Zawartość zarchiwizowana w dniu 2024-06-18

AIRCRAFT INTEGRATED STRUCTURAL HEALTH ASSESSMENT II

Sprawozdania

Informacje na temat projektu

AISHA II

Identyfikator umowy o grant: 212912

Projekt został zamknięty

Data rozpoczęcia
1 Maja 2008

Data zakończenia
31 Października 2011

Finansowanie w ramach
Specific Programme "Cooperation": Transport (including Aeronautics)

Koszt całkowity
€ 5 694 304,38

Wkład UE
€ 4 133 731,00

Koordynowany przez
KATHOLIEKE UNIVERSITEIT LEUVEN
Belgium

Ten projekt został przedstawiony w...

Final Report Summary - AISHA II (Aircraft integrated structural health assessment II)

Project context and objectives:

Introduction and Structural health monitoring (SHM)

In every civilisation, excellent transport systems are required to ensure economic and social welfare. This holds, e.g. for the Roman road network, the Silk Road, the English and Dutch seafaring, as well as modern aviation, container traffic and pipeline systems. To ensure faultless transport of human beings and goods, efficient maintenance and repair of such transport systems have decided and will decide over the success of any economic system.

Nowadays, reliability aspects of transport systems are frequently based on regular, i.e. scheduled inspection cycles. However, it is envisaged that the large cost associated with this approach can be avoided by a condition-based maintenance schedule. Maintenance, repair and overhaul (MRO) in modern aviation is well-elaborated, but relatively expensive and not appropriate in all situations, especially due to the fact that inspections are performed within fixed time intervals. A cheaper and even safer alternative for traditional inspections is offered by SHM. SHM systems can be most efficiently realised by affordable permanent sensor networks that are placed on crucial structural components of an aircraft, comparable to the nervous system in a human body. Since a couple of years, numerous SHM solutions were presented on laboratory scale and even partially implemented in real aircraft parts. However, the final implementation in civil aircrafts is still in an early phase and partially hindered by a number of obstacles, such as missing operational practice, respective technical immaturity and consequently a lack of acceptance by end users.

SHM stands in many cases for technologies using permanently attached sensor networks to enable continuous inspection of structural integrity. Such as illustrated by the number of publications, there has been an exponentially growing interest in SHM systems for different kinds of aircraft in the last two decades. Beside the expected enhancement of safety and maintenance performance, especially economic aspects play an important role. This regards on the one hand the reduction of inspection costs and on the other hand, the possible weight reduction of aircraft parts at the designing phase of an aircraft. The main benefits of SHM are essentially given by cost savings due to the reduction of inspection costs and repair resources, and the possibility to reduce material weight at the design phase: (a) enhancement of operational safety by more frequently applied inspections and enhancement of the detection probability, (b) greening of air transport by reducing replacements of components and (c) weight reductions leading to fuel reduction, as well as avoidance of contamination by toxic fumes.

It is furthermore compulsory that developments achieved within SHM projects finally meet the airworthiness requirements and fulfil all aeronautic standards from the very beginning. With this objective in mind, a specification sheet including airworthiness requirements as well as adaptation to standards has to be created before the initial definition of sensors to be applied for the different SHM methods and technologies in function of its applications.

The AISHA project

The routine implementation of SHM in aircraft is only a question of time. The obstacles, preventing the routine implementation of SHM systems so far, can be avoided by a dedicated implementation strategy. Moreover, end-users, such as operators (airlines), maintenance provider and authorities must be convinced that complete airworthiness is ensured. The development of an effective SHM system must be finally integrated into a SHM system where the data on structural integrity are classified and where procedures of maintenance and allocation of resources are organised (see also the TATEM project, FP6 502909). The AISHA II project wanted to provide an essential contribution to this objective.

The first AISHA project (EU-FP6, STREP 502907, 2004-2007) addressed basic aspects of damage detection in aircraft using ultrasonic plate waves (Lamb waves) for different materials, structures, damages and environmental conditions. Despite of the enormous achievements obtained, a number of challenges remained concerning signal interpretation and durable sensor connections. Within the AISHA II project (EU-FP7, CP 212912, 2008-2011) an essential upscaling concerning size and completeness of the consortium had to be achieved. New challenges had to be tackled by introducing new methods, such as percolation conductivity, ultrasonic time-of-arrival methods, non-linear ultrasound, pseudo-defects and electrochemical impedance spectroscopy. The participation of a leading maintenance provider (Lufthansa-Technik) offers optimum access to realistic implementation areas.

The AISHA II project thus aimed at the development of advanced monitoring systems for the structural state of aircrafts using extended sensor networks. The project started with the establishment of detailed specification sheets where aircraft operators and producers summarised their technical and economical requirements for health monitoring systems. Finally, five challenges for damage detection were investigated in the consortium: fatigue cracks in slat tracks of an Airbus A 380, impact damage in the tail boom of the helicopter EC 153, fatigue cracks in the helicopter tail boom of a Mil8, as well as corrosion in floor beams and fatigue damage in doubler repairs of an Airbus A340.

Such as motivated above, SHM can essentially be considered as a kind of automated sensor network. Therefore, the development and selection of appropriate sensors plays a key role. For the ultrasonic excitation and sensing, array systems are used in different configurations that depend on the size of the full-scale parts applied. These arrays allow a tailoring of waveforms due to their geometric shape and an electronically controlled signal delay. Despite of the sophisticated detection concepts, these sensors has to be low-profile, i.e. they are not made for versatile applications and the price must be relatively low when a high amount of sensors has to be implemented.

The AISHA II project intended to use physical phenomena, such as electrical percolation conductivity, ultrasonic plate waves and electrochemical monitoring in sensor systems to detect different kind of relevant defects. For this target, piezoceramic sensors, Electrochemical, optical fibre and Electromagnetic acoustic transducer (EMAT) sensors were applied in the project. The sensor systems selected require dedicated electronic steering and sensing, this especially holds for tailored electronics for array transducers working at specific values under operational conditions. Also in this case, not only piezoceramic transducers were considered, but also optical fibre equipment and systems for electrochemical sensing.

An essential challenge is the durable integration of transducers. Dedicated adhesives had to be applied to withstand typical temperature and stress variations. A special focus in this context the ability of self-testing of sensor by impedance analysis, for example. Furthermore, pre-stressing is an option that contributes to the mechanical stability of piezoceramic transducers.

Before the selected technologies were applied to full-scale parts, experimental feasibility needed to be checked for simplified samples. Here, basic results were obtained e.g. for the detection of impact damage by acoustic emission using optical fibres, the use of EMATs for crack detection, the detection of corrosive liquids and corrosion by optical fibre - and electrochemical sensors, and the application of pseudo-defects for validation purposes.

The functionality of a complete SHM system not only depends on the quality of signal interpretation but also on the prediction or at least estimation of the remaining life time of the full-scale parts. Based on established models, data obtained from our transducer systems can be used to enable these estimations. At the final stage of the project, sensor systems will be implemented into the above mentioned full-scale parts and extended test programmes will be performed.

Despite of the big importance of tailored transducer systems, extended signal management is required to improve or even enable proper signal excitation and interpretation. This regards standard signal conditioning, but also advanced data processing like pulse-compression and time reversal, as well as imaging technologies for comfortable defect localisation. Moreover, the determination of the optimised sensor positions depending on the individual full-scale part is essential.

However, this apparently easy approach requires focused research and implementation effort using well-coordinated collaborations of many disciplines and expertise in Europe. The European Research Area (ERA) establishes the ideal platform for such a collaborative undertaking, and the considerable financial risks can perfectly be reduced by a great amount by appropriate funding from dedicated European research programmes.

Finally, the consortium was convinced that with the proposed working plan all project partners are enabled to create synergistic effects continuing the strategy to implement SHM systems in operational airliners within the scope of a European project.

Project results:

In contrast to the AISHA I project exclusively focussing on damage detection in aircraft structures using ultrasonic plate waves (Lamb waves) with a relatively small group of project partners, the AISHA II project achieved an essential upscaling concerning size and completeness of the consortium. New challenges were successfully tackled by introducing new methods and technologies, such as percolation conductivity, ultrasonic time-of-arrival methods, non-linear ultrasound, pseudo-defects and electrochemical impedance spectroscopy. The participation of a leading maintenance provider (Lufthansa-Technik) offered optimum access to realistic implementation areas, and within the project, it was possible to bring a floor structure sensor to Technology readiness level 9 (TRL 9). In the last project year, three operational airliners from Lufthansa were equipped with percolation sensors and already now, results are so convincing that Lufthansa-Technik was able to adapt maintenance procedures for floor structures in their Boeing 737 and Boeing 747 fleet. Meanwhile, at the international workshop of SHM at the University of Stanford (IWSHM, 13-15 September 2011), the demonstration of the floor structures sensor was honoured with the most practical SHM application in aerospace award sponsored by AIRBUS).

Diverse solutions were proposed by the AISHA II consortium, and each of them has their own prospects even outside the world of aviation. Whereas the floor structure sensor is heading for commercialisation, other solutions are also advanced, or they are at an early stage, and can be considered as visionary ideas.

- The floor structure sensor - highlighted in the European Union (EU) video - is implemented in a commercial airliner of Lufthansa since April 2011, and it has already proven its airworthiness and usability. The knowledge about where and when liquids are able to penetrate sealed floor structures is already used to review and improve existing procedures for corrosion prevention. Because of the very positive results obtained, on further commercialisation is positively decided and market introduction is expected the following two years. It has also to be emphasised that the sensor is highly generic and negotiations about applications outside aviation are under progress.

- The painted crack gauges concept is also advanced due to its back-to-basics approach. A few final questions still has to be solved concerning the temperature stability and the occurrence of closed cracks.

- The technologies based on ultrasonic and optical fibre sensors belong to the more visionary concepts because they usually require the implementation of on-board electronics that complicates certification efforts. This is especially the case when the sensors need to be active during flight. However, using an optimum implementation strategy practical applications could also be expected the near future.

The European project AIRCRAFT INTEGRATED STRUCTURAL HEALTH ASSESSMENT II is subdivided in different Work package (WP)s that has reflected in a certain sense the procedure how SHM could in the future be implemented as a routine activity.

WP1: Specification sheets and design of final SHM-implementation

This WP was part of the design phase of the project and contained two strongly interrelated main objectives. The first objective regarded the preparation of detailed specification sheets for the pre-selected aircraft parts. The aircraft operators and manufacturers in the consortium gave the necessary input to summarise all the demands the intended SHM system must fulfil. The second objective was the final decision on the SHM implementation strategy to follow. Finally, at least five challenges for damage detection were investigated by the consortium: fatigue cracks in slat tracks of an Airbus A320 and A380, impact damage in the tail boom of the helicopter EC 153, fatigue cracks in the helicopter tail boom of a Mil8, as well as corrosion in floor beams and fatigue damage in doubler repairs of an Airbus A340.

WP2: Non-experimental feasibility study

The WP on non-experimental feasibility studies belonged to the design phase, and it was intended to provide arguments for the decision on the final SHM implementation strategy developed in the WP on specification sheets. The decision was based on measurable parameters derived from in-depth literature study, analytical studies and numerical calculations.

A very interesting aspect of the non-experimental feasibility study was the theoretical study on pseudo-defects performed at partner KU Leuven and the Aviation Institute of Riga Technical University. When new ultrasonic techniques for Non-destructive testing (NDT) are introduced, diverse validation tests are required. Signals obtained from samples with well-characterised natural defects (cracks, flaws) or artificial defects (notches, boreholes) are compared with signals obtained from undamaged samples, and so the NDT technique can be assessed towards reliability and accuracy. The basic idea presented in the project is to replace real defects by non-destructively applied pseudo-defects. For this purpose, a number of analytical and numerical studies were performed that indeed showed that a thickness variation, i.e. a thickening (simulated pseudo defect) or a thinning (simulated damage) of a plate in plates creates similar acoustic responses.

In this context, numerical studies were performed to simulate the dispersion curve of asymmetric composite plates. Those dispersion curves give the propagation velocities in plates as a function of frequency and plate thickness. This is important to understand propagation properties of Lamb waves in real structures. It was found that those calculated curves match quite well with experimentally determined values.

Another study regarded the use of the determination of the stress dependence of the propagation velocity in plate waves. Those relationships might help to get access to new ways of determining stress-strain profiles of materials, especially for the case of material degradation.

WP3: Transducer design

The WP on transducer design belongs to the implementation phase and it is dedicated to the development and validation of dedicated actuators and sensors. As already mentioned in the previous sections, the consortium initially focussed on the use of acoustic surface waves and therefore, piezoelectric transducers have played the dominant role in the design of the SHM technology. For the detection of the acoustic surface waves, piezoelectric sensors and single-mode optical fibres were used.

However, in order to facilitate the interpretation of signals, other physical parameter will be recorded too, such as temperature, strain or the electromechanical impedance.

Percolation is a phenomenon when one material is dispersed in another material in a way that there is continuous contact between the dispersed particles. In the case of electrical conductivity, it is possible to make electrical conducting composites with an isolator as matrix material. In this way, different material properties can be combined. It is also known since a long time that this kind of percolating materials are excellent sensors. In the present project, diverse applications were applied to the aerospace applications, especially at the partner KU Leuven. It is according to us the first time that these kinds of sensors were applied.

For the detection of aqueous liquids, a material was developed that is able to swell under the presence of water. For that case an interruption of the electrical conductance of that material would be measured. This is thus an ideal sensor for detecting all kind of aqueous liquids. The similar principle was applied for sensors detecting hydraulic liquid, mineral oil and kerosene. However, the principle of using percolation material is also useful for detecting cracks in materials. Also here, external stress leads to an interruption of the electrical conductance.

However, there are also optical means for detecting liquids. When an optical fibre is clad with a dedicated metal layer, a specific phenomenon is observed which is called surface plasmon resonance. It is comparable to the resonance in a guitar string and when a specific chemical compound is situated at the outer layer of that cladding, a shift of a typical optical resonance can be measured indicating a change of the environment. Very sensitive liquid sensors can be made in this way.

Moreover, as a tool for detecting cracks in aircraft structures, eddy current systems are used. These are complex versatile devices that require an experienced operator. However, for defect detection at selected hotspots, it is sufficient to place simple flat coil sensors at the expected defect position. The appearance of the crack can be measured by a shift of the electrical impedance at a defined frequency. That sensor was developed on the basis of an etching technique at partner KU Leuven.

At partner Metalogic final lab scale sensor design for corrosion monitoring used instrumented electrically conductive tape like material consisting of a random dispersion of conductive fibres in a polymeric matrix. The type of tape material and lead connection best fitted for the corrosion sensor were determined so that the impedance of the sensor material did not interfere with the impedance of the system to be monitored. The sensing capabilities of the various material combinations were tested for several months in water at different temperatures (25 and 40 degrees of Celsius). The lab scale size sensor showed to be responsive to either chemical or mechanical degradation of the seat track. To assess chemical degradation the seat track instrumented with the corrosion sensor was exposed to different liquids (e.g. coke, water, or orange juice among others) while its response to mechanical damage was tested by scratching the sensor together with the seat track. The impedance response upon mechanical damage of the seat track in the presence of liquids was characterised by several relaxations, which are indicative for corrosion of the aluminium substrate.

For the reliable detection of impact damage in the tailboom E135 two different transducer concepts were designed and tested at partner German Aerospace Centre (DLR). As actuators for the fast Lamb mode, a piezo-composite was applied. It is able to excite the corresponding wave mode in an optimised way. For the detection of Lamb waves it was realised that glued sensors itself act acoustically as defects. Therefore, air-coupled sensors were applied that are attached by foam. This concept was proven to be successful.

In collaboration with partner Meggitt, partner Cedrat Technologies succeeded to design, model and manufacture an 8-channel array transducer for sending and receiving Lamb waves in aluminium plates typical for aircraft structures. The target was to improve the so-called mode selectivity and directivity. All steps from modelling, simulation until manufacturing and integration were accomplished and even a number of highly relevant durability tests were performed, most specifically focussing on temperature tests. The design is based on the use of monolithic comb-like piezoceramics that is potted with a dedicated epoxy compound to achieve optimum acoustic properties. Beside the basic design, also interfaces were design to enable a proper customisation.

The Aviation Institute of the Riga Technical University has modified piezoceramic transducers that they can survive higher loads typically occurring in aircraft structures. This was achieved by a specific pre-stressing of the sensors.

The WP leader Meggitt essentially provided three different types of transducers, firstly it has provided comb-like piezoceramics to be used in the array transducer that is manufactured by Cedrat Technologies. Secondly, bulk transducers were provided for other project according to their specific needs. A specific attention was given to the production of piezoceramic thick films using that technology it is possible to tailor sensors by applying screen printing technology.

Partner Fraunhofer provided expertise in developing so called painted crack gauges. These are electrically conducting composites that are able to indicate the presence of cracks in structures by the interruption of electrical conductivity.

Another interesting application comes from long period grating fibres and microstructured optical fibres for detecting of impact damage. Here, the impact damage is derived from the disturbance of light propagation and from a crossed pattern arrangement, the defect localisation such as studies at the University of Basque Country.

WP4: Electronics for SHM

Excellent driving and sensing electronics, delivered by this WP (part of the implementation phase), represents a self-evident component of every SHM system. One of the ideas was to use combined sensors that would be essential in order to interpret the ultrasonic signals, the data collection of parametric sensors must be supported (temperature, strain, electromechanical impedance, electrochemical signals). Furthermore, a good balance had to be found between innovative developments of new electronic components and the application of systems already available on the market.

There is always the question how structural monitoring must work in operational practice. Is it really necessary and desirable to measure during flight, or is it sufficient to measure on the ground, e.g. when light maintenance (A-check) is performed? In the last case, electronics which is only available at the ground can be plugged into the corresponding connections and an automated test programme can be performed. This could avoid the requirement for airworthiness of the corresponding electronics.

Concerning the operation during flight, schemes are available for implementation to detect the stress during flight. Developed calibration schemes to correct for the influence of extended wires allowing for multitasking from a single and even compact electronic module are also available for test and implementation. Similar devices with enhanced computing power can effectively be adapted and used for ground monitoring.

The electronics developed had different aims with a different degree of complexity. A relatively simple device was for instance developed at the KU Leuven that is acting as a fuse to determine the presence of cracks in slat tracks of e.g. an Airbus A320.

For steering, thus sensing, receiving and controlling of multi-channel ultrasonic signals, a dedicated 24-channel electronic device was developed at the acoustics and thermal physics section of KU Leuven. It also contains a signal modulator and furthermore, concepts were developed to bring this equipment into aircraft.

Also for the electromechanical impedance measurements, dedicated electronics needed to be available. In that specific context, an innovative combination of commercially available components were used and adapted to the needs of the measurements.

At DLR a dedicated interface for a non-contact ultrasonic sensor system was developed. This was necessary because of the stimulating discovery that simple electrets microphones are sufficient to transfer plate wave signals from the investigated areas through the air to the sensors. In this sense, a direct sensor coupling to the structure is not necessary. Furthermore, essential resources were dedicated to wire and control a sensor array for the tailboom of a Eurocopter EC135 helicopter.

Partner Cedrat was leader of the WP on electronics. Beside the development of array transducers and providing expertise to other partners, customised Lamb wave driver and receiver electronics was developed. This includes an 8-channel mother board and in this context, all required steps were taken to enable an easy connection to other devices. Finally, a concept was developed for an electronic datasheet (TEDS) implemented in sensors.

The innovative concept developed at the University of Leipzig of using high-accuracy time-of-flight (TOF) determination of acoustic signals required the development of dedicated electronics. This was done in cooperation with ASI Analog Speed Instrumentation GmBH and the result is a small and mobile device for performing those tests under operation. It finally includes many steps of analogue and digital processing of so-called chirped signals.

At the University of Basque Country, the connections for optical fibres systems for impact detection in composite were developed and adapted.

WP5: Integration of transducers and assessment of the long-term usability

This WP belongs to the implementation phase and it contained two major tasks: on the one hand, it concerned the selection of adequate mechanical connections between sensors and structure to obtain an optimal signal transduction, on the other hand the durability of the connection had to be guaranteed over the period of many years. Finally, methods of durable sensor integration had to focus on durable materials as well as mechanical and chemical protection.

In a continuous health monitoring system for aircraft structures, sensors / actuators will need to be integrated within the structure without causing excessive modifications at the implementation area. One option would be to mount sensors / actuators on the surface of structures. Surface mounting is unavoidable for metallic structures, and an option for other materials. Within this WP efficient surface mounting methodologies for thin film, bulk and fibre based sensors / actuators were developed.

The development of a surface mounting methodology will involve adequate adhesive and curing treatment, preparing test samples and evaluating the performance by investigating signal transfer from sensor/actuator to material and vice versa. The adhesive used must be compatible with the material used and a possible curing process must not induce damage, neither to the sensor/actuator nor to the material itself. It is anticipated that surface mounting on two different materials will be investigated (one metal, one composite) and that the optimal sensor/actuator type will be used which will follow from the WP on electronics. The efficiency of the mounting process will be examined by preparing test samples, by either generating or receiving artificial signals and by measuring the amount of signal energy transferred and the signal to noise ratio.

An interesting step concerning the implementation of SHM sensors was set at the KU Leuven. The idea was to implement sensors directly below or into the protecting primer layer of the respective structure. In this way, the distance with respect to the expected damage area was reduced, furthermore complexity is also reduced and with it the implementation threshold for those SHM systems.

For the German Aerospace Centre, test series for the acoustic coupling of the piezoceramic sensors on composite plates was important. On the one hand, a good signal transmission is important, on the other hand, embedded sensors react acoustically similar as they were defects itself. The solution was to use air-coupled sensors and in this context air-coupled sensors were attached by a dedicated foam, as validated by partner Fraunhofer ⍰ IFAM.

The main purpose of this WP is testing the durability of the sensors and the sensor connection. At partner KU Leuven MTM the successfully installed floor sensor was subjected to intensive fatigue loading representing almost the worst case occurring in airplanes. Furthermore, bending tests were applied as well as temperature and burning tests.

Also for the embedded eddy current sensors (flat coil sensor) a dedicated test programme was developed showing that those sensors purely embedded in the primer layer survive all fatigue loads occurring under realistic simulation of flight conditions.

At the Riga Technical University (RTU), a lot of efforts were dedicated to the durability of lengthy piezoceramic sensors. This was achieved by using pre-stressed sensors that have the possibility to survive much harsher conditions than non-prestressed sensors.

At CTA different fire and burning tests (flammability test) were conducted according to the certification conditions usually applied for aircraft.

The WP leader Fraunhofer IFAM did extensive work on the electrochemical and ⍰mechanical characterisation of adhesively bonded piezoceramics during adhesive cure and during accelerated ageing.

Furthermore, at the Free University of Brussels, impedance measurements of piezoelectric transducers were performed in a climate chamber during static loading. In this context, also the influence of contaminations of the propagation of surface acoustic waves was investigated. As a result, the application of diverse acoustic modes in SHM, such as linear surface waves was questioned.

Also for the optical methods, i.e. optical fibre sensors the durability tests were performed in collaboration between CTA and the University of Basque Country. It was found that many commercial systems were not able to withstand the harsh conditions of the operations typical in helicopters. However, technical solutions were found to solve these problems. In this context, a number of relevant vibration tests were performed.

WP6: Experimental feasibility

The experimental feasibility studies belong to the design phase and partially also to the validation phase. During the design phase for the appropriate SHM strategy within WP1 (specification sheets), a number of specific questions emerged that only could be answered by appropriate experiments. The WP thus provides the necessary information on the experimental feasibility of correlations between damage and signal, as well as on sensor durability under quasi operational conditions. Furthermore, the concept of pseudo-defects was further elaborated to develop it to a powerful tool of validation of damage detection.

For the detection of immediate impact damage at KU Leuven in composite material, optical fibre sensors were used, and it was possible to establish a calibration curve to derive a numerical relation between signal intensity and impact energy for a helicopter tailboom demonstrator from Eurocopter. In this context, the adjustment of the correct electromagnetic polarisation in the optical fibre was always an important issue. A further attempt has been made of using optical fibres to detect the presence of corrosive liquids by application of so called surface plasmon resonance. Those tests were quite successful, and one of the advantages in using optical fibres is that it occupies only a very limited space.

Another concept that was introduced in sensing systems for aircraft maintenance are percolation conductivity sensors, also designed and investigated at the KU Leuven. These sensors feel changes in their environment and respond by changes of their conductivity over a wide range of magnitude. Finally, information on damage can be obtained by a simple multimetre. A first successful application was the floor structure of airplanes; in a lab model it could be shown that ingress of water characteristically changes the electrical resistance of the sensor over many orders of magnitude. But this concept is not only useful for water-like liquids. Using a modified sensor, we were also able to detect aircraft hydraulic liquids, kerosene and diverse mineral oils.

However, the potential of using percolation sensors was not only limited for detecting liquids. Also the presence of cracks can be detected by an interruption of the conducting pathways created by the percolation networks. For this target, specific compounds have been developed and tested by the Fraunhofer Institute and KU Leuven.

Beside the newly introduced percolation sensors, also more classical approaches were followed, such as eddy current testing for determining cracks. Dedicated flat electric coils were designed at KU Leuven and embedded into aluminium structures typical for aircraft. Also here, a clear correlation between damage and signal intensity could be found. An additional advantage is that it is not required to take extensive electronics into the airplane.

A big magnitude of tests was dedicated to the analysis of newly developed ultrasonic sensors and actuators, more specifically the array sensors optimised for Lamb wave propagation in plates. The acoustic and thermal physics section of the KU Leuven has applied different techniques to test the frequency and directivity characteristics of sensors developed by Cedrat and Meggitt. In this context, also the investigation using nonlinear ultrasound was tested and improved. Here the interplay between simulation and experimental results has helped to optimise the experimental set-up.

In addition, at partner Metalogic, the sensitivity of the novel lab scale corrosion sensor was validated by comparison with the measurements obtained using a conventional electrochemical cell. Similar trends were found in the impedance data recorded in both cases. Additional experimentation was performed on the size effect of the damaged area by gradual removal of the seat track coating. By increasing the surface area of the removed coating, the LF amplitude became smaller (vertical arrow), and the mid frequency range became less dominated by the remaining coating's impedance. Both phenomena can be explained by means of a resistor-capacitor (RC) equivalent circuit model and where the effect of the surface damaged area can be taken into account by computing their respective specific values (R sol, R pol, and C dl). While Rsol is expressed as a function of A, Rpol and Cdl are expressed as a function of the fraction of damaged coating surface area A damaged. Additionally, the capacitance is directly proportional to the damaged area while the resistance is inversely proportional to it. The high-frequency (HF) response remains unaltered for an increased fraction of damaged area as this part of the spectrum is dominated by Rsol, which is independent of it. As opposed to this frequency range, the remainder part of the spectrum is effectively influenced by the size of the damaged surface area. This is because Cdl and Rpol are dependent of damaged. However, since Cdl and Rpol have opposed proportionality with damaged, the two extensive quantities show an opposite evolution with time. While Cdl increases, Rpol decreases with damaged.

Up-scaled size corrosion sensors also showed to be sensitive to coating degradation, removal and substrate corrosion by a qualitative evaluation of subsequent impedance data. In the absence of liquids, the impedance spectrum is similar to that of a protective coating (phase shift -90 degrees, and very HF frequency modulus); however, in the presence of liquids coating degradation is induced as shown by the decrease of the modulus at LF. Upon mechanical damage of the seat track, immediate decreases of the impedance modulus as well as phase shift are observed. The location where the coating was removed shortcuts the high-impedance behaviour of the undamaged coating, as a result of which the impedance drastically decreases. Moreover, the sensor detects an evolution in time for the consecutive spectra which probably results from the evolution of the corrosion processes as a function of time. Therefore, the up scaled size sensor is able to detect coating degradation, coating removal and substrate corrosion.

As regards the quantitative analysis of the Electrochemical impedance spectroscopy (EIS) data, using equivalent electrical circuits, the successful and accurate characterisation of the observed phenomena will strongly depend on the dynamics of the system, which changes in time for most of the corrosive systems. Actually, if the time constants of the different relaxations are too close to each other, their impedance response will be interlaced, impeding as such a reliable determination of the characteristic parameters of each of the phenomena. Therefore, a simplified method for determining the remaining life time of the seat track was developed by considering the highest corrosion rate of aluminium, in contact with different liquids, determined ex-situ by potentiodynamic polarisation.

Within DLR, new concepts for Lamb wave actuators based on piezoceramic foil design were designed and successfully tested. Here, the material had to match the big wave length that are typical for those kinds of structures, and dedicated techniques were applied to provide a composite sensor that was able to cope with that challenges. Furthermore, the analysis of classic ultrasonic mapping (C-scan) provided a tool to fine-tune the sensor position a technique that is already patented.

Together with Meggitt, partner Cedrat Technologies has developed array transducers for fine-tuning Lamb waves to achieve improved mode selection and directivity. But also basic aspects of their performance were also tested and as an important part of these investigations, the durability in difficult environmental conditions was intensively explored.

The Aviation Institute of the Riga Technical University (RTU) has performed many studies on the correlation between cracks in aluminium structures and ultrasonic signals obtained by Lamb waves in a far field and near field regime. Here, much attention was given to clearly determine the conditions of ideal sensor positioning and defect identification and sizing. Beside long-range detection of cracks, also near-field analysis around the sensor provided promising results. Finally, a dedicated analysis of the use of pseudo-defects were performed. The theoretical base for pseudo-defects was already established in WP by partner KU Leuven.

Also the partner from the University of Leipzig has dedicated essential resources to the application of Lamb waves for usage and damage detection. Here, different feasibility tests were applied using high-accuracy determination of the velocity of sound (TOF) to determine defects and degradation in material. The experimental work was accompanied by a thorough theoretical analysis that provided new insights in mathematical treatment of mechanical plate waves itself. A further interesting result is related to the establishment of stress dependent dispersion relations for acoustic waves travelling on a chain of point masses. Also here, theoretical and experimental work provided convincing results.

The Free University of Brussels contributed by another method in applying non-linear ultrasound. The use of so-called multi sine broad band excitation provides new options in distinguishing and localisation different kinds of defects. Those tests were accompanied by the visualisation of the propagation of ultrasonic surface waves using scanning laser Doppler vibrometry.

The partner from the University of Basque Country successfully applied Fibre Bragg grating (FBG) sensors for online detection of impact using a dedicated sensor network.

WP7 Signal management

This WP belonged to the implementation phase. It has addressed many aspects of signal management. These aspects are extremely important due to the complex structure of the �full-scale parts� requiring e.g. advanced methods for reducing complexity and high dimensionality of data.

In the project three different approaches were followed. The first approach was to optimise the position of actuators and sensors. The second approach is the application of advanced waveforms. In this context the use of chirps (wave compression) and state-of-the art time-reversal methods was successfully applied. The approach regarded the application of advanced algorithms to obtain unambiguous information on damage size if complex signals are given.

Partner DLR succeeded to develop a tool for the optimisation of the positioning of sensor networks for Lamb wave propagation. Here, as derived from ultrasonic C-scan, the sensor response can be simulated and optimised sensor positions can be determined.

Also partner RTU (Riga Technical University) has made essential progress concerning the positioning of sensors. In all of these cases, it was considered that in aircraft, specific places exist �hot spots� were damage is much more likely than at other positions.

In the case of electrochemical impedance measurements signal management is essential to achieve a correct information on the status of coating degradation. On the base of the computer analysis, an appropriate model is required.

At partner DLR essential efforts were done to achieve data handling. Different challenges had to be tackled, the first is the visualisation of Lamb wave propagation using data obtained from ultrasonic scans, the second challenge is related to the analysis of the ultrasonic data obtained from the designed sensor network.

The contribution of signal management from University of Leipzig essentially concerns normalised differential pulse compression, monitoring based on time reversal techniques and broad band transducers and time selective dispersion analysis by short time Fourier transformation.

WP8: Remaining lifetime models

Also this WP belongs to the implementation phase and concerns an important question of the time dimension of structural reliability. The occurrence of damage in aircraft is usually not an immediate problem. The damage progression, given a certain load pattern is, especially in the case of metals, a predictable process. The objective of this WP was the elaboration of advanced remaining lifetime models and its application to the specific full-scale parts selected for AISHA II. A dedicated software was developed as a powerful tool which delivers the necessary time-parameters for a given number of ultrasonic and load parameters.

Remaining life time is also an issue in electrochemical tests performed at partner METALogic on degradation of coatings. An appropriate approach for deriving the remaining lifetime was developed that gives e.g. an estimate for the schedule in floor structure maintenance. The final approach involves in-situ monitoring of the seat track impedance behaviour by means of the newly developed corrosion sensor and calculation of the remaining lifetime using the □highest corrosion rate worst case scenario determined under lab conditions. It is expected that this adapted approach will be more stringent than the one initially described. The assessed remaining life time may therefore be regarded as a minimum value.

Another concept developed at the University of Leipzig was used to derive stress-strain relationships from the TOF signals obtained from loaded materials.

WP9: Full-scale investigation, implementation and testing

This WP belongs to the design, the implementation and the validation phase and it considers all experimental research activities to be performed on most realistic full-scale parts. On the one hand, the full-scale parts have to be characterised with classic NDT in order to have a basis for the design of a dedicated SHM system to be performed within the initial WP on specification sheets and full-scale characterisation. On the other hand, the SHM system has to be implemented and tested according to operational conditions.

The WP on full-scale investigation and implementation can be considered as the final target of the work programme. An important study was performed by partner KU Leuven on determining the displacement behaviour of the tailboom demonstrator of the helicopter EC135. This was an important step to characterise the Lamb wave propagation in real helicopter structures, especially concerning the relationship between excitation frequency and achieved wavelength.

A first implementation step in a realistic floor structure model was performed to determine early steps of corrosion using ultrasound. The results were not too convincing and another concept was applied, i.e. the determination of the presence of corrosive liquids instead of the determination of corrosion itself. A first successful attempt was the determination of those liquids by an optical fibre sensor. Surface plasmon resonance sensors not only allow indicating the presence of liquids, it is also possible to determine what kind of liquid is present. Despite of the success of the method, some issues remained concerning stability of the signal and complexity of equipment. The final solution was provided by the implementation of percolation sensors into the floor structure. After extended tests using a lab-based model, final implementation was performed into a Boeing 737 of Lufthansa. After one year of data recording, one can clearly state that the sensor fully fulfils all expectations. Meanwhile, also two Boeing 747 (Jumbo-Jet) were equipped with the sensors and now, sensors with an integral length of 50 m are implemented in three operational airliners.

A further full-scale test was performed on a slat track of an Airbus A320. Here, the presence of cracks was detected by crack gauges made from metal stripes or electrically conduction paints (percolation sensors). Also partner KU Leuven of the acoustics and thermal section performed tests on the slat track using non-linear ultrasound. Another application of the non-linear technique was applied to analyse delamination and impact damage on a helicopter tailboom from Eurocopter EC 135. Those tests were performed at partner CTA.

Partner METALogic successfully integrated tape-like corrosion sensors based in a floor structure made from aluminium alloy to check the integrity of coatings in seat tracks. Valuable results were achieved that allows obtaining clear correlations between the signals obtained and the state of degradation. Methods and results are more in details explained in the WP on feasibility.

Partner DLR has developed sensor arrays with air-coupled transducers and an extensive test programme were run at the facilities of CTA. Here, defined impact damage was applied and the response was finally analysed using the analysis software developed.

The Aviation Institute of the Riga Technical University performed an extended test programme on a helicopter Mil8 helicopter. Here, cracks in the aluminium structure and damage of bolt joints were considered. The leading principle was the analysis of the decay of the linear ultrasonic transmission of a plate wave signal with respect to an increasing damage as a function of increasing load. The tests were conducted over a period of several months and there were clear results with respect to damage signal correlation.

For all tests using the helicopter tailboom, partner CTA did excellent work in preparing and conducting fatigue load test campaigns. Moreover, durability tests and flammability tests were conducted.

Partner University of Leipzig performed a wide range of tests on both helicopter tailbooms. In the case of the aluminium structure tailboom, health, load and temperature monitoring was done. This was achieved by high-accuracy acoustic TOF measurements. The experimental data were accompanied by a thorough theoretical analysis of the underlying physics. For the helicopter tailboom, a monitoring of delamination using pseudo-defects was possible. It could be shown that the method is highly sensitive and it appears that the value of the method is not only due to the detection of defects but it also provides information on load monitoring.

WP10: Dissemination

There were a big number of conference participations, proceedings and papers. Over the whole project, 80 dissemination activities were performed and 50 peer review papers were published and the majority is for sure situated in the second reporting period. Also four patent applications were submitted and two patents were already granted.

A successful event was the open project meeting that was organised at the end of the second reporting period by the coordinator. Various participants from industry and academia had the possibility to listen to presentation given by all project partners. The open project meeting was accompanied by a poster session and a small exhibition where SHM set-ups developed in the project were presented.

It has to be mentioned that the dissemination activities are going on, and important results of the project will e.g. be presented at the European Workshop for SHM in Dresden in July 2012.

Potential impact:

The AISHA II project aimed at the development of advanced monitoring systems for the structural state of aircrafts using extended sensor networks. The project started with the establishment of detailed specification sheets where aircraft operators and producers summarised their technical and economical requirements for health monitoring systems. Finally, five solutions for damage detection are investigated in the consortium: fatigue cracks in slat tracks of an Airbus A 380, impact damage in the tail boom of the helicopter EC 153, fatigue cracks in the helicopter tail boom of a Mil8, as well as corrosion in floor beams and fatigue damage in doubler repairs of an Airbus A340.

It had to be ensured that the results obtained within the project are disseminated according to the needs of the ERA and the European aircraft industry. An important event was the open project meeting that was organised at the end of the project. Here, every partner had the task to present the key results of the research obtained in the respective groups. The presentations will finally be a part of dedicated proceedings to be published at an internet journal.

The AISHA II was obviously also a success for the funding policy of the European Commission (EC) within the FP7 programme, and the Directorate General for Research Transport/Aeronautics has decided to highlight the AISHA II sensors to illustrate the EU funding policy to a wider audience, e.g. a video was produced on the occasion of the EC-organised Aerodays 2011 in Madrid where finally just 3 of all recently funded European projects in aeronautics were selected.

Socio-economic impact

With the more detailed description below, we especially try to respond to the challenges formulated in the innovation union

Firstly, the project offers innovative solutions that are required to improve the competitiveness of the Europe in aeronautics, one of the demands of the innovation union.

- The floor structure sensor recently implemented most probably represents the first structural damage sensor in an operational airliner that approaches commercialisation. It is also innovative because of the back to basics approach, e.g. the detection of corrosive liquids is performed by a so-called percolation sensor, and its components could in principle be bought in a do-it-yourself store. Moreover, no electronics is required during flight lowering weight and certification efforts. Nevertheless, the estimated benefits for cost efficiency and safety are considerable.

- The crack detection in slat tracks by painted crack gauges is innovative because the intention is finally just to paint the sensor using a conducting primer during production leading to smart coatings. Reading out of the sensor signal is in principal possible by a simple multimetre ? thus, also here, an innovative back-to-basics approach was followed.

- The online impact detection by optical fibres in composites is innovative because maintenance relies on scheduled inspections determined by the number of flight hours, for example. Online impact detection using single mode fibres would give the maintenance the chance to perform a non-destructive material test according to a real recorded incident. In turn, scheduled inspections could also be reduced. It is possible, for example, that during scheduled inspections now, impacts are overlooked because the skin of the composite material is usually barely affected, even when serious core damage is present.

- The electro-corrosion monitoring using tape-sensors is innovative because it uses newly designed sensors that do not always require online monitoring and where the implementation threshold is low.

- The application of TOF and non-linear ultrasonic methods is innovative because diverse disadvantages related to traditional linear ultrasonics can be avoided, such as limited accuracy, dependency on contamination of surfaces.

- The application of pseudo-defects is innovative because it saves development time when the feasibility of detecting defects in real full-scale parts does not require the destruction of the part.

- The application of array transducers, especially manufactures as comb transducers or by air coupled electrets microphones is innovative because it enables fine-tuning of ultrasonic plate waves and improved defect localisation.

The project also potentially offers solutions to the challenges described in the innovation union, such as clean and smart mobility, climate change and energy challenges and reducing greenhouse gases.

- Traditional aircraft parts are relatively heavy because they must reliably 'survive' the big intervals between regular inspections. Permanent sensor networks allow a quasi-continuous observation of aircraft parts and therefore, those parts can be made much lighter which gives enormous opportunities to essentially reduce fuel costs.

- The replacement of aircraft parts is frequently determined by fixed intervals - and this is not always optimal if the parts are undamaged. Permanent sensor networks allow replacing parts only when they really show defects or abrasion. This offers huge opportunities to reduce waste of resources.

- If permanent sensor networks are present, damage can be detected much earlier than in the past. This allows a more specific allocation of manpower during maintenance, and it essentially reduces repair time. This finally gives opportunity to save costs due to the avoidance of unnecessary out-of-service time of an aircraft that are in the range of approximately EUR 50 000 per day. Moreover, if more airplanes are in service at a certain time interval, the need for new airplanes will in turn be reduced.

MAIN Dissemination activities and exploitation of results

SHM can essentially be considered as a kind of automated sensor network. Therefore, the development and selection of appropriate sensors plays a key role. For the ultrasonic excitation and sensing, array systems are used in different configurations that depend on the size of the full-scale parts applied. These arrays allow a tailoring of waveforms due to their geometric shape and an electronically controlled signal delay. Despite of the sophisticated detection concepts, these sensors has to be low profile, i.e. they are not made for versatile used and the price must be relatively low when a high amount of sensors has to be implemented. Beside piezoceramic sensors, electrochemical, optical fibre and EMAT sensors are successfully applied in the project.

The sensor systems selected require dedicated electronic steering and sensing, this especially holds for tailored electronics for array transducers working at specific values under operational conditions. Also in this case, not only piezoceramic transducers were considered, but also optical fibre equipment and systems for electrochemical sensing.

An essential challenge is durable integration of transducers. Adhesives are under development and are able to withstand typical temperature and stress variations. A special focus in this context is the ability of sensor self-testing e.g. by impedance analysis. Furthermore, we could prove that pre-stressing of sensors can essentially contribute to the mechanical stability of piezoceramic transducers.

Before the selected technologies were applied to full-scale parts, experimental feasibility was checked for simplified samples. Here, basic results were obtained e.g. for the detection of impact damage by acoustic emission using optical fibres, the use of EMATs for crack detection, the detection of corrosive liquids and corrosion by optical fibre and electrochemical sensors, and the application of pseudo-defects for validation purposes.

Despite of the big importance of tailored transducer systems, extended signal management is required to improve or even enable proper signal excitation and interpretation. This regards standard signal conditioning, but also advanced data processing like pulse-compression and time reversal, as well as imaging technologies for comfortable defect localisation. Moreover, the determination of the optimised sensor positions depending on the individual full-scale part is essential.

The functionality of a complete SHM system not only depends on the quality of signal interpretation but also on the prediction or at least estimation of the remaining life time of the full-scale parts. Based on established models, data obtained from our transducer systems can be used to enable these estimations.

At the final stage of the project, sensor systems will be implemented into the above mentioned full-scale parts and extended test programmes will be performed.

Project website: http://www.aisha2.eu

Powiązane dokumenty

Final Report - AISHA II (Aircraft integrated structural health assessment II)

Ostatnia aktualizacja: 18 Stycznia 2013

Permalink: https://cordis.europa.eu/project/id/212912/reporting/pl