Simulation of Ultrasonic Testing of Composite Structures

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Abstract
Inspection of composite structures requires careful preparation of inspection procedures. To do this, the help of simulation is of great interest to understand ultrasonic wave behaviour, to evaluate influent factors and to optimize NDT configurations. In this paper we present simulation tools for ultrasonic testing of composite materials integrated in CIVA. The software module implements a hybridation of CIVA semi-analytical computation in the coupling medium with Finite-Difference in Time Domain computation in the composite material. This approach allows a fine description of the composite material meso-structure with associated complex ultrasonic phenomena due to heterogeneity and anisotropy, together with affordable calculation times. Typical composite flaws like delamination and ply waviness can be simulated in this software version. Validations against experimental data are presented and perspectives for future features are also presented.

Keywords: Ultrasonic Testing, Simulation, Composite, Aerospace

1. Introduction
Fiber reinforced composites are steadily gaining importance in aeronatic applications (20% mass of A380, 50% mass of A350 …), and NonDestructive Testing (NDT) of these structures is a major step in the manufacturing process. The complexity of composite geometries leads to an increasing need for adapted ultrasonic NDT methods. One way to address those problems is to use simulation tools to optimize procedures used for the inspection. According to the various problems (complex geometries, homogeneous or heterogeneous structures…) different modeling strategies can be used: semi-analytical, pure numerical or hybrid (mixing semi-analytical and numerical codes). Semi-analytical (mostly, integral techniques) methods offer high computation performances within their validity range but cannot offer the versatility of pure numerical techniques (FEM, FDTD…). The latest require more computational efforts, as well as expertise from users. In this paper we present a hybrid method that couple semi-analytical solutions and numerical computations to handle more complex cases with high computation performances.

2. A model for composite ultrasonic testing applications

2.1 Composite materials specificity regarding models
Composite materials have heterogenous and anisotropic properties that strongly influence the behaviour of ultrasonic waves used for NDT [1].

2.1.1 Heterogeneity
Ultrasonic testing of composite materials is strongly affected by the heterogeneous nature of the material. Signals from ultrasonic testing of composites are characterized by structural noises which depend on the type of composite. Figure 1 shows an example of experimental signal acquired on a pre-preg Carbon Fibre Composite Materials (CFRP).
The source of this ultrasonic noise is the inner structure of the material. Heterogeneity for ultrasound propagation has to be defined with respect to propagating ultrasonic wavelengths. Typical velocities for longitudinal waves in CFRP are about 3 mm/μs⁻¹. Considering an ultrasonic frequency range of 1 MHz to 15 MHz, corresponding wavelengths range from 0.2 mm to 3 mm. Carbon fibers have diameters of about 7 µm, which is very small compared to propagating wavelengths in the material (~λₘᵢₙ/30). Plies thickness are between 0.1 mm and 0.3 mm, which is very much in the range of the propagating ultrasonic waves. This prior analysis allows simplifying the description of the inner structure of the material and leads to consider the ply scale (meso-scale) as the relevant one for the material description. Micrographic analyses (Figure 2) of pre-preg materials show that plies are separated by thin resin layers which constitute an acoustical impedance mismatch and therefore a source of ultrasonic scattering.

Plies being relatively regular and spatially coherent (with respect to wavelengths) the scattering results in a structured noise whose main frequency corresponds to the back and forth propagation in a unitary ply ([2]).

2.1.2 Anisotropy
The second important feature of ultrasonic propagation in composite materials is the anisotropy, which comes from the fibrous nature of the material. Fibers are much stiffer than the resin, resulting in a strong anisotropy of the materials. An example of anisotropy is illustrated on Figure 3(a) for a unidirectional ply of CFRP through the slowness curves representation. Usually the strong anisotropy of the ply is smoothened by stacking of plies at different angles but speeds in the stacking plane always remain greater than in the orthogonal direction leading to an important effect of anisotropy on the ultrasonic behavior (Figure 3(b)).
In particular it results in deviation of energy speeds from the incident angle leading to deviation of ultrasonic beams during propagation. Following the QL surface, rays coming with a small angle from the normal incidence tend to be deviated in the ply direction ($x_1$) as they propagate. This phenomenon is responsible for complex angular filtering of composite materials. Angles for which energy is emerging from the other side of the material is then dependent on the thickness of the material while for isotropic materials the critical angle is easily found using Snell-Descartes law. This illustrates the importance of accounting for anisotropy when simulating ultrasonic testing of composite materials.

2.2 A model for propagation in composite materials

As described above, ultrasonic propagation in composites is characterized by anisotropy and heterogeneity. When the part is non flat, anisotropy becomes complex since it rotates continuously with the shape of the part. In addition, some typical composite defects such as ply waviness create locally very severe local anisotropy profiles. Recent works [3,4] propose semi-analytical approaches to deal with continuously varying anisotropy, but this so-called Dynamic Ray Tracing (DRT) method remains limited to smoothly varying anisotropy, which is often out of range for our composite configurations with waviness. Besides the DRT method is a homogenization approach which does not deal with heterogeneity of the material.

To deal with these complex and mixed phenomena Airbus Group Innovations has developed numerical codes with a Finite Difference in Time Domain (FDTD) scheme on staggered grids in space and leap-frog in time. The implemented model is a stress-velocity scheme proposed by Virieux [5], which is depicted below.

\[
\begin{align*}
\frac{\partial \sigma_{ij}}{\partial t} &= C_{ijkl} \frac{\partial v_k}{\partial x_l} \\
\frac{\partial v_i}{\partial t} &= \frac{1}{\rho} \text{div} \sigma (v) + F_i
\end{align*}
\]

Figure 4. Finite Difference in Time Domain scheme.
This model considers a propagation medium in which the local material properties are associated to the corresponding cells of the mesh. This allows description of strongly heterogeneous and anisotropic materials such as curved composites with waviness. A Perfectly Matched Layers (PML) model is implemented [6] for the boundary conditions to simulate non-reflective boundaries.

2.3 A model for NDT of composite materials

The numerical FDTD model described above allows computing wave propagation in complex materials. However it is very classical in NDT configurations to have water path of several tens of millimetres, allowing working in the far-field. Simulation of such configuration entirely with the FDTD code would require including the probe in the FDTD box and propagating across the water path, leading to very long computation time and numerical artefacts (dispersion) due to long distance propagation in the fluid. To get rid of these inconvenience, a hybrid model that couples the semi-analytical method described before to the FDTD model was developed and integrated in CIVA. This analytical/numerical approach allows combining the advantages of both methods while minimizing their drawbacks. The FDTD is used in a restricted area surrounding the component; the entrance surface is in the coupling medium as close to the surface as possible to minimize the FDTD calculation in the fluid. The semi-analytical code is used to predict the incident field at the entrance surface of this restricted area. Numerical calculation is performed inside the FDTD box for computation of the complex propagation phenomena. Using the reciprocity principle (considering independent forward and backward processes) the pressure received by the probe is calculated after propagation in the FDTD area.

Figure 5. Principle of the hybrid semi-analytical / FDTD model.

Up to now only the 2D version of the FDTD kernel is available in this CIVA module, allowing simulation of configurations for which the 2.5D approximation is valid.

2.4 Graphical User Interface

A major advantage of the hybrid model implemented in CIVA is also to benefit from the very complete GUI provided by CIVA for NDT applications. Dedicated pieces of interface have been developed in CIVA to define stratified composite structures and configure the hybrid code. Complex parts can be defined using a piecewise description; which defines the neutral axis of the component. After defining the thickness above and below the neutral axis, the number of plies, the presence of a resin layer between each ply the component is drawn as shown in Figure 6. Using the anisotropic properties of the material for a flat composite the code calculates and displays the local anisotropy at each node of the FDTD box. This local orientation of the anisotropy is communicated to the FDTD code for calculation of the strains.
and displacements at each time step. The user can modify the characteristics of each ply or epoxy layer (stiffness or thickness) independently and analyze for example the influence on the structural noise. Defects such as planar defects are introduced as nodes with the Neumann condition (zero stress). Defects such as play waviness are described as a local modification of the ply stackup; local anisotropy after deformation is calculated and communicated to the FDTD code. It is possible to combine several waviness to define complex wrinkle profiles.

Figure 6. Dedicated GUI for composite specimens description for the hybrid model.

3. Example of validation

A first validation of the hybrid model is to analyze the amplitude of the structural noise and backwall echo obtained on a flat composite sample with two transducers operating at different central frequencies. The sample is a Pre-preg stack composed of 28 CFRP plies. The thickness of each ply is assumed to be 0.259 mm including a 15 µm epoxy layer. The two transducers have a diameter of 6 mm and a nominal central frequency of 3.5 and 5 MHz, respectively. Since the most important parameters for the structural noise are the central frequency and the bandwidth of the transducer these two parameters in the model have been adjusted to fit the experimental frontwall echo. The model doesn’t take into account attenuation due to viscoelasticity. It is possible to simulate attenuation by post-processing by applying a sliding window over the signal. Although this is not fully satisfactory for highly damped material, the considered composite material displays a dispersion (velocity variation with frequency) low enough to be neglected. Full attenuation measurements were conducted on those samples by Airbus Group and used as input for the post-processing. The superimposition of the experimental and simulated signals is shown in Fig. 4.

Figure 7. Superimposition of experimental signals with simulated signals using the FDTD code. (Left) 3.5 MHz transducer, (right) 5 MHz transducer.
One can see that simulation shows a pretty good prediction of the amplitude and time of flight of the backwall. It is noticeable that the structure noise amplitudes obtained with these two sensors at different frequencies are significantly different. This is due to the frequency content of the probes as regards to the ply thickness. In this case the ply thickness is about 250 µm, leading to a resonance frequency of about 5.8 MHz, which is highly present in the spectrum of the 5 MHz transducer, but poorly present in the spectrum of the 3.5 MHz one. It is good to see that the model also predicts this important phenomenon on the structure noise. This property is of particular importance if one wants to calculate Signal-to-Noise ratios and the possibility of detecting small defects in the presence of structure noise.

4. Simulation of complex composite parts
4.1 Simulation of a phased array configuration on an Omega stringer

This newly developed CIVA module allows dealing with complex shapes of parts like the omega stringer depicted here under. Here we show some results of simulation on the radius area of the stringer, with a phased array configuration. The probe has 16 elements, a pitch of 1.0 mm, and is curved with a radius equal to the external radius to inspect plus the water path to match the radius shape.

Simulation results can be visualized under the form of probe response (Ascan, Bscan), as depicted in the figure above, but also under the form of field propagation inside the FDTD box. The field propagation includes interaction with defects in the area. Here under (Figure 9) a ply waviness was introduced inside the omega stringer. Simulation results show that the waviness distorts the beam and decreases the amplitude of the transmitted beam.
Figure 9. Field profile through an omega stringer radius. (Left) without waviness, (right) with waviness.

The wave propagation inside the part can be visualized to facilitate understanding of the propagation. The next figure shows snapshots of the propagation in the omega radius.

Figure 10. Snapshots of wave propagation through the omega stringer radius. (Left) without waviness, (right) with waviness.
Such simulation results may be very powerful when setting up NDT configurations for composite materials.

4.2 Simulation of an auto-adaptative technique for composites (SAUL)

SAUL (Surface Adaptive ULtrasound) [7] is an adaptive inspection technique that has been implemented in M2M acquisition system to inspect aeronautical composite structures with complex and variable geometries [10]. In an immersion testing configuration, the technique allows to transmit a wavefront parallel to any complex surface, in real time. This is achieved by means of an iterative algorithm that does not require prior knowledge of the geometrical and acoustical properties of the component. The iterative process begins with the transmission of a plane wave by simultaneously firing all the elements of the array. Time-of-flight for each individual ascan is measured to compute the delay law that is applied to the next shot.

The SAUL process has recently been implemented in a CIVA development version as an option in the delay law computation panel. The resulting delay laws can be loaded and used for a simulation with the hybrid semi-analytical/numerical code presented in this paper.

In what follows the 16 elements probe is flat and SAUL is used to adapt delays laws to the radius. The resulting channel Bscans are displayed below: without SAUL, with one SAUL iteration, and with SAUL after convergence of the adaptive process (4 iterations).

![Figure 11. Simulated Bscans obtained with no SAUL (left), one SAUL iteration (centre), and four SAUL iterations (right)](image)

One can see that the front-wall echoes in the Bscans are becoming flat when the iterative process has converged. Moreover this adaptation also results in an increase in the amplitude of the recorded signals (+3dB between no SAUL and iteration 1, +9dB between no SAUL and iteration 4).

Finally, the following figure shows the field profile in the FDTD box for the three shots (no SAUL, iteration 1, iteration 4). It shows that as the SAUL iteration increases the beam shape inside the part becomes more collimated, providing good conditions for defect detection in the covered area.

![Figure 12. Field profile through the omega stringer radius with no SAUL (left), one SAUL iteration (centre), and four SAUL iterations (right)](image)
This type of result also gives information of the zone coverage of the radius, therefore allowing for relevant NDT configuration set-up.

4.3 Computation times
The FDTD kernel has been parallelization using OpenMP, which allows efficient calculations on multi-core PC. The CIVA computation steps are generally negligible in the overall computation time.
As a matter of example, the calculations showed above on the omega stringer radius take about 6 minutes each to run.
The computation time for one configuration is directly proportional to the size of the FDTD box. From our experience of the tool, calculation times range from 2 minutes (thin parts, small probes) to 30 minutes (thick parts, large probes).
In case of a multi-shots configuration this time has to be multiplied by the number of shots.

5. Perspectives
The SIMPOSIUM project is also the support for developments that will increase the simulation capabilities of this new CIVA module for composites in the future:

- **3D composite parts**: Composite parts that are designed in CATIA with the Composite Design Tool shall be loadable in CIVA for a further NDT simulation using the 3D version of the hybrid semi-analytical / FDTD model. It shall in particular allow dealing with double curvature panels or with parts with shape varying in the two dimensions.

![Figure 13. CATIA view of an omega stringer with thickness changes.](image)

- **Textile composites**: the WiseTex software developed at the Katholic University of Leuven [8] provides a powerful tool for textile composite description as a pre-processor for an NDT simulation using NDT simulation using the 3D version of the hybrid semi-analytical / FDTD model.

![Figure 14. Description of a textile composite pattern in WiseTex.](image)
6. Conclusions
A hybrid “semi-analytical / FDTD” model integrated in CIVA for composite materials has been described, accounting for both anisotropy and heterogeneity. Examples of validation on a simple case and of simulation on complex geometry have been presented, highlighting the power and the potential of this new CIVA module for composites. Perspectives based on running developments made in the framework of the SIMPOSIUM project are also given, mainly about 3D configurations, with application to 3D composite structures and to textile composites.

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