

# Damage Detection in a Helicopter Composite Tailboom by Mode Conversion of Lamb Waves

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## ABSTRACT

Lamb waves (LWs) can be easily excited and received by piezoelectric patches, are able to propagate over large distances and interact with defects. Therefore these waves are attractive for active Structural Health Monitoring (SHM) systems. DLR-FA was involved in the EU project AISHA II. The research was focussed on impact detection in a helicopter EC 135 tailboom. This complex honeycomb sandwich component with a length of about 3.5 m is totally different from “laboratory specimens” because of an asymmetric construction with skins of GFRP and CFRP and several copper mesh foils for flash protection. First investigations show that LWs with frequencies below 30 kHz propagate through the whole thickness what is important for impact detection. The classic method with a network of switched piezoelectric patches used as sensors and actuators failed for damage detection. For analysing the wave interaction with defects a visualisation of the wave field using air-coupled ultrasonic technique has been developed. This visualisation showed mode conversions from  $S_0$  to  $A_0$  at all stiffness changes: core bondings, impacts and even at glued piezoelectric sensors. The more glued sensors the more complex the wave field is. Based on these results a concept of damage detection in the tailboom has been developed. This concept uses mode conversion as an indicator for damages. In order to have a minimal additional distortion of the wave propagation only few actuators are applied on the structure at positions with “natural” mode conversions. The 64 sensors are air-coupled and arranged in eight arrays with multiplexers. This paper presents details about the wave propagation, the demonstrator system, and shows first results of damage detection.

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## INTRODUCTION

The DLR part of AISHA II contains the impact detection in a 3.5 m long EC 135 honeycomb composite Tailboom using Structural Health Monitoring (SHM) based on Lamb Waves (LWs). Several half cell parts were delivered by Eurocopter in France for investigations. This component is totally different from laboratory specimens because of the asymmetric and curved construction, internal core bondings and the lightning protections layers at some positions.

Many authors report that LWs can penetrate large areas with a small attenuation and interact with defects and promise a “push bottom”- inspection without time consuming scanning [1]. However, the “classic LWs” technique consisting of networks of glued piezoelectric patches with are multiplexed for senders and receivers for LWs failed in our application. The received signals are very complex and difficult to interpret. Therefore an air-coupled ultrasonic method for the visualization of the LW propagations has been developed at DLR-FA [2]. Additionally ultrasonic investigations (advanced ultrasonic scanning) were necessary for the support of LWs investigations. For this method an actuator for the excitation and a scanning air-coupled sensor for the recording of the out of plane components of the LWs are used. The recorded full-wave data set contains all relevant data of the LW-field. The investigations showed that a frequency of 22 kHz simultaneously generates an  $S_0$  mode with a phase velocity of 4000 m/s (185 mm wavelength) and an  $A_0$  mode with 550 m/s (25 mm wavelength) into the sandwich part of the EC 135 tailboom. Both modes penetrate both skins as well as the core. This penetration of the whole thickness is important for damage detection. An impact causes damage as well in the skin and in the core. Additionally ultrasonic B-scans showed that the core damage is much larger than those in the skin [3].

It has been already published that impacts cause a mode conversion from  $S_0$  to  $A_0$  [4]. This effect seems to be more successful than the standard methods of LW-testing with a network of PZTs for sending and receiving. This paper describes the LW investigations, hard- and software developments, a demonstrator system and first results of impact detection using mode conversion technique.

## LAMB WAVE INVESTIGATIONS

Fig. 1 shows a video snap-shot a of 1 m long section of the tailboom. In this range a 10 J impact ( $x= 500$  mm) and a core bonding ( $x= 1000$ mm) are situated. The actuator is bonded on the left hand side. The strong wave field indicates the  $A_0$ -propagation from the actuator. While the  $A_0$ -mode does not yet have reached the defect, there is an additional  $A_0$ -mode propagating around the impact. A local  $A_0$  source can also be detected at the internal core bonding ( $x=1000$ mm). These  $A_0$ -modes are generated by mode conversions  $S_0$  to  $A_0$ . Such conversions can be observed at all local stiffness changes, also at glued piezo patches with diameters of 10 mm [4].

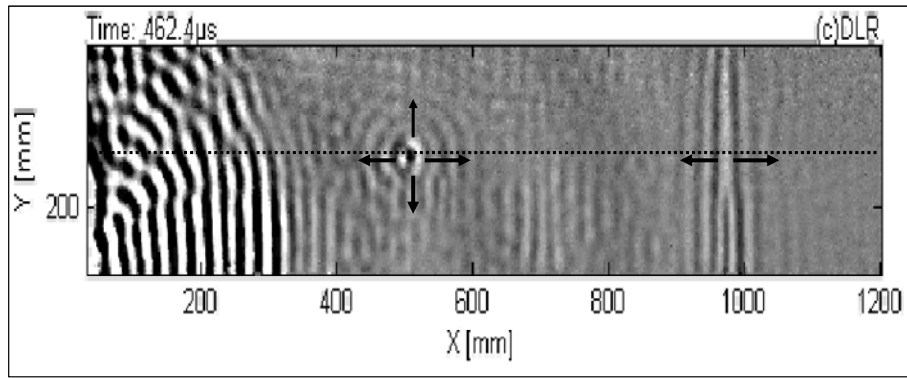


Figure 1. Video snap-shot of the Tailboom.

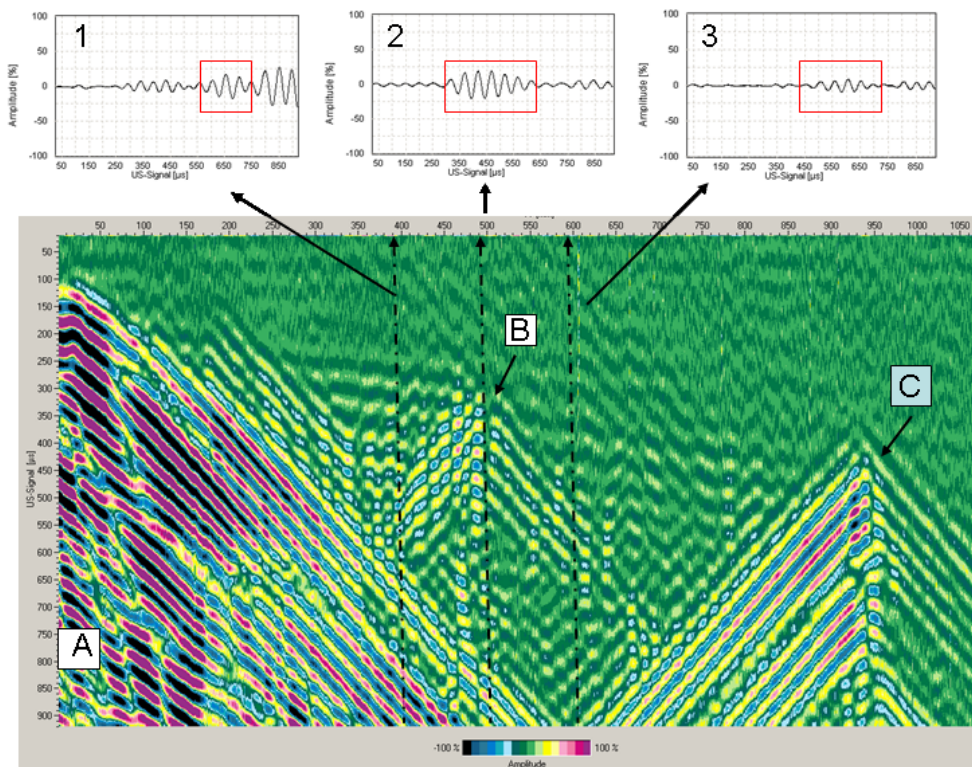


Figure2. LW-B-scan and A-scans 1, 2 and 3.

Figure 2 presents a B-scan along the dashed line in Figure 1. At position A the actuator is situated, position B represents the impact and C the core bonding. The indication of the  $S_0$  mode propagation is very low; the amplitude partially disappears into the noise. In opposite to this the display of the  $A_0$ -mode is very weak. The reason is the different out of plane component of the  $A_0$ - and the  $S_0$ - mode. For low frequencies the out of plane component of the  $A_0$ - mode is much larger than those of the  $S_0$ - mode. The air-coupled sensor is only sensitive for the out of plane component and therefore a mode selective sensor.

Three A-scans (1, 2 and 3) calculated along the dashed lines represent different positions for sensors. A-scan no. 1 is 10 mm away from the impact, no. 2 is directly at

the impact and no. 3 is 10 mm away. The signals caused by mode conversions at the impact are situated in the marked red ranges in the A-scans. The signal to noise ratio is influenced by noise coming from internal layers for lightning protection. Therefore the influence of impacts in the LW-field is limited in a range of about 10 to 15 cm around.

It was already published that even glued piezoelectric patches with diameters of 10 mm influence the wave field by mode conversions in the same way like impacts with energies of 10 J.

## **NEW CONCEPT FOR DAMAGE DETECTION**

For impact detection in the tailboom a new SHM concept based on local mode conversions has been developed:

- Different kind of actuators and sensors
- Because of long range propagation with low attenuation only a few actuators, for  $S_0$ -excitation are necessary
- Core bondings and edges cause wave interacts and therefore are preferential actuator positions
- „Long-range“ LW technique provides a better separation between the S- and A- indications in the receiving signals
- Network of  $A_0$  sensors for the detection of local mode conversions caused by impacts
- Air-coupled sensors in order to generate no additional mode conversions

### *Selection of optimized actuators*

A pair of PZTs bonded back to back on opposite surfaces described in literature [1] did not deliver a mode selection in dependence of in-phase or out-of-phase electrical excitation. Additionally in a practical application it is not useful to have PZTs outside of a tailboom. Another possibility for mode selective sensors is the application of interdigital actuators which provide a wavelength selection [5]. Unfortunately their dimensions are greater than a wavelength (in our case 185 mm), which is much too large for a practical application. Within the AISHA II project a piezocomposite actuator was designed and manufactured. The layout of an appropriate piezocomposite is patented by the German Aerospace Center (DLR) and distributed on a brand name *DuraAct*® by PI Ceramic GmbH [6]. The *DuraAct*® transducer consists of a monolithic piezoceramic plate which is covered by a flexible electrode to provide a reliable and damage tolerant electrical contact. To form a piezocomposite the packaging of piezoceramic material, flexible electrodes and electrical contacts are embedded in a polymer.

### *Optimized sensors*

However, an air-coupled sensor does not interact with LWs and is sensitive to its out-of-plane component. Because of the large mismatch of the acoustic impedance

between air and PZT air-coupled PZT-elements are very ineffective. PZT-foils have much lower acoustic impedances but high electric impedance so that a preamplifier (impedance converter) is necessary. Electret microphone capsules are optimized for air-coupling and include a preamplifier. The frequency curve of such a microphone is specified in the audio range from 20 Hz to 20 kHz. During the last 20 years their technical data have been improved respective to frequency range and signal to noise ratio. Our measurements showed that a selected type can be used up to 30 kHz. Above this frequency we found a resonance and for >35 kHz a steep decay of the sensitivity.

## **HARDWARE AND SOFTWARE FOR A DEMONSTRATOR**

### *Sensor array*

For the damage detection in the sandwich part of the Tailboom eight sensor arrays each with eight sensors are necessary. In a first approach a Rohacell® fixture has been used. However, this material acted like a waveguide for the low frequency LWs so that a cross-talk between the sensors could be measured. Therefore new fixtures for the air-coupled sensors had to be developed. Figure 5 shows the fixtures made of foam material. No cross talk and no interaction with the Lamb waves could be measured.

### *Multiplexer Technique and Electronics*

The new concept requires 64 sensors and 3 actuators. The aim was a solution as simple as possible with a minimum of (shielded) cables from the tailboom to the SHM-system. Integrated SHM networks underlie different kinds of electromagnetic perturbation. A high signal to noise ratio of the measurements requires an optimized cable design and signal processing. On the other hand complex cabling of entire networks accompanies with a high own weight.

A weight-saving solution is a tree-like organization of multiplexer entities. Local groups of sensors can be connected to a multiplexer. Different multiplexers can be arranged together in dependence of the network layout for minimal cable usage. In this way a net-like construction of the network can be realized.

Figure 3 illustrates the tailboom demonstrator. The eight sensors of each array are connected to the sensor multiplexer via mini 50 Ohm coax cables. Its output is amplified by a low-noise pre-amplifier and connected to an array multiplexer so that only one coax cable connection to the SHM system for 64 sensors is necessary. Using a multiplexer with 3 Ohms on-resistance the amplifier at the multiplexer output could be saved. However, during development the demonstrator such a component was undeliverable. In any case the amplifier at the array multiplexer is necessary. A DC-coupled technique between sensors, multiplexer and amplifiers requires only a single 5V DC supply.

The actuators are multiplexed by relays so that only one actuator coax cable to the tailboom is necessary. It is easily possible to replace the relays by solid state relays in order to reduce the power consumption.



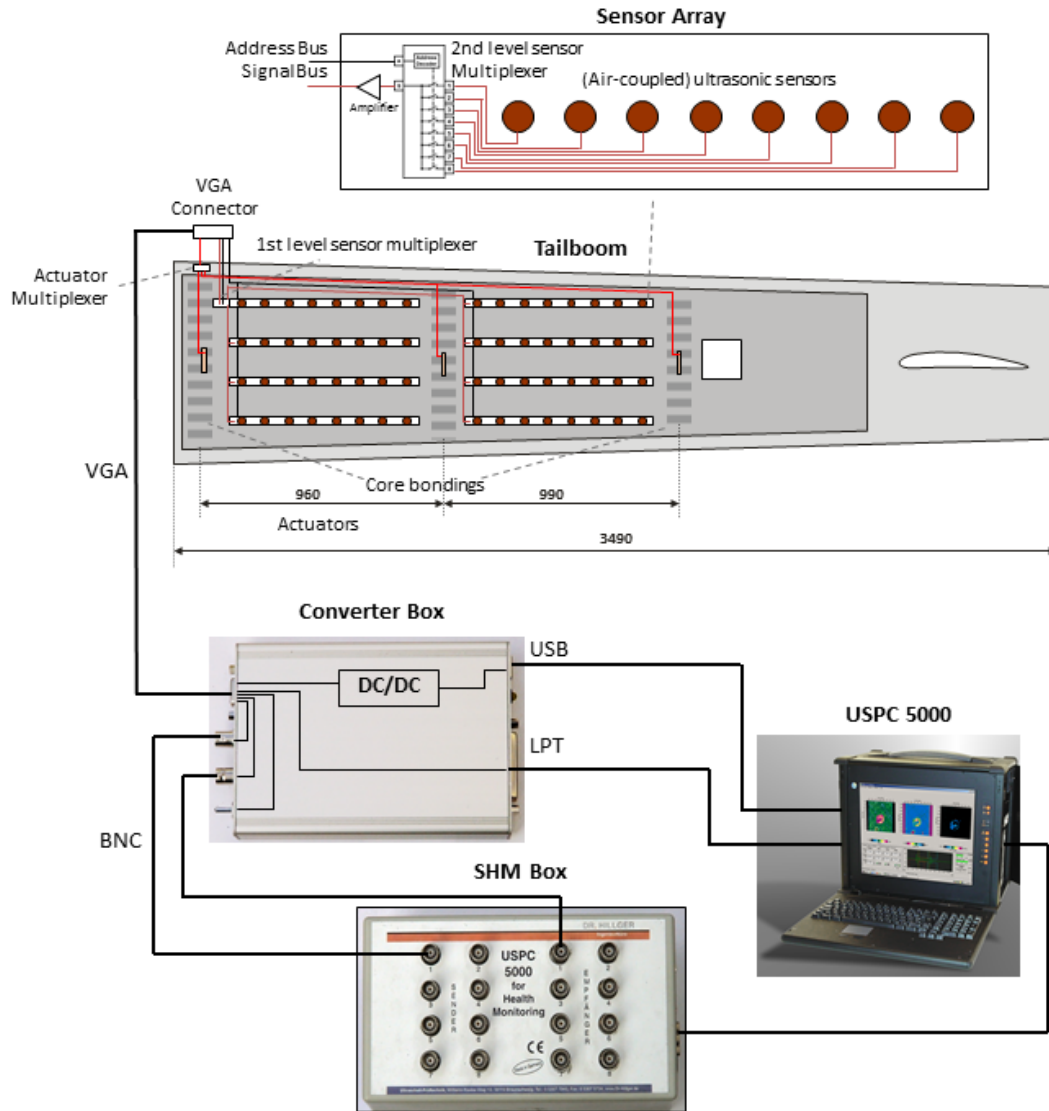


Figure 3. SHM Tailboom Demonstrator.

The addressing of all multiplexers is realized with parallel address busses. Because of just two multiplexer instances a serial bus is not necessary, but will be useful in the case of major networks.

An interface box was built for connecting the existing USPC 5000 equipment to the tailboom via VGA-cable. Such a standard VGA monitor cable contains three shielded coax-cables (75 Ohms) and ten control lines and is easily deliverable up to a length of 10 m. The multiplexed sensor signal and the multiplexed actuator are connected in each case to input one of the USPC 5000 Health Monitoring box. The internal hardware high- and low pass filters as well as software filters enable an optimal signal processing.

The SHM-system USPC 5000 usually operates with 8 actuators and 8 sensors in 64 cycles. Additional Hillgus-software manages a new kind of multiplexing so that the parallel printer port delivers the address data for the multiplexers in the tailboom. This software enables an automatic data recording using one selected actuator.

A DC/DC converter with noise filter and voltage stabilizer powered from an USB port delivers the supply for the multiplexers and pre-amplifiers.

## RESULTS

After recording three baselines of 64 sensors with three different actuators our partner CTA in Spain has implemented another three impacts in the tailboom with energies up to 15 J. The defects are barely visible with the naked eye (BVID: barely visible impact damage). Therefore at Centro de Tecnologias Aeronauticas (CTA) the impacts were verified by Infrared Thermography (IRT) and at DLR-FA with ultrasonic imaging [3].

Figure 4 shows an ultrasonic C-scan in echo-technique of the backwall echo. In opposite to three different defects caused by impacts are clearly indicated (1, 2 and 3). Additionally the internal core bonding ( $x=880\text{mm}$ ) and areas with amplitudes drops are visible. These areas contain lightning protection layers which cause increased attenuation. In opposite to IRT the ultrasonic technique indicates defects in skins and cores.

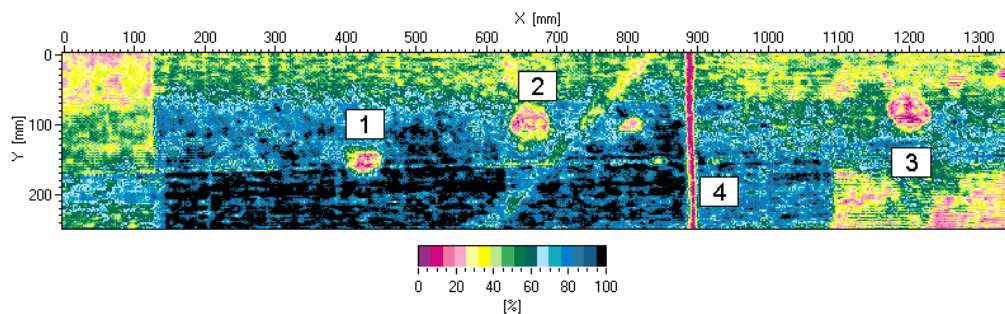


Figure 4. C-scan after Impacting.

In Figure 5 a part of the tailboom with marked propagation paths of the  $S_0$ -mode between the actuator A2 and the impact (red arrow) and between impact and sensor 6 (orange arrow) are shown. The A-scan indicates the difference signal of sensor 6 between the baseline and the signal after impacting. This difference signal with relative amplitude of 14 % is explicitly higher than the difference signal of the defect-free area (3%). This enables clear impact detection.

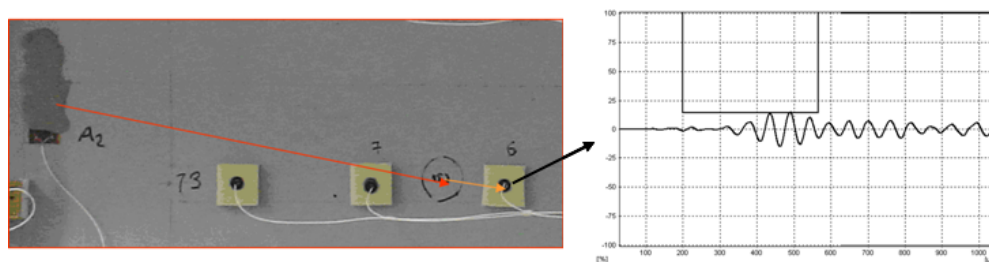


Figure 5. Principle of damage detection and difference A-scan.

## CONCLUSION

The visualization of LW propagation in the tailboom developed at DLR is the key technology for the development SHM systems for damage detection in complex structures like the EC 135 Tailboom. These investigations showed that the S-mode interacts with a mode conversion to the A- mode at a defect. This effect was used for damage detection. Because of the large area propagation of LWs the excitation is carried out only with one of three installed actuators. A network of 64 air- coupled sensors are used for receivers which do not interact with LWs. Actuator and sensor multiplexers enable only one cable from the tailboom to the LW equipment. For each sensor a special time range for damage detection has to be defined. This gate range depends on its position and of the position of the actuator. It seems that a simple difference between the baseline signal and the actual signal enables damage detection. An automatic evaluation is possible with a threshold in a gate range of a difference A-scan. The new develop method of LW mode conversion enables the indication of barely visible damages in complex components like the EC 135 Tailboom.

## 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.

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