PROGRESS ON AIRCRAFT INTEGRATED SAFETY HEALTH ASSESSMENT (AISHA)

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Abstract

The safe use of complex engineering structures such as aircrafts can only be guaranteed when efficient means of damage assessment are available. Whereas aircraft design is based nowadays on a damage tolerance approach and time-based inspection cycles, it is envisaged that the large cost associated with this approach can be drastically reduced by switching to a condition-based maintenance schedule. This does require continuous health monitoring capabilities using integrated sensing technology and autonomous damage assessment. This paper reports on the results of the European project AISHA (aircraft integrated safety health assessment) aiming at aircraft health monitoring technology by exploring the capabilities of ultrasonic Lamb waves as the basic sensing principle.

1 Introduction

1.1 General aspects of Structural Health Monitoring (SHM)

The structural health of engineering structures is threatened by material degradation. Reliable inspection techniques are therefore required to operate the structure safely and failure-free. This especially is needed when the complexity of aircraft structures is increasing more and more [1]. Whereas a time-based inspection scheme has resulted in excellent reliability records for aircrafts, there is an economic drive for the more innovative structural health monitoring procedures. Therefore cost effective non-destructive testing (NDT) methods have to be developed. 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 continuously assessing the structural integrity of the aircraft by a continuous damage monitoring system.

The efforts to establish SHM systems were accelerated by the ALOHA airline incident in 1988 when a part of the fuselage detached from a Boeing 737 due to corrosion defects of riveted joints. Nowadays, more than 500 patents on monitoring techniques exist and a number of big projects were implemented to develop efficient SHM systems. The techniques applied are based on different sensing mechanisms such as vibration, ultrasonic or eddy currents techniques.

However, the main problem of structural health monitoring is, besides remaining technical details, the problem of acceptance by the customers. The main argument for structural health monitoring (SHM) must be the certainty that the system can prove the airworthiness of structures, i.e. we know that there is a problem with the airworthiness when a defect is detected, but is airworthiness guaranteed if SHM defect signals are absent?

The AISHA project (6th Framework STREP project) represents a new effort to establish a breakthrough in SHM for aircraft.

1.2 Lamb waves

Ultrasonic techniques such as ultrasonic C-scan imaging are well-established non-destructive methods because they are able to detect internal defects with a high degree of resolution and reliability [2]. However, this punctual measurement technique requires time-consuming scanning of the integral area [3]. Moreover, modern complex composite structures pose further strong restrictions on the accessibility for conventional ultrasonic testing.

A possible solution is provided by the application of Lamb waves. In contrast to longitudinal waves, Lamb waves can travel over large areas of components, i.e. Lamb waves are guided waves which propagate in plate-like structures [4]. A typical example for Lamb wave damage detection is shown in Fig. 1. A pulse/echo actuator/sensor system emits a wave burst which is partially reflected at a notch which represents the defect. After reflection the emitted burst is captured by the sensor and processed for further data evaluation. From the propagation time of the signal (time of flight (TOF)) and the intensity of the reflected or transmitted signal, the distance and extend of the damage can be assessed.

There are a number of Lamb modes being a function of frequency and plate thickness. For a given frequency at least two modes – one symmetric and one anti-symmetric can be generated. These modes are usually dispersive, i.e. their velocities are frequency-depending. These different Lamb modes show selective sensitivity to different kinds of defects, such as cracks, delaminations and uniform thickness degradation. For the damage detection it is important to select the optimal wave mode and to know the propagation properties as well as the possible interactions with defects.

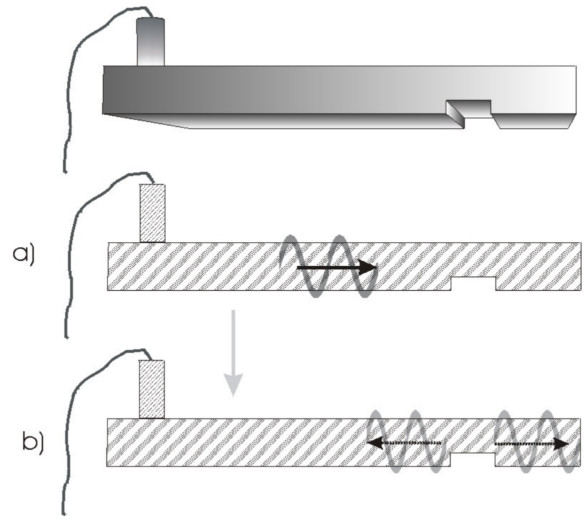

Fig. 1 Reflection of a Lamb wave at a notch, a) incident wave burst, b) reflected and transmitted wave burst

The main goals of our project are the visualisation of the Lamb wave propagation and its interaction with the damage, as well as the analysis of the correlation between progressing damage and the active Lamb wave signals. For this reason appropriate sensor, actuators as well as appropriate electronics and software are developed.

Finally, the information from these guided waves, combined with signal analysis routines and models for remaining lifetime prediction, will be used in a full scale testing action during which the large-scale application of this developed technology will be explored.

1.3 Actuation and detection techniques

Damage detection can be performed using passive or active techniques. A well-known passive technique is acoustic emission which operates analogous to earthquake detection, i.e. the method captures the acoustic signals arising from emerging or growing defects. In the active method, mechanical waves are excited actively and the material responses are received at distinct positions. The interaction of the incident wave with the defect enables damage detection and quantification.

In order to enhance durability and reproducibility of the selected technique, sensors and actuators have to be integrated into the aircraft structure. This can be done by embedding or adhesively attaching the sensors/actuators into the structure or onto the structure's surface.

In order to establish a complete monitoring system a whole network of sensors has to be implemented and operated. Therefore, beside the use of sophisticated Lamb wave transducers, also simple appropriate piezoceramic crystals fixed at defined positions are frequently used as actuators and sensors [5]. The limiting factor is the sensitivity as well as the bandwidth of the transducer system, and the excited wavelength finally decides on the size of the damage which can be detected.

In contrast to sensors consisting of small disk-like transducers, optical fibre sensors can monitor more extended areas without the need to cover the structure with an enormous amount of sensors [6]. Furthermore, optical fibre sensors are insensitive to magnetic and electrical interferences and single mode fibres are also quite inexpensive.

2 Materials and Methods

2.1 Materials

A number of representative materials were selected to be investigated within the AISHA project. This is on the one hand the frequently used aluminium alloy Al 2024-T3 used for fuselage constructions, and the maraging steel used for slat tracks. Furthermore, CFRP (Carbon Fibre Reinforced Plastic) plates and CFRP sandwich panels with both honeycomb and foam core are used.

Fig. 2 Beam of a MI-8 helicopter selected for full-scale fatigue tests

For the lab tests the size of the specimens is standardised to enable a comparison of the results between all partners. Moreover, the size is also determined by the parameters to be handled for the appropriate fatigue test equipment.

For the upcoming full-scale tests, helicopter beams made of aluminium (Fig. 2) and composite were selected which enable to validate the results that were previously obtained in the lab scale experiments.

2.2 Visualisation of Lamb waves

In order to get more information about the propagation of Lamb waves in the components and their interaction with defects it is very helpful to visualise the wave propagation. Usually this is done by laser interferometer which is able to monitor the out-of-plane surface deformation [7]. For our first investigations we used the ultrasonic systems such as HFUS 2400 and HFUS 2400 AirTech. In contrast to the standard systems these devices also provide frequencies below 10 kHz. In order to increase the resolution, we extended the systems with ultra low noise preamplifiers as well as high- and low-pass filters in a frequency range of below 1 MHz. Now the USPC 5000 is available, a portable system providing both ultrasonic imaging and Lamb waves testing [8]. The system for research and development is built in a portable PC. The ultrasonic imaging part of the system enables both the visualisation of the Lamb wave propagation as well as the conventional ultrasonic imaging technique as a reference method for defect detection.

For the visualisation of the Lamb wave fields (Fig. 3) and their interaction, one actuator at a fixed position on the bottom of the specimen has been used as a transmitter. A second PZT-patch is coupled by a water film to the surface and moved by an XY- scanner in a meander track.

Fig. 3 Scanner system of the HFUS 2400 AirTech

2.3 Piezoelectric patches for transmission measurements

The excitation and detection of Lamb waves can be performed by several techniques. One frequently applied method is the use of wedge transducers. Longitudinal waves are irradiated into the structure by an appropriate wedge having a specific angle which is required for the excitation of plate waves according to Snell's law.

But due to the size and the weight of such transducers, other options for the Lamb wave excitation have to be found. It is for instance possible to glue simple appropriate PZT crystals directly onto the metallic or composite surfaces. The adhesive connection prevents that the PZT crystals can oscillate freely, and this enables a Lamb wave excitation without using a wedge and with a fair bandwidth [9].

Those piezo patches can be glued to metallic parts with conductive epoxy glue, which offers both a conductive and strong adhesion.

2.4 Optical fibre techniques

The main advantage of the optical fibre sensor for the detection of Lamb waves is the ability to monitor the signal over the whole width of the specimen. Single mode fibres which are used for the present study [10] typically have a 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.

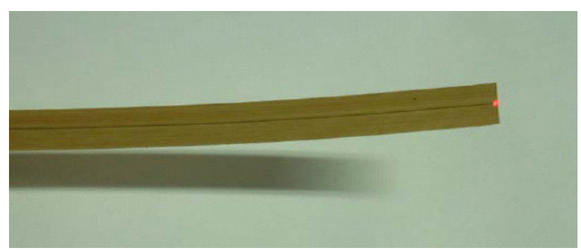

Fig. 4 Single mode optical fibre sensor (SMARTape) [11]

The optical fibre sensor (Fig. 4) is connected to a stabilised laser source which sends light (wavelength = 1310 nm) into the sensing fibre. The photo diode detection unit is coupled to a preamplifier and a filter/amplifier transmitting the filtered and amplified signal to an oscilloscope, and a PC-controlled read-out unit where it will be processed and analysed.

The Lamb waves are excited with piezo-electric patches that have been glued onto the specimen surface with acrylic glue. The patches are driven by a conventional waveform generator.

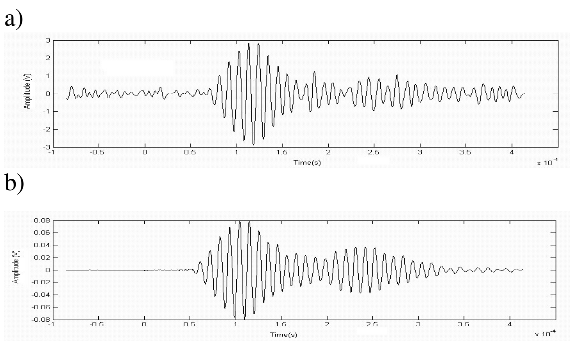

Fig. 5 Signal recorded in a carbon/epoxy specimen after excitation of a 5-cycle sine burst at 100 kHz: a. Signal recorded by a SMARTape sensor; b. Signal recorded by a conventional piezo transducer.

With the use of a SMARTape optical fibre sensor a 5-cycle sine burst signal is recorded which was transmitted into a carbon/epoxy specimen. The signal is compared with one that is recorded by a conventional piezo transducer at the same instance. Both signal recordings signals show good agreement with each other as can be seen in Fig. 5. The signal-to-noise ratio of the optical fibre sensor is lower than that coming from the piezo transducer. But although the optical fibre sensor has a lower sensitivity compared to the piezo transducer, the incident wave is clearly visible. The signal typically consists of a main burst arriving first, followed by several front-to-back edge reflections. The signal investigated for the damage detection is usually obtained from an appropriate time gate.

In the frame of this research programme different material types are used for the validation of the monitoring setup. The selection of these materials is based on their relevance to the aircraft industry. Experiments are conducted on metals such as Al 2024 T3 and composite materials such as CFRP plates.

2.5 The integration and durability of sensors

The integration of the sensor/actuator onto the structural part to be monitored is very crucial in online detection applications. The sensors/actuators should be kept as small as possible in order to preserve the mechanical and structural integrity of the component. Surface mounting and embedding (only for composite materials) of the sensor/actuator are two possible ways to integrate the monitoring system into the structure.

Several optical fibre sensor integration methods for composites are compared in the following paragraph. To simplify the handling of the fragile and brittle optical fibres during the sample preparation, it was preferred to use the SMARTape optical fibre sensor manufactured by the company SMARTEC from Manno, Switzerland. It is a PPS/glass fibre composite tape with an embedded optical fibre developed within the framework of the PDT-coil EC project NNE5/2001/887. This thermoplastic composite tape also protects the optical fibre from external mechanical or chemical influences which could possibly damage the optical sensor in service or during the manufacturing of the composite material with embedded fibre.

Four different optical fibre integration methods that were studied. All experiments are carried out on quasi-isotropic carbon/epoxy samples. For all integration methods a series of impact tests have been carried out, analysing the received Lamb wave signal. The impact energy, and therefore also the damage, is step by step increased during the experiments.

All integration methods show a decreasing trend with increasing damage and are therefore suitable for the detection of impact damage. However big variations in the amplitude ratio and hence in the sensitivity of the detection can be discovered. Our research indicated that the surface mounting gave a higher sensitivity than the integration in the middle of the composites plate. The differences in sensitivity can be explained by the difference in acoustic contact between the monitored specimen and the optical fibre sensor as well as the different displacements characteristic for the specific Lamb mode.

Surface mounting the SMARTape sensor does not only result in the highest sensitivity, it is also the easiest way to integrate the monitoring sensor into the structure. In order to provide a proper bonding between the sensor and the specimen a suitable adhesive has to be chosen which is able to withstand all external influences such as vibrations, temperature gradients, elevated humidity, etc. It is highly important to keep the adhesion between the sensor and the structure to be monitored optimal in all flight conditions because detachment of the sensor leads to lower signal amplitudes which may be falsely interpreted as a degradation of the structure itself.

3 Results

On the way towards the main project goals, a number of results were obtained. A digital and searchable database has been constructed, containing common structural aircraft materials together with their relevant properties and degradation mechanisms. As a first step in the project, optimum Lamb wave mode sets were selected, taking into account the materials under investigation, the loading condition and the damage type. An important result of the project is the improvement of the understanding of the interaction of propagating Lamb waves with material defects in metals and long fibre composite materials. The use of this knowledge is not confined to the study of aircraft materials, but can also be used for the inspection of other structural parts that exhibit defect formation, such as chemical process installations with corrosion cracks or structural composites that are subject to impact or fatigue damage evolution. 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 are to be tolerated by the measurement system in some cases.

A major part of the project is devoted to establish quantitative relations between growing damage phenomena and detected signals. This step will be supported 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 will be 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, a conclusion will have to be drawn about the fitness for service of the structure and the need for repair. This will require an adequate modelling of the damage states, calculating residual properties and predicting the remaining lifetime. A final research action will be devoted to a full scale testing of the obtained laboratory results.

3.1 Visualisation of Lamb waves

Fig. 6 presents four snap-shots out of an animation calculated out of a full wave data set of a Lamb wave testing of a sandwich panel [12]. The snap shots present the propagation 203, 331, 555 and 779 μs after excitation. The first image shows undistorted propagation, but after 331 μs first interference between edge reflected and the primary propagation wave is indicated on the left hand side.

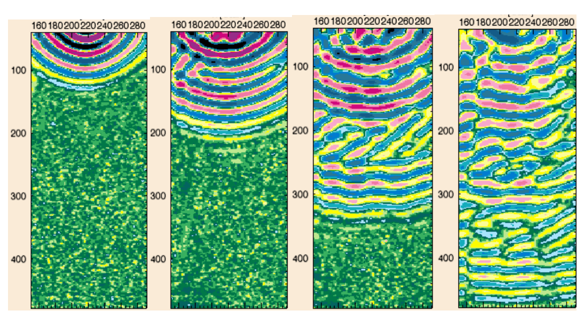

Fig. 6 Lamb wave propagation in sandwich specimen (impacted with energy of 15 J)

Further interferences can be observed in the following images. The snap shot after 779 µs clearly indicates several interferences between the propagating wave in the centre and reflections from the edges (Fig. 6). This is the reason why different sizes of damage do not always result in differences between the received signals.

3.2 Detection of artificial notches in aluminium sheets

For the detection of an artificial notch (dimensions 1000x200x2 mm), two SMARTape sensors are glued to the surface of the specimen over the whole width of a large aluminium plate. A conventional piezo transducer is used to excite the Lamb waves by emitting a 5-cycle sine burst of 100 kHz. The notch is located between the two optical fibre sensors so that the difference between the two received signals can only be due to the effect of the notch on the propagation of the ultrasonic waves. Fig. 7 shows the signals obtained. It is clear that both the S_0 and the A_0 mode are attenuated by the notch.

a)

b)

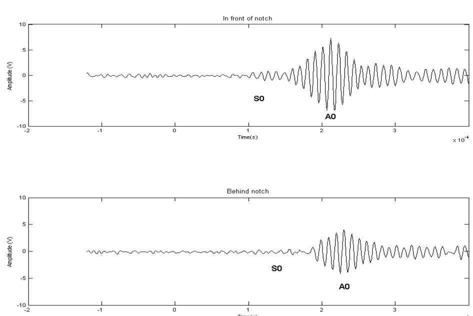

Fig. 7 Signals received in a notched aluminium plate: a. Signal received in front of the notch; b. Signal received behind the notch.

A similar experiment was performed by using two disk-like PZT patches which were adhesively connected to the aluminium sheets. After recording of a reference waveform of the undamaged sheet, holes with increasing diameter were drilled and the corresponding change of Lamb wave response was recorded and analysed (Fig. 8).

It was found that the norm (which is proportional to the RMS value) of a specified time-gated waveform decreased with increasing diameter. This can be explained by the material loss and by a change of the interference pattern. The interference pattern is also responsible for the small maximum at about 5 mm. It corresponds to a fracture of the incident wavelength and a certain constructive interference effect takes place.

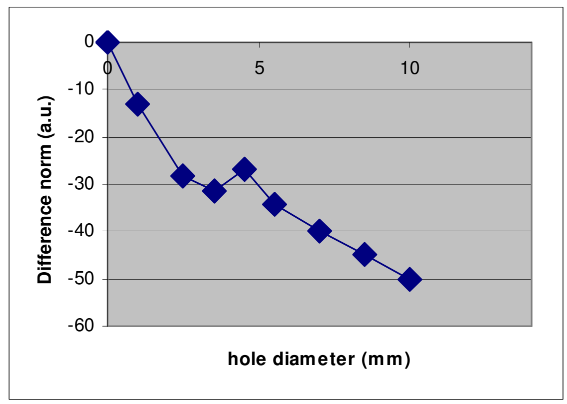

Fig. 8 Lamb wave response determined by piezoelectric patches as a function of increasing size of an artificial hole in an aluminium sheets

3.3 Early stages of corrosion monitored by Lamb waves

The ALOHA airline incident in 1988 was with a high probability caused by maritime corrosion of riveted joints in the stringer constructions of the fuselage. Maritime corrosion occurs if aqueous chloride compounds typical for aerosols above ocean water come in contact with metal structures. This aggressive type of corrosion leads to pitting corrosion [13], which can destabilise essential parts of the construction. The probability of maritime corrosion can be reduced by appropriate coatings but there is nevertheless a need of regular inspections or structural health monitoring.

Fig. 9 Salt mist chamber for simulation of maritime corrosion

The simulation of maritime corrosion can be performed using specialised salt mist chambers (Fig. 9) which allow the establishing of defined conditions of chloride concentration, humidity and temperature. Such chambers are routine instruments in corrosion research and we were able to perform an experiment where early stages of corrosion could be detected by Lamb waves.

We discovered that the aggressive atmosphere also affected the connections of sensor and aluminium sheets. Therefore, that connection was protected from the environment by an appropriate covering.

Corrosion can be followed by optical observation. This enables observation of the growing extend of pitting corrosion, and even a quantification is possible. Corrosion also resulted in the mass loss of the metal sheet as a function of time. The analysis of the corresponding waveforms indicated a continuous increase of the signal intensity as a function of time. This is in contradiction with the intuition that a decrease of the sound intensity should be expected. But a further analysis of the corresponding waveforms is to be found in the changed interference patterns, i.e. variations of the interaction of incident ultrasonic waves with the reflections. This leads finally to a reduction of destructive interferences at the early stages of corrosion. The study is still in progress and we expect to obtain a complete record of all Lamb wave responses during the whole lifetime of an aluminium sheet under simulated maritime corrosion.

3.4 Impact damage detected by optical fibre

The optical fibre monitoring set-up is used to observe the changes in the Lamb wave signal after a series of drop-weight impact tests [10] that are performed on carbon/epoxy samples (dimensions 300x100x2.1 mm). The carbon fibre sheets have a quasi-isotropic lay-up using 1000g/sqm +/-45° UD carbon for the inner layers and 900g/sqm 0°/90° woven carbon fabric for the outer layers. All sheets are made of 120°C HT carbon prepregs.

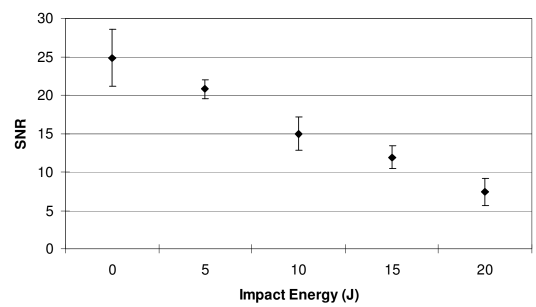

Fig. 10 Decrease of the transmitted sound energy (expressed by the SNR value) as a function of impact energy.

A piezo patch is used to excite the specimen with a 5-cycle sine burst at 82 kHz. Fig. 10 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.

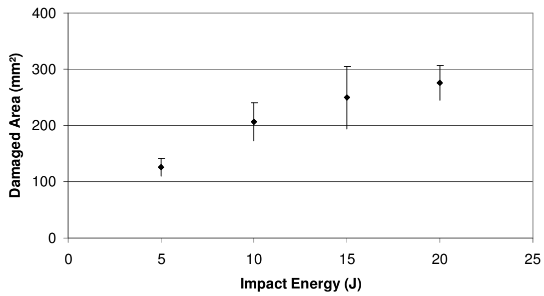

Fig. 11 Increase of the damaged composite area (expressed in mm^2) as a function of the impact energy.

This approach is less influenced by the many edge reflections that arise in small plate samples because the optical fibre sensor returns an integrated response over the whole width of the specimen, which is much less influenced by the interferences.

The calculated damaged areas which were derived from ultrasonic C-scan data increase as a function of increased impact energy (Fig. 11). From the comparison of Fig. 10 and Fig. 11, one can conclude that optical fibre sensors can thus be used in different set-ups for the detection of structural damage, such as the increase of damaged area.

New tests already initiated to monitor fatigue damage have also already yielded some good results. Future work includes further fatigue testing on the quasi-isotropic carbon/epoxy panels, and impact/fatigue testing on carbon/epoxy sandwich specimens with both foam and Nomex® cores.

4. Outlook

After accomplishing all required lab scale tests set up to obtain good signal-damage correlations, full-scale tests will be planned for aluminium and composite helicopter tails. Together with the dedicated electronics and appropriate software, a useful example of a monitoring system will be worked out.

Acknowledgement

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