Structural Health Monitoring: A Contribution to the Intelligent Aircraft Structure

Holger SPECKMANN, Henrik ROESNER, Airbus, Bremen, Germany

Abstract. Future aircrafts will be manufactured out of new and innovative materials and will be assembled by fast and economic assembling technologies. Nevertheless conventional materials will play a role in future design philosophies, as well.
In order to take the benefit from all relevant material technologies and also new assembling technologies new innovative inspection and monitoring technologies need to be developed and implemented.
Today's Non-Destructive Inspection (NDI) technologies are limited due to the inspection can only be carried out if an access to the area to be inspected exits. Only during maintenance checks this can be ensured in most cases. So a continuous or more often inspection is not possible due to economic reasons.
The uses of Structural Health Monitoring (SHM) technologies for future aircraft will not only enable new possibilities for maintenance concepts, but will have a big influence on design concepts and assembling technologies. SHM is aimed to be one of the key technologies to control the structural integrity in future aircrafts providing both maintenance and weight saving benefits.

1. Introduction

Airframe innovations in all relevant technological fields are important for the development of high performance airframes best to satisfy the market needs. Airbus is in the leading position for application of advanced technologies and has accumulated broad experience in all airframe technologies with all types of structural materials. Besides material technologies and innovative design, also smart structures technologies are becoming important for today's large civil aircraft airframes development. Structural Health Monitoring (SHM) is one of the major contributions for future smart structures. Other examples are passive or active adaptive structures and self-healing structures. .

SHM is a new and alternative way of Non-Destructive-Inspection (NDI) in order to ensure the structural integrity of aircraft structures.

1. In the first step (0^{th} and 1^{st} generation) SHM will be used to gain benefits for structural tests, maintenance and maintainability. E.g. studies are predicting a maintenance cost reduction by up to 75% on Service Bulletin (SB) level and a clear increasing of the aircraft availability [1].
2. In the second step (2^{nd} and 3^{rd} generation) SHM will be used to get new concepts for structural design, which will lead to weight reduction for metal and composite structures up to 15% on component level [1].

The gain of maintenance and design benefits is the motivation for SHM. For maintenance the motivation comes directly from the airlines and their current needs. Maintenance aspects are increasingly significant for the reduction of Direct Operating Costs (DOC) since fuel bills, airport fees, etc. have little potential in saving expenses. Therefore decreased maintenance costs and increase aircraft availability have a very positive effect. The airlines themselves are working more and more on “Alternative Means of Compliance” of airworthiness relevant topics. They start to test and apply SHM technologies to enable more economic inspections, which reduces the Direct Maintenance Costs (DMC) and increase the availability of their fleet.

The motivation to use SHM for innovative design approaches is the need of the manufacturers to offer aircraft with increased fuel efficiency. So the key driver is the reduction of structural weight in order to meet market expectations. The application of SHM allows realization of weight reductions for new metallic aircraft design as well as CFRP structures by establishing a new design philosophy based on SHM.

2. Airbus Intelligent Airframe Philosophy

Various aerospace engineering disciplines, such as aircraft structures, systems, flight physics and engines, contribute to the overall aircraft performance. Hence, structure engineering is one of the most important disciplines. Innovative airframe design and the use of innovative materials benefit operators by reducing operating costs (lower fuel consumption and maintenance costs), enhancing the range and payload and increasing passenger comfort, while being more environmentally friendly. For a specific airframe technology decision, a series of aspects (e.g. maturity, program needs, durability, maintenance costs) have to be taken into consideration to ensure optimized overall airframe performance and efficiency. Airbus is in the leading position for application of advanced technologies and has accumulated broad experience in all airframe technologies with all types of structural materials. This has been achieved through extensive research and development activities. As part of Airbus’ “non stop innovation” technology strategy, more than 1.8 billion Euros were spent in research and development in 2004.

For the development of advanced aircraft airframes, we need to consider a series of aspects going far beyond specific material selection. Airbus airframe development is characterized by the so-called “Airbus ‘intelligent’ airframe” approach. This strategy focuses on the follow-up, development and implementation of intelligent solutions and smart structures with intelligent characteristics. For intelligent airframe solutions several basic aspects need to be considered: best innovative materials, optimized design and appropriate material integration [2, 3].
Airbus “intelligent” airframe technology also includes the development and implementation of smart structure technologies. This opens new horizons to drastically reduce both weight and maintenance efforts. In the future, aircraft airframes will implement technologies in a step-by-step way, which will give aircraft structures self-adaptive, self-monitoring and “self-healing” characteristics. Research and technology programs in these technological areas are ongoing.

A possible approach towards future smart structures also includes Nanotechnology, which might lead to significant improvements in airframe performance. Thus, material properties might be improved and tailored (e.g. gradients, local behavior) and in addition, multifunctional materials with sensor and adaptive structure functions might be enabled. Already, new Airbus programmers implement smart structures and system technologies. Smart structure technologies are often developed using a multidisciplinary approach. For instance, the development of a passive adaptive aeroelastic tailored composite wing for future aircrafts requires skills from both the structures and flight physics engineering disciplines. Another example is Structural Health Monitoring (SHM) development [4]. SHM features a combination of an airframe plus an integrated sensor system to monitor health and potentially also airframe loads. In this case, both the aircraft structures and systems aerospace engineering disciplines are required.

3. What is SHM?

SHM is the continuous, autonomous in-service monitoring of the physical condition of a structure by means of embedded or attached sensors with a minimum manual intervention, to monitor the structural integrity of the aircraft. The basic is the application of permanent fixed sensors on the structure. SHM includes all monitoring aspects related to damages, loads, conditions, etc. on aircraft level, which have a direct influence on the structure. The sources are resulting from fatigue, corrosion, impacts, excessive loads, unforeseen conditions, etc.

Monitoring of structures does not necessarily mean knowing the status of the structure at any time. Moreover, a measurement is triggered when the data are requested for inspection. Structures are designed with margins by which it is demonstrated that, after normal or exceptional events, maintenance tasks must be planned at the next appropriate inspection.

Other features of Structural Health Monitoring are:

- Sensors permanently applied to the structure
- No physical access to the inspection area necessary
- No manual operation in the inspection area required
- Safe inspection of hazardous areas
- No use of scanners necessary
- Automated inspection
- Questioning several locations at the same time
- No influence of the Human Factor on inspection results

The final idea is to imitate the human nervous system (see fig. 1).

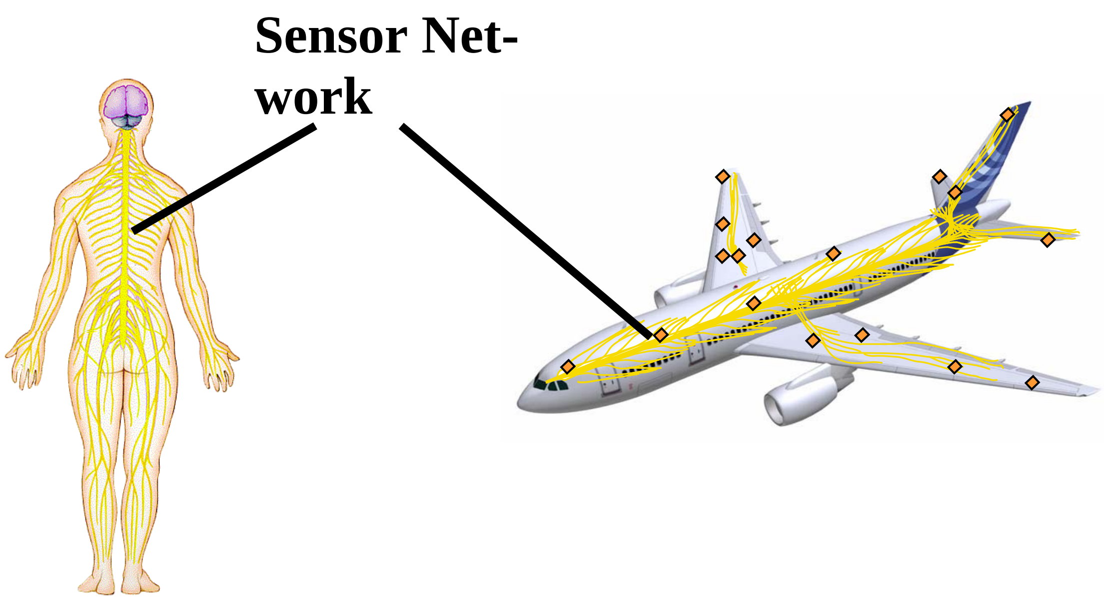

Figure 1: SHM is the imitation of the human nervous system

4. Benefits for Airframes

SHM technology can be applied to aircraft structures in order to achieve advantages with respect to weight, and maintenance.

4.1. Maintenance

SHM as an alternative to conventional NDI will have two major benefits [5] for maintenance. First the reduction of Direct Maintenance Costs (DMC) and second the increase of the availability of Airbus aircrafts.
The maintenance inspections are a significant factor for the Direct Operating Costs (DOC) of the airlines. Inspections have to be performed each time the crew reports an event, which is supposed to having caused significant damage (e.g. hard landing, tail strike, ground collision). Inspections are also done at periodic overhauls, in order to maintain the airworthiness of the aircraft. The frequency of the periodic overhauls is calculated accounting to propagation models of fatigue and corrosion.

The application of SHM in aircraft maintenance are aimed to [1]:

- Reduce the effort of conventional visual and NDT inspection
- Postpone repairs due to crack monitoring)
- Perform corrosion monitoring
- Reduce the burden in case of life extension programs
- Perform loads monitoring of highly stressed areas in order to identify overloads in an early stage

In other words, SHM can simplify any inspection to a large extend: Sensors attached permanently to the structure are activated by the maintenance operator and provide quickly and reliably the requested information for a diagnostic. No difficult access to measurement zone is needed. Altogether, these are the keys to time and cost savings. Another benefit lies in the reliability of the inspection, as other than for conventional NDT reduced human factor is involved by using SHM.

Apart from the benefit of cost reduction for maintenance, a much bigger benefit will be the higher availability of Airbus aircraft. This means, our customers have their aircrafts longer in service than nowadays and they will have higher revenues out of their fleet. The advantage of higher availability is either reached by higher dispatch reliability or by a reduction of down time during scheduled checks.

4.2 Design – Weight Reduction

The major objective of aircraft designers is to achieve new dimensioning philosophy of specific structural items which in turn results in significant weight saving for the whole aircraft [4]. The new design philosophy based on SHM will be available for future aircraft generations, where the modified dimensioning philosophy is applied during the whole design and dimensioning process.
By this philosophy, the damage tolerance design criteria like crack growth and residual strength (Metallic structure) or the compression after impact criteria (composite structures) can be applied in a different way, compared to structure design without SHM. Therefore the design will be optimised, offering the possibilities to save weight on metal and composite

structures while maintaining airworthiness and fulfilling current and future regulations [4]. In this case the SHM system will become a fixed part of the structure.

4.3 Weight Reduction on Metals

The application of SHM for saving weight on metallic structures is possible in areas dimensioned by damage tolerance [1], i.e. mainly by:

- Residual strength
- Crack growth
- Structural damage capability

The basic idea is to implement SHM with challenging design conservatism in the present state-of-the-art dimensioning of metallic structure.

Figure 2 contains an example of SHM application to fuselage structure. It is assumed that the fuselage stringers are permanently monitored by SHM, whereby the skin is visually inspected from outside. The advantage gained by this modification results from the fact that traditional design philosophy assumes a broken stringer under a skin crack, since there is no monitoring of this internal member, and also no sufficient internal inspection. With the modified design philosophy, using SHM, the stiffener will be monitored and may therefore be assumed intact in the calculations, which allows assuming a significant slower crack growth resulting from SHM application. This may be used to increase the allowable stress level by more than 15%, while keeping the inspection interval constant [4]. This means, the skin thickness can be reduced (weight saving) until the next dimensioning criteria will be reached (e.g. static stability). This significant improvement is not possible for areas dimensioned by other design criteria, e.g. static strength).

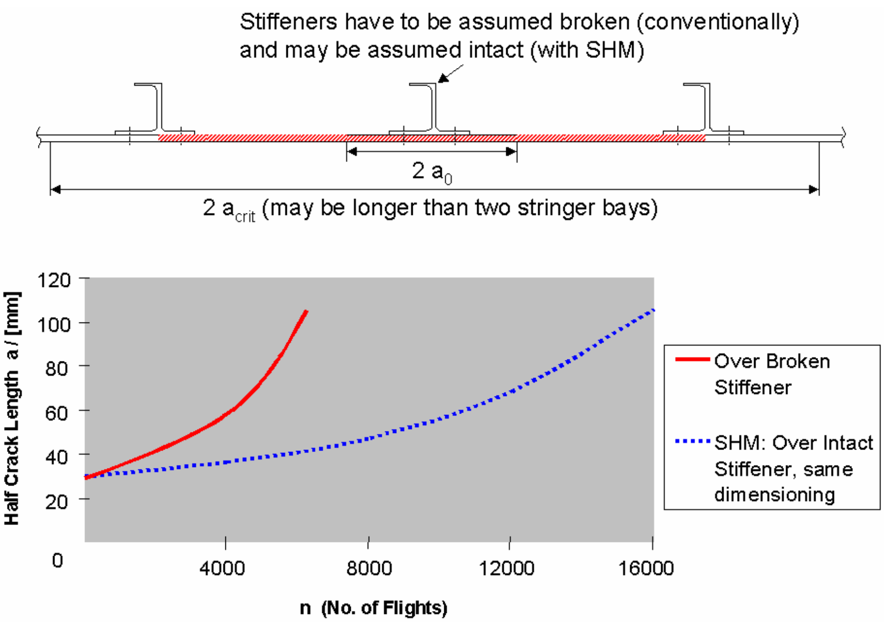

Figure 2: Example for assumed crack growth on fuselage structure, conventionally inspected and with SHM

4.4 Weight Reduction on Composites

In general it is of interest for the design and the maintenance of composite structures (monolithic, bonded or bolted) to obtain information on physical properties, defects, impact events and stress and strain distribution during in-service life. These information can be used in order to re-design structural items or to improve maintenance.
For composites the following eight scenarios of potential SHM applications have been identified in cooperation with specialist from stress, design, maintenance and repair:

1. Impact damage
2. Stringer /skin interface failure
3. Debonding of CFRP co-bonded parts
4. Core / skin sheet debonding in sandwich structures
5. Delamination of CFRP-skin layers
6. Damage of honeycomb structure
7. Detection of missing rivet heads in CFRP structures
8. Detection of loads, stress/ strain distribution in CFRP structures.

For the scenario ‘impact damage’, SHM will benefit for instance with respect to the reliable detection of Barely Visible Impact Damages (BVID): Figure 3 shows the design load requirements versus the detectable damage size [1]· According to this example the structure has to meet Ultimate Load (UL) for undetectable damages. For detectable damages by either Detailed Visual Inspection (DET) or General Visual Inspection (GVI) the required load level is between Limit Loads (LL) and UL depending on the detectable damage size. An example for a 4.16 mm thick CFRP material revealed an improvement of static strength (compression after impact) by 5 percent for a reduced damage size from 2.5 to 1.0 mm (dent depth just after impact), which may be realized due to SHM application. Consequently the SHM application for CFRP structures will lead to significant weight savings [1].

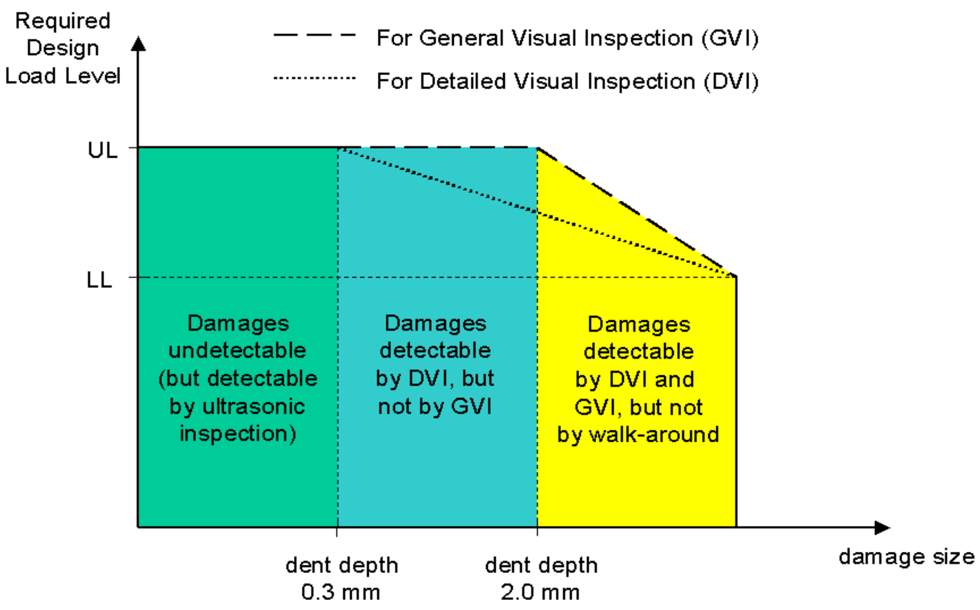

Figure 3: Required design load level versus detectable damage size.

5. Conclusion

Airframe innovations in all the relevant technological fields are important for the development of high performance airframes best to satisfy the market needs. The Airbus "intelligent" airframe is optimized in terms of new materials and advanced design, and implements smart structures technologies step by step.

Beyond simply using the technologies available on the market, it is essential to develop new materials and technologies tailored to the specific requirements. This is exactly what Airbus has been doing and supporting for decades. As the major European aircraft manufacturer, Airbus has been leading this kind of development through to maturity and has finally applied these new technologies in new aircraft programs.

SHM is a new concept whose time has now come, as the required technology is available to take the first steps. Maintenance cost reduction, increased aircraft availability and weight saving are aims which will be reached by SHM. While the maintenance benefits are usable for flying, as well as for new and future aircrafts, the weight saving design benefits can be achieved only for new aircraft programs. Irrespective of which materials will be used in the future, the current design philosophy, which is applied today by the structural designers, will be challenged by the new SHM based design philosophy.

6. Reference

[1] Assler, H., Telgkamp, J. , "Design of aircraft structures under consideration of NDT", WCNDT-World Conference of Non-Destructive Testing, October 2004, Montreal, Canada.

[2] G. Hellard: "Airbus Structure - Leading the Future", AMD Airbus Materials Dialogue 2005 - Key Messages, Bremen, Presentation, April 2005

[3] K. Keller: "Innovative Material Technologies at Airbus- A380 and beyond" EuroMat 2005, Prag, Presentation, September 2005

[4] Schmidt, H.J., Telgkamp, J., Schmidt Brandecker, B., "Application of Structural Health Monitoring to Improve Efficiency of Aircraft Structure", Proc. 2nd European Workshop on SHM, July 2004, Munich, Germany

[5] Beral, B,. Speckmann, H, "Structural Health Monitoring (SHM) for Aircraft Structures", Proc. Forth International Workshop on Structural Health Monitoring, 12-14 September 2003, Stanford, California, USA.