IMPACT DETECTION IN A COMPOSITE TAIL-BOOM STRUCTURE WITH ULTRASONIC IMAGING - AND GUIDED WAVES TECHNIQUES

Wolfgang Hillger, Artur Szewieczek,
GERMAN AEROSPACE CENTER (DLR),
Lilienthalplatz 7, 38108 Braunschweig, Germany,

Abstract

Sandwich components with thin skins of GFRP or CFRP and honeycomb cores are high performance components for aerospace structures with high specific stiffness and strength. However these materials are impact sensitive.

The DLR part of the EU-project AISHA II (Aircraft integrated structural health assessment) is focused on a full-scale test of a 3.5 m long tail-boom oft the EC 135. This component consists of a honeycomb sandwich structure with thin skins out of CFRP and GFRP layers.

For in-field inspections ultrasonic echo-technique has been further developed for one side access. The honeycomb structure only penetrates frequencies below 1 MHz. Therefore a low frequency inspection technique has been developed. The harmonics and the scattering of the material are suppressed on the receiver side by filters. The C-scans clearly show the damaged areas.

A scanning technique like ultrasonic imaging is time consuming and therefore expensive. In opposite to longitudinal waves Guided waves provide a global propagation with relatively low attenuation and can easily be excited and received by piezo patches. Such a structural health monitoring system provides in principle a push-bottom inspection. However, Lamb waves are dispersive and for each frequency there are two wave modes in minimum so that the received signals are very complex.

In order to get more information about the Lamb wave propagation the wave fields have been scanned using a broadband capacitive sensor as a receiver. The full-wave A-scans are stored in a 3D-file. Out of this data, Lamb wave A-, B-, C- and D-scans and video animations can be calculated. Virtual sensors can be placed in the displayed scanning area and the received signal can be computed. Optimizations of sensor layouts and sensor positions are possible.

Video snap-shots show the wave propagation and an interaction with defects like delaminations. The impact causes a mode conversion from the S_0-mode (fast mode) into the A_0-mode (slower mode). The A_0-mode from the excitation piezo-patch and the one from the impact interfere. Therefore the impact detection in the tail-boom structure using Guided waves is a hard challenge.

This paper presents first results of the impact detection using ultrasonic echo- and Guided waves technique. After optimization of the pulse parameters the ultrasonic imaging technique delivers a clear indication of impacts. The received signals of Guided Wave techniques are very complex due to mode conversions not only at defects but also at structural stiffness changes.

1. Introduction

Sandwich components with thin layers of CFRP and GFRP laminates and a honeycomb core are high performance materials not only for lightweight aerospace applications but also for ships, lorries and also for linings in passenger cars [1]. Besides high specific strength and stiffness these components show a damage tolerant behaviour.

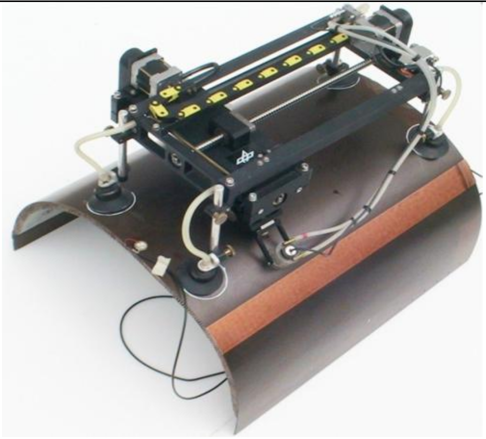
	
Helicopter EC 135	Half-cell tail-boom demonstrator

Figure 1: Helicopter EC 135 and tail boom

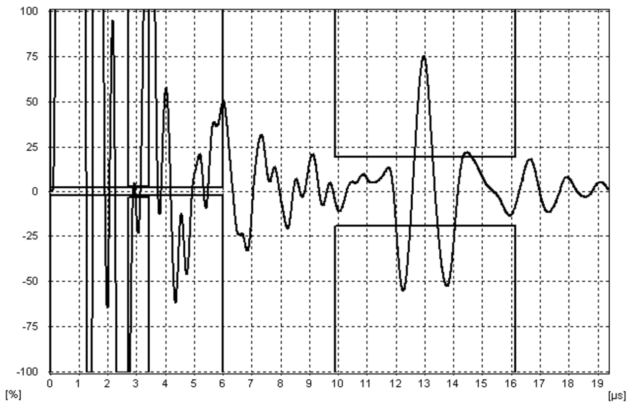
Fig. 1 shows the EC 135 helicopter of the DLR which is used a flying simulator and a tail-boom demonstrator. The 3.49 m long and 0.57 m wide tail boom consists of an anti-symmetric honeycomb sandwich structure (skin thicknesses 1.0 and 0.5 mm). In comparison with laboratory sandwich specimens this “real” component has different skin thicknesses and contains an integrated mash for lightning protection and several inserts (mounting parts). Three tail boom components are investigated within the EU project AISHA (Aircraft integrated structural health assessment) [2]. The ultrasonic technique enables the detection of defects in sandwich components because of the changes of the acoustical impedances. However the inserts and the lightning protection also influence the acoustics properties. Therefore the complex contraction requires optimized and adapted NDT methods for impact detections. Usually the ultrasonic testing of sandwich components is carried out in through transmission with squirter technique [3]. Other ultrasonic methods are air-coupled ultrasonic technique [4] and echo-technique [5].

2. Ultrasonic echo-technique

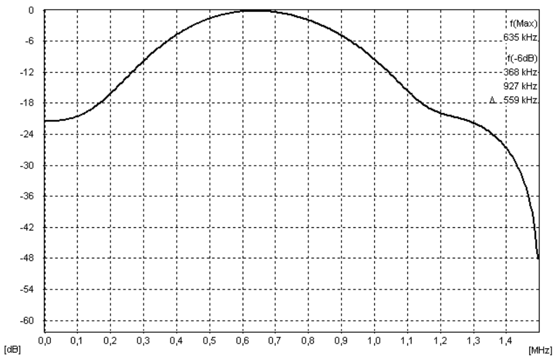
A tail-boom specimen (cut out of another tail-boom) with a 5 J impact has been used for the ultrasonic investigations in echo-technique. Figure 2.1 shows the mobile scanner MUSE on a tail boom specimen. Vacuum pads provide a save fixing of the scanning system. The cardanic fixture of the transducer enables the scanning of curved components. The coupling is carried out by water spilt. The transducer is a broadband type with a frequency range of 0.8 to 3 MHz. For the investigations the USPC 5000 has been used [6]. This portable device contains two systems: one ultrasonic imaging system with a motor controller for the MUSE-scanner and a multiplexed high signal to noise eight channel system with 64 cycles and data logger for Guided waves testing.
The ultrasonic part of the USPC 5000 has been used for the echo-technique investigations. The A-scan (Figure 2.2) shows an overdriven interface echo, a region of scattering and a clear back wall echo 11.2 µs after excitation. The applied broadband excitation with a spike pulse provides a high axial resolution. The sound scattering caused by the inhomogeneous has been reduced by the 3 MHz low-pass filter of the ultrasonic hardware. The spectrum of the back wall echo of the component (measured in the gate showed in 1.2) displays a frequency region of 368-927 kHz (-6 dB). The skins can be penetrated with frequencies up to 15 MHz. However, the honeycomb core only transmits frequencies below 1MHz. The reason is a double mode conversion from longitudinal to Guided waves at the interface between skins and core [7].
During scanning of the tail-boom specimen a full wave data file has been recorded. After scanning data processing were carried out. The A-scans were software filtered using a high-pass of 325 kHz and a low pass of 812 kHz (4^{th} order IIR-filters). The calculated C-scan shown in Figure 2.3 presents a clear indication of the impact. Along the horizontal marked line an echo dynamic curve (Figure 2.5) and a B-scan (Figure 2.5) are calculated. The echo dynamic shows an amplitude decrease of -24 dB caused by the impact. The software filtering enables an additional amplitude decrease of 4 dB, a higher signal to noise ratio and a clearer damage indication in the C-scan.



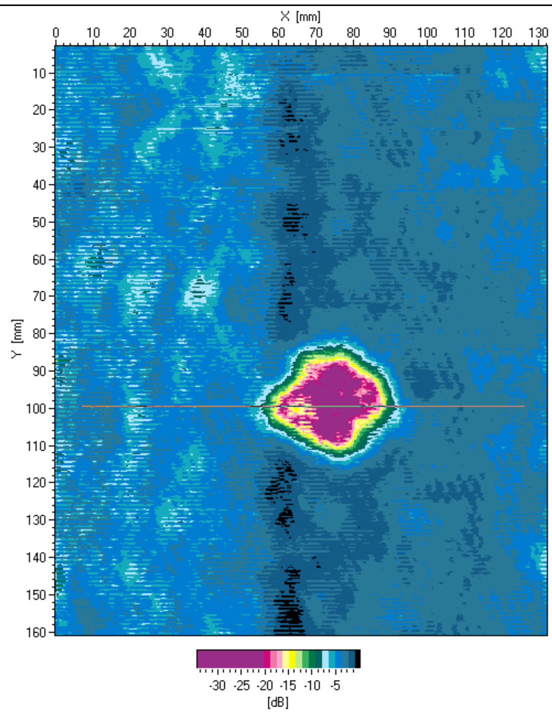
1: MUSE-scanner on the tail-boom specimen



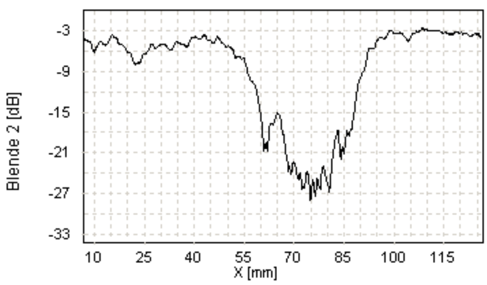
2: A-scan with back wall echo and gate



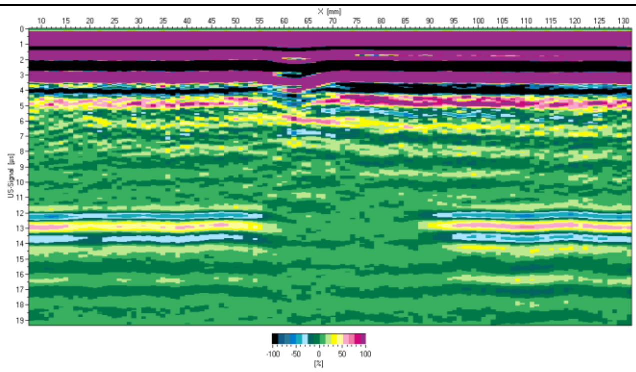
3: FFT of back wall echo, frequency range: 368 - 927 kHz, -6dB



4: C-scan with marked line for echo-dynamic and B-scan



5: Echo-dynamic curve



6: B-scan (longitudinal view)

Figure 2. Ultrasonic testing of the tail-boom with echo-technique

The B-scan indicates the overdriven interface echo (0-5 μs), scattering amplitudes from the upper skin with foils and mash (~5 μs) and the back wall echo (~13 μs) which is missing in the area of the impact. This echo-technique can easily been applied and can also be successfully used for in-field inspections.

3. Guided Waves Techniques

3.1 Survey

The more “classic” ultrasonic imaging technique with longitudinal waves requires an optimization of pulse parameters and delivers high resolution impact detection. Longitudinal waves are testing punctually so that a time consuming scanning is required. Guided waves can penetrate large areas with a small attenuation and interact with defects like delaminations [8]. Piezoelectric lead zirconate titanate (PZT) elements can be successfully used as senders and receivers for Guided waves [9]. For damage detection in a component a network of PZTs is necessary. For an active system usually one PZT is used as an actuator, the PZTs in the surroundings are receivers. However the received signals are much more complex than a classic ultrasonic signal. The reasons are the presents of at least two wave modes for each frequency (anti-symmetric A- and symmetric S-modes) which are dispersive and reflections from edges and stiffness changes. Especially for composite materials the interaction between the propagating wave and a defect is complex and difficult to calculate. There are reflections and mode conversions. A dispersion diagram shows the velocities of the different wave modes in dependence of the product of thickness and frequency. Therefore many authors use a narrowband excitation signal in the lower frequency range in which only the S_0 and the A_0 modes exist [10]. The calculation of a dispersion diagram for the helicopter tail-boom is a challenge because of its complex construction and of the missing of the exact material properties. Therefore experimental methods described below were used.

3.2 Visualization of wave propagation

Because of the complex propagation of Guided waves in sandwich constructions and interactions with defects different methods of visualization of wave propagation have been taken in account. The measurements are usually carried out by scanning laser interferometers [11] which are very expensive. At DLR in Braunschweig, we have experience in ultrasonic imaging techniques for

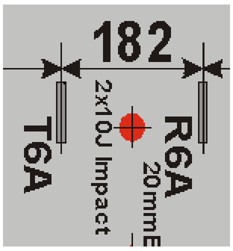
CFRP components. Therefore we have successfully combined Guided waves techniques and ultrasonic imaging in order to visualise the wave propagation. For this enterprise we use one fixed PZT at the component and a scanning sensor as a receiver [12]. First investigations have been carried out with a water slit coupled PZT. The water changes the acoustical properties so that the wave propagation is influenced. Therefore we developed a non contact technique. An air coupled sensor is used [13]. There are air coupled ultrasonic transducers which have usually relative narrowband characteristics with centre frequencies like 50, 120, 200 and 300 kHz [14]. There are also broadband capacitive sensors available in the frequency up to 100 kHz. For the tail boom sandwich structure frequencies below 30 kHz are useful. We developed an ultra low noise preamplifier combined with a high and low pass filter for this type of sensor. The filters not only suppress the electronic noise but also unwanted acoustical noise. The preamplifier is connected to the USPC 5000 ultrasonic system which also generates the burst signal for the excitation.

During scanning a full wave data file up to 20 GBytes is recorded. This is the same file type which is also used for ultrasonic imaging technique. Therefore B-, C-, and D- scans can be calculated. At DLR a software for the calculation of video clips out of full wave files has been developed [15]. Additionally the software provides several signal enhancement tools.

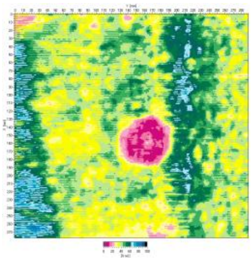
3.3 Tail Boom

The objective is to detect 5 J-impacts in the tail boom using Guided waves. Therefore several impacts have been performed in the tail boom 1. Figure 4.1 shows the position of a 20 J impact between two PZTs. The C-scan (Fig. 4.2 presents a clear indication of the impact.

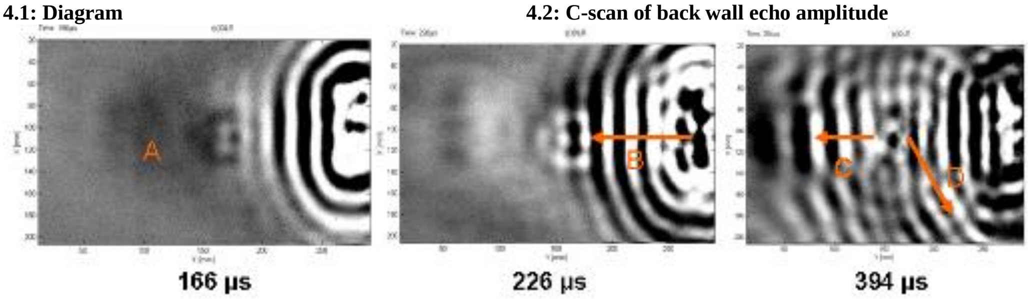
Fig. 4 presents a series of video snap-shots calculated of the recorded 3D-file. The excitation of R6A is carried out with three bursts pulses of 18 kHz. There are two wave modes excited: a faster one (symmetric (S_0)-mode) with very low amplitude and a slower one (anti-symmetric- (A_0-) mode) with high amplitude. The snap-shot 166µs after excitation shows the S_0-mode at position A and the powerful A_0-mode around the excitation zone on the right hand side. The square piezo-patch generates a parallel wave front of the A_0-mode. The S_0-mode interacts with the impact. This interaction produces an additional A_0-mode (video snap shot 226µs) with a circular propagation in opposite to the excited A_0-mode by the piezo-patch (video snap-shot 394µs). The interference of the two A_0- modes is clearly indicated (D in video snap-shot 394µs). Behind the impact the propagation of the A_0-mode is delayed indicated by a displacement of the parallel wave propagation (C in video snap-shot 394µs).



4.1: Diagram



4.2: C-scan of back wall echo amplitude



4.3: Video snap-shots

Fig. 4: Impact between T6A and R6A at tail-boom 1

Using an excitation of 22 kHz the following parameters for A_0-mode and the S_0-are calculated out of a B-scan:

A_0-mode: 550 m/s, wavelength 25 mm

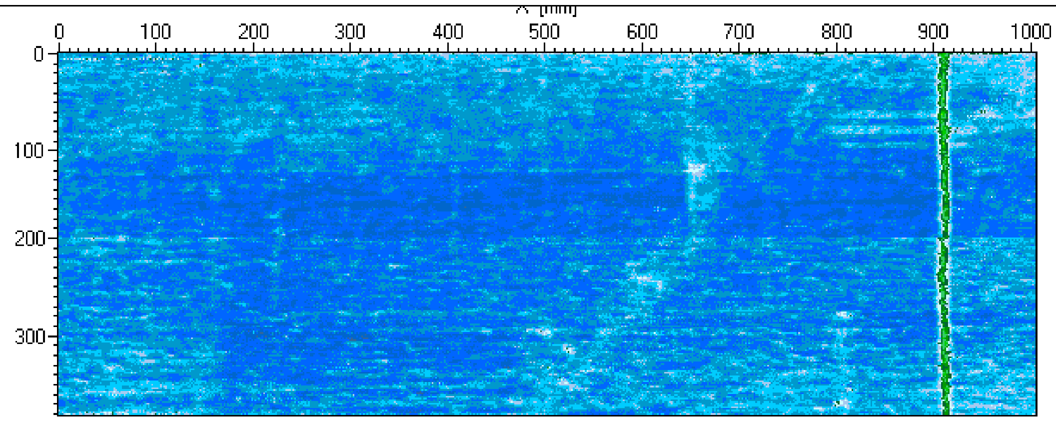
S_0-mode: 4000 m/s, wavelength 185 mm

The idea for damage detection was the application of the mode conversion from S_0- mode to the A_0-mode at defects. The optimum actuator length is equal to the half wavelength of the S_0 mode which means in our application about 93 mm. Because of the curved component the flexible PZT-DuraAct® PZT patches developed at DLR-FA in Braunschweig can successfully be used for the investigations [16]. However a maximal length of 70 mm was possible.

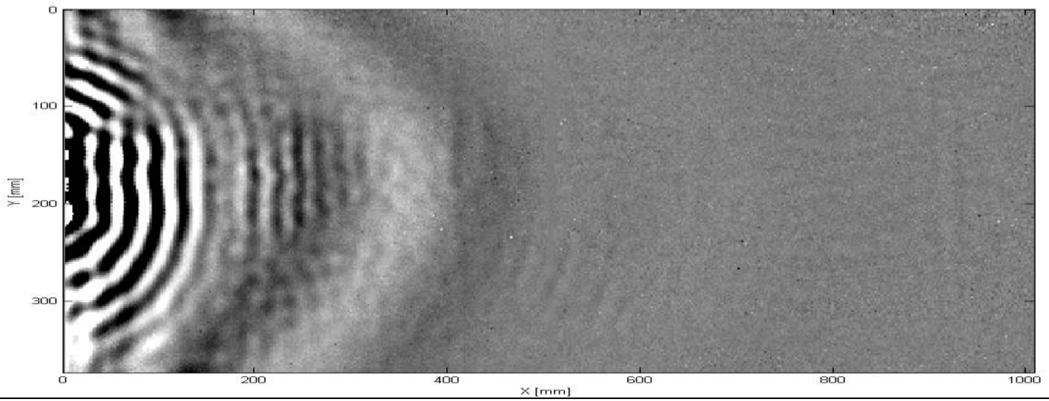
The converted A_0-mode can be picked up by network of several smaller PZTs optimised for a wavelength of 25 mm (diameter ~12 mm).

Before we started the Guided wave investigations at a second non-damaged tail boom ultrasonic inspections in echo-technique were carried out. In order to investigate a larger area the flex-scanner of the DLR with a scanning area of 1x1.5m was used in combination with the HFUS 2400 ultrasonic system.

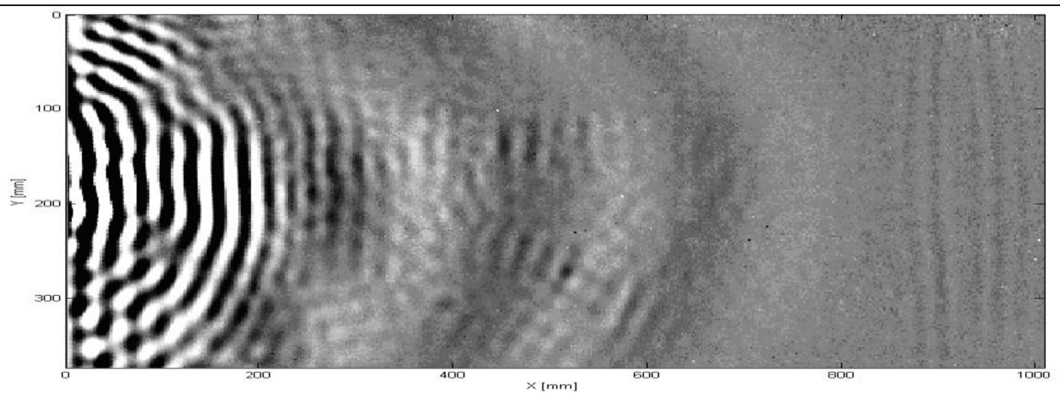
Fig. 5.1 presents the ultrasonic C-scan with an area of 1000 mm to 400 mm. Along the line at x= 910 mm an amplitude decrease of about 12 dB is indicated. The reason for this indication can be an internal bonding between two parts of honeycomb core. This bonding is not visible from outside. Apart from some inhomogeneities no real defects are displayed.



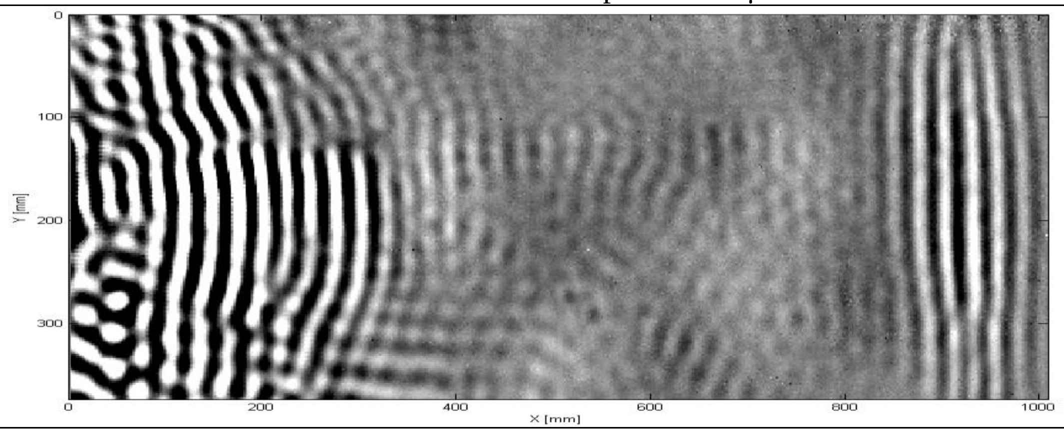
5.1: Echo-technique C-scan



5.2: Video snap-shot 251µs



5.3: Video snap-shot 404 µs



5.4: Video snap-shot 548 µs

Fig. 5: Ultrasonic and Guided waves investigations of the section 1 of tail boom 2

For the following investigations with Guided waves the same flex-scanner and the same ultrasonic system have been used. The excitation of the PZT bonded parallel to the y-axis of the component produce the wave propagation shown in Figures 5.2 to 5.4. The video snap-shot in 5.2 presents the S_0-mode propagation until 400 mm in x-direction, a first weak mode conversion at x=250 mm and the strong propagation of the A-mode on the left hand side. Snap-shot 5.3 indicates a further wave propagation of the strong A_0 mode and the S_0 mode and further a weak mode conversions between x=400 and 600 mm. On the right hand side, a weak converted A_0 mode is displayed.
548 µs after excitation (snap shot 5.4) a strong A_0 mode is visible on the right hand side. However the transmitted A_0-mode by the PZT on the left hand side already has been propagated until x= 350. At the position x=910 where the strong mode conversion is detectible, also in the ultrasonic C-scan a line with an amplitude decrease can be observed (bonding of two core parts?). At this position a virtual A-mode actuator provides plane wave propagation to its left and to its right side.

4. Conclusions

The impact sensitivity of high performance components like sandwich materials with thin layers of GFRP or CFRP and honeycomb cores requires a reliable non-destructive testing. An impact not only damages the skin but also the core. This paper deals with ultrasonic imaging with echo-technique and Guided waves-techniques. The ultrasonic imaging technique for one sided access with echo-technique has been optimized with software high- and low-pass filters and can be used also for in-field inspections.

The complex construction of a “real” sandwich component like the EC 135 tail-boom is totally different from laboratory specimens. The curved construction, inserts and lightning protection layers and internal bondings of honeycomb core is a challenge especially for Guided waves testing. Calculations of the dispersion diagrams were not successful because of the unknown material parameters. The wave propagation in such sandwich components is complex and difficult to predict. Experiments showed that only excitation with frequencies below 30 kHz generate wave modes which propagate in both skins and in the core which is important for damage detection. The evaluation and interpretation of the complex signals received by surface mounted PZT sensors is not possible without the knowledge of the wave propagation and the results of ultrasonic imaging.
The scanning of a Guided wave field with an ultrasonic imaging system, the collection of full-wave A-scans and calculation of B-scans and video-snap-shots deliver all information of the wave propagation in a component. B-scans enable the computation of mode velocities and also clearly show mode conversions. The wave propagation can be impressively demonstrated by videos. At all

positions with changes of the local stiffness mode conversions from the S_0-mode into the A_0-one can be observed. In principal a defect sensitive inspection system can be developed. It should be noted that the large area propagation of the S_0 mode is disturbed by internal bondings between core plates. This additional mode conversion has to be taken in account. The detection of additional A_0 modes can be successfully used for impact detection.

5. Acknowledgement

The investigations have been supported by the European Commission (EU project AISHA :Aircraft integrated structural health assessment, contract no. EU-FP-CP 212912). The authors would like to thank the European Commission and all partners for their support.

5. References

[1] S. T. Peters: Handbook of Composites (2nd Edition), Springer, 1998, ISBN: 978-0-412-54020-2

[2] H. Pfeiffer, M. Wevers, “Aircraft Integrated Structural Health Assessment – Structural Health Monitoring and its implementation within the European project AISHA”, ndt.net, http://www.ndt.net/article/aisha2007/papers/aisha6.pdf .

[3] S. Gripp: A Twin Robot Approach for UT Inspection and Porosity Evaluation of Complex Shaped Helicopter Components, ECNDT 2006 - We.2.1.2 .

[4] W. Hillger, R. Meier, R. Henrich: Inspection of CFRP components by ultrasonic imaging with air coupling, Insight Vol 46 No3 March 2004, pp 147-150.

[5] W. Hillger: Ultrasonic Testing of Composites - From laboratory Research to In-field Inspections, WCNDT Rom 2000, 15. -21.10. 2000, Conf. Proc. on CD ROM and http://www.ndt.net/article/wcndt00/papers/idn559/idn559.htm .

[6] Ultrasonic systems see: www.dr-hillger.de

[7] Stycek, J.O.; Grandia, W.A.; Loertscher, H.: Wave modes produced by aircoupled ultrasound, NDTnet-May 1997, Vol.2 No. 05.

[8] Zhongqing Su, Lin Ye, Ye Lu : Guided Lamb waves for identification of damage in composite structures: A review, Laboratory of Smart Materials and Structures (LSMS), Centre for Advanced Materials Technology (CAMT), School of Aerospace, Mechanical & Mechatronic Engineering, The University of Sydney, NSW 2006, Australia.

[9] R.A. Badcock, E.A. Birt, The use of 0–3 piezocomposite embedded Lamb wave sensors for detection of damage in advanced fibre composites, Smart Materials and Structures 9 (2000) 291–297.

[10] Michael D. Seale* and Barry T. Smith, Lamb wave propagation in thermally damaged composites, The College of William and Mary, Williamsburg, VA 23187.

[11] B. Köhler, M. Kehlenbach, R. Bilgram: Optical Measurement and Visualization of Transient Ultrasonic Wave Fields, Acoustical Imaging, Vol. 27, Edited by W. Arnold and S. Hirsekorn, Kluwer Academic/Plenum Publishers, Dordrecht & New York, 2004, pp.315-322

[12] W. Hillger: Visualisation and Animation of the Lamb Wave Propagation in Composites, Proceedings of the 6th International Workshop on Structural Health Monitoring 2007, Stanford University, Stanford, CA, September 11- 13, 2007,
Vol.1, pp. 145-152.

[13] W. Hillger, A. Szewieczek, Propagation of Guided Waves and their Interactions with Defects in a Composite Tail Boom Structure, Proceedings of the 7th International Workshop on Structural Health Monitoring 2009, Stanford University, Stanford, CA, September 9 - 11, 2009, Vol. 2, pp. 2234 - 2241.

[14] Bhardhwaj, M. C.: High efficiency non-contact transducers and very high coupling piezoelectric composite, 16th World Conference on Non-Destructive Testing, Montréal, Canada, August, 30. to Sep. 03. 2004, Conf. Proc. on CD.

[15] A. Szewieczek, W. Hillger, Analysis of 3D-Acousto Ultrasonic's Data files,, Proceedings of the 7th International Workshop on Structural Health Monitoring 2009, Stanford University, Stanford, CA, September 9 - 11, 2009, Vol. 2, pp. 1375 - 1381.

[16] P. Wierach: "Elektromechanisches Funktionsmodul" (Electro-mechanical functional module), German Patent DE 10051784 C1, August 2002.