Modelling and Simulation of Ultrasonic Wave Propagation in Complex Composite Materials

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Abstract. To simulate ultrasonic inspection of modern materials both an appropriate simulation method and a powerful tool to generate the models have to be provided. Therefore, the Elastodynamic Finite Integration Technique (EFIT) is combined with the software module WiseTex from the Katholieke Universiteit Leuven in Belgium.
This paper presents the modelling of the detailed microstructure of laminate specimens consisting of several layers of woven fabric.
First results of the interactions between the ultrasonic wave and the microstructure are presented.

Introduction

In aerospace industry high quality standards for composite materials are essential. The components are usually inspected by using non-destructive testing methods. Here ultrasonic inspection techniques play a major role. But the application of this common method on new complex materials causes various problems. Thus for a better understanding of the interactions between ultrasonic waves and complex materials simulation tools are indispensable. They shall help to optimise test parameters and to improve the interpretation of results. The pulse-echo technique in water tank (reflection method) serves as basis for the simulations.
As sophisticated numerical simulation method, the Finite Integration Technique was chosen. Originally EFIT was invented by *Weiland* [1] for the calculation of electromagnetic waves. Soon it was adapted for wave propagation phenomena in various fields of science. Among others *Marklein et al.* [2] [3] and *Schubert* [4] used it in the non-destructive testing sector especially for concrete structures.
The EFIT-code and further relevant aspects are implemented with C++. The C++- code provides a user interface and different output opportunities that help to analyse and visualise the simulation results. The possibility of parallel computing to afford bigger and/or more detailed models has been developed for two processors.

The models used for the simulation of propagating ultrasonic waves vary from homogeneous isotropic to heterogeneous transversal-isotropic composite materials. The complex models of laminate specimens are generated with the help of the software module *WiseTex* (Katholieke Universiteit Leuven, Belgium). In this paper the modelling of laminates made of woven fabrics are presented. They are based on materials used in aerospace industry. In the future porosity that is a possible defect in laminates shall be added as well. Therefore micro cut and micro computer tomography images are evaluated.

1. Elastodynamic Finite Integration Technique

To reconstruct the propagation of a wave in a model, it is necessary to calculate the elastodynamic field variables, the stress tensor $\underline{\underline{T}}$ and the particle velocity vector $\underline{v}$. They are linked by

Cauchy's Equation of Motion

$$\iiint_V \rho(R)\underline{\dot{v}}(\underline{R},t)dV = \oiint_S \underline{n}\underline{\underline{T}}(\underline{R},t)dS + \iiint_V \underline{f}(\underline{R},t)dV \tag{1}$$

and *Hooke's Law*

$$\iiint_V \underline{\underline{\dot{T}}}(\underline{R},t)dV = \oiint_S \underline{\underline{C}}\underline{n}\underline{v}(\underline{R},t)dS + \iiint_V \underline{\underline{g}}(\underline{R},t)dV \ . \tag{2}$$

Here, the equilibrium mass density is denoted by ρ, *f* represents the volume force density vector, $\underline{\underline{C}}$ is the elasticity tensor, and $\underline{g}$ the source excitation. The spatial discrete form of these equations results in a three- dimensional cubic staggered grid with the edge length *d*. The normal components of the stress tensor as well as the material parameters are located on the grid nodes, the shear components in the centres of the grid surfaces and the components of the velocity vector in the middle of the grid edges, as shown in Figure 1.
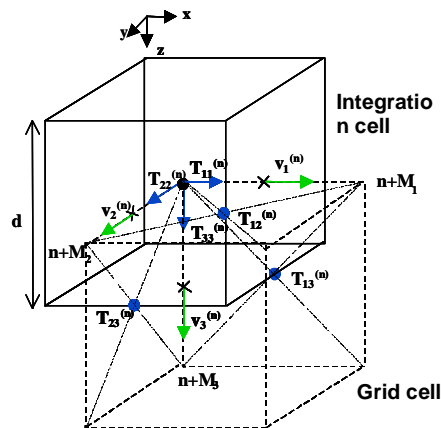

Figure 1: Location of the discrete field variables in the staggered grid

Considering the integration volume of one field variable (in Figure 1 exemplified for the normal components of the stress tensor by the solidly lined box)

the complementary variable is located on the surfaces of the control volume. So the derivative with respect to time of one field variable in a control volume V is given by the surface integral S (with the normal n) of the complementary field variable.

Respectively, the discretisation in time is also staggered. The time derivatives of the field variables are calculated iteratively at alternating half time steps $l\pm\frac{1}{2}$ (leap-frog method) as shown in Equation (3) and (4):

$$v_i^{[l]} = v_i^{[l-1]} + \Delta t \, \dot{v}_i^{[l-\frac{1}{2}]}, \tag{3}$$

$$T_{ij}^{[l+\frac{1}{2}]} = T_{ij}^{[l-\frac{1}{2}]} + \Delta t \, \dot{T}_{ij}^{[l]}. \tag{4}$$

The staggered grid provides more accurate results than grids of other simulation methods using comparable grid sizes. A more detailed mathematical description can be found in [3] and [5]. There the constraints for providing stability and consistency are specified, too. For the boundaries in longitudinal direction (here the x-direction) stress-free boundary conditions are chosen. In order to avoid reflections in the two other directions periodic boundary conditions are implemented.

2. Modelling with *WiseTex*

The software module *WiseTex* is developed by the Department of Metallurgy and Materials Engineering (MTM) of the Katholieke Universiteit Leuven (K.U.Leuven) in Belgium. It serves as an integrated textile pre-processor and affords three-dimensional modelling of the internal geometry and microstructure of undeformed and deformed material respectively. It provides flexible modelling of woven fabrics, two-dimensional braids, unidirectional preforms and multi-axial multi-ply fabrics which can include cracks, channels, and others [6].

All models are based on unit cells which contain all information about the structural and material characteristics. The *WiseTex* module *LamTex* enables to create laminates by piling several unit cells on top of each other. Thereby a random composition of the cells can be chosen as well as a maximum nesting between them.

In this paper the modelling of a laminate of several layers woven fabric is presented. It is designed according to material used in aerospace industry. Data sheets with the material properties as well as micro-computer tomography images have been available. The woven fabric consists of carbon roving (with hot melted resin) and E-glass fibres. The roving and the fibres are manufactured as a plain weave. Figure 2 displays a micro-computer tomography (μ-CT) image of the material and the modelled unit cell. The dark spots on image are caused by porosity.
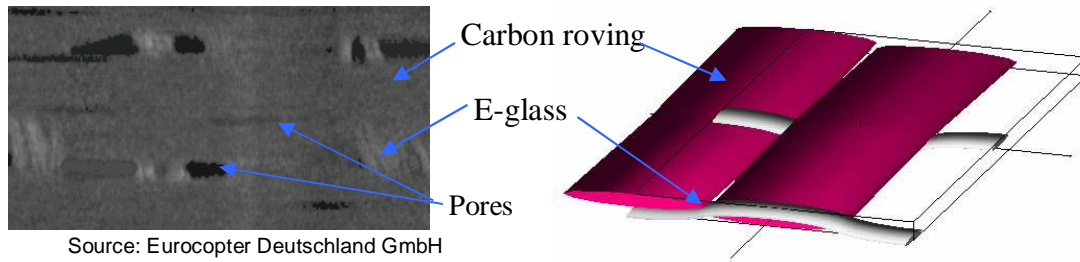
Source: Eurocopter Deutschland GmbH

Figure 2: µ-CT image (left) in comparison with the unit cell generated by *WiseTex* (right)

The dimensions of the unit cell are 2.6 mm x 5.0 mm x 0.173 mm and it has a fibre volume fraction of about 40.3%, before it is compressed to a fibre volume fraction of about 51.4%. Afterwards a laminate of 15 unit cells is build. The layers are arranged in a way that provides a maximal nesting (see Figure 3).
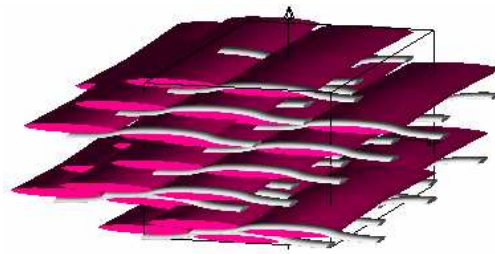

Figure 3: Laminate of 15 layers woven fabric

The dimensions of the laminate are 2.6 mm x 5.01 mm x 2.11 mm. It is discretised in 247 x 477 x 247 grid cells with an edge length *d* of about 10.5 µm.

3. Simulation

Basic simulations that show the interactions between the propagating wave and the microstructure have been performed. Results can be found in [5].
The simulations of the wave propagation in the presented model are not yet finished. However, first results show the high complexity of the model effecting the ultrasonic wave. The simulation is compared to earlier simulations in less complex models: a homogenous aluminium model and a biaxial laminate made of 20 layers ([+ 45°-45°]$_{10}$) shown in Figure 4. More detailed information about this laminate and its simulation results are presented in [7].
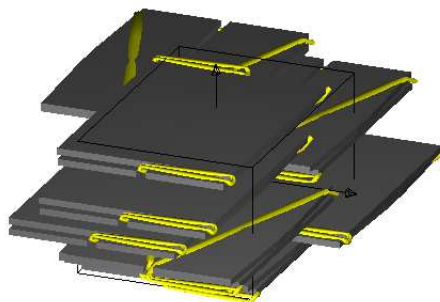

Figure 4: Laminate of biaxial multi-ply fabric

Figure 5 shows the time responses and snapshots of the longitudinal component of the particle velocity vector in homogenous aluminium (left hand side), in the biaxial laminate (centre) and in the laminate of woven fabric (right hand side). Although the dimensions and the time steps are different, the waves are comparable. For all models a raised cosine signal with two cycles f_{RC2} served as excitation pulse. The centre frequency f_C for the simulations in the woven fabric is 5 MHz. The excitation is injected on the surface (for the laminates perpendicular to the layers), so that in the figures the longitudinal direction of the wave is from the left hand side to the right. The f_{RC}- signal is described by the following equation:

$$
\mathrm{f}_{RC2}^{(x=0)} = \begin{cases} (1 - \cos(\pi f_C t))\cos(2\pi f_C t) & \text{für } 0 \leq t \leq \dfrac{2}{f_C} \\ 0 & \text{für } t > \dfrac{2}{f_C} \end{cases} . \tag{5}
$$

The time response recorded on the excited surface can be seen in the upper part of the figure. It reproduces the excitation pulse and the velocities of the particle.

In aluminium there are nearly no velocities recorded after the excitation signal is fully introduced. The wave propagates spherical to all directions. No reflections appear. In the time response of the biaxial laminate noise is recorded. The spherical propagation is partly obstructed by the structure. Various reflections can be observed (compare [7]). The woven fabric shows high scattering after the excitation. In the snapshot it can be seen that the wave is diffused.
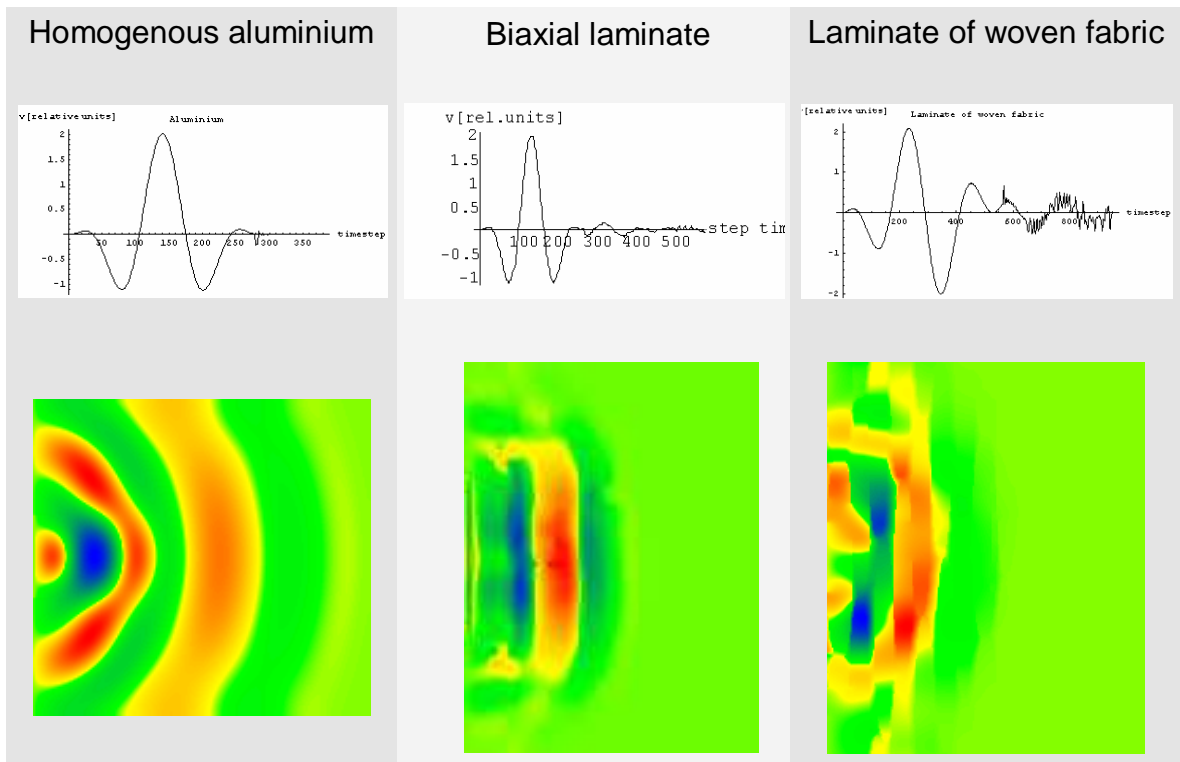

Figure 5: Wave propagation in various models: Time responses and snapshots of the longitudinal component of the velocity vector.

4. Conclusions

First results clearly demonstrate the occurrence of scattering and reflections caused by interactions of the propagating ultrasonic wave with the (micro-) structure. The complex structure of the laminate made of woven fabric shows high influences on the wave. The simulations are suitable to observe these problems.
Further simulations will analyse effects caused by porosity. Moreover the excitation signals will be optimised.

Acknowledgements

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