and for a fixed transmitter the receiving probe is given), the time or frequency if appropriate and the signal (as a real number for A and B scans, in dB for a C scan and as a complex number for frequency output).

Chapter 6

Concluding remarks

The present user guide describes the computer program UTDefect and its preprocessor UTDpre. It is hoped that enough information is given so that most of the questions that can arise when using UTDefect are answered. It is of course also hoped that the program will prove useful and helpful in the ways mentioned in the introduction.

UTDefect has been developed during almost a decade and the possibilities and capabilities have gradually increased. The development with faster computers with larger memories has also been very important in these respects. But there are of course several ways in which the program can be further developed. This concerns both the modelling possibilities, i e the type of defects, probes, back surfaces, etc, but also the methodological and programming aspects.

Concerning the modelling possibilities, new types of defects can of course be added and there are some candidates that may be interesting, like nonplanar or interface cracks. Even more important is probably to add further geometrical configurations like an interface to another material or cladding. Also the list of probes could be increased, an example being a twin crystal probe.

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Appendix A

Computer requirements

The new version 4 of UTDefect differs from previous versions in two important respects. The program now includes anisotropic components and because of this external subroutines are used (eigenvalue solvers, etc.). Previous versions were written in FORTRAN 77, but this language does not permit dynamic storage allocation, and as the program has expanded this has lead to an increased waste of memory. The fixed storage allocation also leads to a fixed upper limit on the frequency times defect diameter (different for different defects). Now the progam has been changed to FORTRAN 90 and dynamic memory allocation is used for all critical matrices. This saves a lot of memory and also pushes the upper limit on the frequency times defect diameter (for reasons of memory requirements, computer running times, numerical stability, etc. there will still be some upper limit, although for most defect types this will be sufficiently high to be of little practical consequence). Also other features of FORTRAN 90, other than dynamic memory allocation, has to a smaller extent been used in version 4 of UTDefect.

Concerning external subroutine libraries, Lapack and BLAS is now used by UTDefect. If not already installed on a computer system, they are freeware and can be found at various places.

Appendix B

Example

In this Appendix an example of running UTDpre and UTDefect is given. Running UTDpre gives the following (user's answers are on lines starting one position to the left):

```
 Welcome to the program UTDefect that simulates some ultrasonic nondestructive
 testing situations with defects in an isotropic or anisotropic and homogeneous
 component.

 This is version 4.0, last change 02-03-28.

 All lengths are measured in millimeters and all times in microseconds.
 All angles are measured in degrees.
 Stiffnesses are measured in GPa and densities in kg/litre.

 The tested component can be:
 1. Isotropic.
 2. Transversely isotropic or orthotropic.
 Choose material type:
1
 First the defect type should be chosen. The following types are possible:
 1. A spherical cavity
 2. A spherical inclusion of a different material
 3. A circular crack that may be partly closed
 4. A spheroidal cavity
 5. A rectangular crack
 7. A strip-like crack
 8. A side-drilled hole
 11-17. As 1-7 but with a close planar back-side
 19. A surface-breaking strip-like crack
 27. A rough strip-like crack
 37. A rough strip-like crack with a close planar back-side
 Choose defect type:
19

 Now some questions about the scanning, that is assumed to be performed in
 a rectangular mesh on a flat side of the component with contact probes.
 Immersion testing is also possible for some defects.
 (For some defect types only a line scan is possible.)
 There may be
 1. one probe acting in pulse-echo
 2. two probes with a fixed separation (tandem insp.)
 3. a fixed transmitter and a moving receiver
 Choose 1, 2 or 3:
1
 The scanning can be done as
 0. Complex signal response at a number of frequencies
 1. A- or B-scan (time traces at selected points)
 3. C-scan (max values in a rectangular mesh)
 Choose 0, 1 or 3:
3
```

```
 A coordinate system xyz is introduced with the x axis as the main scanning
 direction, the y axis as the other scanning direction and the z axis
 upwards from the scanning surface. The origin is located straight above the
 defect. If only one x or y position is wanted, the end value should be less
 or equal to the start value, the increment can then be given arbitrarily.
 Give start, end, and increment in x:
90,120,2

 Give the compressional and shear wavespeeds of the component:
5.94,3.23
 Do you want to include damping? (0=no, 1=yes):
0

 Now some questions about the probe(s).
 The probe(s) can be assumed to operate
 0. in time-dependent mode with automatically set number of frequencies
 1. at a single frequency (often gives reasonable results)
 N. at a specified number of frequencies
 Choose 0, 1, or N by giving 0, 1, or number of frequencies:
1
 Give the centre frequency:
2

 Questions about the (transmitting) probe
 Give the mode type of the probe (1=SH, 2=SV, 3=L,
 11, 12, 13 = line focussed probes,
 21, 22, 23 = point focussed probes,
 4 = immersion probe):
2
 Should the "wrong" wavetype be supressed (1=yes, 0=no):
0
 Give the angle of the probe in degrees:
45
 Give the shape of the effective probe area (1=rectangular, 2=elliptic):
1
 Give the effective length and width of the probe:
20,20
 Give the rotation of the probe relative the x axis in degrees:
0

 Questions about the defect.
 Give the width of the crack:
8
 Give the tilt from the vertical of the crack:
0
 Give the depth to the crack mouth:
100
 Give the tilt from the horizontal of the back-side:
0
 Now some questions about the calibration.
 The following calibrations are possible:
 0. No calibration
 1. Calibration by a side-drilled hole whose axis is parallel to
    the scanning surface and normal to the beam axis
 2. Calibration by a circular crack whose normal is parallel to the beam
    axis (this is an approximation for a flat-bottomed hole which should be
    reasonable when the crack diameter is more than one or two wavelengths)
 Choose 0, 1, or 2:
1
 Give diameter of hole:
6.5
 Give depth to hole centre:
80

 An accuracy index between 1 (lowest) and 5 (highest) should be given.
 Use 3 normally, change index to check accuracy.
 Give 1, 2, 3, 4, or 5:
3
```

The output file from UTDpre then has the following appearance:

```
 1                              isotropic material type
13                              scan type
 90.000, 120.000,   2.000       Xstart, Xend, Xincrement
  0.000,   0.000,   1.000       Ystart, Yend, Yincrement
  5.940,   3.230                wavespeeds Cp, Cs
    1                           number of frequencies
  2.000,   0.000                frequency, bandwidth
 2,  0                          mode type, supr of "wrong" mode
 45.0,   0.0                    angle, rotation
 1,  20.000,  20.000            shape type, Xlength, Ylength
19,  100.000                    defect type, depth
  8.000,   0.0,   0.0           width, tilt, back-side tilt of surf-b strip cr
 1                              calibration type
  6.500,   80.000               diameter and depth of calibrator
 3                              accuracy index 1-5
```

Running UTDefect with this as input file generates the following output:

```
Program UTDefect, version 4.0, last change 02-03-28


NDE program for calculating the ultrasonic response from a defect.

All lengths are measured in mm and all times are measured in microseconds
(velocities are thus measured in mm/microseconds).
Angles are measured in degrees.

The component's compressional and shear wavespeeds are:   5.940   3.230

A C-scan is computed.
Pulse-echo mode is selected.

Scan along x axis, start, end and increment
                   (0 is above the defect):   90.000 120.000   2.000
Scan along y axis, start, end and increment
                   (0 is above the defect):    0.000   0.000   1.000

Probe model with single frequency:  2.00

The probe is of SV type with beam angle:  45.0
Rectangular probe with sides in x and y directions: 20.000 20.000
Probe rotation counterclockwise relative x direction:   0.0

Probe divided into nr of elements in x and y dir:  2  1

Near field length and wavelength:   61.920    1.615

Defect is a surface-breaking strip-like open crack.
The depth to the back surface is:  100.000
The width of the crack is:   8.000
The crack is tilted from the vertical with the angle:    0.0
The back surface is tilted from the horisontal with the angle:    0.0

Calibration by a side-drilled hole with diameter and depth:   6.500  80.000

The accuracy index is: 3

Calibration at distance:    79.000
"True" probe angle:    44.6


Output signal in dB relative the calibration level:  0.8339D+03

The y-value is:   0.00
 x-value    signal

  90.00       6.21
  92.00      10.10
  94.00      12.67
  96.00      14.31
  98.00      15.12
 100.00      15.35
 102.00      15.04
 104.00      14.24
 106.00      12.87
 108.00      11.20
 110.00       8.77
 112.00       6.04
 114.00       2.59
 116.00      -1.71
 118.00      -5.87
 120.00     -10.97
```