Analysis Methods of Lamb Wave Propagation in Complex Composites

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ABSTRACT

Structural Health Monitoring with Lamb Waves in principle allows a detection of defects in complex composite components by mounted PZT sensors. However, the wave behavior is very complex due to dispersive and anisotropic propagation respectively reflections, refractions and mode conversions on local discontinuities like defects. A clear evaluation of received signals poses a hard challenge.

FEM simulations and the visualization of wave propagation under real conditions enable a better understanding of wave behavior. Therefore an ultrasonic scanning technique was adapted for Lamb Wave analysis and visualization. The combination of ultrasonic NDT and Guided Waves testing is carried out by Lamb Wave excitation with a glued PZT transducer and automated air-coupled ultrasonic scanning of the component surface. The technique delivers A-scans of each scanning point which are stored in a special 3D data file.

Such a 3D file of a 1x1 m large laminate with a scanning grid of 1x1 mm includes A-scans of 10e6 measuring points with a dynamic range up to 80 dB (file size up to 50 GB). “Classic” images like B-, C-, and D-scans as well as video animations of the wave propagation can be calculated. Additional algorithms allow different methods of wave analysis, like automatic mode identification and separation, analysis of velocity and attenuation in anisotropic components or referencing of interactions with different kinds of defects. A consideration of mechanical properties of the component allows the calculation of all displacement components of the specimen surface. This enables the application of virtual sensors. Their layout and characteristics can be specified by the analysis software and set on a position within a loaded 3D data file. Special algorithm calculates the expected sensor signal as if an equivalent sensor would be mounted on the specimen surface. The method allows the construction and optimization of entire SHM networks without time consuming and cost intensive series of experiments.

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INTRODUCTION

Classic ultrasonic Non Destructive Testing (NDT) methods use water or air coupled sensors for excitation and receiving of compression waves. The transducer can be moved over a specimen surface and allow the visualization of C-scans and D-scans of the scanning area. This ultrasonic testing technique was adapted for Lamb wave [1,2] analysis based on water coupling [3] and was enhanced for air coupled scanning [4]. A fixed PZT sensor is used for Lamb wave excitation in a test specimen. A broadband air coupled sensor is used for receiving and enables investigations in a large frequency range. The sensor is moved over the specimen surface with a constant air gap of ca. 5 mm. For each scanning point a full-wave A-scan is acquired. The data is stored in a special 3D data file. This allows an offline calculation von B-scans, C-scans and D-scans as well as video animations of the Lamb wave propagation. Figure 1 illustrates the scanning technique and the data file consisting of B-scans. Applying different methods of signal processing the 3D data files enables new methods of analysis and visualization and allows better understanding of wave behavior in complex composite structures [5].

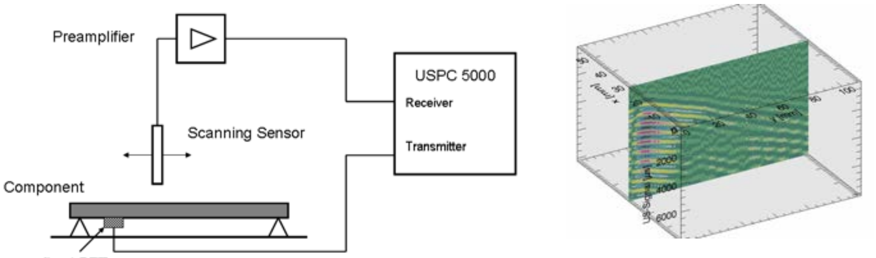


Figure 1. Scanning technique and data file build-up.

In opposite to longitudinal waves, Lamb wave fields are very complex due to anisotropic propagation, dispersion, reflections and refractions. Mode conversions occur on specimen discontinuities like impacts or specific geometry conditions. Under special circumstances which still have to be investigated, even bonded PZT sensors may have an influence. A clear evaluation of Lamb wave propagation in complex structures is necessary for the challenging design of SHM networks.

This paper presents methods of Lamb wave analysis using some examples of mode conversions in different situations. Their influence on impact detection and system development is depicted.

FEM SIMULATIONS

In addition to the experimental analysis of Lamb wave propagation a simulation approach has been chosen to ease the understanding of wave interaction. The commercial FEM-Software ANSYS is used to model a cross-section of a CFRP plate. The obtained results can be converted into the file format used by common ultrasonic hardware. Thus, the same tools can be utilized to analyze experimental and numerical obtained data. For better accuracy, each ply is modeled separately with its associated material properties. Although not the fastest method, the implicit dynamic analysis allows the easy inclusion of piezoelectric elements and unconditional stability is achieved with the correct choice of parameters [6]. This model will be used to gather information about interaction of Lamb waves with defects or structural elements like stiffeners and rivets. For these structural parts different effects have to be quantified over a range of frequencies. Later on, other dependencies such as temperature or mechanical stress can be investigated, too. Wave interaction includes at least transmission, reflection and mode conversion. The influence of attenuation has also to be examined. Additionally a wave package can get divided at a stiffener. First observations show that the wave energy transmitted into such a structural element is effectively lost in the case of lower group velocity inside a larger stringer. It is planned to use the data obtained in this 2D model for a simplified model of a complex structure which will allow the prediction of sensor signals in real aircraft structures. Results close to FEM simulations are expected while remaining moderate computation times. At first, the 2D simulations are used for a better understanding of wave propagation and interaction in different situations. For example, obstacles symmetric to the center plane of the plate do not produce mode conversion. Aside from plate edges and holes, it is hard to find perfect symmetric elements, however small asymmetric characteristics of an otherwise huge obstacle will lead only to minor mode conversion compared to the amount of reflection.

An effective way to visualize wave propagation is a B-scan, especially when simulating a cross section of a plate. In Figure 2 and Figure 3 wave propagation in a quasi-isotropic CFRP plate is presented. The inclusion of a single defect results in a considerably more complex wave field. At the damage location the top ply is missing on 10 mm length.

The actuator on the left emits the symmetric S_0-mode and the asymmetric A_0-mode with similar amplitudes. The faster S_0-mode reaches the damage approximately 60 µs after excitation and transmission, reflection and mode conversion can be observed. At about 200 µs the slower A_0-mode interacts similar with the damage, but mode conversion to the S_0-Mode is only barely visible. This is due to the displayed out-of-plane displacement, since the S_0-modes primary amplitude is in-plane. At the right border the plate edge only leads to reflection as a result of its symmetric nature, while the left border generates additional mode conversion, because the actuator on top of the plate induces asymmetry.

The A-scans shown in Figures 2 and 3 are taken at the dashed lines in the B-scans and contains all information to identify the nearby damage. However, due to the reflection and mode conversion the different wave packages produce a complex signal which can hardly be correlated to a source or wave mode without the knowledge out of the B-scan. Even a simple baseline signal of the undamaged structure will not necessarily hold the key to locate the defect, since these signals are dependent on environmental conditions like temperature or humidity [7].

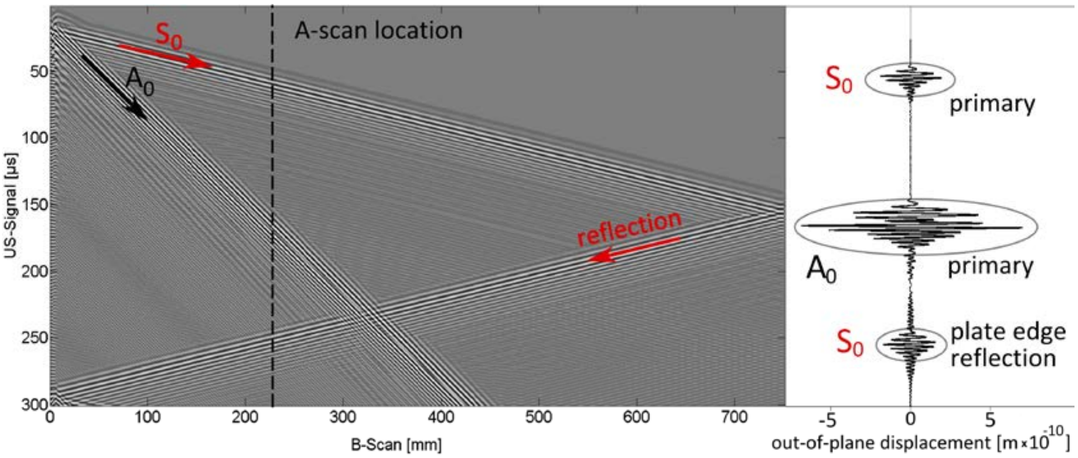


Figure 2. B-scan and A-scan at 300 kHz excitation frequency; out-of-plane displacement; signal filtered in the time domain; undamaged plate.

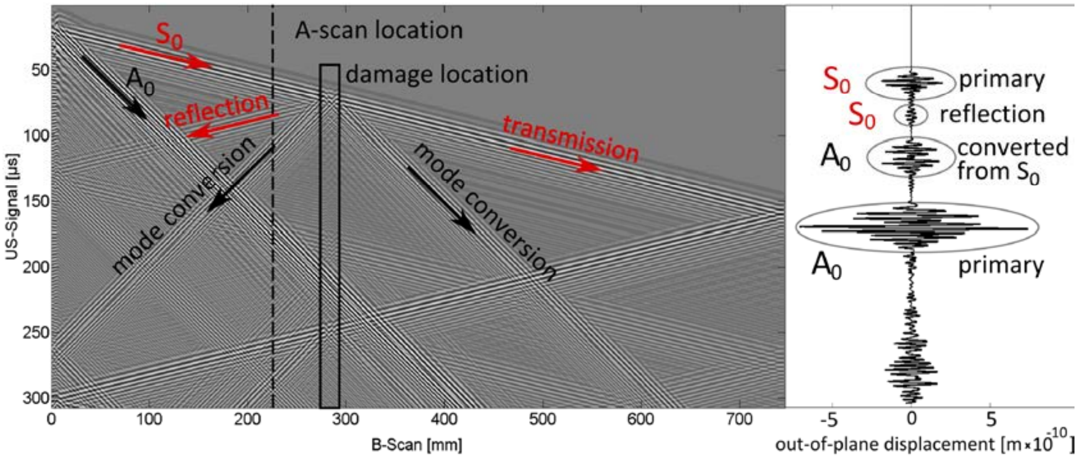


Figure 3. B-scan and A-scan at 300 kHz excitation frequency; out-of-plane displacement; signal filtered in the time domain; plate with defect.

EXPERIMENTAL RESULTS

Quasi-isotropic CFRP laminates with dimensions of 1x1m and a thickness of 2 mm were used for experimental investigations. Figures 4 and 5 show a cut out of a snapshot and a B-scan of wave propagation in such a CFRP panel with an quasi-elliptic notch in y-direction. The notch depth is 1 mm. The center signal frequency is 40 kHz. An A_0 and a S_0 mode with wavelengths of 21 mm and 123 mm propagate in the panel. The S_0 mode with low out-of-plane amplitude is marked in red. A mode conversion occurs at the notch in a distance of 250 mm from the actuator. The black denoted wave front of the converted A_0 mode is equal to the geometry of the artificial defect.

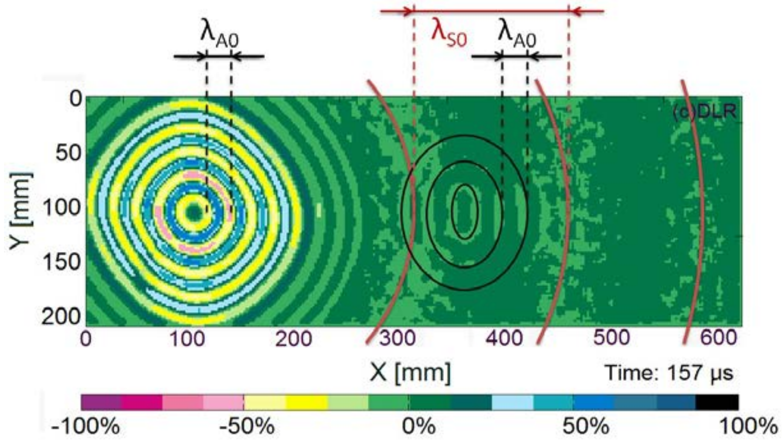


Figure 4. Wave propagation snapshot in a CFRP panel with a notch at x = 360mm.

In Figure 5 a B-Scan of the wave propagation between the actuator center and the right border of the snapshot is shown. Phase velocities of A_0 and S_0 are indicated. Because of its low out-of-plane amplitude, the S_0 wave front is hard to evaluate. However, the mode conversion is easy identifiable. The S_0 mode reaches the position of the notch 100 µs after excitation. The A_0 mode excited by the actuator arrives 120 µs later. Between these two time points a converted A_0 mode is excited from the notch.

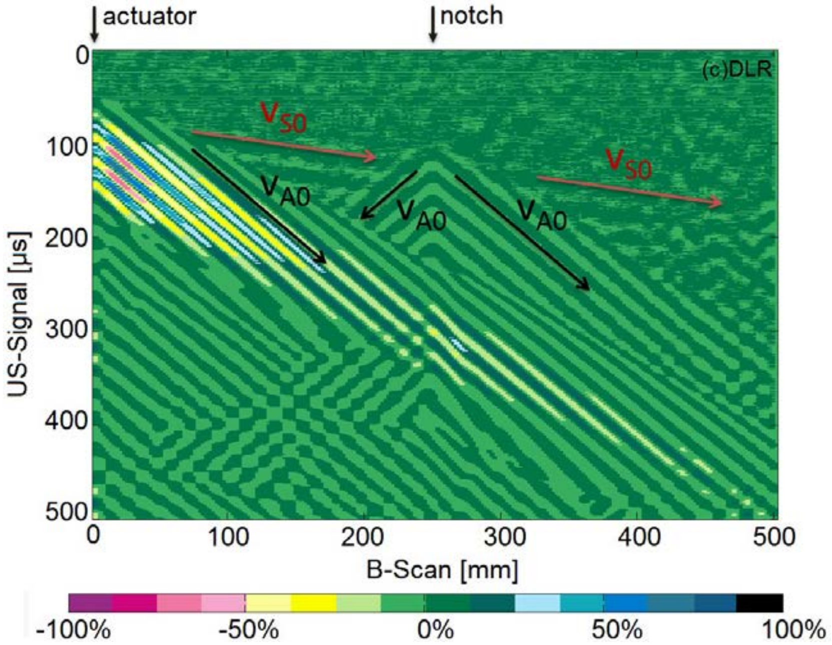
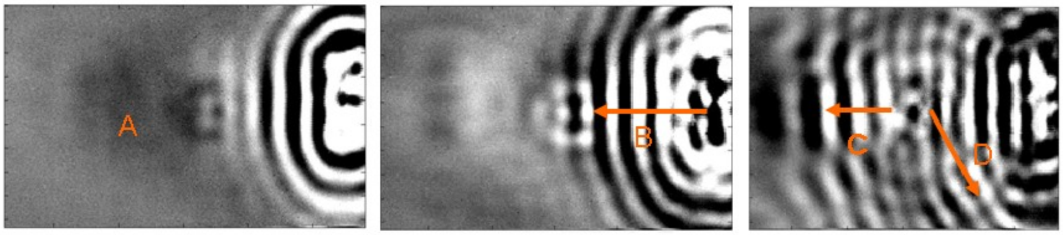


Figure 5. Wave propagation B-Scan of wave field shown in Fig. 1.

Not only monolithic components show mode conversions. Even on complex sandwich structures this behavior can be verified on positions with stiffness discontinuities.

Figure 6 shows the wave propagation in a section of an EC135 Tailboom. Its structure consists out of a honeycomb core, skins out of CFRP and GFRP with a different thickness and additional copper mesh for lightning protection. In the center of the snapshots two 10J impacts on same position were inserted. The excitation signal frequency is 18 kHz. Both basic modes S_0 and A_0 propagate from the actuator on the right. The faster S_0 mode with small out-of-plane amplitude reaches the impacted area (A) in the picture on the left side. The center image shows the mode conversion to the A_0 mode. This one interferes (C and D) with the origin A_0 mode (B) excited from the actuator in the picture on the right side.



166 µs **226 µs** **394 µs**

Figure 6. S-mode at position A *Mode conversion* *Interference of A-modes*

Beyond mode conversions on impacts a high degree of influence of glued PZT sensors was demonstrated in the EC135 Tailboom structure in [8]. Figure 7 shows a 1000mm B-scan along the Tailboom roll axis. At 22 kHz two wave modes propagate. An A_0 mode with a phase velocity of 550 m/s and a wavelength of 25 mm and a S_0 mode with a phase velocity of 4000 m/s and a wavelength of 185 mm.

The actuator is situated at position (I). An artificial defect was positioned 500mm from the actuator (III). Glued PZT sensors with a diameter of 10mm were set on positions (II) and (IV). The picture shows that not only the artificial defect causes a mode conversion. Bonded PZT sensors as well as an internal bonding of two honeycomb core sections on position (V) produce conversions, too.

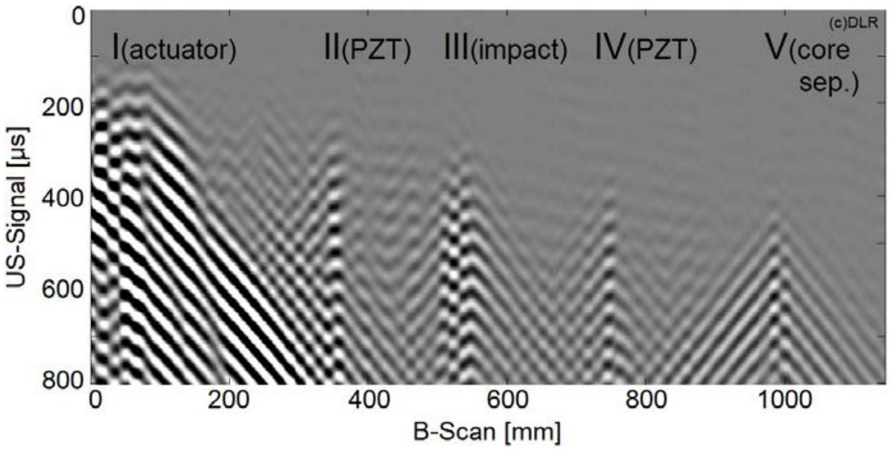


Figure 7. B-Scan of LW propagation in an EC135 Tailboom.

Although mode conversions have a high influence on the received signals, the investigations on the Tailboom show, they seem to be the only suitable principle for impact detection in this structure. Therefore a SHM sensor network based on air-coupled sensors was used in [8]. The air coupled sensors are able to detect mode conversions caused by structure defects after filtering accepted A_0 signal components.

MODE SELECTION

An applicable method for mode selection under utilization of different wavelengths can be realized with PZT electrodes with an interdigital layout [9]. The sensor electrodes are positioned in a distance of a half wavelength of the preferred mode. This kind of PZTs can be used for receiving as well as for excitation. However, in the SHM system for the Tailboom their dimensions are too large. A more indirect way for selective receiving is the usage of air coupled sensors [8]. In this case the large difference between A_0 and S_0 amplitude enables a kind of mode separation.

On the basis of 3D data files different mode selective analysis methods can be applied. B-scans in any propagation direction allow the direct detection and separation of modes with different phase velocity. An applicable method was shown by the authors in [5].

A further tool is the application of virtual sensors. A sensor designed by software can be positioned within the scanning area of a 3D data file. A special algorithm calculates the signal of a congruent PZT sensor under consideration of material parameters and measurement data. Any layout of the virtual sensor is possible which allows mode selective designs with or without directionality [5].

CONCLUSIONS

It was shown that Lamb wave B-scans based on FEM simulations or on real 3D data files enable excellent information of the propagation of basic modes and their interaction with defects and structure elements. The calculated A-scans near a defect indicate relative complex signals with different wave packages.

SHM systems with sensor arrays have to evaluate the complex information of single A-scans. The analysis of entire wave fields would help to select applicable time ranges for their evaluation and affords calculations of optimal sensor positions.

Mode conversions have an essential influence on Lamb wave propagation and the detectability of defects. A detailed study of occurrence conditions in complex structures is necessary for the required understanding of wave behavior and may be decisive for SHM system development.

ACKNOWLEDGMENTS

The DLR Institute of Composite Structures and Adaptive Systems performs research on Structural Health Monitoring within projects of the European Commission and the German Research Foundation (DFG) in cooperation with several partners. The authors would like to thank all involved institutes for their support.

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