# Characterization of Lamb Wave Damage Interactions for Pseudo Damage Development

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## ABSTRACT

In aeronautics delamination damage in composite structures are a crucial factor for the timing of maintenance cycles. Structural health monitoring systems based on ultrasonic guided waves have the potential to find them quickly and consequently save airlines money. For the development of such a system removable pseudo damage are a cost-efficient alternative to enable the necessary quantity of testing. However, to develop a removable pseudo damage, a strategy is needed to classify the wave interactions of delaminations in a way which can also be used to classify those of removable pseudo damage.

Therefore, this paper will showcase a methodology to classify the Guided waves reflection, transmission and S0 to A0 mode conversions induced by delaminations and discuss potential pseudo damage types. The analysis is based on a b-scan taken by an air coupled ultrasonic scanner starting at the actuator and ending behind the damage. The key findings are that the suggested methodology was able to capture the wave interactions of the delaminations as well as the experimental pseudo damage. Thus, it could be used as a tool to test the interactions of pseudo damage and compare it to the ones of delamination. Hence, being the first step towards enabling high-volume damage localisation tests of structural health monitoring systems.

## INTRODUCTION

In the aviation industry, delamination damage in composite structures is a critical factor in planning maintenance cycles and ensuring the structural integrity of aircraft. Early and accurate detection of these delaminations is essential to avoid costly repairs and extended downtime in addition to ensure aircraft safety. In this context, structural health monitoring systems (SHM systems), which are based on guided ultrasound

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waves, are playing an increasingly important role. They offer the possibility of detecting damage within a few minutes and thus enable more efficient maintenance and a reduction in operating costs [1].

The challenge in the development and testing of such SHM systems lies in the need to test the systems under realistic conditions without damaging the structures to be monitored. This is where so-called pseudo-damage comes into play - artificially created damage that serves as replicas for real damage in order to test the performance of the monitoring system in a controlled environment. This allows the same, usually expensive, test structures to be used repeatedly, which is particularly helpful when carrying out a large number of measurements. Pseudo-damage is therefore a cost-effective and practical way of validating test methods and ensuring high reliability of SHM systems.

Lamb waves are a type of body-guided ultrasonic waves that propagate in plate-like structures. Of particular note is their ability to propagate over long distances while being sensitive to structural damage due to mode conversion and different propagation speeds. These properties make them well suited for use in SHM systems [2].

The development of pseudo-damage for the Lamb wave technique presents a challenge, as their interactions with ultrasonic waves can differ from those of real damage, which can result in an SHM system detecting pseudo-damage but not real damage. Due to the complexity of real structures and the lack of realistic models for wave propagation in them, it is crucial that a large number of test measurements can be carried out using pseudo-damage. Only in this way can a damage detection system be correctly trained or calibrated to actually detect impact damage. A precise analysis of these wave interactions is therefore necessary to ensure that pseudo-damage replicates real damage as accurately as possible and can be used as reliable test objects [3].

A central aim of this paper is to develop a method that enables the wave interactions of delaminations and pseudo-damages to be characterized. In particular, the interactions of Lamb waves in terms of reflection, transmission and mode conversion are to be investigated.

In Chapter 1, Acquisition of experimental data, the physical aspects of the experiment and the data acquisition are explained, in Chapter 2, Analysis of the characteristics, the calculation of the characteristics is explained and critically evaluated in the following chapter. Finally, there is a summary with an outlook.

## ACQUISITION OF EXPERIMENTAL DATA

The investigation of the wave interactions with the A0 and S0 modes requires an experimental setup in which the transmission through the damage, the reflection at the damage and the mode conversion of the S0 mode to the A0 mode can be measured. The following describes why a plate size of 50 x 66 cm, two separate excitations and the measurement as a B-scan are chosen.

The waves considered here are so-called Lamb waves, guided ultrasonic waves with dispersed propagation speeds. Different wave modes are formed, especially the fundamental modes A0 and S0. Depending on the excited frequency range, the amplitudes of the individual modes vary and one mode is dominant over the others ([2]). To enable a good characterization of the wave interactions, a single measurement is carried out for each of the interactions of the A0 and S0 modes. To measure the transmission and reflection of the wave, i.e. the wave interactions before and after damage, a B-scan is recorded. This is implemented with an air-coupled ultrasound system.

In the A0 mode, the aim is to achieve the highest possible frequency at which no interfering waves of the S0 mode occur. A high frequency should be selected, as a higher frequency has a shorter wavelength and period duration. This is preferable as in this way the wave packets are narrower in the B-scan, which is explained in more detail later. The excitation frequency for the A0 mode is 90 kHz.

For the S0 mode, a higher frequency should be aimed for, as the wavelengths decrease further and the amplitude of the S0 mode becomes more dominant. However, this cannot be set to any frequency, as the ultrasonic transducer must be able to detect it. Classic ultrasonic transducers work at their resonance frequency (AirTech200), which is why they resonate. This resonance is unsuitable for measuring narrow wave packets. Therefore, a microphone is used which sets the maximum excitation frequency to 150 kHz (DeltaTron Free-field ¼" Microphone Type 4954A). For the same reason, the narrow wave packet, the excitation signal is a 3-cycle sine burst. A DuraAct P-879K025 and an amplifier (WMA 300, Falco Systems) are used for the excitation.

A plain plate was chosen as the propagation medium. A quasiisotropic plate with a layer structure of [0/+45/-45/90/-45/+45/0] and a thickness of 2.2 mm is investigated for comparability with plates from preliminary investigations.

Several plates are provided for the impact damage and pseudo damage characterization tests. They should come from the same batch so that their wave propagation behavior is as similar as possible. For this reason, there is the geometry limit of the mold of at 2 x 2 m x 1 m. A separation of the modes in the S0 B-scan is necessary to such an extent that the different mode interactions can be separated from each other. Figure 1 a) shows an S0 B-scan from preliminary tests with a plate of comparable structure and dimensions as shown in Figure 1 b). The different wave packets are labeled in the B-scan. The wave packets to be observed are shown in Figure 1 c). The B-scan shows that the individual characteristic features, like the transmission S0 and A0 as well as the reflection A0 (corresponding to mode conversion), can be identified. However, interference is present in the areas of the mode converted to A0. A reflection area for the A0 mode with less interference can be realized by increasing the distance between the actuator and the damage. A A0 transmission area with less interference is achieved either by a much later arrival of the trailing edge reflection or by a later arrival of the reflection of the side edges.

As a compromise between minimally greater separation of the modes due to a slight displacement of the actuator and the enlargement of the transmission range A0 due to the displacement of the side edge reflections caused by a larger plate and, on the opposite side, the number of plates in a batch, a plate size of 50x66cm was chosen. The set-up is shown in Figure 1 d).

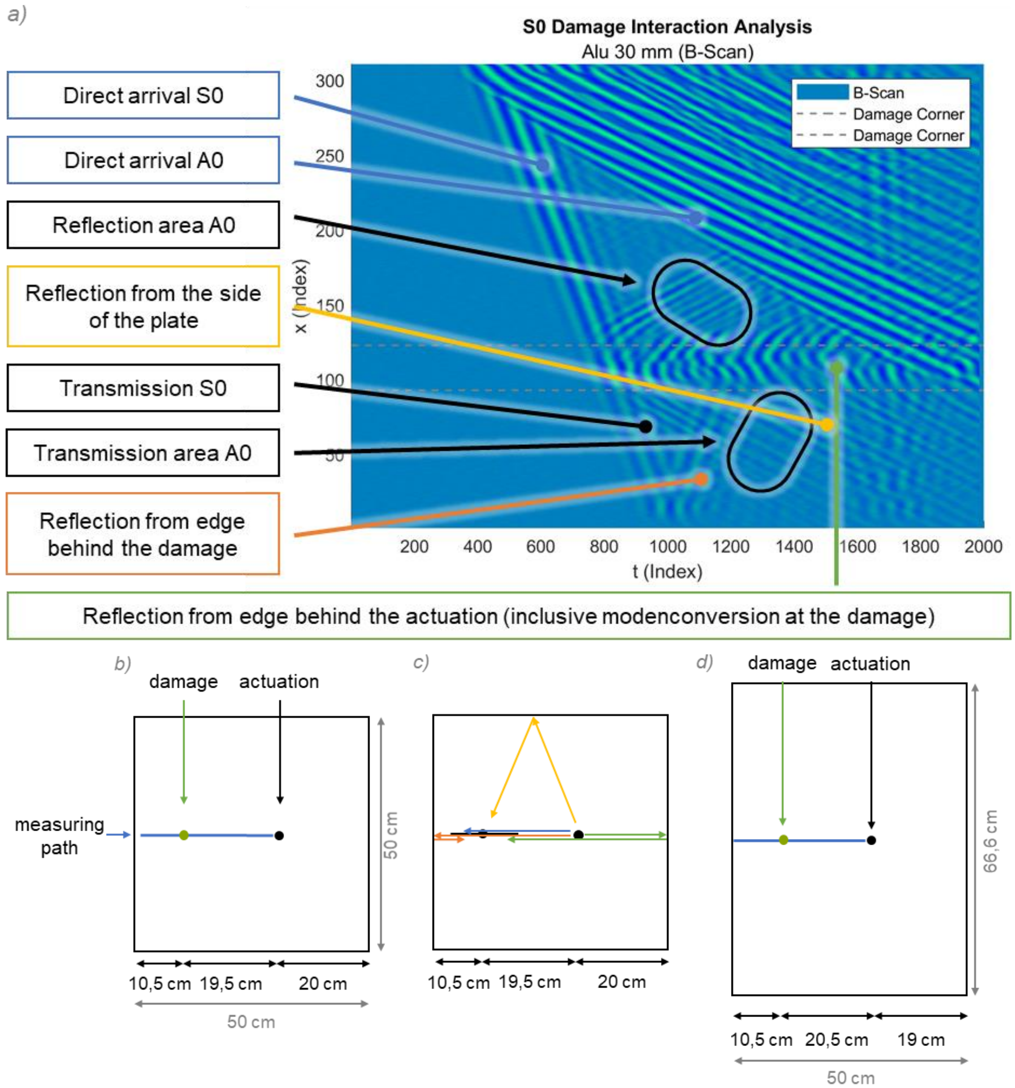


Figure 1. a) B-scan with S0 excitation from preliminary tests with labeled wave packets, b) Pre-test measurement setup, c) Wave packets considered from a), d) Measurement setup of the methodology presented

## ANALYSIS OF THE CHARACTERISTIC FEATURES

The interaction of Lamb waves, the type of wave typically used in damage localization systems, will be characterized in this manuscript. The phenomena to be observed for the A0 excitation are transmission and reflection of the mode, for the S0 excitation additionally also the conversion from S0 to A0. For these two excitation frequencies (A0 and S0), individual B-scan measurements are carried out and analyzed separately. The quantification is explained in this chapter.

The aim is to calculate characteristic values that are comparable between different types of damage. To achieve this, the method presented here uses the amplitude of the wave packets. Due to the interference of decaying wave packets and stochastic variation, areas are defined in the B-scan in which the mean value of the maximum amplitude is formed. For this purpose, the maximum amplitude is determined in the B-scan in the section of the wave packet corresponding to the edge of the respective zone (see Figure 2) and then the mean value is calculated from each section in this zone.

The zones are positioned relative to the leading and trailing edges of the damage. In order to determine the amplitudes of the wave packets converted from S0 to A0, areas with low interference oscillations are selected. The bottom of Figure 2 shows that several zones for these A0 modes are differentiated according to the interaction with damage. In various investigations it can be seen that the wave is "trapped" in the area of the damage, i.e. reflected at the trailing and leading edge of the damage. This means that the A0 mode is distributed in time in front of and behind the damage. (Examples are Figure 2 (below), as well as a simulation [4]) Three zones are defined here in order to depict and record this effect. Due to interference these values can exceed 100%. The position of the zones for calculating the characteristics can be seen in Figure 2.

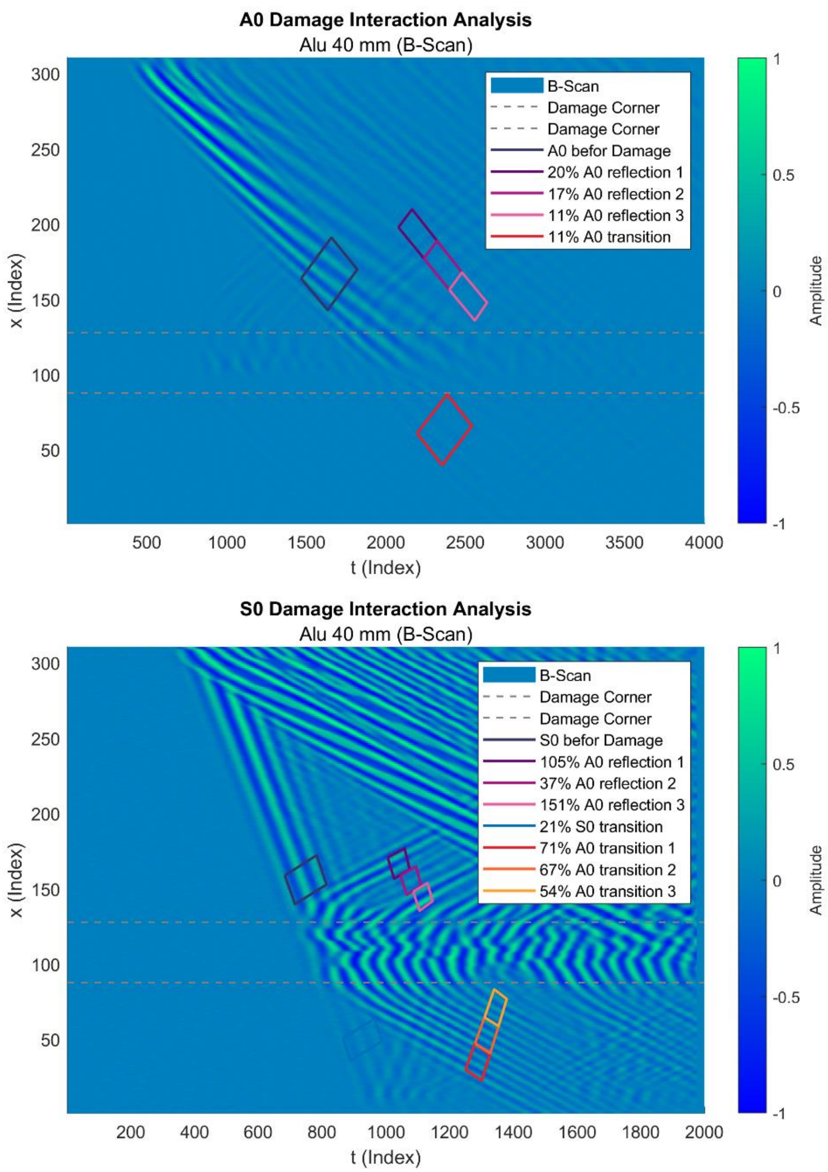


Figure 2. B-scan with marked analysis zones for determining the interaction characteristics (top: A0 excitation, bottom: S0 excitation)

## CRITICAL CONSIDERATION OF THE CHARACTERISTIC VALUES

The reproducibility of the methodology is discussed below based on the characterization of various panels without damage. Subsequently, the method of characterizing Lamb wave damage interactions is considered using some examples.

TABLE I. Characteristics considered for 9 different plates to assess reproducibility

| | A0 | | | | S0 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | A0 Refl. 1 | A0 Refl. 2 | A0 Refl. 3 | A0 Trans. | A0 Refl. 1 | A0 Refl. 2 | A0 Refl. 3 | S0 Trans. | A0 Trans. 1 | A0 Trans. 2 | A0 Trans. 3 |
| *Percentage of the amplitude bevor the damage* | % | % | % | % | % | % | % | % | % | % | % |
| **Plate 1** | 6 | 5 | 6 | 45 | 17 | 18 | 16 | 69 | 36 | 22 | 15 |
| **Plate 2** | 5 | 4 | 4 | 41 | 15 | 14 | 13 | 76 | 23 | 14 | 15 |
| **Plate 3** | 5 | 4 | 5 | 46 | 21 | 17 | 13 | 77 | 28 | 15 | 20 |
| **Plate 5** | 4 | 4 | 4 | 41 | 17 | 13 | 15 | 81 | 39 | 30 | 19 |
| **Plate 6** | 10 | 7 | 7 | 43 | 20 | 22 | 18 | 61 | 28 | 19 | 19 |
| **Plate 7** | 8 | 6 | 6 | 42 | 17 | 22 | 17 | 73 | 33 | 33 | 31 |
| **Plate 8** | 8 | 7 | 6 | 42 | 21 | 17 | 14 | 65 | 38 | 28 | 21 |
| **Plate 9** | 9 | 7 | 7 | 41 | 17 | 20 | 16 | 66 | 29 | 37 | 23 |
| **Plate 10** | 10 | 8 | 8 | 44 | 18 | 14 | 11 | 69 | 32 | 20 | 18 |
| **Standard Deviation** | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 6 | 5 | 8 | 5 |
| **Standard Deviation** (%) | 32 | 27 | 23 | 4 | 12 | 19 | 15 | 9 | 17 | 34 | 24 |

TABLE I lists the characteristics determined for various plates and thus provides a basis for assessing the reproducibility of the test. The standard deviation of the respective column is shown at the bottom of the table, with the standard deviation in relation to the mean value below. With a maximum of 34% relative standard deviation is high, a smaller variation would be desirable and a selection of comparable plates will be taken.

The application of the methodology of this manuscript to a selection of damage combinations for the A0 and S0 wave interactions is now presented.

TABLE II. Characteristics of the A0 wave interaction

| A0 | | A0 Refl. 1 | A0 Refl. 2 | A0 Refl. 3 | A0 Trans. |
|---|---|---|---|---|---|
| *Percentage of the amplitude bevor the damage* | | % | % | % | % |
| **Empty Plate** | **-** | 6 | 5 | 6 | 45 |
| **HDPE + Glue 1** | **25 mm** | 13 | 14 | 15 | 31 |
| **Steel + Glue 1** | **20 mm** | 29 | 11 | 6 | 10 |
| **Steel + Glue 2** | **30 mm** | 11 | 7 | 5 | 21 |
| **Impact 6,5 J** | | 8 | 12 | 12 | 49 |

TABLE II lists the characteristics determined for different types of damage. Tests of a plate without damage, with glued-on discs of different materials and with impact damage are compared. It can be seen that the different tests can be clearly distinguished by the characteristics. In particular, the time of reflection differs greatly between the pseudo damage with adhesive 1 and the impact damage. A very different influence can also be detected for the two adhesives.

TABLE III. Characteristics of the S0 wave interaction

| S0 | | A0 Refl. 1 | A0 Refl. 2 | A0 Refl. 3 | S0 Trans. | A0 Trans. 1 | A0 Trans. 2 | A0 Trans. 3 |
|---|---|---|---|---|---|---|---|---|
| *Percentage of the amplitude bevor the damage* | | % | % | % | % | % | % | % |
| **Empty Plate** | **-** | 17 | 18 | 16 | 69 | 36 | 22 | 15 |
| **Acrylic + Glue 1** | **25 mm** | 41 | 41 | 49 | 37 | 67 | 100 | 68 |
| **Aluminium + Glue 1** | **25 mm** | 34 | 71 | 43 | 42 | 43 | 49 | 32 |
| **Aluminium + Glue 2** | **25 mm** | 26 | 38 | 28 | 59 | 28 | 19 | 33 |
| **Impact 6,5 J** | | 16 | 16 | 23 | 72 | 25 | 21 | 20 |

TABLE III shows the characteristic features of the S0 mode interaction. Here too, clear differences in the calculated characteristics can be seen between the various combinations of adhesive and bonded material.

Finally, it can be said that despite the interferences in the zones of the analysis of the characteristics, a meaningful investigation of the interactions of the Lamb waves with damage can be carried out with this presented methodology.

## SUMMARY AND OUTLOOK

The presented analysis of wave interactions can be used to determine characteristic features of damage, which can serve as a basis for the development and improvement of pseudo-damage. In order to capture these interactions, an experimental setup is developed in which B-scans with an air-coupled ultrasonic scanner capture the wave interactions. The fundamental modes A0 and S0 are used in this work. The characteristic features are determined based on their amplitude before and after the interaction with the damage. Averaging is performed within defined zones to compensate for unwanted interference.

The methodology presented here for the characterization of Lamb wave interactions represents an important step in the further development of structural monitoring systems. It makes it possible to investigate the interactions of Lamb waves with pseudo-damage and is a step towards the qualitative validation of SHM systems. The investigation of the differences in the wave interactions of real damage and pseudo-damage helps to define the limits and possibilities of pseudo-damage as test objects and to optimize their use in the context of damage detection. This study deals with the development and application of this methodology.

In the future, it may be possible to improve the comparability between the individual panels by fine-tuning the zones. It is also planned to use this methodology to characterize different variations and combinations of pseudo-damage. On the one hand, this will provide an insight into the interactions that widespread pseudo-damage such as magnets have on wave propagation. And on the other hand, this is a starting point for the overarching goal that this methodology can be used to develop a pseudo-damage that mimics the wave interactions of an impact damage.

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