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Modeling of ultrasonic wave propagation in composite laminates with realistic discontinuity representation

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ABSTRACT

This paper presents a method for embedding realistic defect geometries of a fiber reinforced material in a finite element modeling environment in order to simulate active ultrasonic inspection. When ultrasonic inspection is used experimentally to investigate the presence of defects in composite materials, the microscopic defect geometry may cause signal characteristics that are difficult to interpret. Hence, modeling of this interaction is key to improve our understanding and way of interpreting the acquired ultrasonic signals. To model the true interaction of the ultrasonic wave field with such defect structures as pores, cracks or delamination, a realistic three dimensional geometry reconstruction is required. We present a 3D-image based reconstruction process which converts computed tomography data in adequate surface representations ready to be embedded for processing with finite element methods. Subsequent modeling using these geometries uses a multi-scale and multi-physics simulation approach which results in quantitative A-Scan ultrasonic signals which can be directly compared with experimental signals. Therefore, besides the properties of the composite material, a full transducer implementation, piezoelectric conversion and simultaneous modeling of the attached circuit is applied. Comparison between simulated and experimental signals provides very good agreement in electrical voltage amplitude and the signal arrival time and thus validates the proposed modeling approach. Simulating ultrasound wave propagation in a medium with a realistic shape of the geometry clearly shows a difference in how the disturbance of the waves takes place and finally allows more realistic modeling of A-scans.

1. Introduction

New designs of aircrafts, cars or wind turbines are making increased use of composite materials instead of metals [1]. In the metallic parts the occurrence of crack growth within its lifecycle is typically allowed and can be predicted in its consequence using fracture mechanics principles. Composite materials have been investigated for many decades, but because their structure combines the properties of more than one constituent material, the damage evolution and their failure mode is not as well understood as it is in the case of metallic structures [2,3]. Due to these difficulties, in fiber reinforced composites the occurrence of inter-ply delamination is only tolerated up to a certain geometrical dimension [2]. Modern fiber reinforced composite materials can have different textile architectures, including stacking of unidirectional fiber plies at different angles, woven fabrics or 3D-textiles such as stitching, crocheting and many more. Furthermore, each ply can be made from different fibers and may contain additional impurities such as fabrication residues or binder materials. In addition, the final composite structure may also include different types of defects like pores, inter-fiber cracks, inter-ply or intra-ply delamination, fiber breakage, ondulations and many more [3]. Delamination can occur due to multiple reasons, ranging from malfunctions in the production process to in-service damage such as impact. As it is compromising the local structural integrity of the composite laminate and may grow substantially at low level fatigue load [4,5], the detection of delamination is one of the most relevant tasks to non-destructive testing (NDT) approaches.

The most commonly used NDT techniques for the defect detection in composite materials are: active ultrasonics, lock-in thermography, shearography, guided wave testing and radiography [6–11]. Active ultrasonic testing (UT) is a well-known and established technique but the detection sensitivity relative to the delamination shape, orientation, general material microstructure is still under investigation [12]. Probability of detection (PoD) is

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usually used as a metric to quantify the reliability of the UT method [13–17]. Estimation studies for PoD curves rely mostly on many experimental trials of the UT procedure using reference specimens with artificial defects. Given the statistical approach used this can be fairly time consuming and, including the costs for the specimen fabrication, also quite expensive. More recently it was proposed to perform such estimations of PoD curves using modeling assistance, hence called MaPoD [18–23]. In order to optimize the UT equipment parameters and to decrease the costs for experimental work much recent research is focused on developing predictive and quantitative numerical models for UT [24–36].

Usually when numerical models are implemented to simulate ultrasonic wave propagation in a composite material, the material microstructure and defect representation suffers a lot from geometric simplifications. This is due to the complexity of the topology, which is fairly inconvenient to reproduce by using only Computer Aided Design (CAD) tools. The topology of internal defects is simplified in most modeling approaches as being round, elliptical, or perfectly flat [37–39]. In experimental UT signals multiple echoes are present due to the complex topology of the defects, such as reflections given by the corners or by two contiguous faces [40]. This kind of detail can easily be present when testing delamination and may have an impact upon the interpretation of the inspection result.

Internal geometry reconstruction of defects from magnetic resonance imaging (MRI) or from computed tomography (CT) can be done using various commercial software packages such as "Simpleware Ltd." or "Materialise Mimics". This results in sophisticated discretized approximations of the volumetric topology of the scanned defect. Surface or volume meshes can be generated from such three-dimensional imaging and can then be used as geometry in numerical modeling tools [41,42].

The present investigation aims to solve the question, whether the particular topology of inter-ply type delamination needs to be accounted for in quantitative numerical modeling of UT. Therefore, a validation scheme to properly implement the UT method in numerical methods is briefly described. Subsequently, an example is presented to perform a geometry reconstruction for a delamination type defect. This makes use of the "Volume Graphics (VG studio Max)" software for visualization and extraction of the computed tomography data. The obtained surface mesh is then post-processed using "MeshLab". Finally, the geometry is implemented in a validated finite element method (FEM) approach using the "Comsol Multiphysics" platform. This approach is meant to demonstrate how the real geometry of an embedded defect interacts with the numerical simulated ultrasonic field. Experiments are then used to validate the accuracy of the numerical model by direct comparison of the modeled and the experimental A-scan signals.

2. Experimental

The plate specimen is fabricated as unidirectional prepreg laminate with a layup configuration of eight plies $[0]_{4sym}$ using the carbon/epoxy system Sigrafil CE1250-230-39. Multiple artificial delamination areas are created by including bags made from 25 μm thick Ethylene tetrafluoroethylene (ETFE) foil at different locations. These are embedded in the laminate prior to curing at the designated locations. X-ray computed tomography and ultrasonic testing is carried out to validate the positions of the artificial delamination. The CT scans were performed using a CT scanner (Nanotom 180, GE systems) with a tube voltage of 80 kV and a tube current of 160 μA. The data was reconstructed using the "Phoenix datos|x2" software. An exemplary CT scan of the probe is shown in Fig. 1 where the delamination can be seen being present at 0.56 mm in the laminate sample between ply No. 3 and 4 from the top surface.

The UT inspection measurements were conducted using an ultrasonic system (USM go+, GE systems) and the single element transducer (V 201-RM, Olympus) operating in pulse-echo mode. For the inspection of the 1.87 mm thick laminate, a delay line made of polystyrene (DLH-1, Olympus) was used to allow far-field inspection conditions. A viscous couplant (Couplant B-Glycerin, Olympus) was used between the delay line and the transducer as well as in contact to the composite specimen to increase the transmission of the ultrasonic waves. A square-wave pulse with 100 ns width was used to generate the ultrasonic waves at a center frequency of 5 MHz. The initial pulse was triggered with 500 Hz repetition frequency. All signals were received with a gain of 34.2 dB. The calibration of the experimental setup was done using a steel step wedge according to ASTM E797.

The experimentally investigated areas are those in the area of the artificial delamination, but also reference areas, where no artificial defects were present. The latter is used for validation of the composite material model. Measurements were carried out at different locations in the region of the artificial delamination (cf. Fig. 2a), as additional challenges of the ultrasonic measurements arise due to edge effects [43]. For each location a total number of five A-Scan signals were recorded.

Examples of the A-scans are shown in Fig. 3. In Fig. 3a the reference signal in a region without artificial delamination is plotted. Besides the surface echo (SE) the signal predominantlly yields the 1st and 2nd backwall echo (BWE) given by the first and second reflection at the specimen bottom. In Fig. 3b the A-scan is taken at the location when the transducers is at position offset to the right of the delamination area (III). The signal shows the presence of the SE, BWE but also an echo given by the presence of the delamination (DE), which is located between SE and BWE in the immediate vicinity of the SE. Based on the longitudinal sound velocity of 3133 m/s in the out-of-plane direction of the composite this yields a depth location of 0.64 mm, which is in good agreement with actual position of 0.59 mm as obtained from the CT measurements.

3. Numerical modeling of ultrasonic testing

Modeling ultrasonic testing of a composite material sample includes three important steps: transducer modeling, wave propagation modeling and realistic description of the internal discontinuities. All steps need to be validated through experimental results. The entire modeling concept followed herein is summarized in the scheme presented in Fig. 4.

Because of the electromechanical coupling between ultrasonic waves in solids and fluids and the piezoelectric effect for converting the detected wave into an electrical signal, multiphysics approaches are needed to perform quantitative modeling of ultrasonic testing. Commercial multiphysics FEM platforms are already being used with great success to model ultrasonic wave propagation and its interaction with the complex material structure [44–49].

3.1. Transducer implementation

3.1.1. Geometry implementation

In order to obtain realistic results from the FEM approach, the model setup should reflect as much as possible the experimental conditions. For this reason, a realistic transducer model is introduced in the FEM environment. In accordance with our experimental setup, a V201 RM type transducer from Olympus was modeled. It represents a typical single element contact transducer with an attached delay line. The level of detail to reconstruct the trans-