EU Project Meeting on Aircraft Integrated Structural Health Assessment (AISHA), Leuven, Belgium, June 2007
For more papers of this publication click: www.ndt.net/search/docs.php3?MainSource=69

Aircraft Integrated Structural Health Assessment – Structural Health Monitoring and its implementation within the European project AISHA

Helge Pfeiffer [1,2 *], Martine Wevers [2]

[1] METALogic, Technologielaan 11, 3001, Leuven, Belgium
[2] Katholieke Universiteit Leuven – Group: Materials performance and Non-destructive Evaluation, 3001 Leuven, Belgium,
* Corresponding author. Tel.: +32-16-321232; fax: +32-16-321990.
E-mail address: helge.pfeiffer@mtm.kuleuven.be (H. Pfeiffer).

Abstract
Today's aircraft inspection procedures are excellent, but expensive and not appropriate in all situations. A cheaper alternative for damage detection could be offered by "structural health monitoring (SHM)". With such SHM systems, a permanent sensor network, comparable to the nervous system in a human body, is placed at crucial structural components of an aircraft. However, this apparently easy solution requires a quite complex research and implementation effort using well-coordinated collaborations of many disciplines and expertises. The European Research Area establishes the ideal platform for such a collaborative undertaking, and the considerable financial risks can partially be reduced by appropriate funding from dedicated European research programmes. This paper reviews some general issues related to the state-of-the-art of structural health monitoring in aircraft and gives some information on the European Project "Aircraft Integrated Structural Health Assessment – AISHA"

Keywords: Structural Health Monitoring, ultrasonics, Lamb waves, European Project

1. Introduction

In every developed civilisation in history, excellent transport systems were a prerequisite 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. Therefore, the development and in particular, the efficient maintenance and repair of such transport systems decided and decide over the success of a specific kind of economic system.

Nowadays, reliability aspects of transport systems are mostly based on time-based inspection cycles together with the safe-life or the damage tolerance approach. However, it is envisaged that the large cost associated with this approach can be drastically reduced by switching to a condition-based maintenance schedule.

Every aircraft is subjected to a specific maintenance schedule, which can be further subdivided into Line, Light and Heavy Maintenance ("BASE-maintenance" according to the EASA rules). The specific procedures concerning timetable as well as inspection and repair requirements are determined with the MSG-3 method (Maintenance Steering Group) and specified within the MPD (Maintenance Planning Data) by the respective manufacturers. This document establishes the basis for the maintenance schedule. There are also Inspection Service Bulletins supplied by the manufacturer which describe inspections or modifications, and an operator can decide to include it into the maintenance programme depending of the expected improvements or lowering of costs. Line Maintenance includes pre-flight, daily and weekly inspections during normal operations. Light Maintenance consists of the A-checks performed in the hangar overnight or within 24 hours, and the interval between such routine checks is about 2 months. The so-called Base Maintenance includes the C and D checks requiring one until five weeks time, and they will be performed with an approximate interval of two until ten years.

Since a couple of years, a number of SHM solutions were already presented on laboratory scale, and even partially implemented in real aircraft. There is thus in principle enough experimental evidence that such systems are able to deliver all required information. However, the final implementation is still in an early phase, and it is partially hindered by a number of obstacles (technical immaturity, lack of acceptance by end-users). Some SHM systems are already in operation such as load monitoring systems or acoustic emission facilities, but they are mostly applied in military aircraft.

2. Structural Health Monitoring

2.1 Basics

"Structural health monitoring" (SHM) is a collective term for cutting-edge technologies using permanently attached sensor networks to enable the continuous inspection of the reliability of structures. In the last years there has been an increasing interest in structural health monitoring systems for all kinds of aircraft. Beside the expected enhancement of safety and maintenance performance, also economic aspects play an important role. This regards on the one hand the reduction of unnecessary inspection and repair 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 given in Table 1.

Cost savings by reduction of inspection and repair costs and the possibility to reduce the weight at the design phase	Enhancement of safety by much more frequently applied automated inspections	Enhancement of passenger throughput by reduction of unnecessary maintenance

Table 1 Main benefits of Structural Health Monitoring

The introduction of structural health monitoring in routine aircraft maintenance seems to be only a question of time. The later-described obstacles, which have so far prevented the earlier introduction of SHM systems, can be avoided by an integrated approach combining modern technical and organisational principles on a large scale. Moreover, end-users such as manufacturers and operators (airlines) must be convinced that a mature SHM concept ensures complete airworthiness. Projects must provide an essential contribution to these objectives. The development of an effective structural health monitoring system must finally be integrated into a structural health management system where the data on structural integrity are classified and where procedures of maintenance and allocation of resources are organised.

2.2 European dimension of structural health monitoring

Nowadays, not only efficiency and economic aspects play a role in order to assess the quality of a specific transport system, but also safety, environmental and ethic aspects are more and more important. Therefore, the European transport policy is also forced to focus on the development of integrated, safer, “greener” and “smarter” pan-transport systems. An important issue is the good balance between different kinds of transport systems, such as railways, aircraft, seafaring or road network. Also this balance must be determined by environmental, safety and economic aspects.

Many of the main objectives of the European transport policy refer to the year 2020. The year 2020 marks the deadline when the goals of the so-called *Vision 2020* must be achieved. At the moment, the air traffic increases with five percent per year (related to the number of passengers) and this means that at 2020, there will be a threefold of air traffic compared to the beginning of the millennium. Until 2020, one expects a worldwide market demand for 14.000 new aircraft for replacing old aircrafts and responding to the additional requirements due to the enhanced number of passengers.

In order to respond to these challenges, in 2001 the Advisory Council for Aeronautics Research in Europe (ACARE) has been established as a multinational initiative. They have finally formulated the *Vision 2020*. The main challenges of this ambitious programme are *ACARE* [1]:

- More affordable, safer, cleaner and quieter air transport systems
    - Quality and affordability
    - Substantial reduction in travel charges
    - Time spent in airports minimised (15 to 30 minutes, max), delays (99% of all flights within 15 minutes)
    - Environmental impact minimised (Halve noise, reduce CO_2 by 50% and NO_x by 80%)
    - Five-fold reduction of accident rate
    - Time to market halved
- Improved Security
- Education policies to provide essential future skills

It has to be mentioned that these objectives of *ACARE* are not always realistic and partially unachievable due to practical constraints. A turn-around time of 15 à 30 minutes in airports is 30 minutes at the most because already the boarding and deboarding of passengers will require half an hour. This number is also only applicable for narrow-body aircraft (100 to 200 passengers). For wide-body aircraft flying for long distances, turn-around times are in the range of 2-3 hours (The refuelling of an Boeing 747 needs alone 1,5 hours). However, there is always potential to improve safety, even if the specific objectives of *ACARE* are not realistic in every case. Thus, the structural health monitoring systems can essentially contribute to the objectives of *Vision 2020* in four different ways which are cost savings, enhancement of safety and improvement of maintenance performance and ensuring high passenger throughput.

2.3 State-of-the-art of SHM in general

A clear indicator for the increased importance of SHM is the number of hits (publications, patents, etc.) related to structural health monitoring obtained with academic search engines. The data in Fig. 1 clearly show that the number of published topics is exponentially growing since more than 15 years. Moreover, structural health monitoring is a well-established technology already operational in a number of appropriate civil structures, such as bridges and chemical installations.

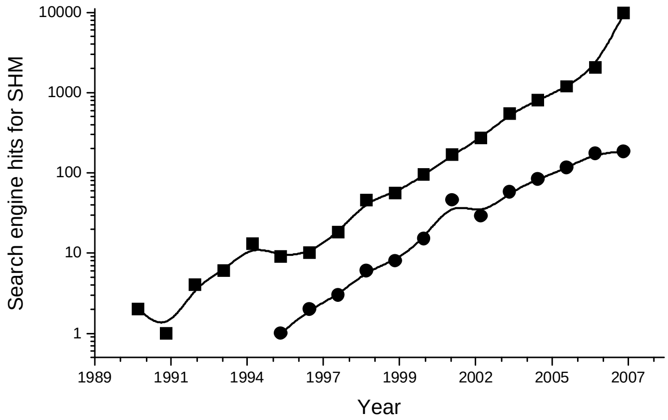

Fig. 1 Number of hits obtained for "structural health monitoring" in ISI Web of Science ® (circles) and Scirus

In contrast to the above mentioned structures, SHM for civil aviation is nowadays still in an experimental phase. The concepts followed are partially based on a number of different well-established NDT techniques, such as ultrasonic inspection or eddy current methods. The following table gives an overview on the applied sensor technology with respect to the damage-related properties. These properties change when e.g. cracks, corrosion, impact damage, delaminations in metals and/or composite material etc. emerge.

Sensor technology / Property sensitive to structural damage	Crack propagation gauges	Comparative vacuum monitoring	Optical Fibre sensors	Piezo-ceramic transducers	Foil eddy current sensors	Electro-chemical sensors
Material displacement due to Cracks	MMMM	MM				
Characteristic vibration pattern			MMMM CC	MMMM CC		
Stress/Strain relationships			MMMM CCCC	MM CCCC		
Scattering of Lamb wave propagation due to cracks, delaminations etc			MMMM CCCC	MMMM CCCC		
Acoustic Emission			MM C	MMM CC		
Electro-mechanical impedance				MMM		
Interrupted or reduced electrical conductivity					MMMM	
Corrosion/ damaged coatings						M

Table 2 Selected sensor technologies in relation to studied phenomena sensitive or arising from structural damage, C=composite, M=metal

It appears that vibration and Lamb wave scattering are the most prominent phenomena that are studied and used. The most important and versatile sensors applied are piezoelectric patches and optical fibre sensors [2, 3]. But one should not underestimate the potential of further phenomena and sensors, such as impact detection by acoustic emission, electromechanical impedance by piezoceramic sensors, direct crack detection by comparative vacuum monitoring or embedded eddy current sensors. Beside the appropriate technology used, also the presentation of data is very important, such as the presentation of detected cracks by “structural radar” an interesting approach giving an 2-D representation of structural damage [4, 5].

All approaches were thoroughly investigated on lab-scale. Moreover, a group of technologies is for validation purposes already installed in civil airplanes that are in-service. Bragg Fibre Gratings, impact and crack monitoring facilities, such as acoustic emission, eddy current and CVM sensors are installed in an AIRBUS A320 and an AIRBUS A340-600. Also during the full-scale fatigue test of the fuselage of the Airbus A380, diverse SHM technology such as crack wires, CVM or acoustic emission sensors were present [6].

A modern SHM system has to fulfil not less than four conditions, airworthiness, satisfactory defect detection capabilities, cost efficiency, and durability. The last condition establishes probably the hardest restriction. Producers and customers demand that a SHM system must have about the same lifetime such as an aircraft which is in the range of 30 years. This means that the sensor network should be durable than the structure under investigation. A related issue if the challenge of SHM systems to address all the environmental conditions that occur during operations. At the outside of the fuselage e.g., changes in temperature range up to 200 K. These temperature changes e.g. strongly influence the Lamb wave behaviour [7]. Finally, such as mentioned above, the data obtained from SHM systems must finally be integrated into a structural health management systems.

The implementation of an SHM system has to be accompanied by all the certification procedures that are required if analogous aircraft systems are replaced or modified. Recently, a steering group was founded bringing together the most important stake holders (OEM, government, customers, academia) to establish guidelines and recommendation on the use of SHM systems in implementation and service (AISC – SHM, Aerospace Industry Steering Committee for SHM) [6].

There is a big amount of literature available on structural health monitoring. Very recently, a whole edition (15 papers, compiled by K. Worden and C.R. Farrar), of the Philosophical Transactions of the Royal Society is dedicated to different aspects of SHM [8]. A good overview on the state-of-the-art of SHM in aircraft is given by Staszewski and co-workers within their book “Health Monitoring of Aerospace structures” [9]. It also contains a compilation of the results of the European project MONITOR (Monitoring On-Line Integrated Technologies for Operational Reliability). Other good reviews are given in [6, 10, 11]. Last but not least, the Encyclopaedia of Structural Health Monitoring is expected to be published in January of 2009 [12]. A number of journals addressing regularly the issue of structural health monitoring, and

one of them, “Structural Health Monitoring – An International Journal” is even dedicated to this cutting-edge technology:
Finally, an excellent podium to get in touch with the SHM community are the regular Workshops on Structural Health Monitoring, alternately organised in the United States and in Europe.

2.4 Remaining obstacles

The main shortcomings of existing SHM systems and the obstacles concerning an introduction on the market can be summarised as follows:

<u>Lack of technical maturity</u>

- Most of the proposed solutions only solve specific problems of a SHM system. The respective focus regards sensor technology, data analysis, signal-damage correlation etc. End-users still miss an integrated overall-concept on a larger scale
- It is difficult to match all the environmental parameters such as temperatures, loads, chemical contaminants, which occur at operational conditions.
- A complete health monitoring system for one aircraft is impossible to implement given the available level of technology, i.e. the huge surface area of an aircraft structure requires e.g. a huge amount of sensors with all the required data analysis.

<u>Lack of acceptance by end-users</u>

- Complicated and long-term certification process expected
- Inertia of current manual inspection interval procedures
- Scepticism against new technologies with minimal service data
- Cost implications for new hardware, software and training
- Pessimistic expectations concerning the return-of-investment

Although, a number of applications are operational in a number of special cases, the airworthiness requires a really long-term reliability of the SHM systems under the harsh operational conditions. It is therefore required to have a system where all kind of tests were performed which are typical for in-service tests of usual aircraft components [13]. But even in the case that a successful certification processes is present, a number of obstacles is encountered. The proposed final system must give an answer to all of these questions.

3. AISHA – Damage detection by Lamb waves

3.1 Project summary

The European project "Aircraft Integrated Structural Health Assessment (AISHA) – EU-FP6, priority 4 - STREP project nr. 502907) which was essentially accomplished in June 2007 was dedicated to the establishment of the basic elements of a health monitoring systems based on ultrasonic Lamb waves. The project was coordinated by Metalogic, a SME from Belgium which is specialised in corrosion services, research and consulting. The other partners were the Katholieke Universiteit Leuven (Belgium), DLR Braunschweig (Germany), Cedrat Technologies (France), Eurocopter-Marseille (France), Riga Technical University (Latvia), CTA (Spain) and ASCO Industries (Belgium).

The project AISHA aimed to contribute in 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 Lamb waves (see a schematic representation in) are guided acoustic waves propagating in plate-like structures. In the case of damages, the propagation of an ultrasonic Lamb wave will be disturbed resulting in a characteristic reflection and attenuation pattern. During this interaction, there is also the possibility that the acoustic mode is partially changed. The particular reflection or attenuation characteristics can be detected, and if the correct functional relationship between signal-damage is known, the state of damage can be assessed. The functional relationships between signal and damage are obtained theoretically or experimentally, but a combined approach including advanced data analysis provides the best results.

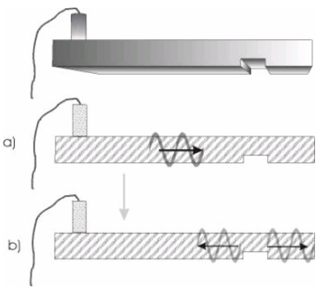

Fig. 2 Interaction of a Lamb wave with an artificial notch reflection and attenuated transmission

Lamb waves are usually excited by appropriate ultrasonic transducers, and it is possible to excite different modes depending on frequency and transducer geometry. The detection can essentially be performed by a number of sensing techniques such ultrasonic sensing, optical fibre sensors and LASER vibrometry.

The AISHA project started with an inventory of materials, structures and damages typically occurring in aircraft. Based on this information, the required Lamb wave propagation properties were identified on a theoretical and experimental base. This gave important clues for the selection of appropriate Lamb modes which could be applied in the further course of the project.

Helicopter tailboom EC135 | Helicopter tailboom MI-8 | AIRBUS 320 - Slat track

Fig. 3 Full scale parts used in AISHA

A further step was the development and selection of appropriate sensor systems and dedicated electronics. For the excitation of Lamb waves, piezoelectric patches were selected and piezoelectric patches as well as single mode optical fibres were used as sensors. The use of piezoelectric patches and optical fibre sensors for detection is complementary in many cases and both methods can be implemented in real aircraft.

Experiments performed within AISHA on lab-scale and on selected full-scale parts showed the ability of Lamb waves or other guided waves to give information on correlations between acoustic parameters and damage in structural parts. The validation of the results was performed by established state-of-the-art NDT techniques, such as ultrasonic C-scan methods.

3.2 Future of AISHA

In May 2008 started the project AISHA II. It is based on the consortium of AISHA, but the "chain of expertise" was extended with a couple of new partners, InSensor (Denmark), Fraunhofer Institut IFAM (Germany), University of Leipzig (Germany), University of Basque Country (Spain), Free University of Brussels (Belgium) and Lufthansa Technik (Germany). The goal is not only to continue the work which was started in the AISHA I project, but the work plan contains further innovative aspects.

Acknowledgement

This research was supported by the 6th Frame Programme of the European Commission (STREP Project Number: 502907 - Aircraft Integrated Structural Health Assessment (AISHA)). We want to express our gratitude to the whole AISHA consortium (Metalogic (Belgium), KU Leuven (Belgium), DLR (German Aerospace Centre), Cedrat Technologies (France), Eurocopter- Marignane (France), Riga Technical University (Latvia), CTA (Spain), ASCO (Belgium) for their support.

References

1. http://www.acare4europe.org
2. G. Thursby, B. Sorazu, F. Dong and B. Culshaw, Damage Detection in Structural Materials using Polarimetric Fibre Optic Sensors Smart Structures and Materials, Proceedings of SPIE 5050 (2003) 61-70.
3. M. Wevers and F. Fransens. Proceedings for the European Conference of Non-Destructive Testing, Berlin 2006.
4. V. Giurgiutiu and J.J. Bao, Embedded-ultrasonics Structural Radar for In Situ Structural Health Monitoring of Thin-wall Structures Structural Health Monitoring 3 (2004) 121-144.
5. J. Peña, C.P. Melguizo, R. Martínez-Oña, Y. Gómez Ullate, F. Montero de Espinosa Freijo and G. Kawiecki. Proceedings of the Third European Workshop on Structural Health Monitoring, Granada 2006.
6. H. Speckmann. International Maintenance Review Board Policy Board (IMRBPB) Meeting, EASA, April 22, 2007, Cologne 2007.

7. G. Konstantinidis, B.W. Drinkwater and P.D. Wilcox, The temperature stability of guided wave structural health monitoring systems Smart Materials & Structures 15 (2006) 967-976.
8. K. Worden and C.R. Farrar, Theme issue: Structural Health Monitoring Philos. Trans. R. Soc. London, A 365 (2007).
9. W. Staszewski, C. Boller and J.R. Tomlinson, Health Monitoring of Aerospace Structures: Smart Sensor Technologies and Signal Processing, Wiley, Chichester, 2004.
10. D. Roach and K. Rackow. Conference paper 9th Joint Conference on Aging Aircraft, Atlanta 2006.
11. S. Hoon, C.R. Farrar, F.M. Hemez, D.D. Shunk, D.W. Stinemates and B.R. Nadler. Los Alamos National Laboratory Report, LA-13976-MS 2003.
12. C. Boller, F.K. Chang and Y. Fujino, Encyclopedia of Structural Health Monitoring, Wiley 2009.