SIXTH FRAMEWORK PROGRAMME PRIORITY 4

Project n°AST3-CT-2003-502907

Project acronym AISHA
Aircraft Integrated Structural Health Assessment

STREP instrument
Aeronautics and space

CONTENT:

Publishable Final Report

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PUBLISHABLE FINAL REPORT

1 INTRODUCTION

The structural health of engineering structures is threatened by material degradation due to corrosion, abrasion, fatigue stress and other sources. Reliable means of inspection are therefore required to operate the structure safely and failure-free. Based on this inspection, maintenance actions must be undertaken. Whereas a time-based inspection scheme has resulted in excellent reliability records for aircrafts, there is an essentially economic drive for the more innovative health automated monitoring procedures. Therefore, it has been proposed to switch from time-based towards condition-based procedures, where maintenance is only performed when a component is actually degraded. This requires a means of quasi-continuously assessing the structural integrity of the aircraft by a continuous damage monitoring system.

The project aims at realising an aircraft monitoring technology by using ultrasonic Lambwaves as the basic sensing principle. The special potential of Lambwaves for damage detection arises from their propagation capabilities (Fig. 1), i.e. Lamb waves are guided waves which propagate in-plane structures. There are a number of Lamb modes being a function of frequency and plate geometry. These different Lamb modes show selective sensitivity to different kinds of defects, such as cracks, delaminations and uniform thickness degradation. Both active and passive wave inspection will be explored, if possible also by including the innovative concept of multimode wave generation and reception. The information from these guided waves, combined with signal analysis routines and models for remaining lifetime prediction, is used in a full scale testing action during which the possibilities for large-scale application will be explored.

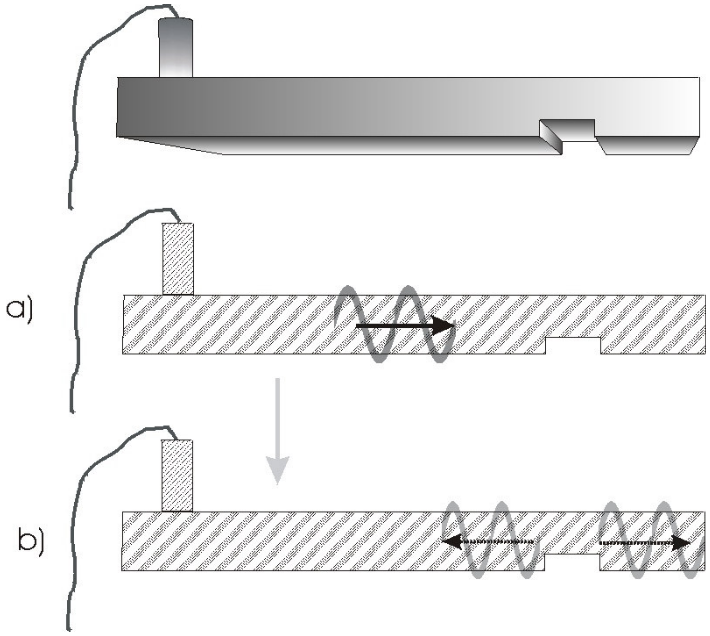


Fig. 1 Idealised representation of a reflection of a Lamb wave at a notch representing an artificial damage

The final goal of the project was to apply the selected automated NDT techniques to full-scale parts which can represent a broad spectrum of possible applications in operating aircraft. A special focus was the use of realistic environmental conditions which is in contrast to many other results from different projects where structural health monitoring systems are only applied under idealised laboratory conditions.

For the investigations of widely used aluminium alloy structures, such as frame-stringer constructions, we chose a helicopter tail boom from a MI-8 helicopter to install a sensor network to follow stress induced crack propagation by ultrasonic waves. A dedicated test rig was installed to simulate real flight conditions to enable a realistic validation of the technique applied.

Another full-scale part was the slat-track of the AIRBUS A320. This structural part is a moving beam that connects the wing with the leading-edge slats to vary the surface of the wings available for the aerodynamic lift. The main problem in installing a sensor network is the complex structure of the beam and the tiny space available for the installation of sensors and cables. The final goal is to follow cracks occurring at points with high stress intensity.

2 PARTNERS

A consortium with a broad and multidisciplinary expertise has been formed, combining the competences from high-tech SMEs, university research groups, end users and a certification laboratory. **METALogic n.v. (Leuven, Belgium)** is specialised in material degradation, corrosion processes in general, Lamb wave testing, Lamb wave modelling, sensor development and signal analysis. It is the coordinating company (http://www.metalogic.be). **Katholieke Unversiteit Leuven – Group: Materials performance and non-destructive evaluation, Department MTM (Leuven, Belgium).** This university group is experienced in material degradation, mechanical testing, acoustic emission, optical fibres and signal analysis. **Deutsches Zentrum für Luft und Raumfahrt e.V. (German Aerospace, Braunschweig, DLR)** DLR is the Aerospace Research Centre as well as the Space Agency of Germany. The participating institute (Institute of Composite Structures and Adaptive Systems) is specialised in Lamb wave modelling, PZT sensor protection, remaining lifetime prediction, impact and hydraulic testing, material degradation and complimentary NDT techniques (http://www.dlr.de). **CEDRAT Technologies S.A. (Meylan, France)** is a SME working on the field of sensor design/development/modelling as well as the development of associated electronics and hardware (http://www.cedrat.com/). **Eurocopter (Marseille, France)**

This corporate group known for its helicopter production represents an end-user delivering important part for the full-scale tests. Their expertise includes possibilities for health and usage monitoring (http://www.eurocopter.com). **Riga Technical University – RTU (Riga, Latvia)** has expertise on modelling of airframe components, mechanical testing, full scale testing and acoustic emission (http://www.rtuasd.lv/). **CTA (Vitoria, Spain)** is a certification centre for mechanical testing, environmental degradation and full scale testing (http://www.ctaero.com/en/CTA.html). **ASCO Industries N.V. (Zaventem, Belgium)** The Asco consortium is currently the world leader of slat actuation systems and a leader in flap actuation devices (http://www.asco.be/).

3 RESULTS

3.1 Database and selection of modes, modelling

A digital and searchable database has been constructed, containing an inventory of common structural aircraft materials together with their relevant properties and degradation mechanisms. In this context, a summary of 22 types of representative aircraft material groups was established (metallic: aluminium, steel, titanium; long fibre composites), it contained information on their degradation under different loading conditions (Failure by distributed and interacting damage modes, fatigue, environmental degradation, interlaminar fracture) and NDT inspection techniques. As a result, complete information about 56 different materials is available by a software-based database.

Furthermore, numerical methods were applied to model the Lamb wave propagation in the materials under investigation. This gave valuable insight into basic properties of the sound propagation in that material and the expected damage-signal behaviour. The dispersion curves obtained were verified by experimental methods at representative frequencies.

Due to the extraordinary complex structure of a number of aircraft components, it is with the available numerical techniques not possible to model every aspect of ultrasonic propagation in those structures. Therefore, experience and tests must frequently be in place to design appropriate structural health monitoring systems.

3.2 Electronics and sensors, functioning and durability

A special attention was given to the development or selection of the dedicated hardware (electronics and sensors). In this context, a Lamb wave driver and receiver system was designed (Fig. 2). It enables the generation of Lamb wave signals over a wide range of frequencies.

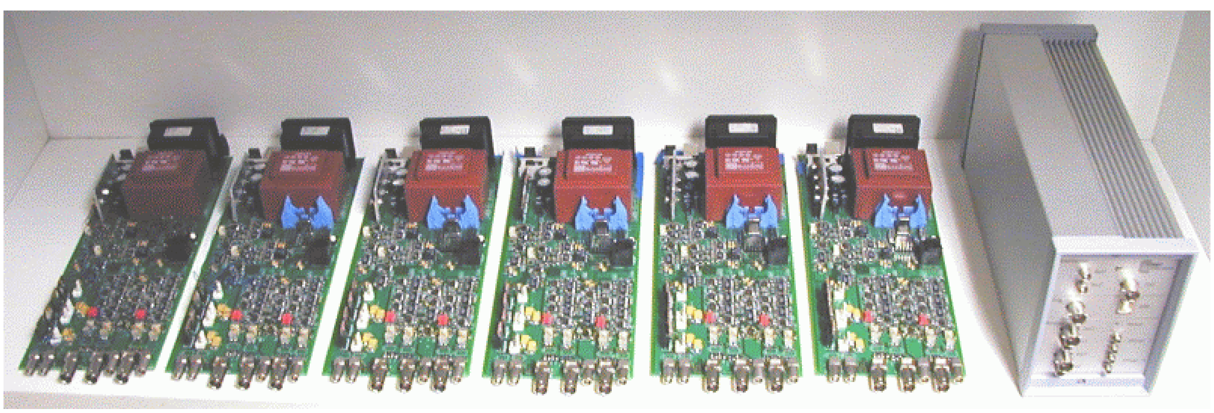


Fig. 2 Batch of LWDS designed and produced for the AISHA project

It was used by the partners in diverse experiments and it has the potential to be a prototype for a series of tailored electronics for Lamb wave generation and detection. The specific demands of Lamb wave drivers concern the specific frequency range, moderate amplitude requirements and dynamic ranges. A further important point is size and cost of the proposed systems.

3.3 Experiments on laboratory scale with fatigue, impact and environmental degradation

An essential part of the project is devoted to establishing of quantitative relations between growing damage phenomena and detected signals. This step was aided by the development of automated signal analysis strategies, which aim at providing either a visualisation of the data or a multidimensional analysis. A separate action was devoted to providing the link between the monitoring results and the actual structural condition. Based on a sound knowledge of the amount of damage present, conclusions could be drawn about the fitness for service of the structure and the need for repair.

By different partners, such as at DLR, a comprehensive network of various ultrasonic testing systems was designed to provide flexible means of data analysis and visualization (Fig. 3). All ultrasonic methods like phased array-, pulse/echo- and air-coupled ultrasonic technique deliver volume data sets from full-wave data recordings. These systems provide an excellent base for the developments within AISHA.

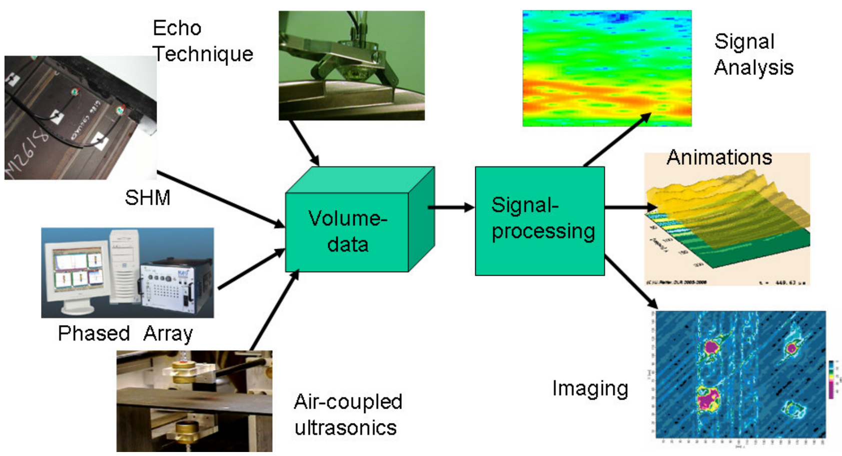


Fig. 3: Network of different NDT-methods

Within this project, the advanced ultrasonic inspection system USPC 5000 was used. It provides both full featured conventional ultrasonic imaging system as well as an eight channel Lamb wave system with eight different transmitters and eight receivers, resulting in a matrix of 64 measuring cycles. For generating and sensing waves, piezoelectric transducers are used in different shapes. Electrical excitation is done by bipolar rectangular burst pulses. The fundamental frequency is fairly low at a few 10 kHz due to wave propagation limitations in fibre composites. Usually, two dominant wave modes (A_0 and S_0) are generated. Typical wavelength for A_0 is 2.5 cm. Emerging harmonics are filtered out by high-order band-pass filtering on the receiver side. Ultra low-noise pre-amplifiers deliver the signals into 14bit digitizers with typically 10 MHz sampling rate. Signals are stored as full wave form, allowing very flexible data analysis like frequency filtering, gate analysis, imaging, animations or time-frequency plots.

For the visualisation of Lamb wave fields and their interaction, a lamb-wave scanning technique was developed and optimized: Lamb wave generation was performed at one fixed position by an actuator that was glued at the bottom of the specimen (Fig. 4). Its excitation is carried out by the built-in rectangle burst generator from the conventional ultrasonic imaging part of the USPC 5000.

For wave recording, a second PZT-patch is coupled by a water film to the surface and moved by an XY- scanner in a meander track. Because of the water coupling only Lamb waves with low amplitudes are received. Therefore an ultra-low noise preamplifier and a band pass filter are necessary. The data conversion, timing and the scanner control are carried out by the USPC 5000. The transmitter consistently generates single wave packages propagating over the specimen. At each point of the scanning grid, a full wave Lamb-wave A-scan is recorded, providing a 3-dimensional dataset [x,y,t].

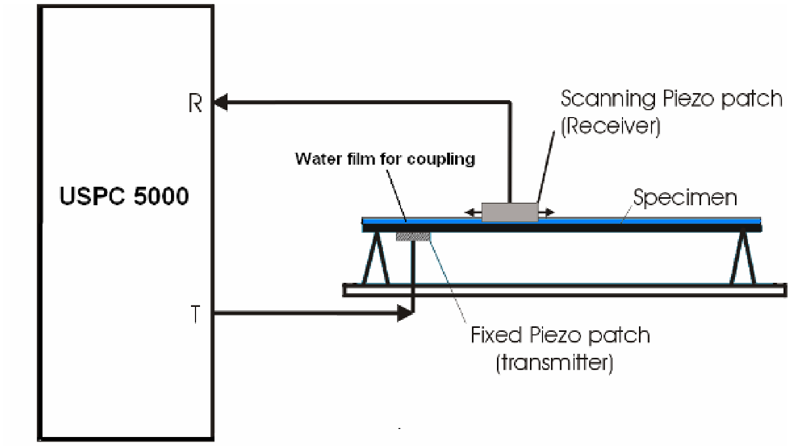
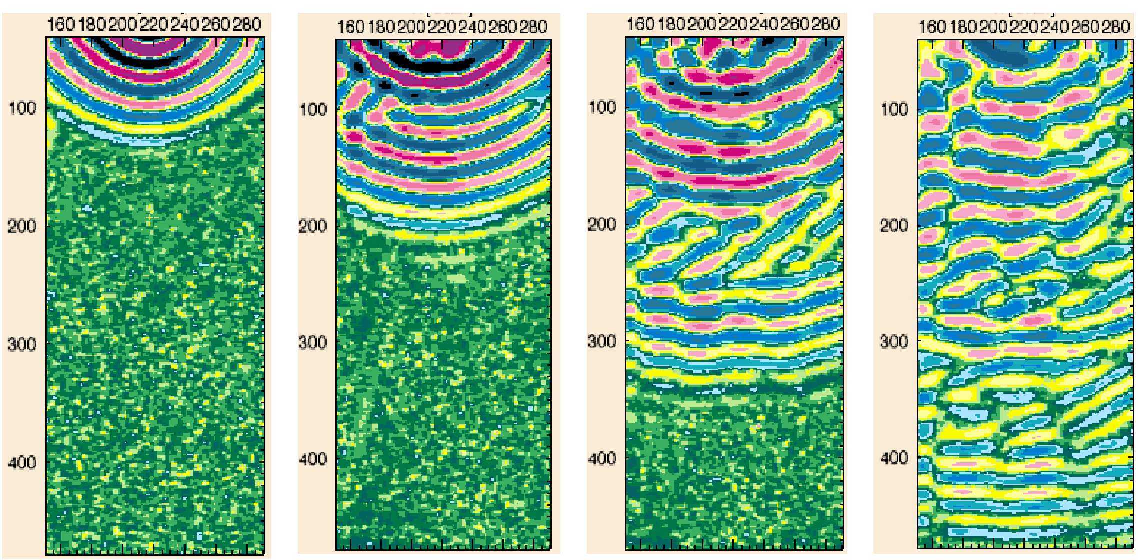


Fig. 4: Experimental setup for wave visualisation with direct coupling

Fig. 5 presents four snap-shots out of an animation calculated out of a full Lamb-wave data set from a sandwich specimen. In the first image, the propagation is still undistorted. After 331µs, first interference between an edge reflection and the initial propagation wave is indicated on the left hand side, further interferences can be observed in the following images. The snap shot after 779µs clearly indicates several interferences between the propagating wave in the centre and reflections from the edges. At the lower edge of the plate, the received signal is dominated by lots of interferences.



203µs | 331 µs | 555 µs | 779 µs

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

Although there is damage in the centre of the plate, and this damage indeed effects the wave propagation, it cannot be identified any more when the initial wave reaches the lower edge of the plate.

For reliable wave transmission and reception, proper bonding to the laminate is essential. The combination of signal excitation by the bonded patch and a conventional scanning transducer for sensing can be used for imaging of the coupling area (Fig. 6 left).

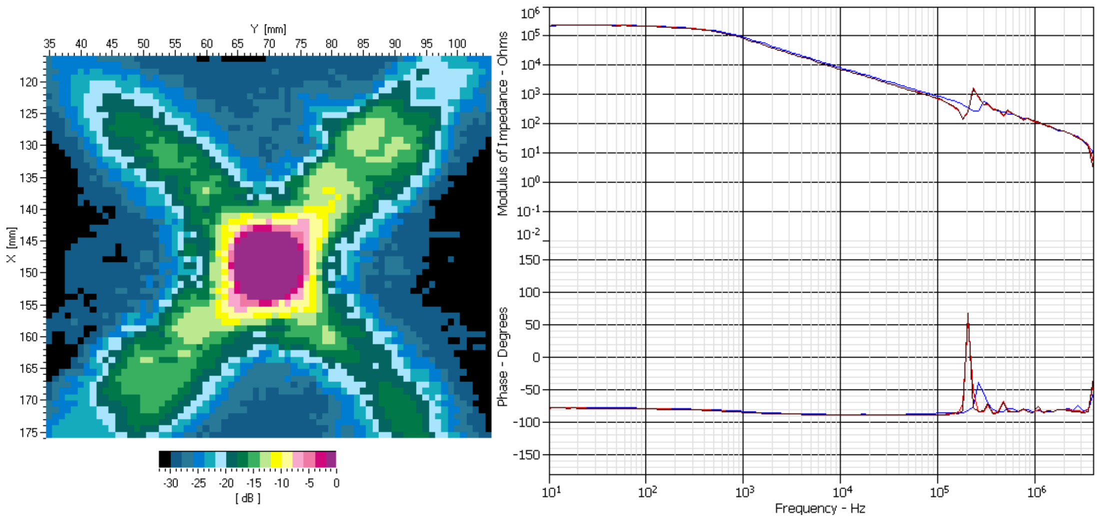


Fig. 6 Left: Ultrasonic imaging of the piezo patch bonding by a focused 10 MHz transducer in immersion technique. Right: Impedance of the PI Patch PCL 255 10x0.5 (black = free air operation; Red = water coupled; Blue = glued; Green = glued after 10 min)

Suboptimal bonding can also be detected by a change in electrical properties. Both the quality of bonding and partly debonded piezos can be evaluated by measuring the resonance frequency. 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. Typically the gain-phase-meter performs a frequency sweep from 10 Hz up to 4 MHz and plots both amplitude and phase of the reflected signal. Fig. 6 (right) shows the typical effect: At 200 kHz we can identify the resonance at the flipping in the phase plot. jAlso in the impedance plot there is a typical signature for resonance: loss of amplitude just below the resonance frequency and a peak in amplitude due to resonance. The resonance frequency shifts significantly after gluing.

Tests on laboratory samples

Within AISHA, DLR investigated monolithic CFRP specimens as well as sandwich plates with both honeycomb and foam core. Due to the setup for fatigue loading, standard specimen dimensions of approx. 350x100 mm² were defined. On each end, glass fibre patches are attached for clamping support, resulting in an area of approx. 150x100 mm² for Lamb wave investigations. Three types of piezo patch configurations were used. For quick time-of-flight measurements, transducer arrays were coupled by high-viscosity fluids (Fig. 7). Detailed analysis of the effect of the damage on the wave propagation was performed by bonded PZT patches. Round PZT patches (PCL 255 ø10x0.5) were used as well as rectangular ones (70x10x0.2). In order to limit disturbance by reflections, the patches were glue closely to the edges.

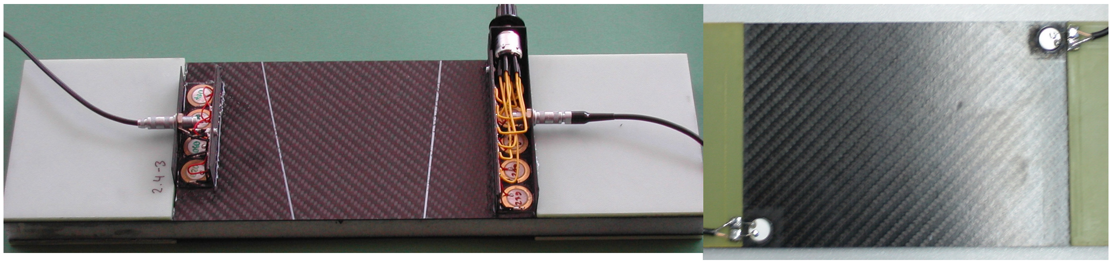


Fig. 7 left: Reusable transducer arrays, generating straight wave fronts right: Glued PZT patches (PCL 255 ø10x0,5) at optimized positions

For building a correlation between damage and Lamb wave signal, each type of specimen (monolithic, Nomex core sandwich and foam core sandwich) was impacted with energies of 5, 10, 15 and 20 Joules. For reference, one specimen of each type remained undamaged. Conventional ultrasonic imaging of each specimen after each type of damage confirmed stable correlation between impact damage and damage size (Fig. 8 and Fig. 9).

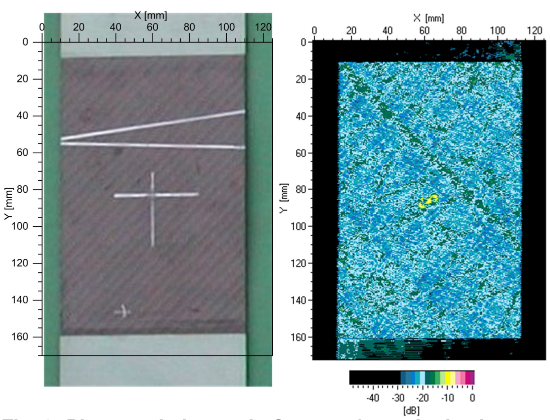


Fig. 8: Photo and ultrasonic C-scan after 5 Joules impact

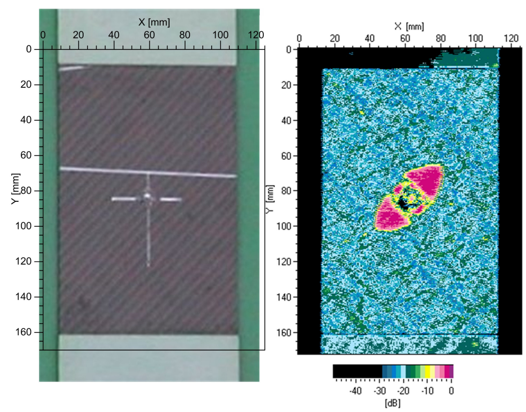


Fig. 9: Photo and ultrasonic C-scan after 20 Joules impact

For the Nomex core sandwiches, an optimal excitation frequency was found at approx. 17 kHz. In spite of the relatively small specimen dimensions compared to the wave length, two undisturbed modes could be identified. Their amplitude changes significantly with the impact energy, but there is no clear correlation between energy and amplitude (see Fig. 10 left). Lamb wave evaluation in foam sandwiches was performed at 39 kHz. There is hardly any correlation between damage and signal (see Fig. 10 right). Only the undamaged state can be identified in the amplitude of the first arriving wave package.

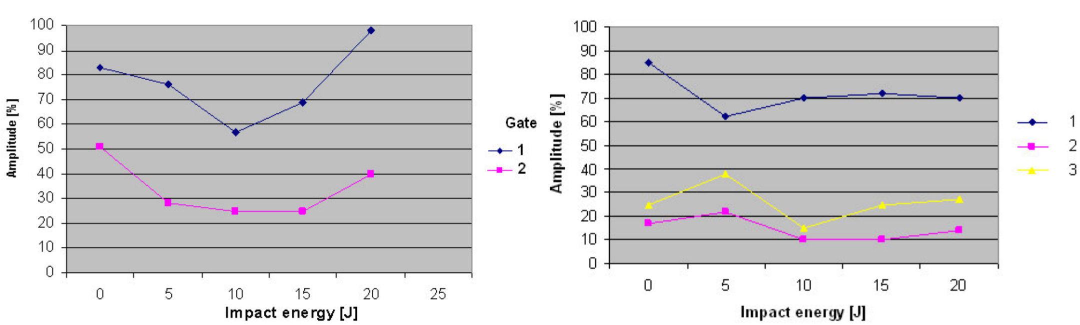


Fig. 10 left: Amplitude of two different wave packages in dependence of the impact energy in Nomex core sandwich specimens; right: Amplitude of three wave packages in Foam core sandwiches

For monolithic specimens (Fig. 11), there is correlation between signal amplitude and damage in the second and third identified wave package.

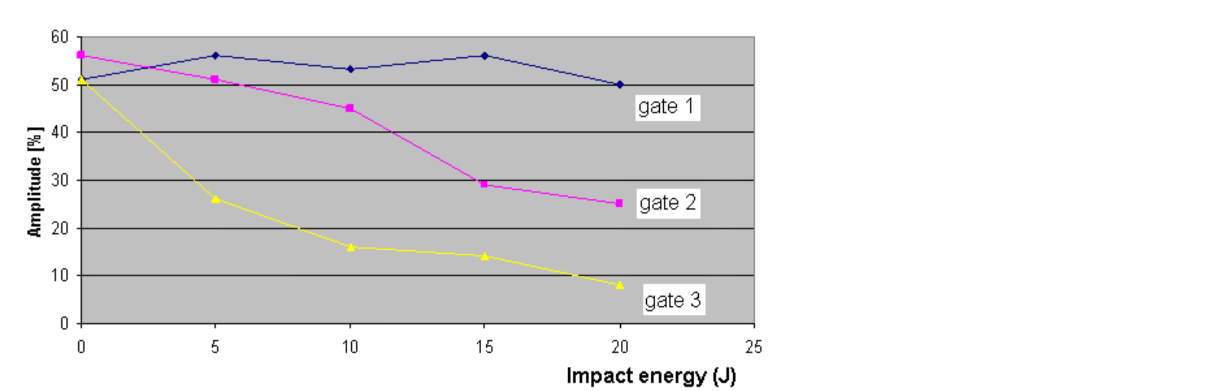


Fig. 11 Amplitudes measured in three different gates in dependence of the impact energy in monolithic specimens

After impact damage, the specimen underwent additional fatigue testing (approx. 100000 cycles of ±20kN) until considerable damage growth could be identified. Although there is a change of amplitude of almost every wave package after fatigue testing, we cannot observe a uniform trend. Some amplitudes raise after fatigue, others decrease.

This is consistent with our findings from the visualizations of the Lamb wave fields: There is a very clear interaction between damage and wave propagation. Both amplitude and time-of-flight are considerably changed behind the damage. But at the location of the bonded sensor the effect cannot be measured any more, because the measurement at that position is dominated by interferences and waves that are not affected by the damage.

The environmental testing was focused on the evaluation of the durability of glue and piezo. Conventional ultrasonic imaging confirmed no effect on the material properties of the specimen itself. For the piezo and glue durability tests, we prepared one specimen with 4 transmitting piezo patches and 4 receiving ones. The patch type was the same (PI PLC 255, 10x0.5 mm, PR44+0226), but 4 different glues were used: “Epibond 1590”, “Araldite AW 106”, “UHU plus schnellfest” and “Conrad Rapid 200”.

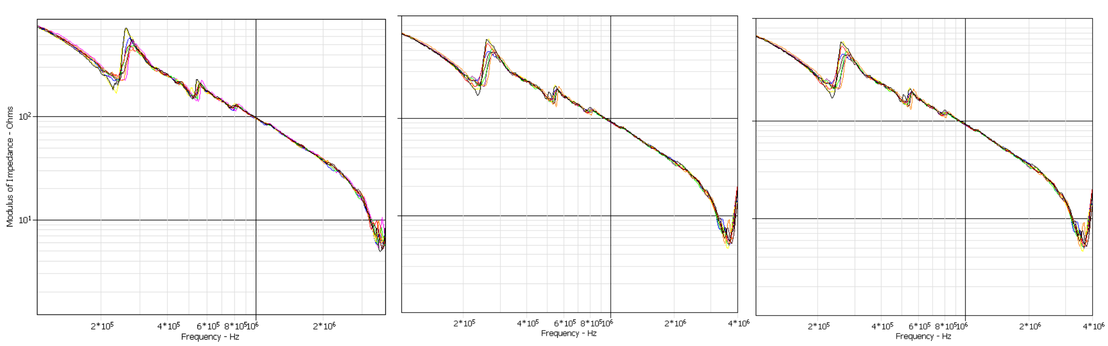


Fig. 12: Impedance Test before Loading(left), after 1h at +100°C (center) and -20°C for 2.5h (right)

As seen in Fig. 12, temperature ranges between -20° and +100°C have no relevant effect on the electro-mechanical conditions of piezo patch and bonding. This is true for all used glues. However, there is recommendation for “UHU plus” due to its potlive of 5 min and ease of use.

Lab scale tests on metal structures with piezoelectric patches

As fatigue is one of the most important damage mechanisms to appear in aircraft structures, an extensive fatigue testing programme was planned for the aluminium structures frequently applied in aircraft. Load levels and configurations were selected to resemble flight conditions as close as possible, whilst still provoking significant damage within an acceptable time frame. For fatigue testing there was selected thin-walled material Alclad 2024-T3 with a thickness of 1 mm.

Types of aluminum alloy samples

Nr of type	Brief description of a sample
1	Flat sheet sample (Al2024-T3) with central hole (the diameter 4 mm)
1*	Flat sheet sample(Al2024-T3) with central hole (the diameters 1.5, 4, 5 mm)
2	Model of rivet-joint (with 1 fastening point), material Al2024-T3
3	Model of rivet-joint (with 2 fastening points), material Al2024-T3

The total number of tested samples is 48.

The objective of this task was to conduct an extensive fatigue testing program on selected aircraft materials and to correlate Lamb wave monitoring results to complimentary NDT analysis.

Performed work summary. All three types of samples were tested in the accordance with program and the initial cracks (0.3…1.5mm) were obtained. For the validation of the results, different NDI methods were used such as eddy current, acoustic emission and penetration for initial cracks detection.

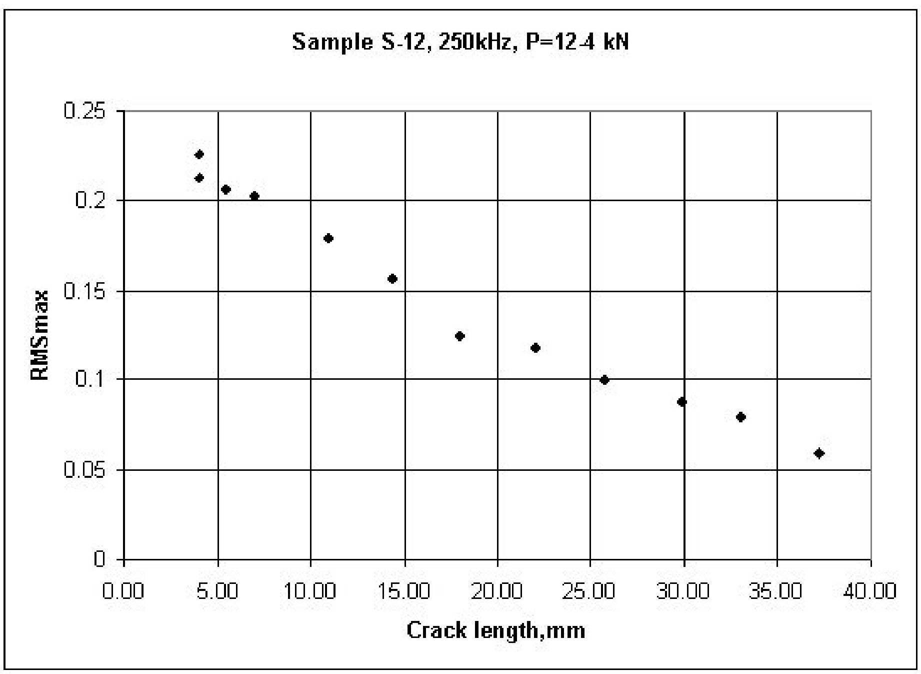


Fig. 13 Example of signal/damage correlation

During the next stage, the loading was periodically interrupted for the Lamb's waves detection with the half length of crack approximately 2.5, 5.0, 7.5,10.5, ... mm. This allowed to obtain reliable correlations between signal and damage (length of crack)".

Conclusions

- There is a strong correlation between signal and damage (fatigue crack) growing for all three kinds of samples
- RMS is a stable parameter representing the signal intensity, and it decreases as a function of the length of a crack.
- The coupling of the sensors with the surface of the sample remained stable during the testing
- If a sensor is installed in direction of the load and it is coupled directly with deformable surface, then the fatigue effect to coupling appears for used piezoceramics sensor at middle level of the stress (Figure 6.2).
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Environmental degradation

The objective of this task is to conduct an extensive testing program for environmental degradation on selected aircraft materials and to correlate Lamb wave monitoring results to complimentary NDT analysis.

Performed work summary.

The equipment and technology description of creation of corrosion damage was designed and prepared. Three samples of different types were located in the test box for artificial corrosion (Fig. 14) during four weeks. Then the fatigue test for each type of the samples with surface corrosion (Fig. 15) was performed.
Main results:
1. Parameter of the signal intensity (RMS) allows reliably detect the surface corrosion.
2. RMS reaction to a hole or to a fatigue crack is similar with non-corroded sample.
3. The sensor coupling was stable during all test (corrosion+fatigue).

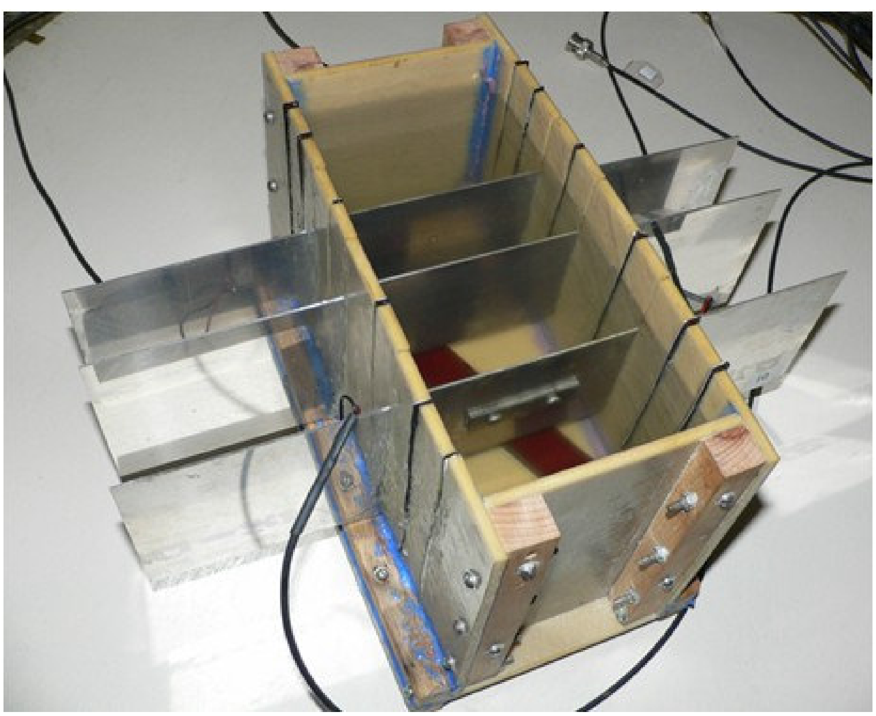


Fig. 14 A general view a box with three inserted samples for corrosion test

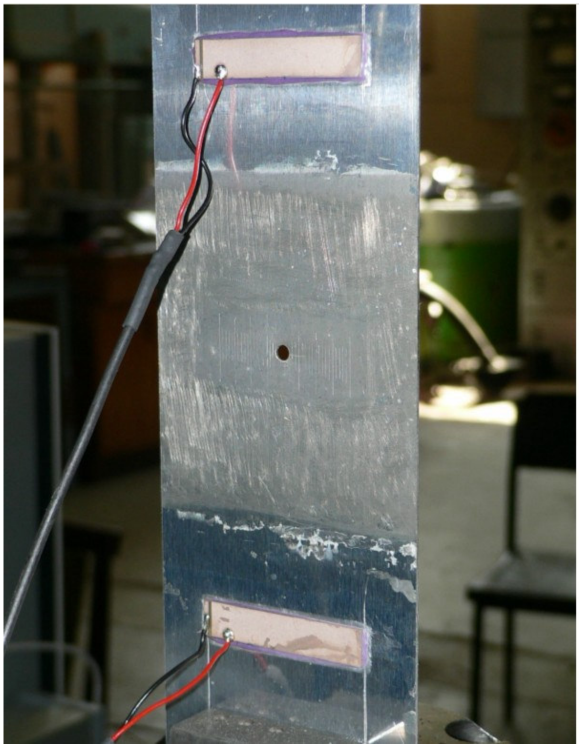


Fig. 15 Sample of Al2024-T3 with artificial surface corrosion

Lab scale tests on composite with optical fibre sensors

The Lamb waves are excited with piezo-electric patches that have been glued onto the specimen surface with acrylic glue. These patches are thin (500 µm), cheap and easy to handle, which makes them very suitable for the use in the envisaged health monitoring applications. The piezo patches can be glued to metallic parts with conductive epoxy glue, which offers both a conductive and strong adhesion. Ground cables can then be attached to the sample surface. For composite materials, a thin copper film is glued to the bottom of the piezo-electric patch to ensure an easy connection to the ground cable. The patch with copper film can then be glued to the sample with a regular epoxy adhesive. The patches are driven by a waveform generator (Agilent 33250A).

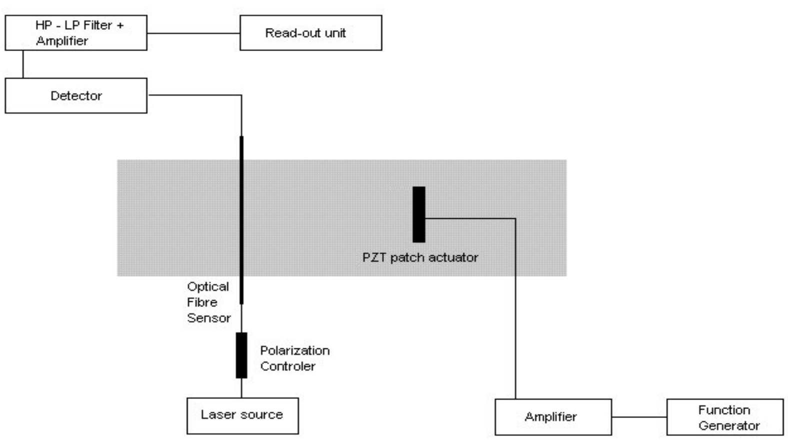


Fig. 16 Single mode optical fibre sensor in a polarimetric setup for the detection of impact damage

The main advantage of the optical fibre sensor is the ability to monitor the signal over the whole width of the specimen (Fig. 16). Single mode fibres typically have low attenuation so the optical signal can be transported over several meters without loosing much of its sensitivity. In addition, the received signal is the integrated response over the whole length of the sensing part of the optical fibre sensor, which makes this setup less dependent on local constructive or destructive interferences in the Lamb wave propagation pattern as is the case for point sensors. The use of piezo patches of a 50mm width also contributes to this effect, since they emit a more beam-like wave whereas point sensors emit a radial wave front which will more often lead to side edge reflections.

A piezo patch is used to excite the specimen with a 5 cycle sine burst of 82 kHz. Fig. 17 shows a curve that illustrates the SNR as a function of the impact energy that is released onto the specimens. The ultrasonic wave that interacts with the optical fibre sensor decreases in energy when the impact energy is increased. The higher the impact energy the more the damage state is developed, which reduces the energy content of the arriving Lamb wave due to scattering, absorption and reflection.

This approach is less influenced by the many edge reflections that arise in small plate samples. Because the edge reflections give rise to complicated interference patterns in the Lamb wave propagation, even a small change in the location of a point sensor could lead to a large difference in the received signal. The optical fibre sensor however returns an integrated response over the whole width of the specimen, which is much less influenced by the interferences.

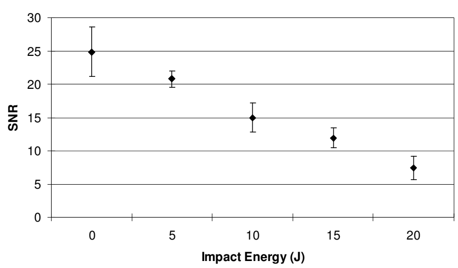


Fig. 17 Curve showing the RMS-based SNR for quasi-isotropic carbon/epoxy samples impacted at different energy levels.

3.4 Signal analysis and remaining lifetime

It is required to develop adequate models for linking the damage state with the remaining lifetime. The objective was to develop principles on a conceptual level and to validate the principles by using the results obtained during the course of the project (for the test stand see Fig. 17).

The first model applied is the remaining lifetime model at the fatigue damage of aluminium structure. Basic regularities of the fatigue failure of thin-walled structure were analyzed as a base for the remaining lifetime model. Both the remaining lifetime and remaining strength estimation are estimated by the methods of linear fracture mechanics. The problem of the damage tolerance in aircraft structures was discussed as a very important element of the model.

Finally, the programme code for remaining lifetime prediction was elaborated and tested. After simple adaptation this code can be included in a SHM system.

The second model is the model of environmental degradation of an aluminium structure. Fundamentals of the predicting of remaining lifetime are the same as at pure fatigue stres. Special features of the simulation of the corrosive damage must be

- The corrosion crack grows at dynamic and static stresses.
- The special constants of crack-resistance for small crack at the modelling of corrosive damage

Some versions of composite degradation and remaining lifetime predicting were analyzed. Three kinds of the model of remaining lifetime predicting

- Eenvironmental model
- Mechanical model
- Combined environmental-mechanical model.

Remaining stiffness prediction is selected as the main phenomena for the environmental models for damaged composite. The most effective is the damage growth models.

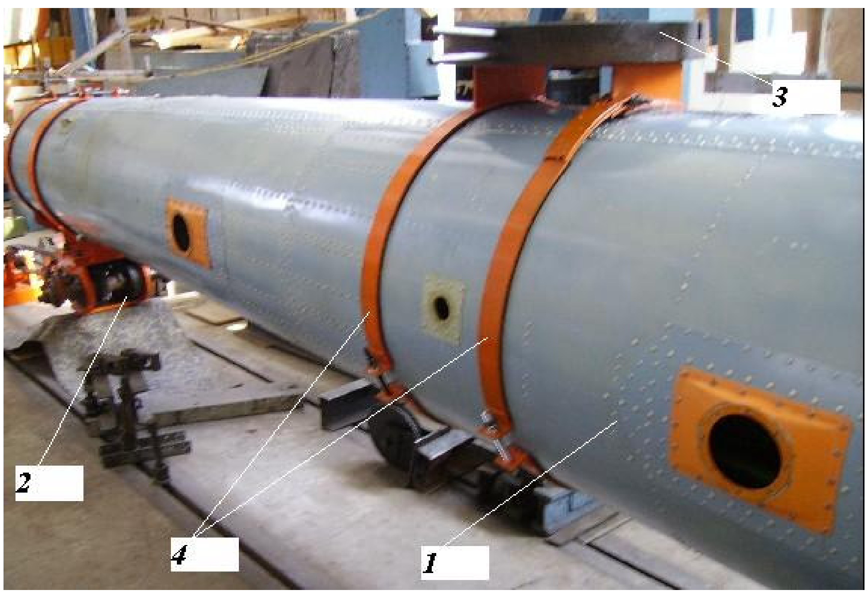


Fig. 18 General view of the stand

3.5 Full-scale results

Successful efforts were made to develop novel sensors/actuators for selectively generating and detecting Lamb wave modes. Methodologies for the integration of sensors and actuators into the structure are explored. This especially regards the trade-off between the needs for a sensitive detection of ultrasonic waves and the severe operational conditions in aircraft where for instance temperature differences of more than 150K has to be tolerated by the measurement system.

This required an adequate modelling of damage states, calculating residual properties and predicting the remaining lifetime. A final research action was devoted to a full-scale testing of the obtained laboratory results. Results were obtained for the detection of impact damage at a helicopter beam made of composite material (Eurocopter EC 135, Fig. 19), a helicopter beam made of aluminium alloy (MI-8, Fig. 18) and a slat track (Airbus A 320, Fig. 28) made of maraging steel.

The main interest of the end-user Eurocopter within the AISHA consortium is the use of Lamb wave's technology for impact damages detection on composites parts. The cost of the maintenance of the structure accounts for approximately 8% of the total maintenance cost of a helicopter. The effects of the maintenance can be important on the availability of a helicopter (example: the change of a frame is equivalent to 10 days of unavailability of the aircraft). The impact of the SHM on helicopter will be especially to improve the availability of the aircraft (reduction of 30% of the unavailability). In the event of incident, a SHM solution would make it possible to reduce 50% of the time reserved for inspection. Another example regards the impact damage in the composite structure of helicopters (in the present project Eurocopter EC-135 tail boom). Although, the composite material shows an excellent material performance with low fatigue degradation, impact can lead to fatal failure of structure within a short period. If those helicopters operate with a busy regular flight schedule, such as for oil platforms, an efficient SHM system can also provide quick damage information therefore related to high throughput of passengers.

The excellent stability given by the composite material is almost exclusively endangered by sudden impact created by birds and other sources. Severe damage which is almost invisible to the naked eye in many cases, can lead to fatal failure of the structure within a short period. A monitoring technique giving clear information on impact and impact effects would establish an enormous enhancement of operation safety. It will help to save costs (by increasing inspection interval) and improve the safety. So, we always research efficient means of damage assessment with two major interests: real time detection (quick damage information, local monitoring) and reduction of maintenance time.

The main requirements in Structural Health Measurement technology are the following:

- High integration of the system into the structure (Wireless sensors, long battery life, relevant location)
- Validation on Full Scale Tests for qualification
- Integration into the operational scenario

In AISHA, promising results were obtained with ultrasonic and optical fibre techniques, especially for the online impact detection.

Fig. 19 Eurocopter EC-135

Fig. 20 Photographs of the demonstrator

In this work package, the achievements from the laboratory tests on small samples are transferred to a real large scale component. A tail boom demonstrator of the EC 135 was selected for the full-scale test by Eurocopter France. It is a specimen with complex setup and various discontinuities like inserts, holes and both artificial and impact-induced defects.

First laboratory evaluations on a cut-out allowed optimizations on piezo type and positions as well as electrical excitation (Fig. 21). It could be demonstrated, that Lamb-waves in a frequency range from 8 to 18 kHz penetrate the whole sandwich (skins as well as the core). Consecutively, impact damages and holes were put into the specimen. The component's dimension is large enough compared to the typical wave length. Therefore we have no disturbing reflections and could achieve good damage detection capability, especially at 8 kHz. Both artificial holes and impact damages result in a significant increase of time-of-flight in that sound path and, even more significantly, a decrease of amplitude.

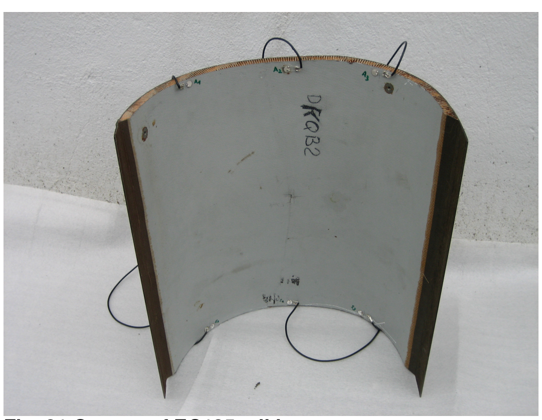
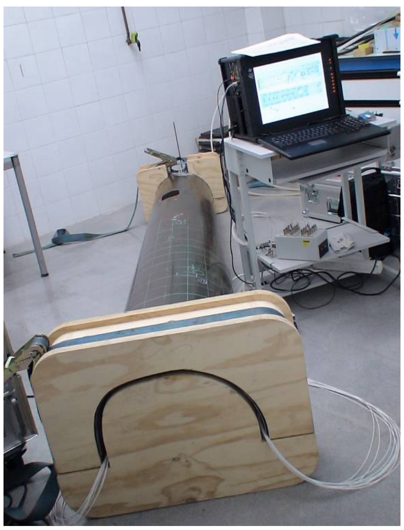


Fig. 21 Cut-out of EC135 tail boom

The large scale test was performed at CTA (Fig. 22), Spain. Before, the tail unit was equipped with rectangular piezo patches. During the test, transmitters T1-T8 and receivers R1-R8 were in use.

The setup of the USPC5000 allowed semiautomatic Lamb wave measurements during the fatigue test. Every 5000 cycles, all 64 possible sound paths T1-R1 to T8-R8 were used to record the wave propagation.

Broad band excitation was used in order to record a frequency range 15 – 35 kHz at a time. Analysis of single modes require small band filtering which can be done retrospectively by the analysis software. Filtered by band pass to 6-10 kHz, the measurements are able to clearly identify the damages by analysing the amplitude of selected wave packages (Fig. 23). However, this could not be confirmed by the large scale test itself, because there was no increase in damage during the 67000 cycles of the test. Both conventional NDT (thermography measurements) and the Lamb wave evaluation showed constant damages throughout the test. Therefore, a further improvement of the experimental setup is in progress.



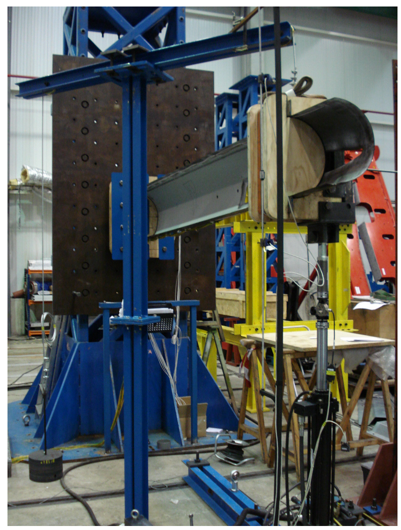


Fig. 22 Preparation (left) and execution of the large scale test at CTA

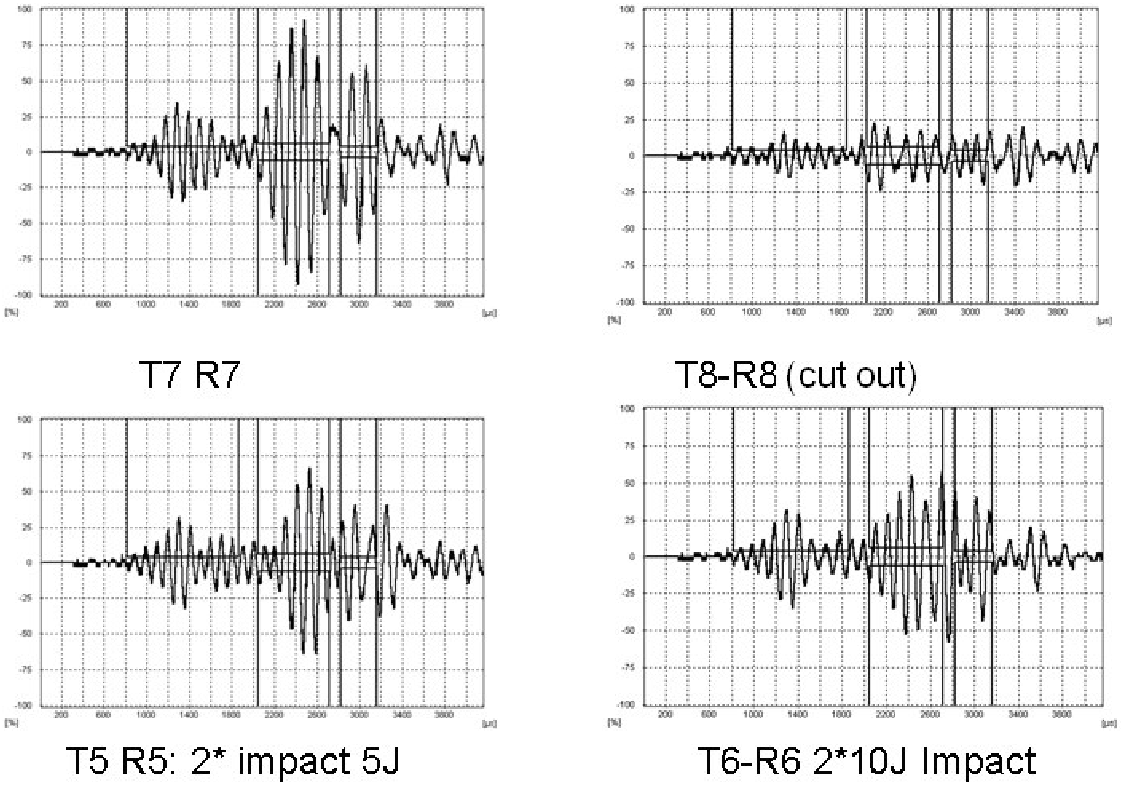


Fig. 23 Software-filtered (6-10 kHz) signals received from different transmitter and receiver combinations

Full-scale test on EC 135 with an optical fibre sensor network

Two SMARTape optical fibre sensors have been attached to the tail boom. They were placed along side the rows of PZT’s. During impact testing, acoustic emission measurements were made. Both the PZT sensors and the optical fibre sensor were used. This means that no intrinsic acoustic emission sensors were used, but the patches already present to perform active ultrasonic Lamb wave tests. To detect the signals coming from the PZT sensors a 14 channel Vallen read-out unit was applied.

Also active Lamb wave testing was performed. At the KU-Leuven the SMARTape was used as receiver and the PZT’s were applied as actuators. All possible combinations were tested to register signals by the SMARTape immediately when generated (same side) and by the PZT after of the PZT generated signal through the impacted area (opposite side) before and after the additional impacts.

The time-frequency images (Fig. 24) represent how the power spectrum of the signal changes in time. They are obtained using the Short Time Fourier Transform (STFT). Considering the signal array in time, in each step a window with size W is used for calculating the power spectrum. Here applied rectangular windows were applied. In the next step the window is shifted with I=W/2. Then the power spectrum of each window is plotted in function of time, this way a 3 dimensional graph, or a coloured image is obtained.

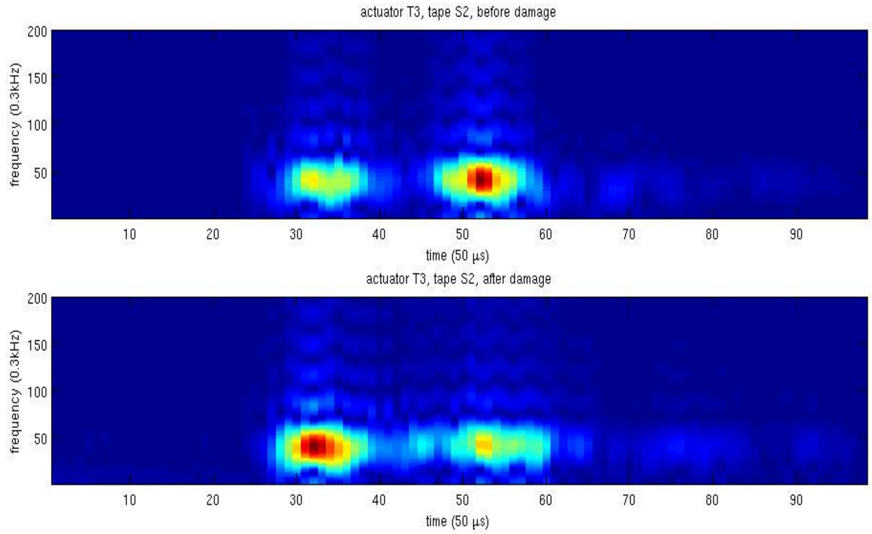


Fig. 24 The time frequency images of the signals obtained using the optical fibre S2, and the actuator T3, before and after the impact was made. The frequency of the signal is 12 kHz, length of the signal arrays is N=25000, window size W=500, l=250.

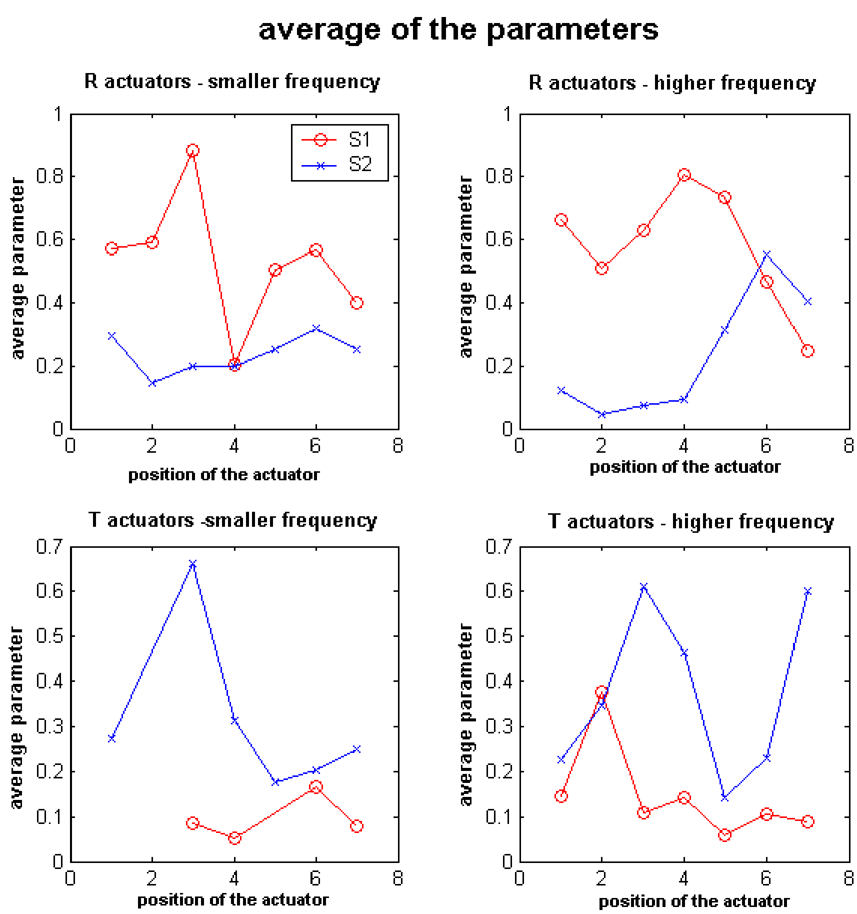


Fig. 25 The 8 different parameters calculated were averaged after all of them were scaled to the [0,1] interval, for the 4 different measurements using the R and T actuators with smaller and higher frequency ranges. On each graph circles (crosses) note the measurements obtained with S1 (S2) optical fibres

Signal processing methods based on comparing the time-frequency images of signals obtained before and after the impact are used for detecting damage in composite materials. The method was tested on data obtained in a large-scale experiment made on a helicopter tail, using of real impacts and a small-scale experiment of using pseudo-defects. The results show that in spite of big fluctuations a global view of all 7 parameters calculated and averaged can show, with a very good approximation, the position of the damage (Fig. 25).

Full-scale test on the Mil 8 helicopter

The tail beam of helicopter MI-8 (Fig. 18) was selected as the object for full-scale testing on aluminium structures. The dynamic properties of the tail beam have been calculated and two variants of loading were selected. First of them is the forced vibration using the second natural frequency. The source of excitation in this case is the mechanical vibrator. In the second variant, the harmonic loading will be excited by a hydraulic actuator at lower frequency. Two zones of the structure were selected for integrating the NDT equipment, and ten piezoceramic sensors 10x50mm and 0.5mm (thickness) were installed in the critical zone of a structure (Fig. 26).

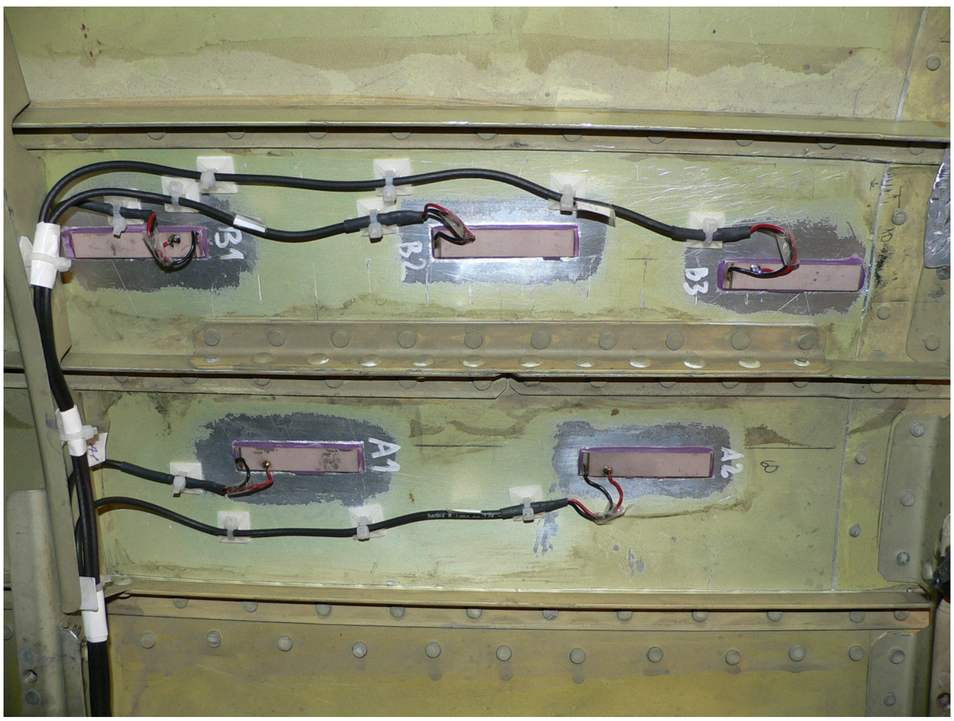


Fig. 26 Sensors location in a zone between 7th and 8th frames (inner view)

<u>Main results of the full scale testing:</u>

1. The used configuration of the non-destructive inspection based on Lamb wave technology is able to reliably detect the fatigue cracks in the riveted aluminium structure. All cracks located in an inspecting zone cause the response reaction that can be detected by the sensors.

2. Piezoceramic sensors are able to keep their functional ability under intensive mechanical vibrations during the whole fatigue test. But investigation on the reliability of the system should be continued.

Full-scale test on AIRBUS A 320 slat track

Lamb waves are inappropriate to detect damages in slat tracks due to the mismatch between the size of the slat track, the corresponding wavelength and the size of the defect. The application of Rayleighwaves providing a smaller wavelength was proven to be an alternative, but it appeared that the use of classical wedge sensors is inappropriate due to restrictions of the slat-track when it is in function (see picture of the mounted slat-track).

Fig. 27 Slat track for AIRBUS A320

Fig. 28 Mounted Slat track for AIRBUS A320

Because adhesively bonded piezoelectric patches are able to generate Lambwave in plates, they should also be able to drive Rayleighwaves in structures similar to slat-tracks if appropriate frequency and geometric conditions are met. A disadvantage of this concept is the fact that also other propagating modes are excited, but we wanted to try whether an adapted data analyse could circumvent this drawback. A final analysis of the data obtained showed that the mix of ultrasonic modes generated by this actuator configuration could give excellent results for the correlation of damage and signal.

A real slat track was mounted into another spark erosion facility and the response of the acoustic signal was recorded with a set-up very similar to the experiment described before. The response was measured at different frequencies.

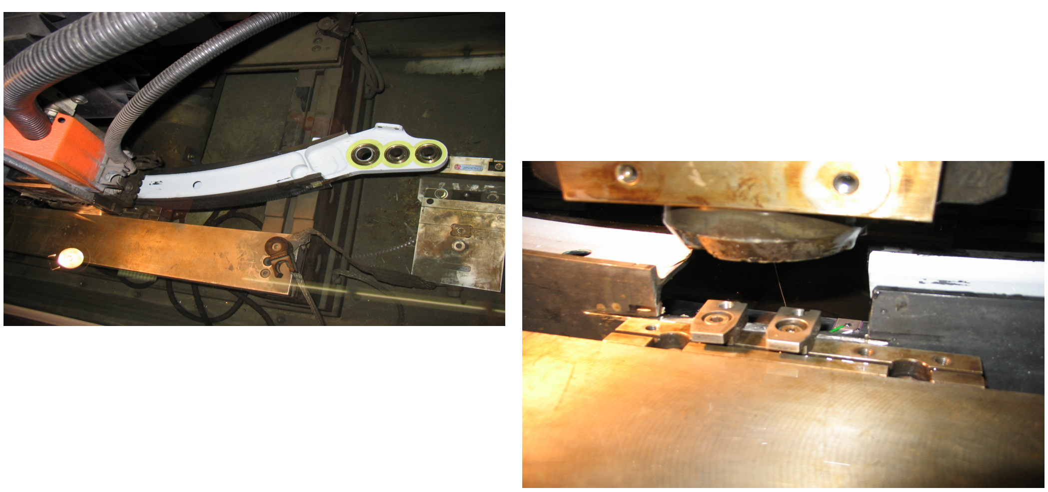


Fig. 29 Slat-track of an AIRBUS A320 mounted in an spark erosion facility. The red circe marks the position of the wire (unvisible at this foto)

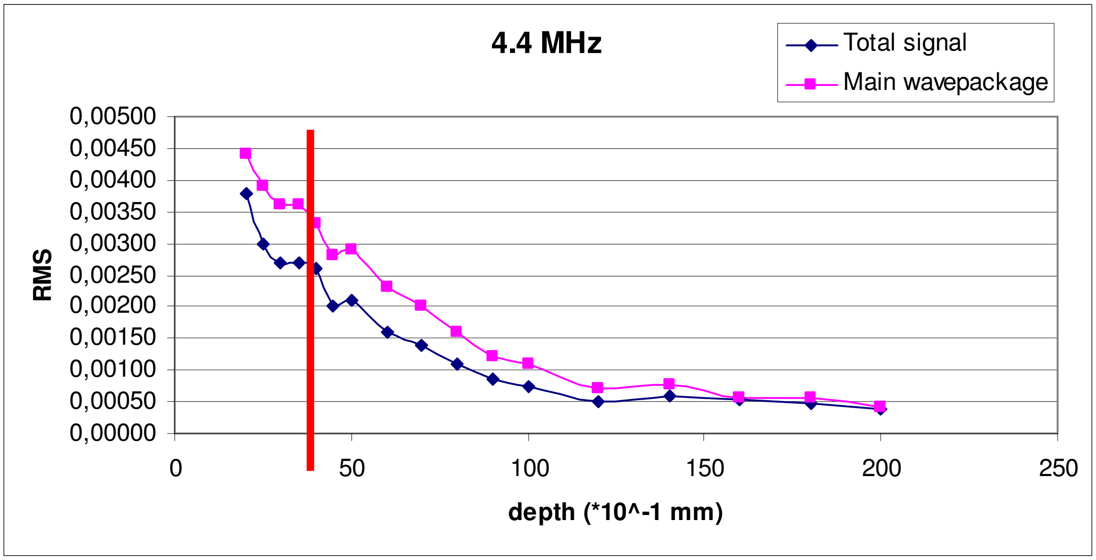


Fig. 30 RMS values for different notch depth recorded at 4,4 MHz. The red line indicates the threshold important for operational practice.

There is a clear trend in the signals, the RMR analysis of the total signal or of the main wavepackage gives a clear correlation with the damage size.

The final test however was performed in the subsequent period using a fatigue facility where the dynamic load about the whole lifetime of an aircraft (> 30.000 flights) was simulated. The next pictures shows two slat tracks under investigation. The left one has a cut-out for applying the artificial damage with the spark erosion facility. The right one is a complete slat track during preparation for the fatigue test.

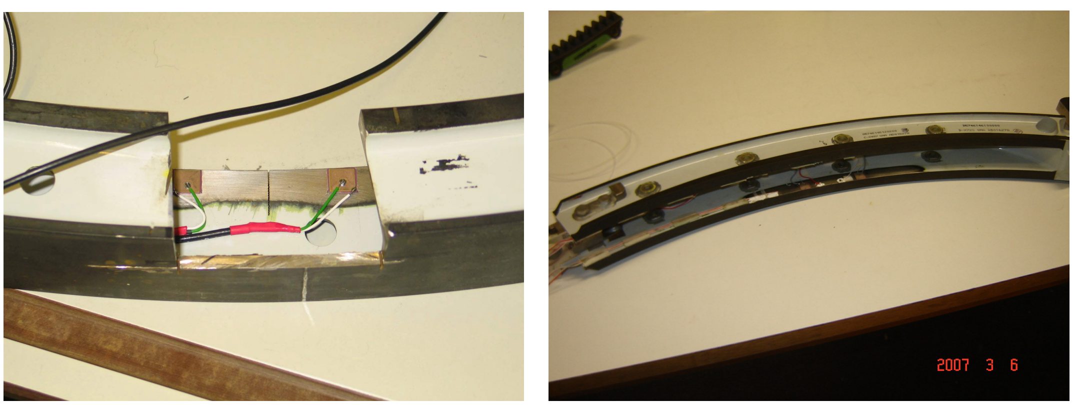


Fig. 31 Different slat track for testing with the spark erosion facility and the test rig for fatigue testing.

Fig. 32 Test rig of ASCO at the VUB (Free University of Brussels). In the foreground, a bi-axial test rig can be seen.

The test was performed using an uni-axial test rig and here, and the sensor connection was ensured during the whole process, such as proven by measurements of the electric impedance of the sensors. Also in this case, the growth of the crack was visible by a strong response of the ultrasonic signal. The tests are still in progress and therefore, not all results are available at the moment. A particular feature of this measurement is that the cracks are only open if the slat track is under load. This corresponds to operational conditions, where potential cracks would only be open during the start and landing of the aircraft. Therefore, ultrasonic measurements were performed under load and without load to get information on both cases.

4 INTENTIONS FOR USE AND IMPACT

The most innovating results are regularly published by the different partners. This is done by submitting papers to international and national conferences and meetings, but also by publishing in scientific publications and magazines.

For innovative and unique solutions which can be used for selected technical problems, further exploitation and commercialisation is intended. Moreover, partners were encouraged to think about follow-up projects to deepen the knowledge acquired within the AISHA project. In this context, the consortium applied for a new European project (AISHA II) in the frame of the 7th frame programme.

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