Laser-Vibrometric Measurement and Numerical Modeling of Local and Continuous Mode Conversion of Lamb Waves in CFRP Plates

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ABSTRACT

Lamb waves based methods of structural health monitoring (SHM) of CFRP structures take advantage of mode conversions and wave reflections at distinguished discontinuities, which simply can be measured with piezoelectric sensors. This well known behaviour can be used to identify structural failures, such as cracks, delaminations and other structural discontinuities. In addition to this source of mode conversion, recently we have found another type of mode conversion from S_0 to A_0 occurring continuously in certain CFRP laminates including twill fabric layers. This phenomenon was visualized by scanning laser vibrometry and partially clarified with help of finite element analysis.

The paper describes the experimental setup and the wave mode interpretation using mode selection methods. B- and C-scans of the propagating waves clearly show the continuous conversion from the S_0 to the A_0 mode. This unexpected behaviour has also been found in finite element simulations taking into account the micro-structure of the composite.

INTRODUCTION

Lamb wave based structural health monitoring systems are a promising approach to monitor thin walled structures [1; 2]. As bulk ultrasonic waves used for non-destructive testing [3], Lamb waves also interact with damages and therefore are of interest for monitoring large areas of lightweight CFRP (composite fibres reinforced plastics) structures, e.g. wings of airplanes. It is possible to bridge great distances or surfaces with a relatively small number of sensors and actuators. Lamb waves have complex properties, particularly in CFRP materials. They are dispersive and exist in at least two basic modes, a symmetric S_0 and an anti-symmetric A_0 mode. At higher frequencies, higher order modes can occur, which are denoted as A_1, S_1, A_2, S_2, etc. modes [4; 5]. Under certain conditions these modes can convert into each other. However, modes can only convert into other modes viable at the same frequency [6].

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The mode conversion can be used for damage detection. The A_0 mode is significantly slower than the S_0 mode. If a pure A_0 mode is excited all signals arriving before this mode must have been caused by a mode conversion to the S_0 mode. This may happen, for instance, at a local discontinuity, e.g. delaminations, cracks etc. [2]. To make mode conversion usable for damage detection, the wave behavior at different types of discontinuities has to be well understood. The first part of this paper is dedicated to this kind of mode conversion.

During laser scanning measurements of propagating waves in composite structures, a continuous mode conversion has been observed, which was definitely not caused by significant structural discontinuities. This effect was observed at CFRP plates that are partially manufactured from fabric layers. In CFRP materials containing fabric layers a continuous conversion from the S_0 to the A_0 mode was found. In the second part of this paper this phenomenon of continuous mode conversion (CMC) is verified using experimental and numerical considerations. Even in a still oversimplified finite element model this mode conversions takes place at composites including fabric layers.

EXPERIMENTAL SETUP

The experimental investigations are performed with 1D and 3D scanning laser vibrometers from Polytec (PSV 300, PSV 400 3D). Laser scanning vibrometry is widely used for the experimental investigation of Lamb waves [7; 8; 9]. The vibrometer measures the velocity of a surface point in the direction of the laser beam using the Doppler shift. The laser vibrometer has a good spatial resolution and does not need any couplant. With the three lasers of the PSV 400 3D device all space components of the point's velocity v_1, v_2 and v_3 can be estimated visualizing the three-dimensional wave field.

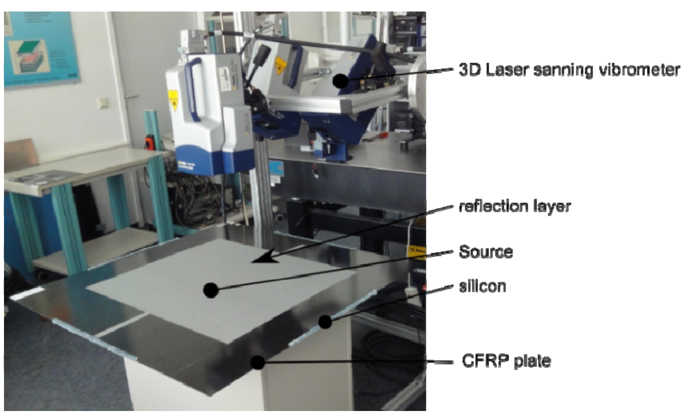


Figure 1: Experimental setup.

The experimental setup is shown in Fig. 1. The three laser scanning vibrometers scan the top surface of a CFRP plate (1 m×1 m×2.02 mm) fixed on foam to minimize the interaction of the wave field by the supports. The stacking sequence of the investigated CFRP plate is given in Tab. 1. The center layer is made of plain fabric and the top and bottom surfaces are made of twill fabric. The average distances between the lasers and the plate are within 0.62 m and 0.94 m.

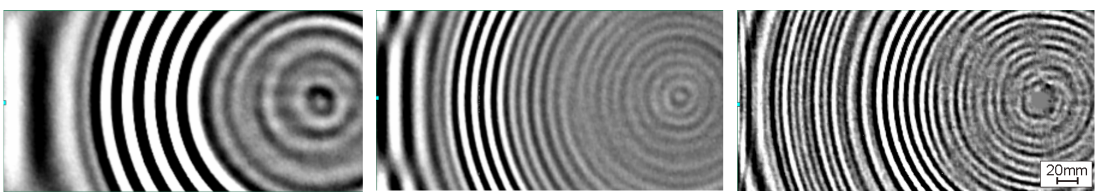
The Lamb waves are excited by a piezo-ceramic actuator of 20 mm diameter and a 1 mm thickness made from Marco FPM2024 material. For a stiff but also reversible coupling the actuator is attached with paraffin at the center of bottom surface. The edges of the plate are silicon damped to reduce the wave reflections. The top surface is coated by a retro-reflective layer to enhance the signal-to-noise-ratio of the measurement signals. For excitation, a 5-cycle sine burst amplified by a NF-HSA-4011-amplifier is fed to the actuator. During the measurement the sine burst is repeated for each measurement point thus creating a C-scan.

Table 1. Stacking sequence of the CFRP plate (1 m x 1 m x 2.02 mm).

Layer	Orientation [°]	Type	Layer thickness [mm]
1	0/90	Twill fabric	0.4
2	+45	UD layer	0.25
3	-45	UD layer	0.25
4	0/90	Plain fabric	0.22
5	-45	UD layer	0.25
6	+45	UD layer	0.25
7	0/90	Twill fabric	0.4

MODECONVERSION AT DEFECTS

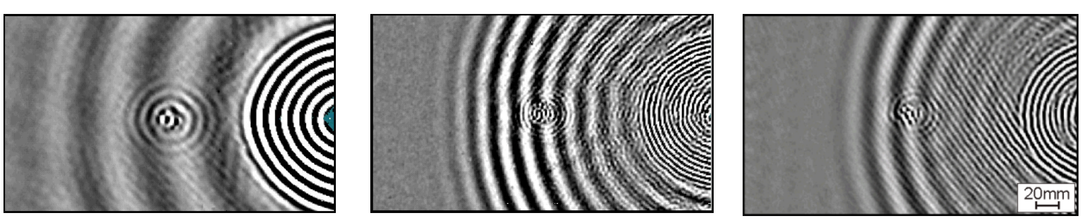
Fig. 2 and Fig. 3 illustrate the Lamb wave behaviour at two different kinds of discontinuities. The first discontinuity is the edge of an isotropic plate made of PMMA. The reflection of the symmetric as well as the anti-symmetric mode can be seen. No mode conversion occurs.



a) 50 kHz **b) 100 kHz** **c) 168 kHz**

Figure 2. S_0 edge reflection in a PMMA plate without mode conversion.

In Fig. 3 the Lamb wave travels through a flat bottom hole in a CFRP plate (Tab. 1). The conversion from the S_0 to the A_0 mode at the flat bottom hole clearly can be observed. Fig. 3 presents the results at three different frequencies. A part of the energy of the S_0 mode is transferred into the A_0 mode. This effect can be used for damage detection.



a) 100 kHz **b) 200 kHz** **c) 300 kHz**

Figure 3. Reflection and mode conversion from S_0 at a 50% flat bottom hole of 20 mm diameter in a CFRP plate according to Tab. 1.

With help of analytical and numerical analysis it has been found that only non-symmetric damages with respect to the center plane of a plate cause mode conversions. Fig. 4 shows some results of a numerical study made with the semi-analytical finite element method (SAFE) [10]. The SAFE describes the Lamb wave propagation in an infinite plate combining an analytical ansatz in plate direction with a finite element ansatz normal to the plate mid-plane. At damages or at boundaries of a finite region the SAFE is combined with dimensional finite elements (see Fig 4). The right handed curves of Fig. 4 illustrate the amplitudes for the A_0 mode (ii) and for the S_0 mode (iii), respectively. A pure Lamb mode is sent through the boundary. If only reflection takes place one curve equals zero (S_0 if the anti-symmetric mode is excited and vice versa). In Fig. 4 c) the right curves change in both diagrams because of mode conversion at non-symmetric boundaries. The sum of the amplitudes of all modes of a specific frequency has to be one. Several other types of boundaries are tested and all of them show the same results.

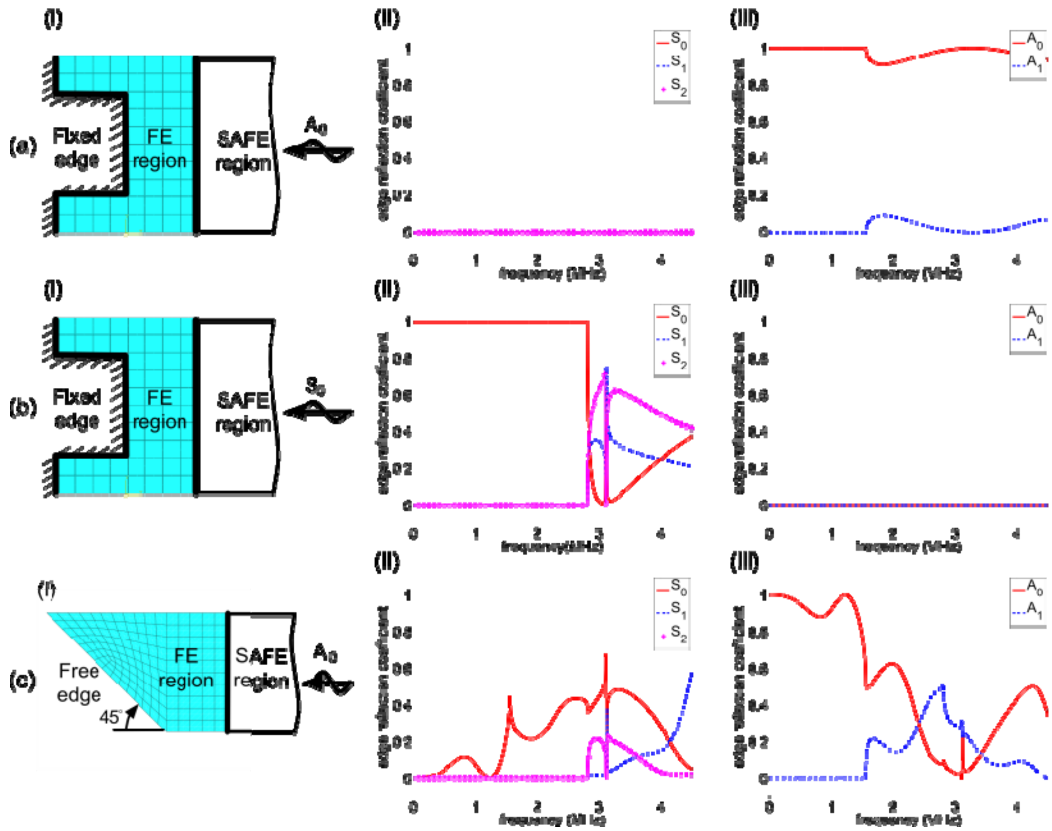


Figure 4. (a) A_0 mode reflection by a fixed symmetric end plate: i) SAFE-FE model, ii) symmetric mode reflection, and iii) anti-symmetric mode reflection; (b) S_0 mode reflection by a fixed symmetric end plate: i) SAFE-FE model, ii) symmetric mode reflection, and iii) anti-symmetric mode reflection; (c) A0 mode reflection by an inclined free edge (45°): i) SAFE-FE model, ii) symmetric mode reflection, and iii) anti-symmetric mode reflection.

In summary, for a mode conversion the Lamb wave has to travel through a non-symmetric discontinuity with respect to the center plane of the plate and vice versa [10; 11]. These findings agree with the experimental results. The C-scan of Fig. 2 correlates to a symmetric discontinuity and Fig. 3 to a non-symmetric one. Typically, damages are non-symmetric and the edges are symmetric. Therefore, the use of the mode conversion is a helpful tool to determine damages.

DESCRIPTION AND IDENTIFICATION OF CONTINUOUS MODE CONVERSION

The phenomenon of continuous mode conversion is first time mentioned in Willberg et al. [12]. It influences not only the received signal, but, it reduces the amplitudes of the energy losing mode and amplifies the amplitudes of another one. Fig. 5 shows the C-scan of an undamaged CFRP plate excited at a frequency of 200 kHz.

As illustrated in Fig. 1, a circular piezo-electric actuator excites the wave at the center of the bottom surface of the plate. The x_1-axis corresponds to the zero degree orientation of the CFRP plate. It can be seen that two primary modes occur, a fast S_0 mode (long circular wavelength) and a slower A_0 mode (short circular wavelength). Due to their different velocities the modes shown in Fig. 5 are already separated each from other. The term primary means that both modes are excited immediately by the piezo-electric actuator in the center of the plate. For all presented scans only the out-of-pane displacements are shown.

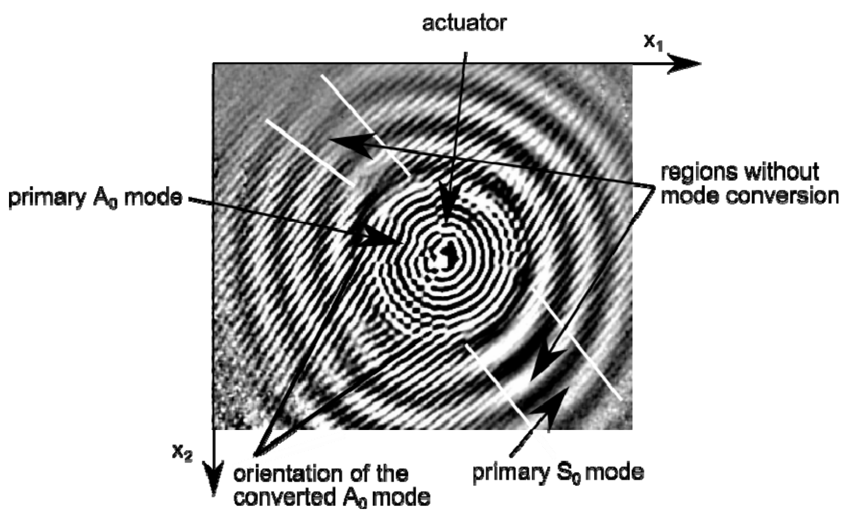
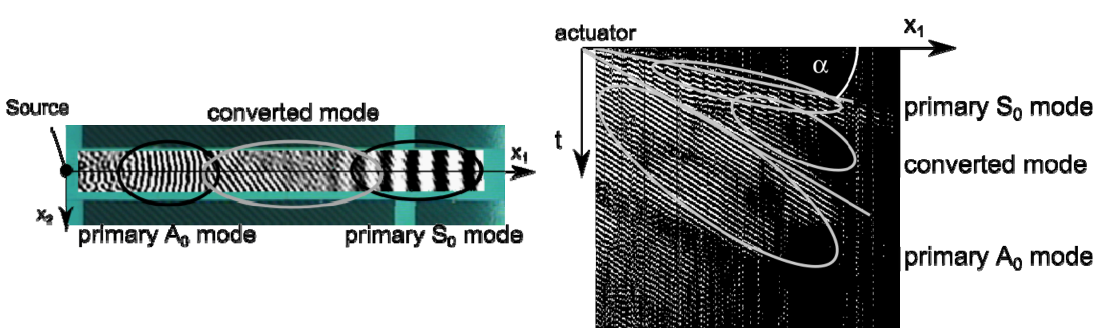


Figure 5. Lamb wave propagation in a CFRP plate at 200 kHz, excited by an actuator in the center (displayed area 300 mm x 250 mm).

The in-plane components measured by the 3D laser scanning vibrometer are used to enhance the identification of the S_0 mode. However, no additional information could be obtained by the 3D scans.

Inside the S_0 mode new waves occur that have not been excited primarily. These new waves are characterized by plane wave fronts. The orientation of the wave front of the new mode depends on the region where the mode arises. In the bottom left of Fig. 5 the different orientation between two wave fronts is shown.

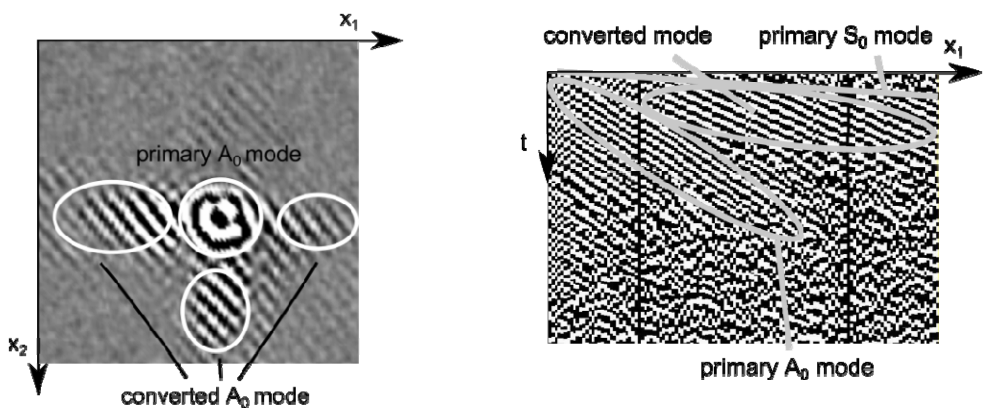


a) ***C-scan of a strip*** ***b)*** ***B-scan of a strip***

Figure 6. Analysis of the new mode at 200 kHz.

Fig 6 shows a strip of a C-scan (a) and the corresponding B-scan (b). According to the velocity depended inclination of the wave lines in the B-scan the new mode could be identified as A_0 mode. A comparison with the dispersion curves of the CFRP plate underlines this finding.

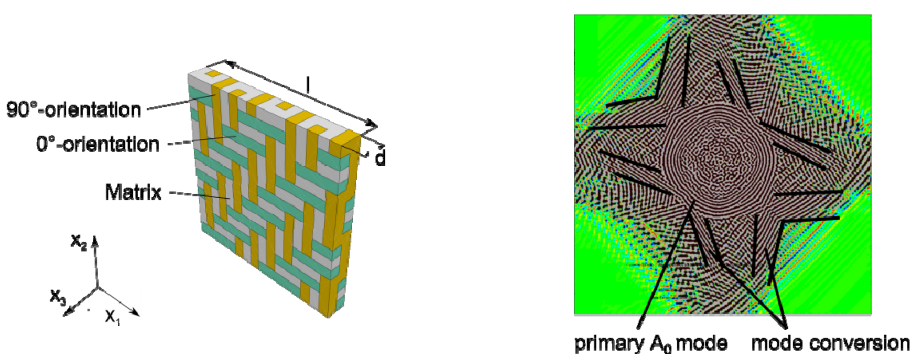
This effect of continuous mode conversion has been observed only in plates that contain fabric material in at least one layer. Obviously, the fabric is the source for CMC. Therefore, a single layer twill fabric plate (1 m × 1 m × 0.3 mm) has been studied. In Fig. 7 a) the C-scan of the plate is displayed. The S_0 mode cannot be seen due to its weak appearance. However, an A_0 mode occurs outside the primary wave front of the A_0 mode excited by the actuator.



a) C-scan with actuator at the center (displayed area 100 mm x 100 mm) ***b) B-scan***

Figure 7. Experimental results for a single layer twill fabric plate at 50 kHz.

These modes are converted from the primary S_0 mode. The B-scan shown in Fig. 7 b) supports this argument. The new mode is generated within the S_0 mode. The inclination of the wave lines in the B-scan corresponds to the group velocity and equals that of the primary A_0 mode. Therefore, the new mode must be converted from the S_0 mode as it appears outside the region of the primarily excited A_0 mode. The black lines in Fig 7 b) are overranged measurement points.



a) Twill fabric model (l=32 mm; d=2 mm) ***b) Numerical result of twill fabric***

Figure 8. Numerical model and solution of a twill fabric plate at 250 kHz.

To validate the experimental findings a numerical model has been created. Fig. 8 a) shows the setup of the simplified numerical twill fabric model. The results of the calculations made with ABAQUS are plotted in Fig. 8 b). The appearance of the A_0 mode outside the primary one can be seen very clearly. However, the orientation of these new modes does not agree well with the experimental results; more detailed simulations are under progress.

CONCLUSION

In this work some phenomena of mode conversion are presented. The investigations have been done experimentally as well as numerically. For the well known mode conversion at discontinuities in plates it has been found that the effect only occurs if the discontinuity is non-symmetric with respect to the center plane of the plate.

Moreover, the phenomenon of continuous mode conversion is discussed. It has been shown that this effect takes place in plates fully or partially made of fabric material. A first simplified numerical model has given evidences of the existence of continuous mode conversion, even if not all details could be theoretically explained at the moment. It is assumed that similar effects could also be observed at other types of composite materials. Such phenomena have to be taken into consideration if ultrasonic waves are applied for health monitoring of composite structures.

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