Ultrasonic Imaging of Defects in Known Anisotropic and Inhomogeneous Structures with Fast Synthetic Aperture Methods

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Abstract

Imaging methods like Synthetic Aperture Focusing Technique (SAFT) are based on the principle of propagation of the measured ultrasonic wave field back to field sources. In the case of a pulse-echo measurement, this back propagation under some approximating conditions leads to an image of the scattering object with well known properties and imperfections. The back propagation through the object which is under concern needs the knowledge of material properties in respect of the wave propagation. If these properties are known, we can use imaging algorithms like SAFT with all their advantages (computational speed and robustness) not only for isotropic but also for anisotropic material; moreover, the inverse propagation concept allows crossing boundaries between materials, even if the materials are anisotropic. Examples of this concept are given with modelled and measured data for tendon duct imaging in concrete structures, for 3D imaging of air cavities in wood specimens and for imaging of defects in anisotropic welds.

Keywords: NDT, SAFT, pulse-echo technique, back propagation, inverse scattering, image reconstruction

1. Introduction

Imaging of defects with ultrasound in NDT can be classified into two categories. The first category could be described as 'solving an inverse problem' which tries to estimate geometrical parameters of the concerning defect under inclusion of sophisticated mathematical models. These methods can be very time consuming and results are difficult to interpret, especially if the data are not complete and the assumed model is not a correct description of the underlying physical experiment [1]. The second category - here named as imaging algorithms - tries to copy the human sensor mechanism for waves - i.e. eyes and ears - to get an image of an object illuminated by ultrasonic or electromagnetic waves. Humans, as part of the evaluation process, are then optimally suited to recognize and to assess imaging results for cases in which the measured data and the assumptions are not perfectly known [2]. In this second category we find the migration algorithm which is well known in the NDT community as SAFT (Synthetic Aperture Focusing Technique) and which follows the principle, that the defect information is collected at a position in space by superposition of information of all sampling points of the measurement surface at a moment, when the transmitted pulse was able to travel to the defect and back to the transducer [3]. Indeed, we get an image as for computed tomography, but with the scattering properties of the observed space as result. This well defined method can be justified mathematically and then we get the additional perception: under which conditions such a reconstructed image is a reproduction of the scattering object and which problems may arise.

Following the theoretical derivation, we finally come to the conclusion, that a SAFT image under the assumption of a pulse echo measurement (transmitter and receiver position are identical) corresponds to a wave propagation through a medium in time reversed direction, with the velocity which must be half in respect of the original medium. Stopping the wave propagation at a particular time which corresponds to the moment of the pulse excitation (since the wave propagation is time reversed) gives us the image according to the original
SAFT algorithm. The same principle holds for the Kirchhoff migration. We also can perform the inverse wave propagation of the data by Huygens' principle – a wavefront in space can be expressed as the superposition of elementary waves which have their origin within the measurement surface – and the result is the A-scan driven approach of a SAFT implementation. From these considerations of SAFT we see that the well known principles of optics about wave focusing and refraction can be transferred immediately. A further application can be learned from optics: the presentation by the Huygens' principle works also for transmission through transparent boundaries, i.e. through boundaries between two wave transporting media. When formulating the boundary condition for the respective physical effect, at least the ‘phase matching condition’ remains intact in any case. This means, that the time dependency behind a surface for the respective component of the total field is identical with the time dependency of the component of the total field in front of the surface. The exact amplitude is defined by the boundary condition. If we perform an imaging process according to category 2, we get an image of the scattering object behind boundaries by neglecting the change of amplitude of the wave field in front and behind the boundary. Loss of amplitude can happen anyway because of limited aperture, limited transducers opening angle, and refraction effects at the scattering. The idea of the proposed method therefore consists in considering the boundary between different media as transfer point of time signals which arrive at the boundary through medium 1 and serve as sources according to the Huygens' principle for the medium 2.

Restricting us to pulse echo experiments and neglecting multiple scattering and mode conversion – we assume that the waves take the same way from the transmitter to the scatterer and from the scatterer back to the receiver – we simply have to replace the velocities of all media by its half values. Then the back propagation of the measured data delivers the SAFT or FT-SAFT image (FT stands for processing by Fourier techniques [4]) in all the different media with the mentioned assumptions and restrictions.

2. Imaging Method for Inhomogeneous Anisotropic Media

2.1 Basic principle and comparison to existing implementations

Considering the elastic wave propagation in isotropic media [5], we find that it is described by three independent material constants: the mass density $\rho$, and the Lamé constants $\lambda$ and $\mu$. A wave propagation results described by scalar and vector fields of - in the far field - longitudinal pressure (P) and transversal shear (S) waves. Neglecting mode conversion (there exists a conversion of wave types at material inhomogeneities) the SAFT method is used for pressure and shear waves likewise. The vector character of shear waves leads to polarization dependent imaging results because the back scattering properties of e.g. curved surfaces depend on the polarization of the incident field. If it is possible to gather the vector components of the scattered field, an elastic formulation of diffraction tomography can be used to improve the imaging results [3].

A much more complicated condition occurs if the materials concerned have an anisotropic behaviour for elastic waves. This is the case, if the elastic properties have a certain preferred direction caused by a fine or a coarse crystalline structure as in e.g. cladding, welds, fibre composites, or wood. In these cases, the elementary waves do not propagate spherically, nevertheless we can here – assuming linearity – formulate a Huygens' principle which reduces the complex wave propagation by a superposition of elementary waves, in this case however based on dyadic Green’s functions [5].
Typical for the propagation of waves in anisotropic media is the necessary distinction between phase and group velocities. Following the wave propagation of a punctiform and short excitation in space and time respectively (under consideration of the polarization relative to the orientation of the material), we observe typical direction dependent wavefronts, which obviously describe the energy propagation. Mathematically, we observe the group velocity here. This means: excited by a short pulse, a wave reaches a point in space – and therefore a point at a boundary surface to a different medium – with the group velocity.

Metaphorically speaking: sitting on the wavefront of such an elementary wave, we see that the neighbourhood of this point seems to oscillate in a different direction than the group velocity vector does. Here we recognize that the propagation of the phase – the phase velocity vector – may obviously be different from the group velocity vector in contrast to a spherical wave in isotropic media, where these directions coincide. Theoretical considerations show that the phase velocity is that velocity, which we observe if we follow an infinite extended plane wavefront in the direction of oscillation.

The difference of both kinds of description – point source versus plane wave – leads us to two different algorithms: a) Space and time domain, b) Space frequency and time frequency domain - which we reach by Fourier transform of the respective quantities. This is comparable to SAFT and FT-SAFT (SAFT with Fourier Techniques) calculations. Both methods are formulated and implemented [6]. The advantage of the Fourier version is the strict mathematical background and the fast processing by Fast Fourier Transforms [7]. The disadvantage is the limitation to homogeneous (maybe anisotropic) media, and that is what we want to overcome here. The past implementation of the space/time method is based on virtual rays, which are emitted at the transducer position in many directions through the anisotropic medium [8, 9]. If these rays hit a surface, the transmission to the new media is calculated by ray methods and the result is in a new ray (or are new rays) behind the boundary, which then can be emitted into the new medium. This explicit transmission between media is very extensive and – although it is only a high frequency approximation – it is very time consuming, because many of such rays have to be calculated, so that the destination area (which for SAFT is the whole discrete reconstruction area) is hit by enough rays and an effective superposition is possible.

2.2 Imaging with Huygens' principle

The disadvantages of the methods mentioned above do not occur when applying the proposed method. The waves, which lead to the reconstructed image, are processed by the Huygens' principle completely to the next boundary and from there through the medium behind that boundary to further boundaries. By the use of Huygens' principle it is assured that all parts of the wave field reaches the respective next boundary with correct phase. If the data to all boundaries are processed, the data are used as input data to calculate a SAFT processing into the region behind the respective boundary. For the calculation from boundary to boundary and for the calculation from boundary to region the isotropic or anisotropic parameters of the crossed medium are used. The position of the boundaries is not important in principle, but we have to distinguish in which direction the wave field crosses the boundary. With that method, even a reflection at boundaries can be used to process data which reach the transducer over a mirroring boundary, e.g. the back wall of a specimen. The boundaries need not be plane.

Before we start with examples of realistic applications, the principle should be explained for a simple geometry. The SAFT method is a linear superposition of information out of the
measured A-Scans. This means: if we pick out a single time sample of a single A-Scan, the SAFT method for isotropic materials will create from that data point a semicircle in the reconstruction area. This is displayed in Fig. 1a. The respective group velocity diagram is a circle as seen in Fig. 1d. In fact we have replaced the A-Scan by a single raised cosine pulse of 2 cycles in order to have a band limited signal. If we replace the material properties so, that we get anisotropic behaviour (the group velocity diagram is given in Fig. 1d - spruce wood), the anisotropic SAFT will give a result which is displayed in Fig. 1b. The group velocity for that material already shows that an ambiguity is possible: even if we send only one single pulse there may be more than one pulse which hits a scattering object. Therefore, a selection is necessary: the selected part of the group velocity is shown with red colour in Fig. 1e. The next step of complexity is to divide the reconstruction area in inhomogeneous regions. Fig. 1c shows the reconstruction area divided into 4 sub regions. The regions are processed separately by anisotropic SAFT like in Fig. 1b, but the data are taken from the surrounding boundaries. This means the data are processed from boundary to boundary and then from boundary to the enclosed region. The material properties in the different regions are equal, therefore the result should be the same as in Fig. 1b. The differences are explained by numerical effects of the discretization and corners of the boundary shape, but the structure is modelled well. In Fig. 1f the material properties of region D are replaced by those of an anisotropic material with rotated crystal axes (15° clockwise against material of Fig. 1b). The travel times are changed and we can observe refracting effects as it would be seen for real media as well. Because of the scalar ansatz of the algorithm, mode conversion is of course excluded.

Figure 1. Imaging result for a single pulse as input data: a) Isotropic case with velocity according (d). b) Anisotropic case with group velocity according (e). c) Separated areas, data transported over boundaries, medium according (e). f) Separated areas, different anisotropic orientation in region D.
2.3 Comparison of the method with homogeneous anisotropic FT-SAFT

In this example we want to compare roughly results of the 2D homogeneous anisotropic FT-SAFT (HAFT-SAFT) of Zimmer [6] with the proposed time domain method. In this case the background material is assumed to be homogeneous for the whole specimen. This means, we do not have to calculate data towards boundaries, the ‘easy’ case which is explained by isochrones of the form in Fig. 1b can be used. In the framework of the EU project SPIQANR (Signal Processing and Improved Qualification for Non-destructive testing of Aging Reactors) a homogeneous anisotropic specimen was fabricated by the British company SERCO Assurance. The size of the body is 0.1 m x 0.08 m x 0.06 m and it consists of 100% homogeneous anisotropic welded material of Inconel 182. We assume that the material is macroscopically transversal isotropic. The surfaces of the block are parallel or orthogonal to the crystallographic axes. The measurements were performed by the Fraunhofer IZFP with a piezoelectric pressure wave transducer Krautkrämer MSWQC at 2.25 MHz and a diameter of 9 mm. The measurement with a wedge for a 45° incident angle in steel out of many others is used to compare the results. In [6] Zimmer performed the imaging process on an average of 50 scan lines. The averaged data and the HAFT-SAFT result is shown in Fig. 3b and 3c respectively. Based on the same data the result for one slice with the proposed anisotropic time domain SAFT is displayed in Fig. 3c. According to the measurement coordinate system, our result has to be mirrored along the x-axis. The stacked 2D anisotropic SAFT reconstruction is shown in Fig. 4. We see a C-image at the depth of 12 mm, a (zx)-B-image at y=37 mm and a (zy)-B-image at x=24 mm, and a 3D view together with an isosurface displaying the contour of 30% relative to the maximum in all images. Assuming the same material properties as Zimmer (the Fourier algorithm uses the slowness of the phase velocity for the mapping in Fourier space) we get a comparable result with the group velocity imaging.

Figure 2. Homogenous anisotropic Inconel 182 specimen with holes.

Figure 3a. Sketch of the Inconel specimen.

Figure 3b. Averaged B-Scan with 45° MSWQC at 2.25 MHz (with permission from Zimmer [7]).
2.4 Comparison of the method with InASAFT [8, 9]

To demonstrate the capabilities of imaging in inhomogeneous anisotropic structures we use the example ‘Weld#1’ in Shlivinski [9]. The example shows a rough crack located on the right side of a uniform anisotropic perpendicular grain structured weld embedded between two isotropic steel areas. The elastic parameters of the austenitic material are $C_{11}=216$ GPa, $C_{33}=262.75$ GPa, $C_{44}=82.25$ GPa, $C_{66}=129$ GPa, $C_{13}=145$ GPa, $C_{23}=98.25$ GPa, and $\rho = 7800$ kg/m$^3$. The parameters of the other areas are given in Fig. 5a. The data are not taken by an experiment but are calculated by an EFIT [10, 11] wave propagation simulation. The scanning is done at 160 points along a 80 mm path. The transducer is assumed as a 45° P-
wave emitting device generating a one cycle raised cosine (RC1) pulse with centre frequency at 2 MHz. The numerous echoes which can be recognized in the B-scan (Fig. 5b) result from various scattering mechanisms and are explained in detail in [9]. The imaging algorithms used there is the InASAft algorithm which is based on ray techniques, we compare it with our Huygens’ type algorithm. To see the effect of the anisotropic algorithms, we show the result of conventional isotropic SAFT in Fig. 6a. In contrast to [9] the imaging is done with reduced opening angle of ±15° around a 45° incident angle. This suppresses some artefacts and the indication of the back wall, as it would be for a real experiment. Figure 6b shows the reconstruction with the Huygens’ type algorithm. The collected data are processed to the left boundary of the weld through the homogeneous isotropic steel region, and from there they are imaged into the weld region under the assumption of the anisotropic weld material. This image is then superimposed to the anisotropic SAFT image of the data on the top of the weld. As a result we recognize, that the positions of the crack tips are correct and well focused. Even points along the rough crack which give reflections back to the transducer are well focused, so that we can follow the structure of the crack along the right side of the weld. The result is very similar to the InASAFT result in [9], with the advantage that we do not have to follow a sufficient number of rays, but the wave field itself gives us the image. The calculation is done for that example for two dimensions and it can be calculated in a few seconds on a conventional PC, therefore it is possible to adjust reconstruction and material parameters interactively to get an optimum focused imaging result.

Figure 5a. Sketch of the modelled arrangement. Figure 5b. B-Scan (x,t) image of the EFIT simulated 2.25MHz pulse echo experiment.

Figure 6a. Isotropic SAFT image of the anisotropic weld data of Fig. 5. Figure 6b. Inhomogeneous anisotropic SAFT image with the assumed knowledge of the austenitic weld.
2.4 Application for NDT of wooden building elements

The structural anatomy of wood [12, 13] with the definitions of planes is illustrated in Fig. 7a. A large group of the wood species crystals are orthotropic with nine independent elastic stiffness constants and show strong anisotropy. Imaging of anomalies in wood is up to now only possible in very restricted arrangements. The reason is the local dependence of the anisotropic parameters, which is usually unknown in the inner and hidden structure of the wood but has a very strong impact to the wave propagation and to the inverse problem in a much higher degree. For the anisotropic SAFT we have to know the material parameters in advance and this may be possible for some wooden building elements. More details can be found in [14]. Here we present the result for 3D imaging in a spruce specimen which was fabricated at BAM, Berlin. The block is a glue laminated timber of pine (Fig. 7b) of 0.5 m x 0.3 m x 0.15 m. The small wood strips are glued together using melamine resin glue. A defect was fabricated from the back wall as a ca. 20 mm x 10 mm L-formed drilling. To achieve the necessary resolution for such a small defect, only one pair out of 24 transducers of a ACSYS A1220 shear wave transducer was used at 50 kHz centre frequency. In Fig. 8 we see the data of one scan-line before (left figure) and after processing (right figure). The anisotropic characteristic of the wood was taken from indications of the assumed defect in the data itself (blue curve in Fig. 8b). The travel time curve indicates, that the quasi pressure wave in that case holds the most dominant information. Because of the small transducers we get a lot information from surface waves, which are not useful for the scalar imaging process and are therefore reduced by an adaptive averaging technique. The result of anisotropic SAFT is displayed as C-image in the depth of 10 cm and as a B-image cutting the defect. The L-shaped defect is clearly visible and the depth distribution of the defect and the indication of the back wall in a depth of 15 cm can be recognized.
Figure 8. Measured (left) and pre-processed (right) B-scan (x,t) image of the pine wood specimen.

Figure 9. Left: C-image of anisotropic stacked 2D-SAFT at z=0.10 m. Right: B-image (x,z), cut through the defect area. Data of Fig. 8.

3. Conclusions

Ultrasonic imaging in anisotropic materials with the time domain anisotropic SAFT algorithm is proposed and demonstrated for applications in steel and wood. The use of Huygens' principle allows to cross boundaries in known anisotropic structures and the inverse propagation wave field focuses on scatterers as it is theoretically proven for isotropic materials. The resulting algorithm is very fast compared to previously used ray based methods and can be used for 3D imaging as well.
Acknowledgements

Automated ultrasonic measurement on wood specimens was performed by U. Effner and Th. Nowak. This research work is funded by the Federal Office for Building and Regional Planning (BBR, Germany).

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