Structural Health Monitoring Using Lamb Waves

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Abstract. In opposite to longitudinal waves which are used for local testing with high resolution, Lamb waves can penetrate large areas of components. However, for a given frequency at least two modes – one symmetric and one anti-symmetric – are generated. These modes are dispersive, which means that their velocities are frequency-depending. For the damage detection it is important to select the optimal wave mode and to know the propagation and the interaction with defects. Therefore research fields are: sensors, excitation, bonding/embedding of sensors, excitation, propagation, interaction with defects, signal processing and signal evaluation. Our research topics are visualisation of the Lamb wave propagation and its interaction with damages, as well as analysis of the correlation between progressing damage types and active Lamb wave signals. The ultrasonic imaging technique has been adapted for the visualisation of Lamb waves. DLR is involved in the EU-project AISHA (Aircraft integrated structural health assessment) together with METALogic (coordinator, SME), Katholieke Unversiteit Leuven – MTM, CEDRAT Technologies Eurocopter France, Riga Technical University, Fundacion Centro de Tecnologias Aeronauticas, TGA (SME) and ASCO. This paper presents results about the interaction between Lamb waves and damage types caused by impacts and Lamb waves in CFRP- sandwich components with honeycomb cores.

1. Introduction

Carbon fibre reinforced composites (CFRP) provide high specific stiffness and strength. In order to take advantage of the specific properties, the complexity of the aircraft structures increases more and more [1]. On the other hand, costs and time-consumption for in-service inspection need to be decreased. Therefore cost effective Non-Destructive Testing (NDT) methods have to be developed.

A well established NDT-method is the ultrasonic imaging technique, which is able to detect internal defects with a high degree of resolution and reliability [2]. However, this punctual measurement technique requires time consuming scanning of the whole area to inspect. Modern complex composite structures (e.g. sandwiches, double shell fuselage) pose further strong restrictions on the accessibility for conventional ultrasonic testing. Lamb wave can penetrate large areas of components and therefore are able to provide fast in-service inspections without time consuming scanning [3, 4, 5, 6]. There are passive and active methods. During occurrence of a damage Lamb waves are generated, which can be received by PZT transducers (acoustic emission technique). In the active method, Lamb waves are excitated and received at distinct positions.

Piezo patches at fixed positions of the structure are often used as actuators and as sensors [7]. These patches can be embedded in the component or attached to the surface. In opposite to longitudinal waves used for ultrasonic imaging techniques, at a certain frequency at least two Lamb wave modes with different phase velocities exist: a symmetric and an asymmetric one [8]. Usually, Lamb wave propagation is highly dispersive. The received signals are a complex mixture from different modes and therefore difficult to evaluate. Besides this, there doesn't exist any theory for the prediction of the Lamb wave amplitudes.

Research topics at DLR are visualisation of the Lamb wave propagation and the interaction between damages and signal correlations between progressing damage types and active Lamb wave signals.

2. Hard- and Software for Lamb Wave Investigations

For the investigation with Lamb waves, special equipment is required:

- sensors and actuators,
- transmitter (pulser) for the excitation
- pre-amplifier, HP- and LP- filters and digitizer
- software for the evaluation of the detected signals

Table 1 describes the differences between standard ultrasonic imaging and Lamb-wave testing.

	Ultrasonic Imaging	**Lamb wave testing**
Transducer(s)	Scanning	Fixed on the component
Frequency range	0.5 to 20 MHz	10 kHz to 2 MHz
Bandwidth	Broadband	Narrowband
Excitation	Spike pulse, rectangle, burst	Modulated sinus, burst
Evaluation of the pulse response	Amplitude, time of flight, A-, B-, C- and D- scans	Time of flight, amplitude, FFT, STFT

Table 1. Ultrasonic imaging and Lamb wave testing

In order to generate only a few Lamb wave modes, narrowband technique is necessary, whereas conventional ultrasonic testing in pulse-echo-technique requires a broadband system for high resolution. Also the frequency ranges for ultrasonic testing and Lamb wave testing are different. In Lamb wave testing, mostly the s_0 and a_0 modes are used. These modes have frequencies below 1 MHz. Standard ultrasonic testing mostly uses frequencies in the range of 1 to 20 MHz. For the first investigations we used our existing ultrasonic systems such as HFUS 2400 and HFUS 2400 AirTech. In opposite to standard systems these devices also provide frequencies below 10 kHz. In order to increase the resolution, we extended the systems with ultra low noise preamplifiers as well as high- and low-pass filters in a frequency range of below 1 MHz. Now the USPC 5000 is available, a portable system providing both ultrasonic imaging and Lamb waves testing [9]. The system for research and development is built in a portable PC. The Lamb wave part consists of an 8 channels transmitter and eight channels receiver system. The automatic data recording provides 64 cycles; each transmitter signal can be received by any receiver. The ultrasonic imaging part of the system enables both the visualisation of the Lamb wave propagation as well as conventional ultrasonic imaging technique as a reference method for defect detection.

3. Specimens

Within the scope of the AISHA project, monolithic CFRP and sandwich with both honeycomb and foam core are used. The dimensions of the specimens, as shown in Fig. 2, are due to the setup for the fatigue loading, which requires also lateral anti-buckling support.

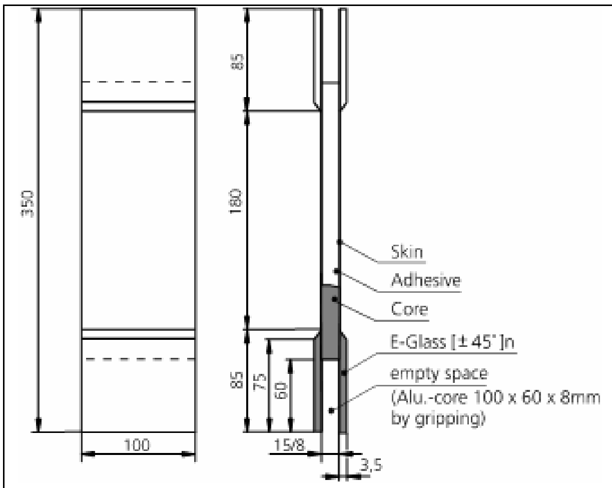


Fig. 2: Dimensions of specimens

ID	Primary damage	Secondary Damage: Fatigue (R=-1, f=5Hz)		
1 . 1 - 1	Thermal Cycling	fatigue		
1 . 1 - 2	Thermal Cycling	fatigue		
1 . 1 - 3	Thermal Cycling	fatigue		
1 . 1 - 4	Thermal Cycling	fatigue		
1 . 2 - 1	Impact 5J			
1 . 2 - 2	Impact 10J			
1 . 2 - 3	Impact 15J			
1 . 2 - 4	Impact 20J			
1 . 3 - 1	Impact 5J	F=±15kN, N=100 000lc	F=±20kN, N=+50 000lc	F=±25kN, N=+15 461lc
1 . 3 - 2	reference			
1 . 3 - 3	Impact 15J	F=±15kN, N=50 000lc	F=±15kN, N=+50 000lc	F=±17,5kN, N=+44 943lc
1 . 3 - 4	reserve			
1 . 4 - 1	Impact 10J	F=±15kN, N=50 000lc	F=±15kN, N=+50 000lc	F=±20kN, N=+6 766lc
1 . 4 - 2	Impact 20J	F=±15kN, N=12 748lc		
1 . 4 - 3	reserve			
1 . 4 - 4	reserve			

Tab. 2: Sandwich specimens for Lamb wave investigations

Table 2 presents an overview of the honeycomb specimens. For each type of specimen there remains one reference sample without loading. This is important for the optimisation of the test parameter for Lamb waves. The table also gives information on the type of loading such as thermal cycling (degradation), impact and fatigue.

The number of specimens is larger than minimally required. The reason is that for fatigue testing a large number of load cycles is required for damage growth. Because of the scattering of the results is possible that some specimens brake down during loading.

4. Results

In order to have quick Lamb wave testing of different specimens, a number of piezo-patches used as transmitters and receivers have been glued onto two thin U-shaped CFRP-adapters. The thickness of the CFRP material is only 0.5 mm. The length of the array is equal to the specimen's width (100 mm) so that the positioning is very easy. The transmitter and the receiver array are put to opposite edges of the specimen, close to the fiber glass clamping support. The coupling of the piezo array is carried out with sugar beets syrup (usually breakfast food).

Two arrays have been constructed, one with four elements, another one with six elements. The array with six elements is used as a receiver; a built-in change-over switch (multiplexer) selects one piezo. The output is connected to a Lemo 00-connector. Using these arrays, several Lamb wave tests have been carried out. For the sandwich specimens with Nomex core, a test frequency of 20 kHz was used. A velocity of about 1000 m/s gives a wavelength of 20 mm.

Fig 2 shows the results of 10 different damaged Nomex-core sandwich specimens, each at six positions. The time of flight of the reference specimen is shown, too. All measurements show the same behavior (except for one result at receiver 6) and the same time of flight with a difference of 5 % in spite of damaged or undamaged specimens. This kind of Lamb wave measurement does not provide damage detection.

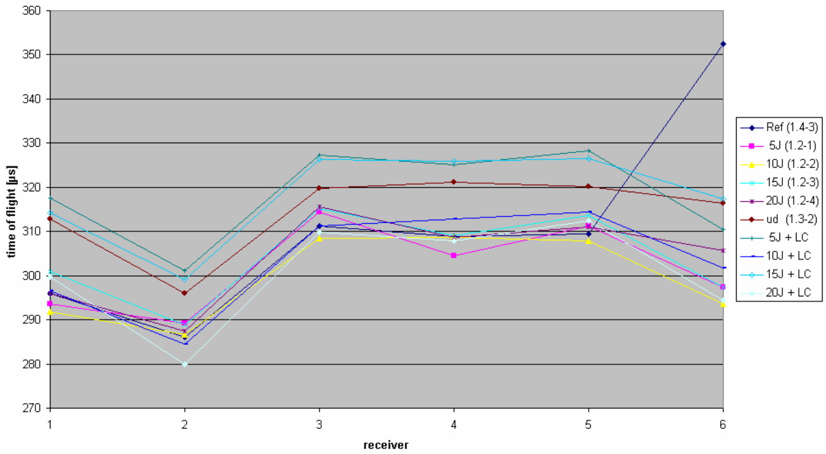


Fig. 2: Time of flight at six positions of sandwich specimens with different loadings

5. Imaging of Lamb Wave Propagation

In order to get more information about the propagation of Lamb waves in components and their interaction with defects it is very helpful to visualise the wave propagation. Usually this is done by laser interferometer which is able to monitor the out-of-plane surface deformation [10].

Fig. 3 describes the combination between ultrasonic imaging and Lamb wave testing which is carried out at DLR. All ultrasonic methods like phased array-, echo- and air-coupled ultrasonic technique deliver volume data sets from full-wave data recordings and also the Lamb wave method described later. All data can be processed by our software and after signal processing there is the option of imaging, animation and evaluation by signal analysis.

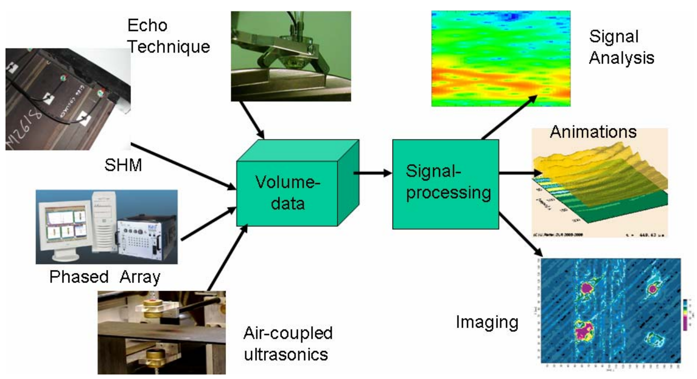


Fig. 3: Network of different NDT-methods

For the visualisation of the Lamb wave fields and their interaction, one actuator at a fixed position on the bottom of the specimen has been used as a transmitter (Fig. 4). The excitation is carried out by the rectangle burst generator via a driver for a VMOS-transistor and a matching device. These components deliver a narrow band signal because of the filtering of the harmonics.

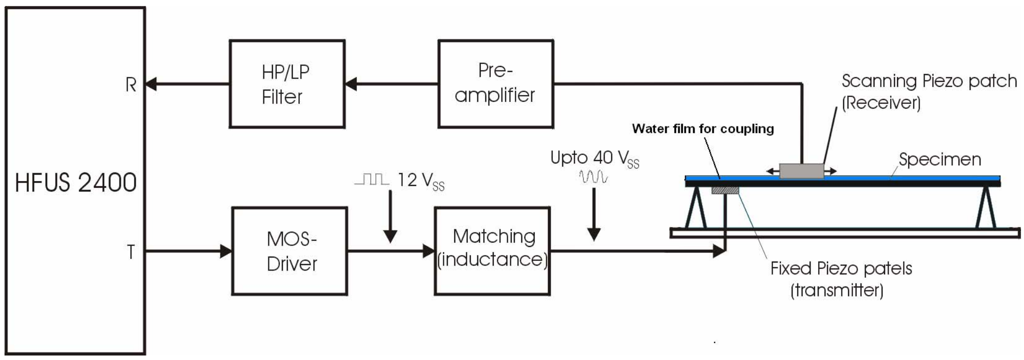
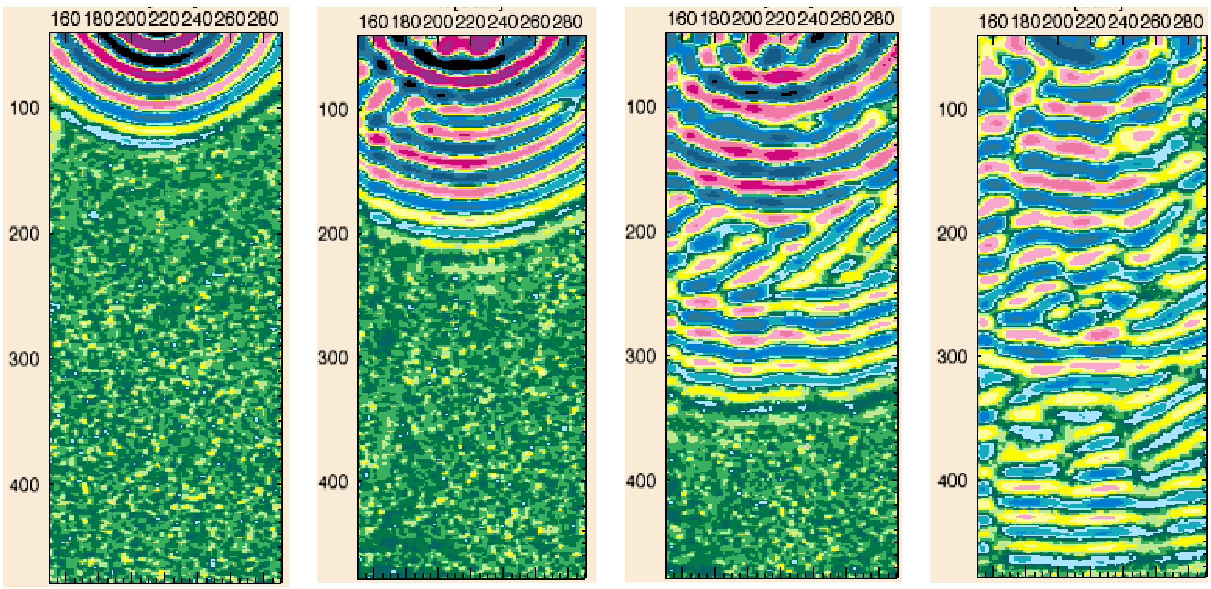


Fig. 4: Experimental setup for wave visualisation with direct coupling

A second PZT-patch is coupled by water film to the surface and moved by an XY-scanner in a meander track. Because of the water coupling, Lamb waves are received with low amplitude only. Therefore an ultra-low noise preamplifier and a band pass filter are necessary. Data conversion, timing and scanner control are carried out by the HFUS 2400. At each point of the scanning grid, a full wave Lamb-wave A-scan is recorded. Out of the 3D-data files several presentations can be calculated and presented:

- 2D Amplitude images, showing the maximal amplitude during a selected time interval [t_1, t_2] ("C-Scan").
- 2D time-of-flight image within a certain time interval [t_1, t_2] ("D-Scan").
- The Lamb wave A-scan at any recorded position together with spectral analysis.
- Slices [x, t], [y, t] similar to B-Scans in conventional ultrasonic technique
- Video-animations showing the wave propagation.



203µs　　331 µs　　555 µs　　779 µs

Fig. 5: Lamb wave propagation in sandwich specimen 1.2.3 (impacted with energy of 15 J)

Fig. 5 presents four snap-shots out of an animation calculated out of a full wave data set of a Lamb wave testing of a sandwich specimen (Sample 1.2.3). The snap shots present the propagation 203, 331, 555 and 779 µs after excitation. The first image shows undistorted propagation, but after 331 µs first interference between edge reflected and the primary propagation wave is indicated on the left hand side. Further interferences can be observed in the following images. The snap shot after 779 µs clearly indicates several interferences between the propagating wave in the centre and reflections from the edges. This is the reason why different damages do not result in differences between the received signals (see Fig. 2).

7. Results after Optimisations

Based on the visualisation of Lamb wave propagation in the sandwich specimens, the position of the actuator and the sensor could be optimized. In spite of the small dimensions of the specimens compared to the wave length, significant changes in the receiving signal could be indicated. The positions of the two patches are the upper right corner and the lower left corner. Using the USPC 5000 system, the two Lamb wave A-scans in Fig. 6 were received. The A-scan on the right hand side represents the signal from specimen 1.3.2 (reference, without defect), the second A-scan from specimen 1.2.3 (15 J impact). The signal was evaluated with two gate ranges, the amplitudes in the first gate are 41% (0J) and 13 % (15J). The amplitudes in gate 2 are 91 and 61 %.

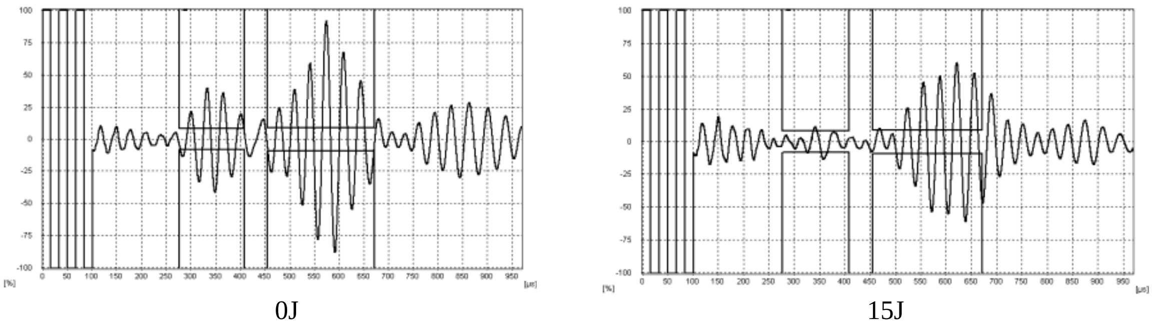


Fig. 6: Lamb wave A-scans received from sandwich specimens without impact and with a 15 J impact

8. Conclusions

The results show that not only the generation of at least two modes at one frequency but also the non-directional propagation of the Lamb waves in components makes the evaluation of the received signals difficult. The size of the specimens used in this project is too small compared to the wave length. Therefore many edge reflections interfere with the main propagating wave. The visualisation of the wave propagation is very helpful and enables the optimisation of a Lamb wave system for the detection of defects in components. The ultrasonic imaging technique is practicable for this application, especially with full wave data recording. The 3D-data files of Lamb wave fields also allow the calculation of video-animations which show impressively the propagation.

9. Acknowledgements

The authors would like to thank the European Commission and all AISHA-partners for their support.

10. References

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