Lamb Wave Interactions in CFRP Plates

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Abstract. Lamb waves are promising for Structural Health Monitoring (SHM) in plate-like components from carbon fibre-reinforced plastics (CFRP). They may be excited and received by plane piezoelectric elements embedded in or attached onto the material.

The paper presents experimental results of Lamb wave propagation and defect interaction obtained with a scanning laser vibrometer, aimed to a better understanding of the effects of interaction of Lamb waves with flaws. One effect of interaction is velocity variation of the wave travelling over these defects. This variation results in local phase shifts of the Lamb wave field. Beside this, Lamb waves are reflected and even converted from the symmetric mode into the anti-symmetric mode. These effects are evaluated by B- and C-scan imaging.

Two types of inhomogeneities are regarded. The first type does not cause conversion from one wave mode into another. All symmetric inhomogeneities like edges belong to this type.

The second type of inhomogeneities causes wave mode conversion from the symmetric to the anti-symmetric mode. These inhomogeneities are asymmetric defects like flat bottom holes, stringers or piezoelectric actuators or even the material itself. This effect is called continuous wave mode conversion (CMC) at internal material structures not being defects. Some types of woven CFRP material like twill show this surprising phenomenon.

1. Introduction

The requirements for lightweight constructions are continually increasing. In order to open up the full potential of such structures, new safety and maintenance concepts are needed. Current research focuses on integrated systems for structural health monitoring able to detect structural damage without external inspection. These integrated systems ensure high level security of lightweight structures and allow for damage-based maintenance concepts meeting the growing economical demands.

The detection of hidden damages in thin fibre composites by integrated sensors is subject of intense international research [1-4]. Integrated monitoring gains importance especially for fibre composite structures because of the risk of invisible damage in the laminate. Lamb waves are a promising approach for structural health monitoring (SHM) of aerospace systems. These elastic ultrasonic waves occur in thin plate-like structures. They are characterized by low geometrical and material attenuation [5] and high interactivity even with small damages due to their small wavelength [6]. Figure 1 gives an idea how Lamb waves could be used for monitoring of lightweight CFRP (carbon fibre-reinforced...
plastics) structures, e.g. aeronautical structures. Large surfaces may be monitored with a low number of sensors and actuators.

Fig. 1. Lamb waves for structural health monitoring

However, Lamb waves are of complex nature, particularly in CFRP materials. They are dispersive and exist in at least two basic modes, a symmetric (S0) and simultaneously an anti-symmetric (A0) mode. At higher frequencies higher order modes occur [7, 8] and under specific conditions the modes may convert into each other.

Most often piezoceramic actuators and sensors are used for transmitting and receiving Lamb waves [5]. Our investigation addresses the understanding of Lamb wave propagation and interaction with the material [9]. The following results summarize basic interactions of fundamental S0 and A0 modes with different defects. The physical nature of a defect is the local change of the acoustic impedance of the plate. Therefore, all defects transmit and reflect parts of the acoustic energy of the incident wave. An additional important difference in defect behaviour is whether it partially converts energy from one mode to another or not.

2. Experimental Setup

Different methods are known to visualize acoustic surface waves. The most popular setup uses a scanning laser vibrometer, picking up the out-of-plane component of the surface displacement or velocity [10, 11]. Figure 2 shows this setup schematically. To improve the optical reflectivity of the surface it is covered by a retro reflective film, reflecting most of the laser light back to its origin. The edges of the CFRP plate are damped with silicone to reduce edge reflection of the Lamb waves. A piezoelectric actuator attached to the back side of the plate is excited by bursts of sinusoidal voltage with a peak-to-peak amplitude of 60 to 80 volts. In the resultant image two fundamental Lamb wave modes clearly can be observed. The fast long wave symmetric mode runs ahead (big circles) and the slow short wave anti-symmetric mode (small circles) lags behind.
3. Non Mode Converting Inhomogeneities

The edge of the plate may be regarded as a large "defect" located symmetrically to the mid plane of the plate. Figure 3 shows the edge reflection at three frequencies. At the left side of each image the reflection of $A_0$ or $S_0$ may be observed. In the frequency range of exclusive existence of basic modes no mode conversion takes place.

![Fig. 2. Experimental setup of Lamb wave visualization](image)

![Fig. 3. Edge reflection of $A_0$ and $S_0$ mode in a quasi-isotropic CFRP-plate at three frequencies](image)

This effect corresponds with theoretical investigations of Ahmad [12] who revealed asymmetry as a prerequisite for wave mode conversion.
4. Mode converting inhomogeneities

4.1 Interactions with Asymmetric Wall Thickness Changes

Ideal asymmetric defects of high repeatability are artificial flat bottom holes. They represent a local decrease of stiffness due to the local thickness reduction. The Lamb wave velocity of both fundamental modes depends on plate thickness [8]. At reduced thickness the \( A_0 \) mode gets slower while the \( S_0 \) mode accelerates as shown in the dispersion diagrams in Figure 1. Due to this velocity change the transmitted wave is phase shifted compared to the wave next to the defect. As the result of velocity change the acoustic impedance also changes. The defect acts as a boundary partially reflecting the acoustic energy. But this reflection only takes place if the wave length is shorter than the defect size.

Fig. 4. Asymmetric inhomogeneities partially convert symmetric to anti-symmetric Lamb wave mode, a) flat bottom hole and b) piezoelectric actuator.

The most interesting result is the clearly visible mode conversion at these defects even when the defect is smaller than the wave length. Figure 4a) shows the occurrence of \( S_0 \) to \( A_0 \) mode conversion at a flat bottom hole. When the long waves of the \( S_0 \) mode cross this obstacle, they are partially converted into the short wave \( A_0 \) mode. The defect acts as a source of the converted \( A_0 \) mode. This way, the occurrence of \( A_0 \) waves at places, not being reached by the primary \( A_0 \) mode at this time could be an indication of the existence of an asymmetric inhomogeneity.

In contrast to flat bottom holes piezoelectric elements of a SHM system locally increase the plate thickness and stiffness. Due to the different size of the compared obstacles the frequency has been adopted to maintain the same wave length to defect size ratio. Figure 4b) brings up the \( S_0 \) to \( A_0 \) mode conversion at these obstacles. No principal difference can be seen between the \( A_0 \) modes converted at a flat bottom hole and at an actuator.
To get a closer insight into the details of Lamb wave interaction the B-scans have been recorded. The B-scan in Figure 4a) clearly brings up the primary $S_0$ and $A_0$ modes. The $S_0$ waves are reflected at the left edge of the plate. Additionally, the mode conversion to $A'_0$ mode becomes obvious. Moreover, the conversion happens at the defect entry and also at its exit. In every direction two $A'_0$ wave packages can be noticed. In the lower part of this B-scan two $A_0$ wave packages are indicated resulting from the reflection of the primary $A_0$ wave at defect entry and exit.

The B-scan at the piezoelectric actuator in Figure 4b) gives a slightly different image. The $S_0$ to $A_0$ mode conversion is noticeable but it seems to result predominantly from the actuator exit.

### 4.2 Interactions with Stringers

Stringers are structural components to increase the stiffness of the structure. In aircrafts they are located at the inner side of the wall. This way they are of asymmetric nature and should cause mode conversion when they are hit by Lamb waves. So called omega stringers, characterized by a closed profile and two feet contacting the plate, mostly are used. The upper part of Figure 5 gives an idea of this construction. From the wave propagation point of view the stringer is a double obstacle plus a bypass for the waves in the plate.

![Fig. 5. Lamb wave interactions in a stringer plate with impact damage at 75 kHz burst excitation](image)

The plate under investigation additionally was impacted to produce a local delamination. Impact damages are typically of asymmetric nature. Figure 5 summarizes the wave interactions at burst excitation of 75 kHz. The wave travels from the actuator over the
impact to the stringer. The upper C-scan is a snapshot when \( S_0 \) has passed the impact and has just reached the stringer. While no interaction of \( S_0 \) with the impact can be observed the interaction with the first stringer foot is obvious. The dominating effect is mode conversion from \( A_0 \) to \( S_0 \), where \( A'_0 \) travels in both directions.

The middle C-Scan and the B-scan of Figure 5 give an evidence of this effect. Moreover, a similar effect happens at the second stringer foot filling the plate over the stringer with converted \( A'_0 \) waves. The lower C-scan and the B-scan show that \( S_0 \) waves are continued behind the stringer. The B-scan additionally brings up an \( S_0 \) phase shift. It is quite possible that \( S_0 \) is divided into a fraction travelling along the plate and a fraction travelling along the stringer. Behind the stringer both fractions superimpose. Further studies should clarify the character of this superposition and the influence of stringer properties. Surprisingly, no \( S_0 \) reflection at the first stringer foot is noticeable.

An interaction with the impact damage can only be seen with the \( A_0 \) mode. The lower C-scan shows the wave front deformation resulting from the wave's phase shift due to its reduced velocity over the defect. Additionally, a part of the \( A_0 \) incident wave is back reflected as can seen in the B-scan.

The reason for the absence of \( S_0 \) mode interaction with the impact and the absence of \( S_0 \) mode reflection at the stringer may be the big wave length of this mode at 75 kHz. Therefore, the excitation was increased to 200 kHz.

![Fig. 6. Lamb wave interactions in a stringer plate with impact damage at 200 kHz burst excitation](image)

The shorter wave length at 200 kHz results into a noticeable interaction of \( S_0 \) mode with the impact. The C-Scan in Figure 6 brings up the impact damage as a source of a weakly converted \( A'_0 \) mode. Unfortunately, this conversion remains invisible in the B-scan.

The \( S_0 \) mode reflection at the stringer entry is clearly visible in the C-scan as well as in the B-scan of Figure 6. The other mode conversion effects mentioned at 75 kHz also take place at 200 kHz.
4.3 Interactions with Stringer Defects

How the interaction will change when the stringer is locally delaminated from the plate? This defect may already occur due to imperfect production or due to impact damage during exploitation. Figure 7 presents the comparison between an undamaged stringer and a stringer with a local debonding at the first (right) foot. This debonding was induced by a defined impact and confirmed by classic ultrasonic inspection at the DLR Braunschweig.

![Fig. 7. Comparison of Lamb wave interactions with an undamaged stringer and an impacted stringer at 200 kHz burst excitation](image)

The C-scans in Figure 7 clearly bring up the local stringer debonding in the middle of the first stringer foot. The debonding causes $S_0$ to $A_0$ conversion interfering with the conversion caused by the stringer foot. Both of them can be differentiated by the shape of the $A'_0$ wave front.

The comparison of the B-scans in Figure 7 shows a significant difference at the first foot. At the damaged stringer the duration of $S_0$ wave interaction is much longer than that at the undamaged stringer. It is suggested that at this interaction Lamb waves are converted to volume waves. The interaction of converted volume waves and the primary $S_0$ mode can be recognized easy.

4.4 Continuous Mode Conversion

The effect of continuous mode conversion first has been described in [13] for laminates partially consisting of twill fabric layers and further investigated in [14]. It was supposed that not a single local inhomogeneity but the inherent inhomogeneity of this material cause this $S_0$ to $A_0$ conversion. To get more details of this mode conversion a thin double layer plate of twill fabric has been evaluated. Figure 8 compares the results with the 7 layer plate at about 200 kHz.
Fig. 8. Lamb wave propagation in a CFRP plate accompanied by continuous S$_0$ to A$_0$ mode conversion. The actuator is located in the centre of the scanned area.

The S$_0$ wave field of the 7 layer plate in Figure 8 a) is almost round due to the quasi-isotropic structure if this laminate. The S$_0$ wave field in Figure 8 b) is of rhombic shape due to the anisotropy of Lamb wave velocity along and across the fibres [15]. In contrast, the A$_0$ wave field of both plates is nearly unaffected.

Inside the S$_0$ wave field short waves occur not being excited by the actuator. These new waves are characterized by plane wave fronts being nearly parallel to each other. The orientation of these wave fronts depends on the characteristic diagonal pattern of twill fabric also known as the wale. According to this pattern the rovings change the z-component of their orientation thus changing the local stiffness in the same manner. These asymmetric to the plate's mid plane stiffness changes are regarded as the source of mode conversion.

**Conclusion**

The discussed Lamb wave interactions in CFRP plates may be divided into mode converting and non mode converting interactions. Local inhomogeneities cause mode conversion when they are of asymmetric nature according to the plate's mid plane. Some basic inhomogeneities like edges are symmetric and do not cause mode conversion. This way, the occurrence of mode conversion may give a first hint about the nature of the inhomogeneity.

But mode conversion must not be used as the only criterion for the classification of a found inhomogeneity. Stringers, for instance, of course are no defects but also produce mode conversion. The shape of the converted wave can be used as an additional criterion.

On the other hand, obviously homogeneous plates can cause mode conversion if they at least partially are made of fabric layers.
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References


