STRUCTURAL HEALTH MONITORING (SHM) – OVERVIEW ON TECHNOLOGIES UNDER DEVELOPMENT

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Abstract: The continued growth in air traffic has placed an increasing demand on the aerospace industry to manufacture aircraft at lower costs, while ensuring the products are efficient to operate, friendly to the environment and that the required level of safety is maintained. The primary objective of the aerospace industry is to offer products that not only meet the operating criteria in terms of payloads and range but also significantly reduce the Direct Operating Costs (DOCs) incurred by their customers, the airlines.

The structure of today's commercial transport aircraft is designed considering the current and forthcoming airworthiness regulations, the customers‘ requirements and manufacturing aspects. No health monitoring systems were considered for today's large transport aircraft.

In the future Health Monitoring Systems will play a major rule in ensuring the structural integrity of aircraft structures. A bundle of SHM related technologies are needed to fulfill the requirements of the aircraft manufacturer and the operator.

The presentation will give an overview about the activities on SHM and on the technologies under research and development within Airbus. It will start with the description of these technologies and will end with a statement about the requirements, which have to be fulfilled to use SHM systems in In-Service aircraft.

An outlook on Upstream technologies in the field of SHM, like Nanotechnology and intelligent coatings, will finalize the presentation.

Introduction: The continued growth in air traffic has placed an increasing demand on the aerospace industry to manufacture aircraft at lower costs, while ensuring the products are efficient to operate, friendly to the environment and that the required level of safety is maintained. The primary objective of the aerospace industry is to offer products that not only meet the operating criteria in terms of payloads and range but also significantly reduce the Direct Operating Costs (DOCs) incurred by their customers, the airlines. The structure of today's commercial transport aircraft is designed considering the current and forthcoming airworthiness regulations, the customers‘ requirements and manufacturing aspects. No health monitoring systems were considered for today's large transport aircraft. Loads monitoring systems with on-board evaluation to adjust the maintenance programs were evaluated in the past but were not introduced after cost / benefit trades were carried out. Reducing the structural weight and enhancing the customer’s satisfaction by decreasing the maintenance cost are some of the key drivers to become competitive in the future. Using this technology permits new advanced metallic, integral fuselage design as well as optimized CFRP structures to ensure structural integrity. Maintenance aspects are increasingly significant in reducing the Direct Maintenance Costs (DMC) as most other DOCs such as fuel, airport fees, etc. have little potential for further reduction.

Decreased maintenance costs will have a very positive effect, especially for airlines that are running into trouble with their costs. The biggest challenge is to find appropriate SHM technologies that can be used under in-service conditions. These technologies must prove that they are able to monitor the integrity of aircraft structures, while being reliable and durable.

What is SHM? What is Structural Health Monitoring (SHM) from the point of view of an aircraft manufacturer? The basic approach is to make non-destructive testing technology to become an integral part of the aircraft structure itself. Different techniques can be used such as measuring loads and predicting actual fatigue life or sending waves being either of an acoustic, electromagnetic, thermal or any other physical nature through the structure for direct damage monitoring. Different implementations of these methods as well as sensors are available or are under development. It is therefore essential to know:

- Which is the typical behaviour of different types of damage, what are the mechanisms and which physical principle is best for their detection?
- Which of the different monitoring methods have the respective strength for monitoring aircraft components prone to damage?

- Which technologies are able to fulfil the requirements for new and improved maintenance concepts?
- What scheme can be applied such that a SHM system can still be continuously updated with new sensing and sensor signal processing technology to emerge?

It is true that the systems available have been used for aircraft monitoring for some time, but these are mostly loads monitoring systems (strain gages, etc.) or systems that determine flight parameters and enable conclusions to be drawn concerning the load levels that occurred during flight. Direct monitoring of hot spots as well as monitoring of large areas to detect a wide range of damage has never been applied as solutions in in-service aircraft.

Basic Idea: The basic idea of SHM is to build a system that is similar to the human nervous system (see Figure 1). It will work in the same manner but will differ some case: Within the human body we have areas that do not contain any nerves, e.g. bones. If you break your leg, it may be that you do not notice it or there is only a slight pain. This is because the bones have no nerves, i.e. no "SHM System". In case of aircraft, the sensors (that are the nerves) must be right at the place where an area is to be monitored to ensure the structural integrity. In case of damage, the sensors directly identify the location and follow-up actions can be taken.

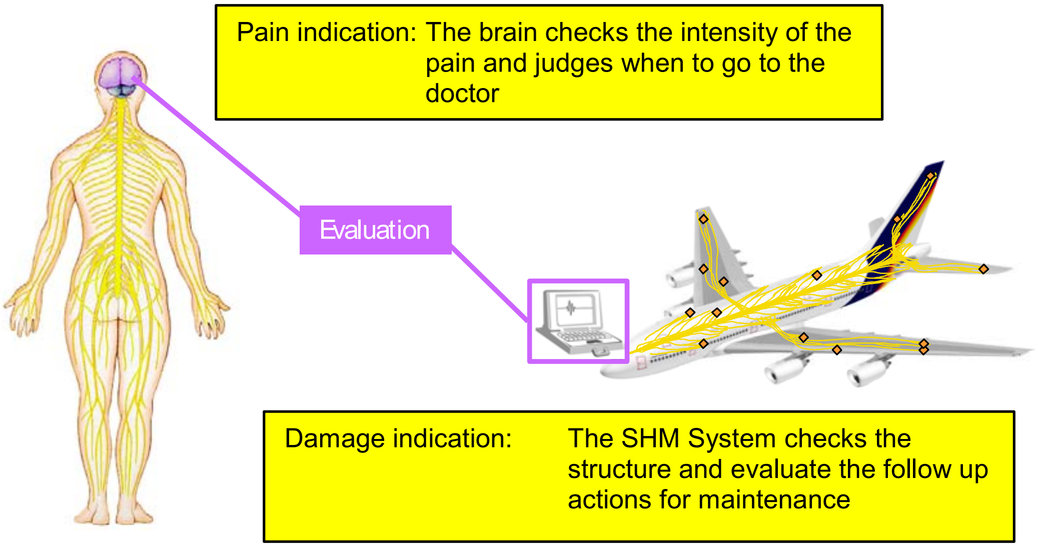

Figure 1 - Comparison of systems

SHM Technologies: Unlike conventional NDT systems, SHM systems are not independent of the aircraft infrastructure. Since the sensors, and for some technologies the equipment as well, remain on the aircraft during flight operations they exert a considerable influence on the aircraft systems (e.g. hydraulic, electric, pneumatic, avionic systems, etc.). How far the systems are influenced depends on the SHM technology.
The following criteria apply:

Active Sensors
- Sensors can be used as both receiver and actuator
- Location and magnitude of damage are determined by means of signals
- E.g. systems based on ultrasonic or eddy current

Passive Sensors
- Sensors are used only as receivers
- Detection of damage from external sources (e.g. in-flight loads)

Online Systems
- Equipment on-board
- Monitoring cracks (while the structure is loaded/in-flight)

- Measuring during flight
- Data are sent to a storage device or evaluation computer for further processing

Offline Systems

- Equipment off-board
- Monitoring cracks on unloaded structures
- Activation on demand
- Producing data when necessary or wanted (mostly during normal checks)
- No data storage in-flight

A short overview on some technologies is given in the following table. It is clearly identified, that each technologies has its special field of application in the future, so that there is no competition. Quiet the contrary; each technology will complete the other.

Technology		**Basic physical principle**	**Detectable damage types**	**Detection area**	**Target materials**	**Detection mode**
Fibre Bragg Gratings	FBG	Gratings written on the fibre core are subjected to strains (variation in length), which are caused by temperature changes (temp. sensor), or by local material strain, transmitted to the fibre.	“Loads” Impacts Delaminations	Local	Metallic and composites	On-line
Acousto-Ultrasonics	AU	Acoustic waves are sent through the material and received by specific transducers. A change in the material local behaviour (and hence a damage) can be picked up and localised by an array of such sensors.	Delaminations Cracks	Global	Metallic and composites	Off-line
Comparative Vacuum Monitoring	CVM	Open cracks generate leaks in a series of galleries bonded to the structures. A remote monitoring device tracks the pressure drop.	Cracks Corrosion Debondings	Local	Metallic and Composites	Off-line
Acoustic Emission	AE	Acoustic waves generated by small structural events (impacts, crack initiation, crack growth, delamination) are recorded by specific transducers when they occur.	Impacts Cracks Delaminations	Global	Metallic and composites	On-line
Sensitive Coatings	SC	Coatings with integrated piezo- and ferro-electric elements, being directly able to be bonded on a component’s surface or even integrated into a composite.	Corrosion, Cracks	Global	Metallic and composites	Off-line
Environmental Degradation Monitoring Sensors	EDMS	Multifunctional sensors capable of monitoring parameters such as temperature, humidity, time of wetness and pH. In conjunction with a corrosion model, corrosion prediction and detection is possible.	Corrosion	Local to sensor position	Metallic and composites	On-line
Micro Wave sensors	µW	Micro waves are send and received in a pitch-catch mode inside the material, and provide a picture of the water content.	Water ingress	Local	Composites Sandwich	Off-line

Technology		Basic physical principle	Detectable damage types	Detection area	Target materials	Detection mode
Imaging Ultrasonics	IU	Classical ultrasound 2D images generated by newly developed integrated and miniaturized sensor networks	All damages caught by ultrasonic methods	Local	Metallic and composites	Off-line
Foil Eddy Current sensors	ET	Eddy currents are generated in the structure. Their pattern and frequency distribution varies according to the presence of crack or other damages	Cracks, Corrosion	Local	Metallic	Off-line

In the following chapter some of these technologies are described in detail.

Comparative Vacuum Monitoring (CVM): CVM offers an effective method for in-situ, real time monitoring of crack initiation and/or propagation. CVM is a measure of the differential pressure between fine galleries containing a low vacuum alternating with galleries at atmosphere in a simple manifold (s. Fig. 2). CVM has the ability to monitor external surfaces of materials for crack initiation, propagation and corrosion. In addition, CVM sensors can also be embedded between components (e.g. lap joints) or within material compounds such as composite fibre. In this way, problems related to cracking, fatigue and corrosion can be detected when and where they are initiated. This technique offers a quick and easy way to monitor "Hot Spot" areas and thus improve the operational efficiency of the aircraft.

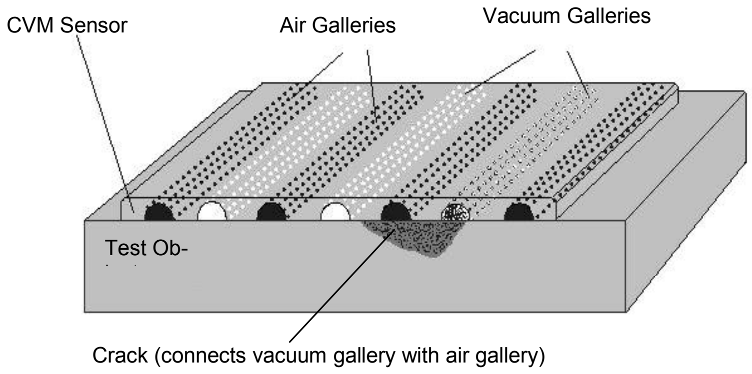

Figure 2: CVM Principle

Micro Wave Antenna: The use of microwave antennas for nondestructive testing is completely new. The system is based on the changes of electromagnetic field parameters that are disturbed by the presence of water.
The antennas (l=30mm and dia.=8mm) will generate an EM field inside the closed structure. A coaxial cable will carry the energy to the antenna. This way a very compact system with an intrinsic measurement capability will be developed. The application of this type of antenna can be foreseen for all type of CFRP/Nomex structure liable to suffer from water ingress. Studies have been carried out by to validate the concept of the sandwich CFRP structure behavior as wave guide for this type of application with success.

Acoustic Emission: AE technology involves the use of ultrasonic transducers (20Khz-1Mhz) to listen for the sounds of failure occurring in materials and structures. *Crack growth* due to fatigue, *hydrogen embrittlement*, *stress corrosion*, and *creep* can be detected and located by the use of AE technology. In addition high pressure leaks can also be detected and located. AE technology is also finding wide application in the nondestructive testing for structural integrity of composite materials and structures made from composite materials. Fiber breakage, matrix cracking, and delamination are three mechanisms that can produce AE signals when stress is applied to the material or structure.

Eddy Current Foil Sensors: Eddy current sensors (s. Fig. 3) are commonly used in current maintenance operations. Their main application is to detect cracks in metallic parts. Handheld sensors are moved over wide areas and the reading of an acquisition system allows to detect surface crack or crack invisible from the surface. Foil eddy current sensors are an alternative technology to this classical one. The copper winding is printed on a substrate, just like an electronic track. Their potential is very important because due to their thin geometry, they can be mounted on interfaces between structural parts their topology can be tailored to many different part shapes (around bolts, in corners, etc.) the connection can be part of the printed track and can therefore also be integrated, giving access to very remote places once integrated in difficult-to-reach places (or impossible to inspect locations), a periodic reading can give information on the structural health.

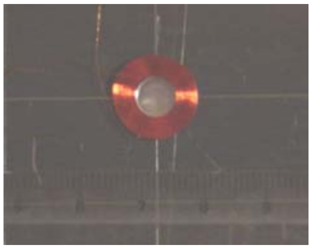

Figure 3 : Micro Coiled ET Sensor

Fibre Bragg Gratings (FBG) : A fibre optic Bragg grating is formed when a periodic variation of the index of refraction is created along a section of an optical fibre by exposing the core of the optical fibre to an interference pattern of intense UV-laser light (s. Fig. 4). This technology allows the measurement of either tensile or compressive strain that is applied along the grating length. There is a linear relationship between the change in wavelength of the reflected light and the strain in the fibre caused through externally applied loads or thermal expansion. To operate multiple sensors along a single optical fibre, the various Bragg gratings should have different Bragg wavelengths in order to differentiate between them. Optical fibres are typically made up of a central core of glass through which the light passes, clad with another layer of glass and a protective coating. The typical length of a grating is 10 mm and the grating period is about 0.5mm. The diameter of the cladding of the optical fibre is 125 µm, while a total outside diameter is about 250 µm for a typical polyamide-coated fibre.

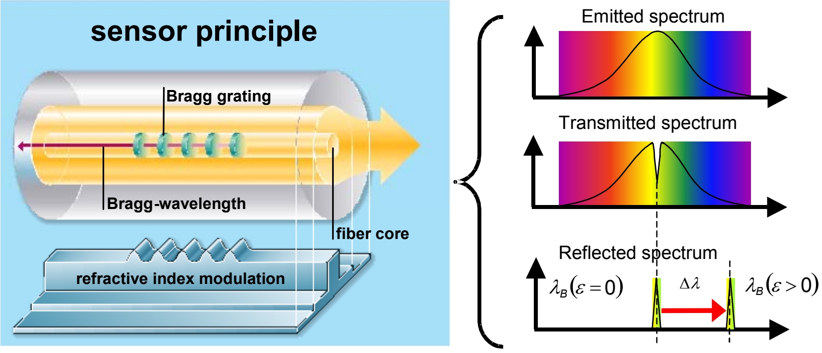

Figure 4: Fibre Bragg Grating Principle

Acousto Ultrasonic: Acousto-ultrasonic (AU) interrogation is a single-sided nondestructive evaluation (NDE) technique employing separated sending and receiving transducers. It is used for assessing the microstructural condition and distributed damage state of the material between the transducers. AU is complementary to more traditional NDE methods, such as ultrasonic c-scan, x-ray radiography, and thermographic inspection, which tend to be used primarily for discrete flaw detection. Throughout its history, AU has been used to inspect polymer matrix composites, metal matrix composites, ceramic matrix composites, and even monolithic metallic materials. The integration and adaptation of small actuation and sensing elements such as piezoelectrics, MEMS or even nanostructures into and onto the structures to be monitored has allowed to reliably observe cracks in structures from the size of 5 mm upwards currently. Acousto-ultrasonics has been proven to effectively work on laboratory scaled specimens, however proof of concept in real structures under in-service operational conditions is still lacking like for most of all SHM technologies.

Future Technologies: As the idea of SHM becomes more and more "popular" an increasing number of new and innovative technologies show up in this field. In the future intelligent coatings can be used to identify corrosion in a very early stage. As well intelligent structures based on Nanotechnology will play an important rule in future SHM philosophies. As such, it is prudent to pursue the development of sensing technologies that can be integrated into structural material systems at any point in the component fabrication process, and in doing so produce multifunctional materials that will create further gains in payload capacity.

Assessment criteria for SHM : Numerous damage monitoring technologies have been developed and built worldwide for use in structural health monitoring. Most of this work is done by small and medium enterprises, which act as suppliers to the larger assembling industries. The aeronautics industry belongs to this latter category; they have to carefully formulate their requirements with regard to structure-integrated damage monitoring systems and then assess the different monitoring options on the market.
The assessment criteria can be divided into two major sections:

- Information required
- System requirements

The information required section covers all relevant data and information about the SHM system. These assessment criteria will be confined to facts that give an overview of the chosen technology. The system requirements section deals with open requirements, which have to be fulfilled to enable SHM systems to be employed on in-service aircraft. These requirements can vary from application to application but they are generally valid for most cases.

Information required: As with any new technology the major questions focus on the basic principles, the advantages, the fundamentals and the impact it has on the operation and even the design of the aircraft.
The information required is divided into three subsections:

- system information
- handling information
- sensor/equipment data

System requirements: The second criterion used for assessment of SHM systems is the SYSTEM REQUIREMENTS. There are some overlaps with the INFORMATION REQUIRED section because some system requirements are simultaneously information requirements. Requirements, however, are the decisive criterion where the application of the systems in the aircraft is concerned. Here all the important criteria are detailed that are to be fulfilled when a system is to be put into operation under in-service conditions. The non-fulfillment of some of the requirements, such as durability, does not mean that an SHM system cannot be employed. It does mean that using the SHM system for a sufficient length of time should use the SHM system in an area where durability of the SHM system is not a 'killer criterion' and where mission durability information can be subsequently obtained. The requirements are subdivided into two sections:

- system requirements – general
- system requirements – sensor/equipment

This list of requirements does not lay claim to completeness and will be supplemented by specifications in the course of preparation. As part of the requirement definition process, the preparation of specifications for qualifying SHM systems is to be taken into consideration. Contrary to the current procedures applicable to NDT technology, the qualification of SHM systems requires new specifications. They are a prerequisite for qualification and thus certification.

Conclusion: Airbus works since 1990's with an increased effort on the subject of SHM for civil aircraft airframe design in cooperation with worldwide leading R&T institutes and other subcontractors. Airbus was the first civil aircraft manufacturer working on this topic to have it available for the whole product range. It has been identified that SHM is one of the key technologies to ensure the integrity of aircraft structure in future aircraft. Due to the current maturity level of the SHM technologies, the economical benefits of SHM technology are not yet available for the customer and cannot be realistically reached before 2008. Nevertheless, further development and stepwise implementation to the flying aircraft will provide these benefits in the future.

The use of SHM will permit new approaches both in the design and maintenance of structures, with the following specific advantages: The use of SHM will contribute to reduce structural weight by changing design principles

- SHM will benefit future design for Composites and Metals Maintenance costs will be reduced Aircraft availability can be increased
- SHM will enable new maintenance concepts

For the time being Airbus is developing a variety of SHM technologies, as different SHM technologies are required depending on the kind of application. However, some of these technologies turn out to be competitive. The technology readiness of some of these technologies will be reached in 2008. This means not Entry Into Service (EIS) up to 2008, because after the technology readiness the programs will decide where and how to use SHM to benefit our products. It means just that after that date SHM can be deployed and verified in Airbus aircrafts until EIS. The EIS will vary from application to application and can thus not be determined exactly today.

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