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Structural Heath Monitoring using Lamb waves and visualization of their propagation in composites

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Abstract

Structural Health Monitoring (SHM) with Lamb waves principally provides an inspection of large areas without time-consuming scanning. Piezoelectric lead zirconate titanate elements (PZTs) are often used as senders and receivers for Lamb waves. However, the complex interaction between defects and Lamb waves -especially for composites, the present of two wave modes in minimum and its dispersive behaviour and reflections from all structure elements contribute to receiver signals which are very difficult to predict and to evaluate.

For SHM investigation we are using ultrasonic imaging as a complementary method which delivers the exact information about defects such as delaminations. This technique can also be used for the visualization of Lamb wave propagation in composites. For this method one bonded piezoelectric element is used as a sender and another one is scanned in a meander over the component. During scanning a full wave data recording is carried out. The data can used for the calculation of Lamb wave A-, B-, C- and D-scans and for video animations which show the propagation impressively. The control of the PZTs and of their acoustic coupling to the component is very important and can be carried with impedance spectroscopy. The phase of the complex impedance in the range of the resonance frequency delivers the best information.

Impact detection in CFRP laminates is possible with Lamb waves in spite of edge reflections using gated amplitude measurements.

Keywords: Lamb waves, visualization of Lamb wave propagation, ultrasonic imaging techniques, carbon fibre composites, damage detection, Structural Health Monitoring (SHM)

1. Introduction

Damage Detection in industrial components is usually carried out by „classic“ Non-destructive testing (NDT) -methods like visual inspections, ultrasonic (imaging) testing, thermography, tap testing, eddy currents, and others [1]. The NDT-procedures are used for a quality control during or after fabrication, and during periodic scheduled inspections of critical parts such as primary aircraft components. These techniques have in common that the sensors and the equipment are not combined with the components to be inspected. In opposite to these classic“ NDT-methods Structural Health Monitoring (SHM) uses sensors and actuators which are permanently attached to the component.

The first step in direction of SHM was carried out by A. Vary who introduced the Acousto Ultrasonics [2-4] in the late 70th. Acousto Ultrasonics combines parts of ultrasonic testing, guided wave techniques and acoustic emission. Acoustic emission is a passive method; the sensors are permanently active and only receive a signal during damaging. Therefore no excitation is required.

Acousto Ultrasonics (AU) means the penetration of stress waves into a component, using a probe for the excitation and another one at another position for the reception. Due to the high frequency (broadband) excitation (above 0.5 MHz) a large number of different modes are generated. The received signal is very complex and difficult to evaluate. The evaluation of the “stress wave energy” is often carried out by acoustic emission parameters.

In opposite to AU Guided Waves Ultrasonics is based on well-defined wave modes. The generated waves can penetrate large areas and interact with defects and structural inhomogeneities. This “long-range ultrasonics” enables a damage detection and SHM without time consuming scanning. The most used guided waves are surface waves like Rayleigh waves and Lamb waves. These types of waves interact with defects and material discontinuities.

Lamb waves are the most used guided waves for damage detection. H. Lamb discovered these dispersive plate waves which are propagating in solid plate with free boundaries [5].
Lamb wave based damage detection provides the possibility to inspect large and complex structures in service.

However, the receiver signals of a Lamb wave based inspection system are complex because of the existence of two dispersive modes in minimum, the reflections from borders and structural changes and of the mode conversions at defects. Therefore the strategy of monitoring is extremely important for a successful damage detection [6]. In spite of hundreds of papers concerning Lamb wave testing only a few industrial applications are carried out. Lamb wave inspections of CFRP-components require a lot of research and developments.

2. Active Acousto ultrasonic system

2.1 Survey

Tab.1 displays the differences between ultrasonic imaging (UI) and Lamb wave testing. Using UI the transducer is moved by a manipulation system during inspection, Lamb wave based inspection is carried out with fixed transducers on the component. In order to generate defined Lamb wave modes, a narrowband technique is necessary. For UI in echo-technique, a broadband system is useful for high resolution. Also the frequency ranges for UI and Lamb wave testing are different. In Lamb wave testing mostly the s_0 and a_0 modes are used. These modes require frequencies below 1 MHz. Standard UI mostly uses frequencies in the range of 1 to 20 MHz.
For the evaluation of the received signals measurements of time of flight and gated amplitude measurements are carried out for UI, for Lamb waves testing additional FFT and STFT (short time frequency transformation) and further sophisticated signal processing methods are used [6].

	Ultrasonic imaging	**Lamb wave testing**
Transducer(s)	Scanning during inspection with manipulation systems	Fixed on the component, without device motion during inspection
Frequency range	0.5 to 20 MHz	10 kHz to ~1 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

Tab. 1: Ultrasonic imaging and Lamb-wave testing

2.2 Laboratory system

Fig. 1 shows the block diagram of a computer controlled laboratory system for active acoustic ultrasonics in order to identify defects in material components. The pulse generator (1) delivers the electrical excitation, which is amplified (2) and switched over to eight actuators situated on the component (4). In principle, each channel can be multiplexed by a second multiplexer 1:8 so that the number of channels increases to 64 channels.

Embedded or applied piezoelectric disks (PZTs) can be used as a transmitter and/or receiver for ultrasonic waves such as Lamb-waves. The wave modes penetrate the whole component and can be received by PZTs, air-coupled ultrasonic transducers, laser interferometers or optical fibres. In any cases the received wave signal is converted to an electrical signal which can be multiplexed (5) and amplified by a low-noise preamplifier (6). The further analogue signals processing are carried out by a high- (7) and a low-pass filter (8). The interface between the analogue and digital world is the analogue to digital converter (ADC) (9). The digital signal processing and evaluation is carried out by a PC with special software. An example of such a system is the USPC 5000 [7]. Differences in the receiving signals between the „baseline“ (reference, unloaded component) and the actual signal (e. g. after loading) provide damage detection. Because of these small differences a constant temperature during testing or temperature compensation is useful.

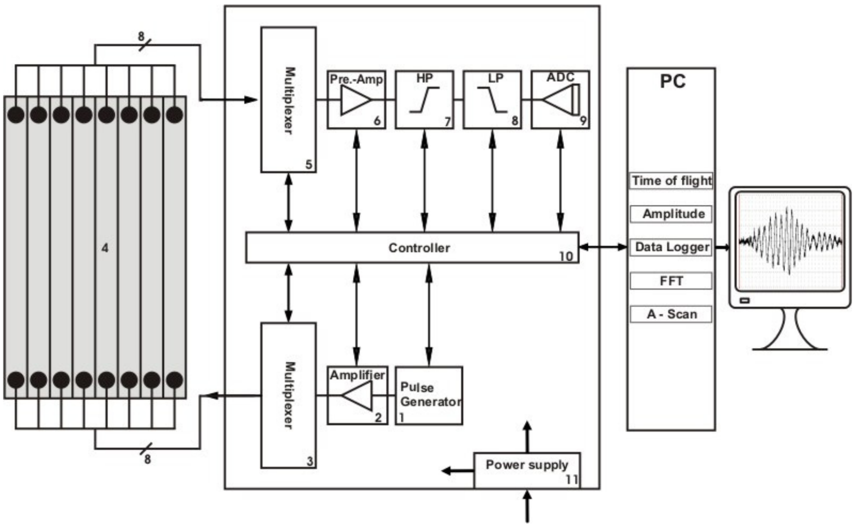


Fig. 1: Block diagram of an Acousto-Ultrasonics system

2.3 Piezoelectric elements

Because of their low weight (i.e. 0.6 g for a 10 Ø mm disk), low cost and broadband frequency range Piezoelectric lead zirconate titanate elements (PZTs) are the most widely used sensors and actuators for acousto ultrasonics. They can be successfully used for the excitation and reception of acoustic ultrasonic waves [8-10]. PZTs deliver an excellent performance in Lamb wave generation; their relative low impedance requires only a low driving voltage for the actuators (low power consumption). Because of the high degree of effiency from mechanical energy to electric one only a relative low gain of the receiver signal is required. Both the low impedance and the low gain provide a high signal-to-noise ratio of the received signal. A disc-like PZT wave actuator avoids uneven wave propagation. Equation (1) describes a criterium for an optimal design [11]:

$$2R = \frac{v_{wave}}{f}(n + \frac{1}{2}) = \lambda_{wave}(n + \frac{1}{2}), \quad \text{n= 1, 2, 3 …} \qquad (1)$$

R is the radius of PZT disk; v_{wave}, wave velocity, f_e frequency and λ_{wav} wavelength of a concerned Lamb mode, respectively.

The maximum driving voltage V of a PZT without depolarising is given by the maximum electrical field strength E:

$$E = \frac{V}{d} \leq 250 - 300 \text{ V/mm } [12] (2)$$

Equation (2) delivers f. e. the maximum driving voltage of 30V for a PZT with a thickness of 0.1 mm.

Fig. 2 shows a PZT disc with, 0.1 mm thickness (PI Ceramics, Germany) with a wrap-around electrode. This one provides a one sided electrical connection. The back side can be holohedrally bonded on the component so that an optimal acoustic coupling is reached. A coaxial cable (RG 174) is used for the connection between the PZT and the preamplifier. The shielding of this cable eliminates the electromagnetic noise coming from high power radio and navigation transmitters which are present in densely populated countries like Germany. The frequency range of these long wave- and medium wave transmitters is equal to that one for Lamb waves and acousto ultrasonics (100 kHz to 1.7 MHz).

The soldering terminal (right hand side of Fig. 2) eliminates the tensile loading from the coax cable. A tensile loading of a direct soldered cable would damage the silver contacting of the PZT. Therefore a one sided electrical connection of the PZT to the soldering terminal is carried by thin copper wires (20 µm Ø).

Fig. 2: PZT with wrap-around electrode (produced by PI Ceramics, Germany), soldering terminal bonded on CFRP specimen, and a coax-cable (RG 174)

3. Detection of impact damages in CFRP laminates

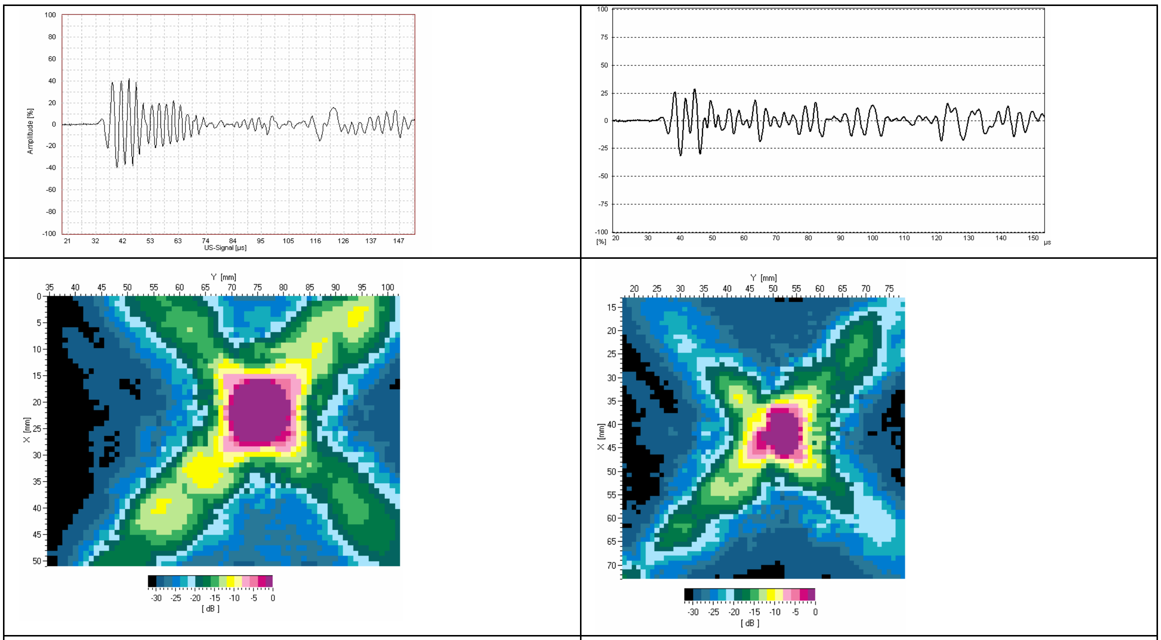
3.1 Lessons learned

First results of Lamb wave testing of CFRP laminates showed very large differences in the received signal before and after an 30 J impact (see Fig. 3, above). The impact was situated between the transducer and receiver PZTs. Because of the broadband excitation, simultaneously different wave modes are generated.

Receiving quite different receiver signals it is useful to check to PZTs and their acoustic coupling to the component.

The MUSE (Mobile Ultrasonic Equipment) [13] which provides ultrasonic imaging was used for quality control of the bonding of the PZTs. The system was set up in through-transmission mode. The PZT-patch under investigation is used as a sender. The CFRP component on the opposite side was used scanned by water gab coupled transducer. The C-scans in Fig. 2 present the area of the bonding before and after impacting the specimen. The position of the PZT patch is clearly visible (round red area). The constant amplitude indicates a perfect bonding. The sound spreads mostly in 45°- direction, which is the orientation of the fibres. In comparison with Fig. 2 left hand side, the dark red area of the patch on the right hand side is not round any more. This C-scan indicates debondings between the PZT and the component.

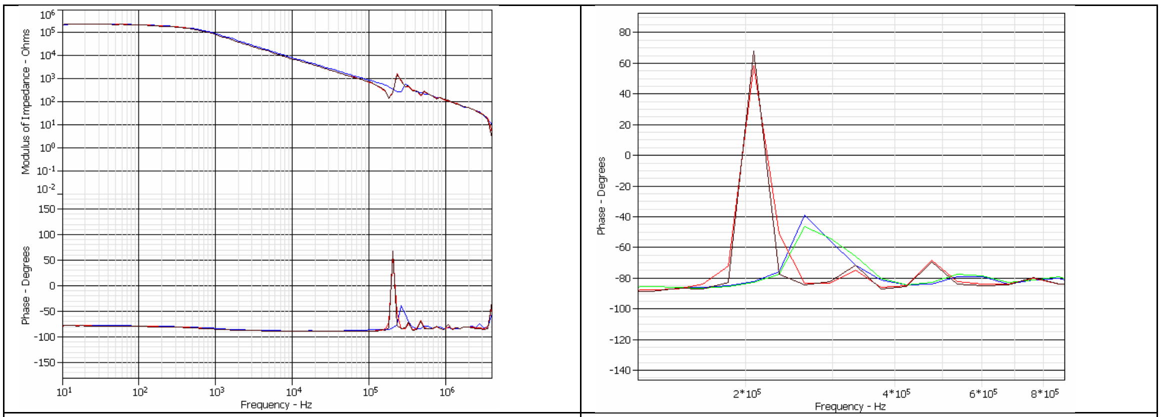
It is clearly visible that the propagation of Lamb waves is quite different compared to the situation before impacting. These results demonstrate the importance of a bonding control. A quantitative measurement of the bonding area can be provided by an amplitude histogram evaluation of the C-scans.



Received reference signal and C-scan of bonded PZT

Received signal after a 30 J impact and C-scan of a partly debonded PZT

Fig. 3: Received signals and C-scans of the bonded PZT before and after a 30J impact



Modulus of impedance and phase

Relevant part of phase plot

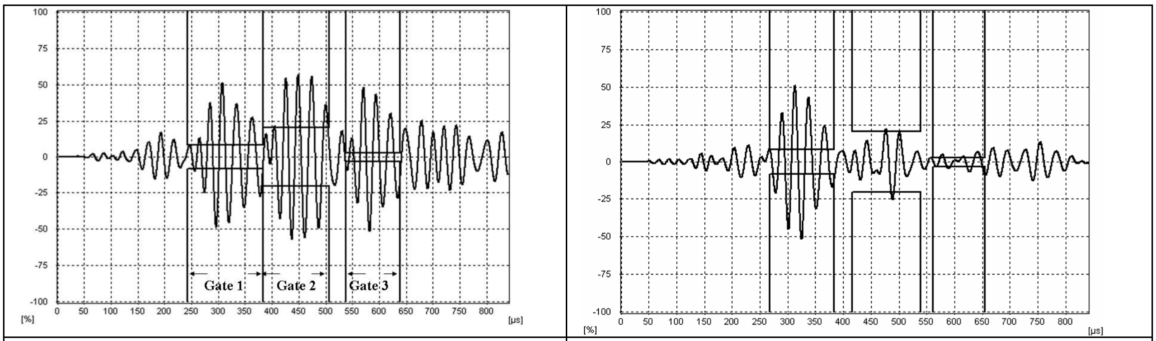
Fig. 4: Modulus of impedance and phase of the PI Patch PCL 255 10x0.5, black = free air operation; Red = water coupled; Blue = glued; Green = glued 10 min)

In order to get the results faster and easier the electro-mechanical impedance spectroscopy can be used for the testing of the PZT and of its acoustical coupling to the component [14-16]. The electrical properties of PZTs do not only depend on the PZTs itself and their electrical wirings but also very much on the acoustical coupling. The resonance frequency of a PZT without mechanical contact is different to the case where it is bonded to another solids. Also the quality of the bond can be analyzed with this method. This provides good potential for the application of SHM. By just monitoring the impedance in an appropriate frequency range we can identify good or weak bondings as well as (partial) separations/debondings. The USB-device C-60 (Cypher instruments) directly provides measurement of both impedance and phase within a frequency range of 10 Hz to 4 MHz.

Fig. 4 (left hand side) shows four curves of the modulus of the impedance and four ones of the phases of a PZT. The black curves are received from a free air operation, the red ones identify water coupled, the blue ones are recorded shortly after gluing on a CFRP component ("UHU plus" glue) and the green ones 10 minutes after gluing.
The operation in water does not differ significantly from operation in free air. But when glued, the PZT`s resonance frequency is shifted to a higher value. Also it is possible to identify that the resonance effect to the modulus of the impedance is lower when bonded to a solid. Fig. 4 (right hand side) shows the relevant part of the phase curves. The differences between glued and operation in air and water are clearly indicated at different frequencies and values of the phase.

3.2 Impact detection in CFRP laminates

A series of 2 mm thick CFRP specimens with dimensions of 360 mm to 100 mm with GFRP - cap strips (100mm to 100 mm) for the clamping of the test machine were used. Two PZTs for each specimen has been glued diagonal at the left side on the top and on the right side below of the CFRP area. A non diagonal placement of the PZTs would be effected a much higher interference by edge reflections (see 4.3). A burst excitation with 2 bursts and a frequency of 41.3 kHz was used. The harmonics have been suppressed by hard- and software filters on the receiver side (high pass 27.4 kHz, low pass 72,2 kHz). This excitation provides a relatively large bandwidth of 20.5 kHz which means 50% of the centre frequency. A smaller bandwidth which is in many cases benefiting for Lamb wave testing can easily be achieved by setting the receiver filter frequencies. However a smaller bandwidth gives longer pulse responses so that a separation of the three signals situated in the gate ranges (black rectangles) in Fig. 5 is not possible. The frequency spectrum of all wave packages is nearly constant.



Reference specimen (3.7.1)

Specimen with 20 J impact (3.6.4)

Fig. 5: Lamb-wave A-scans with gate ranges 1, 2 and 3 of monolithic specimens

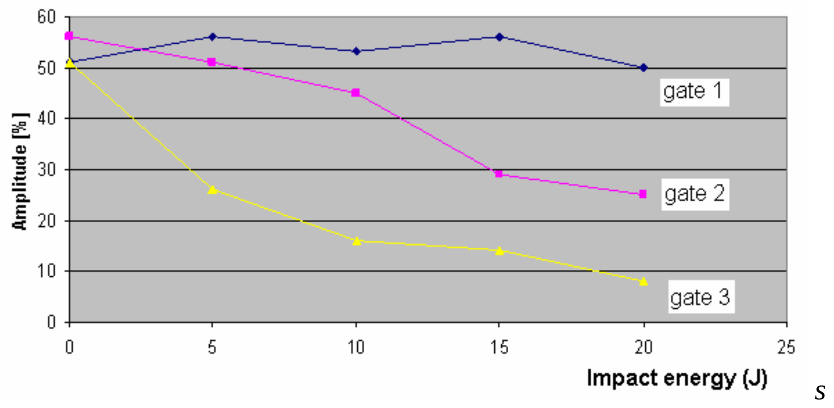


Fig. 6: Amplitudes measured in three different gates in dependence of the impact energy

The A-scans (Fig. 5) indicate four different wave packages, the first small signal starting at 50 µs, the second at 206 µs, the third at 380, and the fourth at 530 µs. The first wave package delivers no useful information; therefore the other three ones are evaluated with three gates. Fig. 6 presents the measured amplitudes in the different gates in dependence of the impact energy. Gate 2 and three are “interface triggered” by the threshold in gate 1. The amplitude in gate 1 is nearly constant and independent from the impact energy. This signal can be used for the system check. The second wave package presents a clear dependence of the impact energy. The amplitude decreases from 55% (0J) to 25% (20J). The amplitude in gate 3 changes from 51% to 9%. The reason that only the 3rd and the 4th wave package can be used for the damage detection is the interference between the directly propagating and the reflected waves.

4. Visualization of Lamb wave propagation

4.1 State of the art

The knowledge of the propagation of different Lamb wave modes and their complex interactions with structure elements, discontinuities and defects is a requirement for interpreting of the complex receiver signals and for optimizing all parameters of Lamb wave system such as test frequency, design, number and distribution of the transducers, required signal procession– and evaluation. Only for simple geometries the Lamb wave propagation can be calculated. Therefore experimental methods are used in order to get this important information.

A Scanning Laser Doppler Vibrometer (SLDV) measures the velocity component of the vibration in laser beam direction, usually in out-of-plane direction. The surface is scanned by the SLDV at points on a defined grid. Evaluating the data enables an experimental visualization of the wave propagation [17-19].

4.2 Visualization by ultrasonic imaging techniques

Another interesting method for the experimental visualization of the propagation of guided waves is the ultrasonic imaging technique. For this challenge, the USPC 5000 has been used which provides both ultrasonic imaging (reference method for defect detection) and Lamb waves testing. The ultrasonic imaging part of the system was used for the visualization of the Lamb wave propagation. One actuator at a fixed position on the bottom of the specimen has been used as a transmitter [20]. The excitation is carried out by a burst generator. Because of the harmonics a filter on the receiver side is used which provides a desired narrow band signal. A second PZT-patch is moved by an XY- scanner in a meander track. A scanning grid of 1.0 mm is used, which is smaller than a tenth of the Lamb wavelength. In order to get a reproducible acoustic coupling between the sensor and the component, a water gab coupling is used. During scanning at each point of the scanning grid, a full wave Lamb-wave A-scan is recorded. This 3D data file contains the amplitude information as a function of y- direction (scanning axis), x-direction (index axis), and of t (the time of flight).

Out of the 3D-data files several presentations like A-, B-, C- and D-scans and animations (videos) of the wave propagation can be calculated and presented [21].

4.3 Results

Fig. 7 presents on the left hand side the wave propagation in a defect free monolithic CFRP specimen (description see 3.2) with free edges. The actuator (PZT) is situated on the left hand side in the middle of the specimen. The three snap shots of a video animation are recorded after 100, 150, and 180 µs. An excitation frequency of 50 kHz was used. 100 µs after excitation the propagating is already nearly circular around the PZT. After 150µs the wave arrived at the right edge of the specimen, however edge reflections cause interferences with the direct propagating wave. After 180µs the reflected wave at the right edge delivers an additional interference so that the chaos is complete. Because of these distracting interferences the detection of defects becomes very difficult.

An additional acoustic damping of the upper and lower edges of the specimen reduces their reflectivity. For these procedures a special specimen attachment with Plasticine™ at the upper and lower edges has been developed. As a result (see Fig. 7, right hand side) a nearly undisturbed wave reaches the right edge of the specimen 150µs after excitation. The reflected wave indicates the PZT by a white circled area (180µs) which means a local change in the stiffness of the specimen.

5. Conclusions

SHM with Lamb waves provides defect detection without time consuming scanning. PZTs enable an effective excitation and a high dynamic reception signal. Lamb waves penetrate large areas, propagate with low damping and interact with defects. However, the received signals are very complex compared with echoes which have to be evaluated using ultrasonic imaging with longitudinal waves.

This paper reports results of the EU project AISHA. It has been found out that the received signal after an impact was totally different from the base line signal. The reason was not the not interaction between the defect and the Lamb waves but a partly disbanded PZT. The disbanding after impacting has been indicated by ultrasonic imaging. Therefore it is important to check the PZTs and their acoustical coupling before performing a Lamb wave test. Besides ultrasonic imaging the electro mechanical impedance spectroscopy is suited for the control of the PZTs and their acoustical coupling. Especially the phase of the complex impedance changes dramatically in the range of the PZT resonance frequency in dependence of coupling quality.

Ultrasonic imaging techniques are not only useful as a complementary method to Lamb wave testing in order to have a quality control of the test components and a 3D-information about defects but also for the visualization of Lamb wave propagation. The interaction with defects is important to know but difficult to predict. It was shown that the edge reflections in relatively small specimens produce a chaotic Lamb wave field. An acoustical edge damping with Plasticine™ provides a nearly undisturbed propagation so that impacts with energies from 5 to

20 J can be detected with Lamb wave testing. The visualization technique will also give important information for the optimization for a Lamb wave system for a helicopter tail boom full scale test.

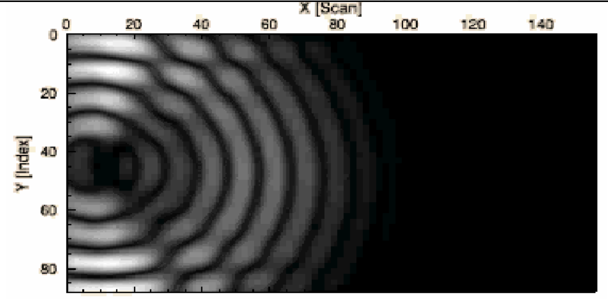
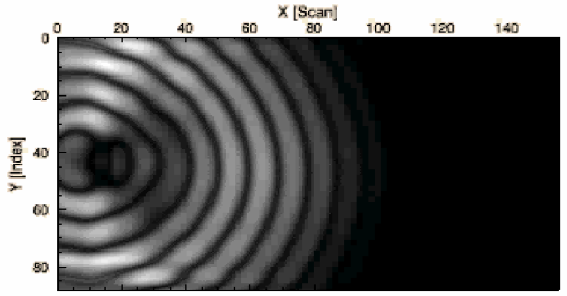
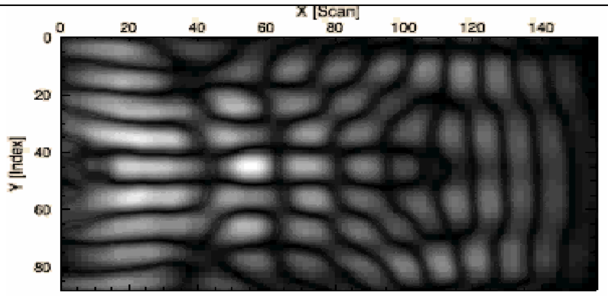
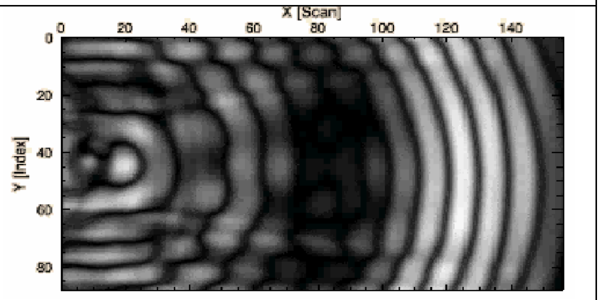
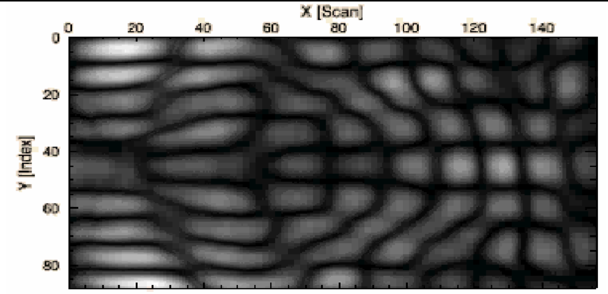
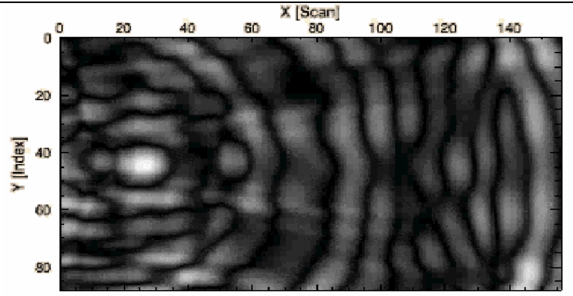
	Without acoustical edge damping	With acoustical edge damping
100µs		
150µs		
180µs		

Fig. 7: Snap shots form video animations with and without edge damping

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