

Simulation of Propagating Ultrasonic Waves in Complex Composite Material

Julia HEGEMANN, Björn VAN DEN BROUCKE, Alexander PEIFFER,
Rudolf BILGRAM, EADS Deutschland, Munich, Germany
Horst BAIER; Technische Universität München, Munich, Germany

Abstract. The Elastodynamic Finite Integration Technique (EFIT) is a numerical method to simulate the propagation of ultrasonic waves through complex material structures. In this paper the simulation method is applied to composite laminate materials. The detailed microstructure models of the laminate specimens are generated by the software module *WiseTex* from the Katholieke Universiteit Leuven in Belgium.

The simulation results of ultrasonic wave propagation in multi-axial multi-ply laminates are presented.

Introduction

In aerospace industry high quality standards for surveillance and maintenance of composite structures require frequent testing for instance by using ultrasonic inspection techniques. Due to interactions between ultrasonic waves and complex structures there is still the need of simulation tools in order to better the understanding of the underlying phenomena. This enables an optimising of test parameters and the reliable interpretation of results

The Elastodynamic Finite Integration Technique EFIT is a promising numerical simulation method which supports this objective. It has its origin in the work of *Weiland* [1] for the calculation of electromagnetic waves and is transferable to various wave propagation phenomena. The application of EFIT to elastodynamic ultrasonic waves in the field of non-destructive testing of concrete structures was introduced by *Marklein et al.* [2] [3] and *Schubert* [4]. In this paper the simulation is performed in complex composite material in order to study the interactions of ultrasonic waves with the (micro-) structure. In addition to the heterogeneity of the material consisting of carbon fibres, resin, voids etc. the carbon fibres possess orthotropic material properties. For the generation of this sophisticated geometrical arrangement the software module *WiseTex* was chosen.

The EFIT- code and further relevant aspects are implemented in C++. The C++-code provides an interface for the user and enables the output of different quantities that help to analyse the simulation results.

The combination of EFIT and *WiseTex* is described and first results for selected examples are presented. The results are visualised by the software VGStudio Max 1.1. of Volume Graphics.

1. Elastodynamic Finite Integration Technique

1.1 Equations of Motion and Hooke's Law

EFIT is based upon the basic elastodynamic equations, the Newton-Cauchy equations of motion and Hooke's law. These equations connect the most important elastodynamic field variables, the stress tensor \underline{T} and the particle velocity vector \underline{v} . The integral form of the equation of motion is:

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

and Hooke's law:

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

ρ stands for the equilibrium mass density, \underline{f} for the volume force density vector, \underline{C} is the elasticity tensor and \underline{g} the source excitation. 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 \underline{n}) of the complementary field variable. The transformations are done using Gauss law.

In the presented examples the excitation out of the passive state is always realised through the volume force density in the longitudinal direction (x - direction). Therefore all other components of the volume force density and the surface excitation are neglected in the following.

1.2 Discretisation for Transversal-Isotropic Heterogeneous Material

The discretisation of the equations yields a spatial and temporal discrete form. Therefore the model is embedded in a three-dimensional cubic staggered grid with the edge length d . The components of the stress tensor are located on the grid nodes and the components of the velocity vector in the middle of the grid edges, as shown in Figure 1.

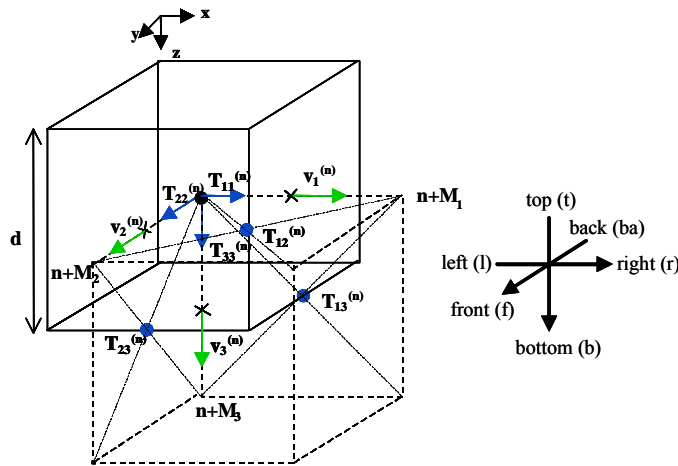


Figure 1: Location of the Discrete Field Variables in the Staggered Grid

Respectively, the discretisation in time is also staggered. The time derivatives of the field variables are calculated iteratively at alternating half time steps (leap-frog method). Equations (3) and (4) exemplify the discrete forms whereas Equations (5) and (6) present the difference quotient discrete in time for time step 1:

$$\rho \dot{v}_1^{(n)} d = T_{11}^{(r)} - T_{11}^{(n)} + T_{12}^{(n)} - T_{12}^{(ba)} + T_{13}^{(n)} - T_{13}^{(t)} + f_1 d, \quad (3)$$

$$\begin{aligned} \dot{T}_{11}^{(n)} d = & C_{11}(v_1^{(n)} - v_1^{(l)}) + C_{12}(v_2^{(n)} - v_2^{(ba)}) + C_{13}(v_3^{(n)} - v_3^{(ba)}) + C_{14}(v_2^{(b)} - v_2^{(n)} + v_3^{(f)} - v_3^{(n)}) \\ & + C_{15}(v_1^{(u)} - v_1^{(n)} + v_3^{(f)} - v_3^{(n)}) + C_{16}(v_1^{(f)} - v_1^{(n)} + v_2^{(f)} - v_2^{(n)}) \end{aligned}, \quad (4)$$

$$v_1^{[l]} = v_1^{[l-1]} + \Delta t \dot{v}_1^{[l-\frac{1}{2}]}, \quad (5)$$

$$T_{ij}^{[l+\frac{1}{2}]} = T_{ij}^{[l-\frac{1}{2}]} + \Delta t \dot{T}_{ij}^{[l]}. \quad (6)$$

All constraints for providing stability and consistency are adhered. For the boundaries in longitudinal direction (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*

WiseTex is a software module of 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. For example, it provides flexible modelling of multi-axial multi-ply fabrics which include cracks, channels, and others [5].

For this work Professor Lomov from the K.U.Leuven provided validated models of unit cells. The models represented here are stitched multi-axial multi-ply fabrics. For a quadriaxial one of them, the geometric data and the information about the different layers are shown in Table 1 and Table 2.

Table 1: Geometric Data of the Unit Cell

Size	8,2 x 5,1 x 0,923 mm
Areal density	667,9 g/m ²
Porosity (inter-yarn)	99,4 %
Fibre Volume Fraction V_f	41,2 %

Table 2: Data of the Fibre in the Plies

Ply	Fibre Orientation grad	V_f, average %	V_f average %	Channel/Crack	Width mm	Length mm
1	0	45,0	51,7	Channel	0,66	n/a
2	45	45,0	45,8	Crack	0,18	2,6
3	90	45,0	45,8	Crack	0,18	2,6
4	-45	45,0	51,5	Crack	0,48	7,3

The single plies and the 3D image of this unit cell are shown in Figure 2. Cracks and channels that are filled with resin in the simulation can be seen very well.

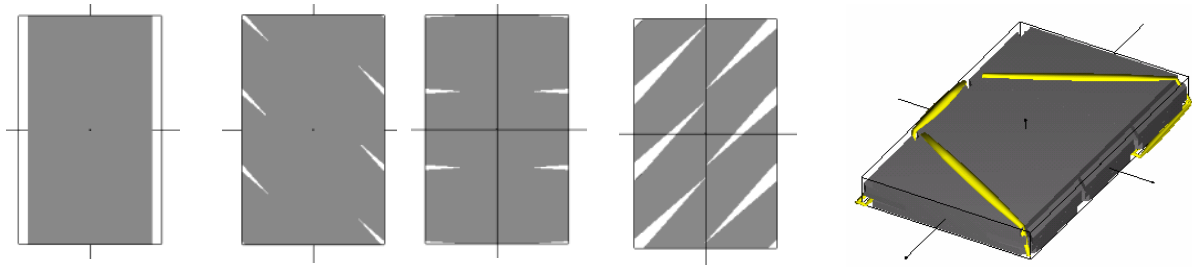


Figure 2: The Four Plies and the 3D Image of the Unit Cell

The next step for realising a model as realistic as possible is to compress the unit cell to increase the fibre volume fraction up to 60 %, before building a laminate of four unit cells. By mirroring a symmetrical composition is implemented.

In the same way a second laminate is build up by ten biaxial unit cells (fibre orientation 0° and 90°) [6]. The laminates (see Figure 3) are then discretised and used as input for the simulations.

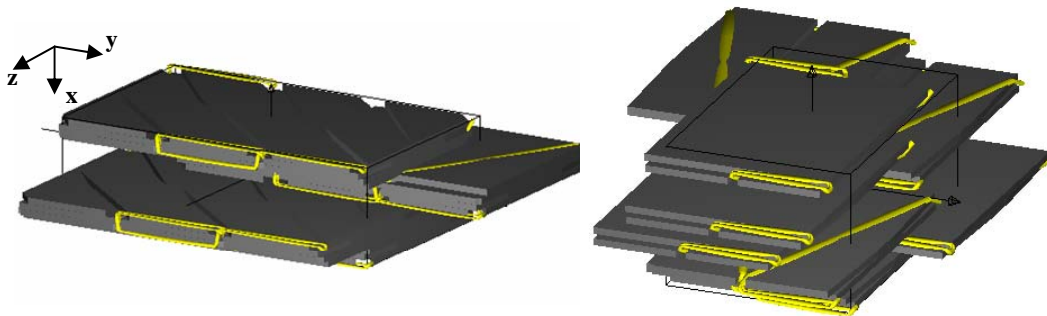


Figure 3: Laminates of Four Quadriaxial Unit Cells and of Ten Biaxial Unit Cells

3. First Results

For both models a raised cosine signal with two cycles f_{RC2} serves as excitation pulse. The centre frequency f_C is 1 MHz. A maximum occurring frequency of 4 MHz is assumed. The excitation is introduced on the surface of the laminate (in x-direction). The f_{RC} - signal is described by the following equation:

$$f_{RC2}^{(x=0)} = \begin{cases} (1 - \cos(\pi f_C t)) \cos(2\pi f_C t) & \text{für } 0 \leq t \leq \frac{2}{f_C} \\ 0 & \text{für } t > \frac{2}{f_C} \end{cases} \quad (7)$$

The first discrete model consists of $101 \times 213 \times 342$ cubic cells. For the interpretation of the results the wave propagation is considered in relation to the density of the model. The density model is shown on the left hand side in Figure 4. The plies with the

different orientations are in the colours green and red, resin is presented in blue. The turquoise material is a stitching yarn. On the right hand side a cross-section through a three-dimensional snapshot of the simulated wave propagation is illustrated. The excitation pulse is nearly totally introduced. The particle velocity is blue for negative and red for positive velocity.

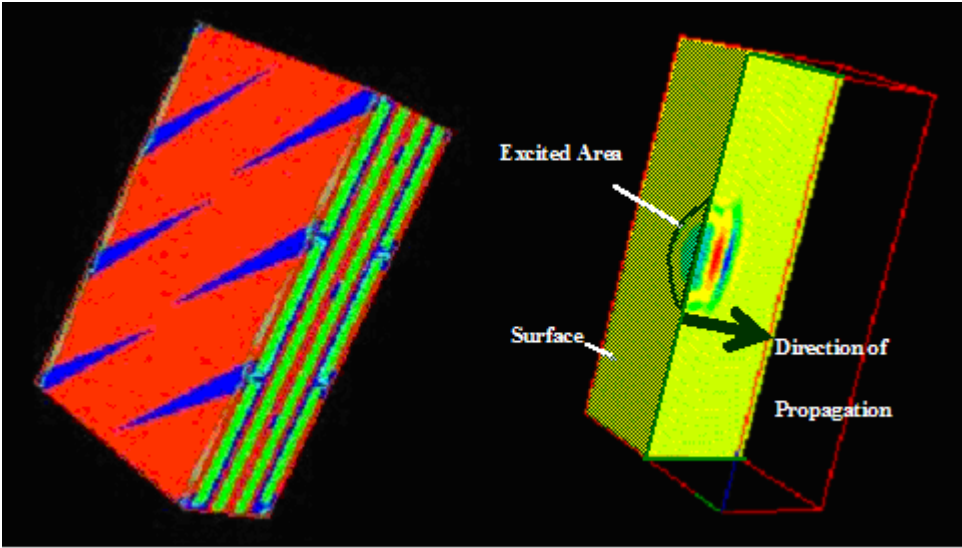


Figure 4: Density Model and Cut of a Snapshot through the Simulated Wave Propagation

In Figure 5 there are four consecutive cuts both through the density model and the snapshot of the simulated wave propagation. The cuts are made normal to the longitudinal direction of the wave propagation. In the fourth cut a channel filled with resin can be seen. But already in the first cut the effects caused by the channel are visible. In the orange circle there is a brighter square inside. The particle velocity is lower there caused by the lower density of the resin compared to the density of the carbon fibres. The wave is scattered at the contact surface. Inside the resin the wave is slowed down.

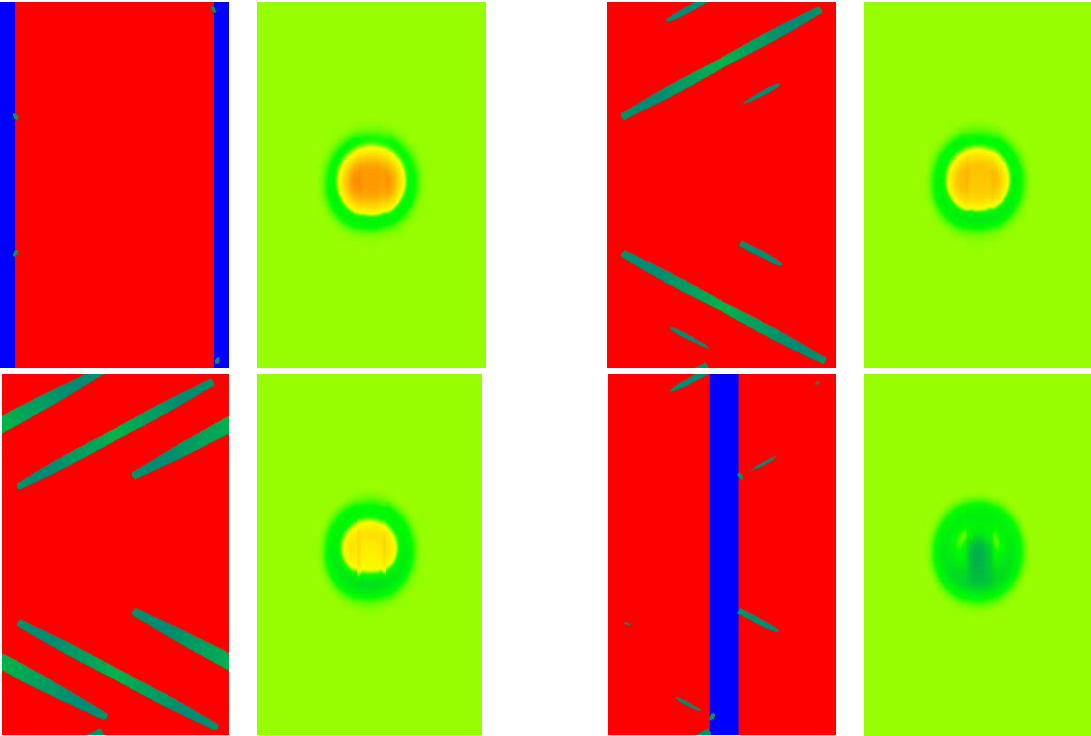


Figure 5: Cuts through the Density Model and the Snapshot of the Simulated Wave Propagation of the Quadriaxial Model

The second laminate consists of $108 \times 206 \times 143$ cubic cells in its discrete form. In Figure 6 an axial, a sagittal, and a frontal cut through the wave propagation snapshot in relation to the respective density cut are presented. It is visible that the wave propagation is not symmetrical in both transversal directions due to the fibre orientation in the layers. Some effects caused by resin accumulations and the stitching yarn are marked by circles and arrows. There the scattering and the dispersion can be connected directly to the (micro-) structure.

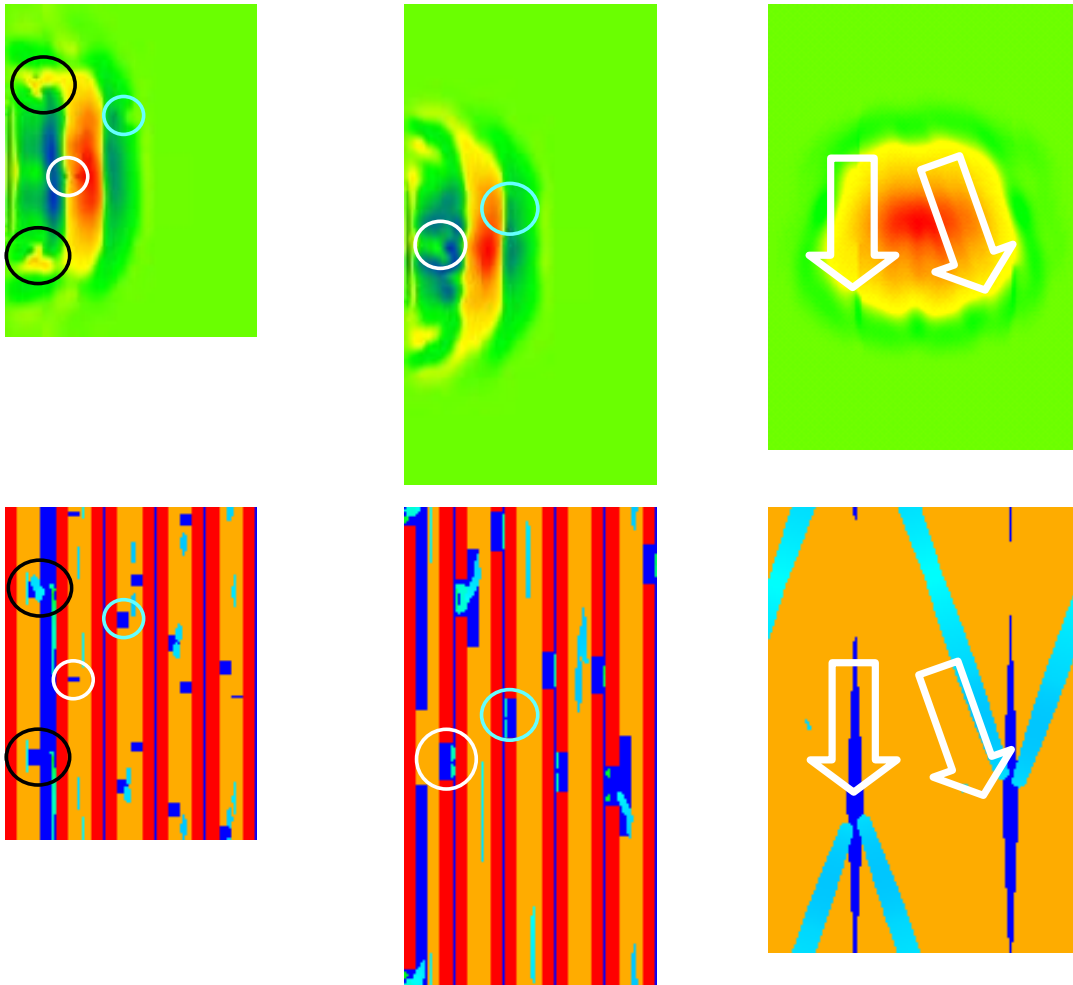


Figure 6: Cuts through the Density Model and the Snapshot of the Simulated Wave Propagation of the Biaxial Model

4. Conclusions

First results clearly demonstrate scattering, reflections, and other effects on the received modelled ultrasonic signals produced by interactions with the (micro-) structure.

Further simulations will analyse effects caused by porosity and undulation. It is also planned to parallelise the C++-code to perform the simulations on a cluster. This offers the possibility of simulating larger models. Moreover the excitation signals shall be optimised.

Acknowledgements

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