Onboard - SHM System Using Fibre Optical Sensor and LAMB Wave Technology for Life Time Prediction and Damage Detection on Aircraft Structure

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7th European Workshop on Structural Health Monitoring
July 8-11, 2014. La Cité, Nantes, France

ONBOARD – SHM SYSTEM USING FIBRE OPTICAL SENSOR AND LAMB WAVE TECHNOLOGY FOR LIFE TIME PREDICTION AND DAMAGE DETECTION ON AIRCRAFT STRUCTURE

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ABSTRACT

Structural Health Monitoring (SHM) is often understood as the monitoring of the structure's fatigue. The fatigue consumption of an aeronautic structure is performed either by load or respectively strain monitoring and the analysis of the strain spectra or by identifying the fatigue crack initiation in-service. The fatigue life estimation in such cases is only possible with respect to the macroscopic crack growth.

This paper is split in two parts. On one hand, it will give an overview about the IABG activities regarding the development and aeronautic application of SHM systems. Therein, it is demonstrated that a combined usage of fibre optical sensors as well as Lamb wave analysis on the fatigue test of an aircraft structural component allows precise conclusion regarding fatigue life consumption. It further allows to benchmark both technologies. Therefore, a specific concept and development of an on-board SHM System for the in-service use on an aircraft is presented.

On the other hand, the requirements in order to technically qualify a generic SHM-system are illustrated and how IABG can support the SHM developer in this process, especially when higher requirements of Technology Readiness Levels are to be validated by the developer.

KEYWORDS : *Structural Health Monitoring, Fibre Optical Sensor, Lamb Wave, Life Time Prediction, Damage Detection*

INTRODUCTION

Structural Health Monitoring (SHM) aims to increase safety and to reduce maintenance costs. Neunaber [1] describes in detail the SHM-system of the military aircraft PANAVIA Tornado. He elaborates on how the SHM-system enables the optimization of maintenance, thus leading to a significant reduction of costs during the aircraft usage in service. Numerous changes of the missions and outboard store configurations result in a high scatter of the individual aircraft usage and generate deviations from the specification load profile. According to Neunaber [1] an adapted SHM-system is required to assess the individual life consumption. This is particularly beneficial for military aircraft, which are used beyond the originally planned out of service date. Staszewski et al. [2] give an overview of life extension of many civil and military aircraft. They explain SHM-systems for various aircraft types, e.g. the PANAVIA Tornado or the AIRBUS A320.

The monitoring technologies using fibre optical and piezoceramic sensors, presented by Staszewski et al. [2], will also be used in this paper. Further application in aerospace and civil engineering can be found at Adams [3] and Balageas et al. [4].

To qualify the specification load profile mentioned above, a prototype of the main airframe will be tested in an extensive Full-scale Fatigue Test. Paget et al. [5] demonstrate the qualification of special SHM-sensors for future monitoring application during the Full-scale Fatigue Test of the AIRBUS A380, undertaken at IABG. Currently, further investigations regarding qualifying SHM-sensors for application on tests conducted at IABG are undertaken. The successful use of fibre optical sensors could be demonstrated during the last structural tests. However the application of piezoceramic sensors is planned for the future and will be presented later.

To assess the severity of an in-Service load spectrum compared to a load spectrum applied during a fatigue fest, technologies to measure strains are obligatory. Furthermore periodic non-destructive testing for damage detection is necessary during the maintenance. The maintenance effort can be reduced permanently by using monitoring technologies which are suitable for measuring stresses and for detection of damages simultaneously.

This paper presents results of laboratory experiments regarding simultaneous stress measurement and damage detection, of which some measurements have been successfully realized on in-service aircraft. The usage of fibre optical sensors for strain measurements as well as the usage of piezoceramic sensors for damage detection will be shown. Both technologies are able to monitor fatigue life consumption during fatigue tests. The implementation in an A/C could lead to a considerable reduction of the maintenance effort if automatized monitoring can be realized.

1 SHM TECHNOLOGIES

1.1 SHM using Piezoelectrics Sensors

Piezoelectric sensors are based on piezoceramic materials. Bonded on structures they are suitable for generating or measuring mechanical strain depending on the applied electric field. Changes of the electric field lead to changes in the mechanical strains, thus causing wave propagation. In solid bodies so called LAMB Waves can be excited. They propagate along great distances and are reflected by damages. By the comparison of the excitation of the wave and the corresponding reflection suitable information on damage in materials can be obtained.

SHM using LAMB Wave compares the wave propagation before and after structural damage. In an ideal case it results into three types of information:

1. The difference between the original and the actual condition, which can be taken as a damage value,
2. the localisation of the „damage“,
3. and the specification of the ”damage” concerning type (crack, delamination), dimension, type (fatigue, impact), direction, growth and so on.

At Giurgiutiu [6] a very detailed presentation of this technology can be found. The success of damage inspection is very sensitive to the optimization of several parameters (Berger [7]). For example, the exciting frequency as well as the exciting signal type, the sensor size and the material isotropy, all play an important role. Berger [7] presents a possible way of optimizing all parameters independent of the material isotropy using Finite-Element-Analysis as well as easy laboratory experiments. This optimization technique reduces significantly the measurement effort. Investigations into the sensor layout in a network and algorithms for damage detection can be found by Su et. al. [8].

1.2 SHM using Fibre Optical Sensors

Fibre optical sensors (FOS) are a very interesting alternative for the well-known stress analysis with common electric strain gauges (DMS). Numerous publications during recent years in the field of sensor- and hardware production made increasing use of this technology possible. The Guideline VDI/VDE 2660 [9] cites fundamentals and comments particular characteristics for successful application of FOS based on fibre Bragg gratings. Fibre Bragg gratings are optical interference filters which are inscribed into optical waveguides [9] and which reflect a defined wavelength of the incident light. The part of the optical waveguide which includes the fibre Bragg grating has to be bonded to the structure. Changes of the structure strain lead to changes of the grating period and of the reflected wavelength as shown in Figure 1.
Many advantages and disadvantages can be found in literature. FOS are insensitive to electromagnetic disturbance, difference of potential, humidity and are suitable for use in explosive areas like fuel tanks. The fibre, which works as sensor as well as signal transmission medium, allows inscribing numerous gratings on different positions. This reduces the effort of installation and associated cost compared to an application using electric strain gauges. The fatigue behaviour of FOS is much better than that of DMS. FOS can resist strains up to a level of 10000µm/m.

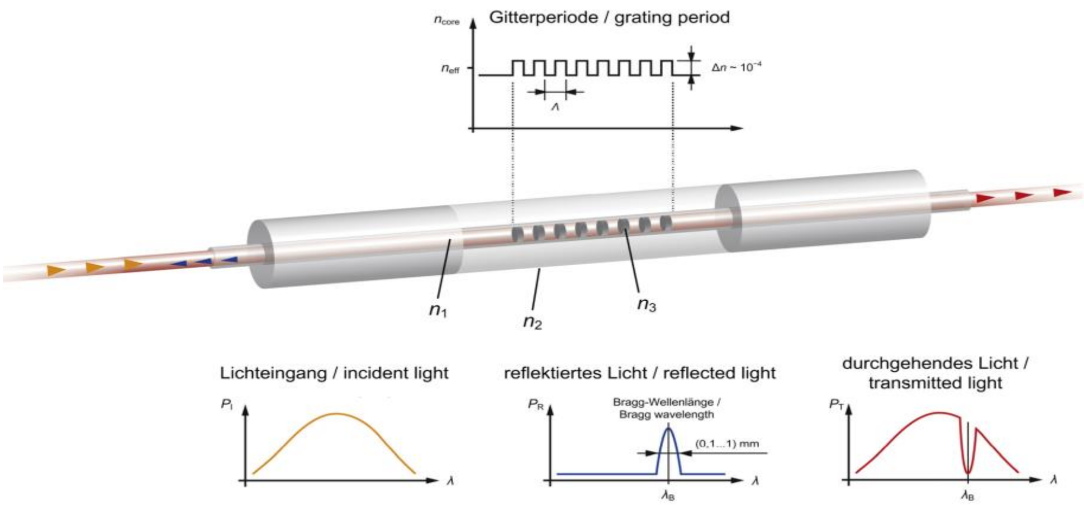

Figure 1: Caption of the figure Operation principle of a fibre Bragg grating in the optical waveguide [10]

The disadvantages of FOS are their temperature sensitivity, which need special compensation methods. Pressure loads and shear forces can cause birefringence and measurement errors caused by additional signal reflection peaks. FOS are used for aerospace applications as well as in the energy industry, in medical technology and civil engineering, for example for the monitoring of bridges, buildings and dams. Glisic [10] presents many applications. Müller [11] uses FOS for structural monitoring and displacement field estimations.

1.3 Onboard –SHM – System for PANAVIA Tornado

During the last years IABG developed a measurement system for onboard SHM- applications especially on the aircraft PANAVIA Tornado. This system is used for life time monitoring and damage detection by using fibre optical sensors and piezoelectric sensors. In addition, it can be upgraded to integrate acceleration or temperature sensors thanks to its modular architecture. Figure 2 shows the inside of the device with dismounted top and front plate.

Figure 2: Onboard SHM-System for the aircraft PA200 Tornado

2 THE SHM TECHNICAL QUALIFICATION PROCESS IN TERMS OF AERONAUTIC STRUCTURES

2.1 SHM & Technology Readiness Levels (TRL)

Technology Readiness Levels (TRL 1 to TRL 9) are used to assess the maturity of evolving aerospace technologies, such as SHM technologies and systematically incorporate them into aerospace systems when they reach a high TRL. The guided technology development is performed in such a way that the given order to fulfill requirements and to perform the corresponding development work should be maintained and followed from TRL 1 to TRL 9. In order to reach a certain maturity level (TRL) each requirement has to be completely fulfilled starting from TRL 1 onwards. In this way the maturity assessment is performed in an objective way, in contrary to the most common subjective maturity assessment which is performed on the bases of loosely defined TRL, requirements and criteria [12].
There exist several TRL definitions, general (from NASA) and SHM specific (see [12], derived from NASA's definitions). Any of the available TRL definitions to monitor and assess the maturity of SHM technologies can be used for an effective and guided SHM system development.

2.2 SHM & IABG competencies

Before any system, such as a Structural Health Monitoring (SHM) system or others, can be adopted in an aircraft, it has to pass a successive process of validation and verification, qualification and certification by following the TRL definitions. That means that the product, such as an SHM system, has to be checked as to whether all performance and airworthiness requirements are met.
IABG has more than 50 years of experience in testing the strength and endurance of full-scale aircraft and aircraft components, civil and military and is today also busy in other domains such as wind energy, automotive or space industry. With the unique expertise and trend-setting technology IABG is Europe's leading test and qualification enterprise for the aviation industry. With its accredited laboratories, IABG offers the possibility to technically qualify not only structures but also systems that monitor the structure integrity while in-service.
As IABG covers the whole qualification test pyramid, starting from the coupon level to element and aircraft component level up to the full-scale aircraft tests (see Figure 3), SHM systems of any technology readiness level can be implemented and tested appropriately.

Figure 3: IABG's test pyramid for aeronautic structures

2.3 Technical qualification of SHM systems for aeronautic applications

A recently published guideline on how to follow this procedure is described in the SAE ARP6461 [12]. In this document, the condensed and harmonized input of many stakeholders i.e. Regulatory Agencies, Airlines, Original Equipment Manufacturers (OEM), Academia and Equipment Suppliers who are crucial to the process of certifying viable SHM solutions is presented.
IABG offers the support in development & verification/ qualification especially on component and full-scale level of SHM system according to the SAE ARP6461 via

- Providing its long-term expertise in the scope of aerospace structural test definition, preparation and performance
- Providing its test facility infrastructure and processes ready to fulfill quality requirements up to EN9100
- Providing, in particular, the opportunity to investigate and verify the SHM system on a larger scale by integrating them into component & full-scale tests

Thus, IABG is able to cooperate as an executive partner with the SHM developer in the final process of technical verification of SHM systems.

3 EXPERIMENTAL INVESTIGATIONS

The results of a fatigue test on an aluminium structure loaded by bending are presented. Both fibre optical and piezoceramic sensors are used for structural health monitoring. Current results on signal analysis and optimization of excitation parameters have already been presented by Berger [13]. Figure 4 shows both the specimen on the left and the test setup on the right. The fatigue test ends with a crack on the lower side of the frame which is also shown in Figure 4.
Normally the damage zone of the frame is assembled on both sides with metallic parts and therefore common electric strain gauges cannot be used to monitor stresses directly at the crack nitiation point. However fibre optical sensor can be used. Without going into the detailed FOS systematic, the sensors are currently tested successfully on aircraft.
A small thin groove was cut into the metallic layers and the optical wave guide was put inside the groove so the sensors could not be damaged. Because of the dominating bending loads in the crack zone a fatigue crack is generated. The layout of all sensors can be seen in the Figure 5.

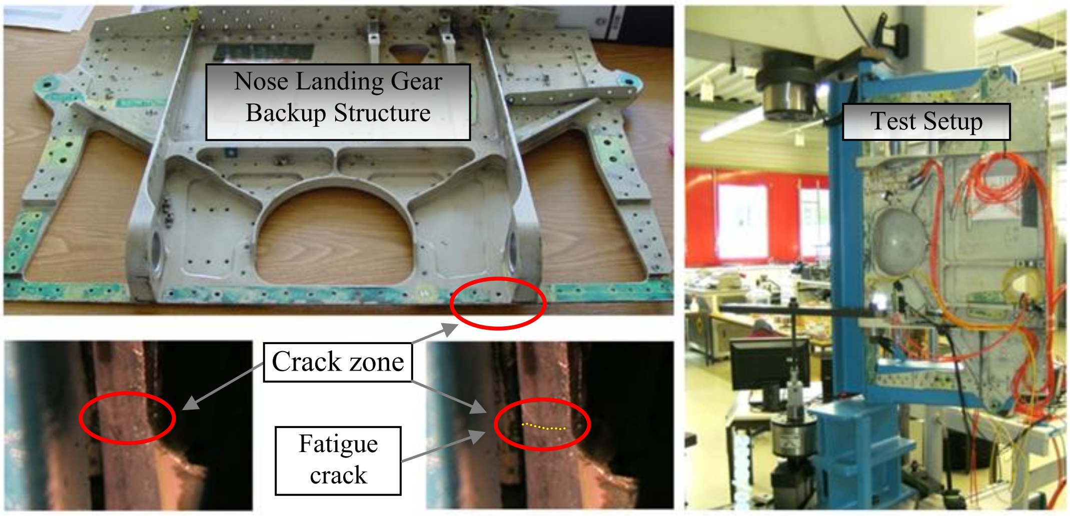

Figure 4: Nose Landing Gear Backup Structure mounted into test machine

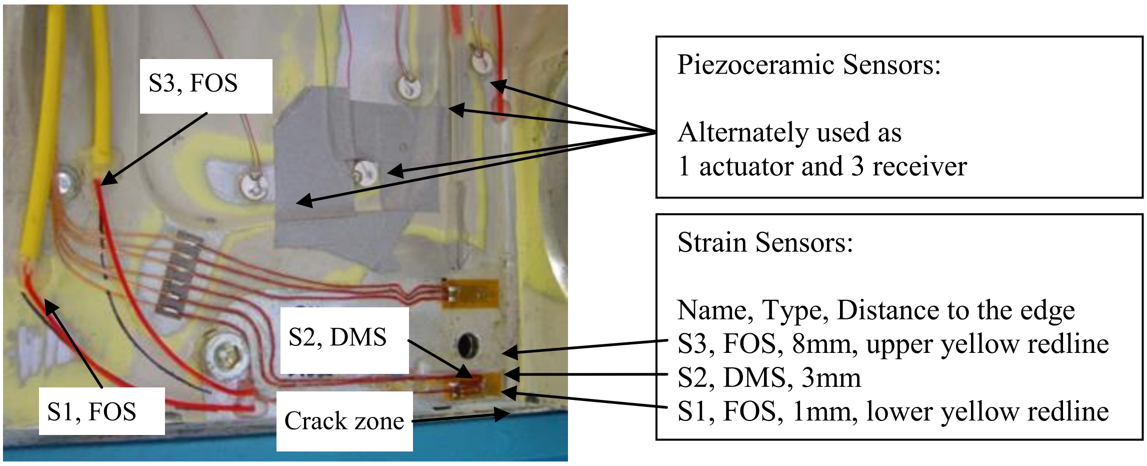

Figure 5: Layout using fibre optical, electric and piezoelectric sensors

The LAMB wave based investigation was performed in cooperation with the *Fraunhofer Institute for Non-Destructive Testing, Dresden*. Altogether four piezoceramic sensors work as an actuator and three as receivers. Each sensor excites LAMB waves which are measured by the sensors working as receivers. The load cycles were permanently measured by the FOS. At every 2500 cycles the experiment was stopped and a LAMB wave based investigation was performed with and without a static preload. Each investigation contains several configurations of excitation parameters which were specified by former investigations [13].

The two horizontal applied FOS (S1, S3) with a distance of 1mm and 8mm to the crack initiation point measured the strain caused by the applied loads with a high accuracy. To allow a direct comparison with the strain measured during the Full-scale Fatigue Test, an additional electric strain gauge (S2, distance 3mm) of the same design was used. This electric strain gage was not applied to the in-service aircraft. The whole test was undertaken by an accredited test laboratory at IABG.

The results are shown in Figure 6. The horizontal axis stands for LAMB Wave measurements. That means each measurement contains 2500 load cycles. Depending on the distance to the crack initiation point the strains decrease with increasing cycle number because of plastification, respectively cold working.

After measurement 18 (equal 40000 load cycles) sensor S1 shows a reduction of strain, while strain level of the other sensors S2 and S3 remain at the same level. The strain curves shown in Figure 6 allow the change in strain during the fatigue test to be analysed.
Of interest is the strain after a particular number of cycles have been applied in relation to the strain at the start of the test. A delta of 100µm/m was considered to indicate the beginning of fatigue behaviour from a practical view. This level corresponds to a plastic strain which is assumed to be that of the proportional limit of static stress-strain curve. Then, after 45000 load cycles sensor S2 with a distance of 3mm shows a plastic strain limit as described above and for sensor S3 with a distance of 8mm it takes 57500 load cycles for this threshold to be reached. A visible crack could be seen under loading at around 60000 load cycles.
For the LAMB wave investigation it is important to transform the complex signal analysis into an easy to use feature like a damage indicator DI (Berger [13]). The results have shown that loading the structure opens the crack and improves the reflective behaviour. However with and without applied load the damage indicator shows a first increase between measurements 19 to 21. From then on strong reflections can be measured under load. Without load the introduced plastification results in a compressive stress which contributes to crack closure, thus leading to worse reflective characteristics of the damage.
Therefore the LAMB wave damage indicator remains static until longer crack lengths. After measurement 27 to 28, i.e. 62500 load cycles, the damage indicator starts to increase even if the LAMB wave investigation is undertaken on the unloaded component.

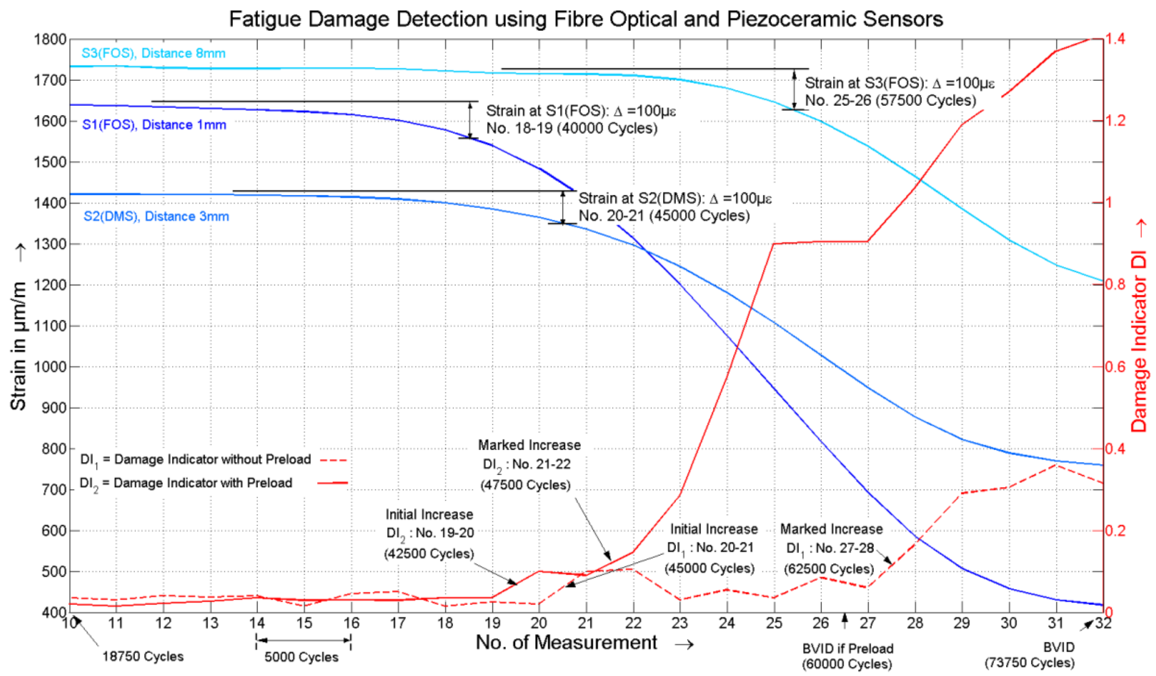

Figure 6: Fatigue Damage Detection starting from the Proportional Limit Stress

Both methods, i.e. fibre optical and piezoceramic sensors enable the detection of the fatigue crack and the monitoring of its growth with nearly the same resolution. Looking at the load cycles the damage detection starts at two-thirds of the final life. To achieve early damage detection, the usage of FOS requires a defined and repeatable load cycle, whilst using LAMB wave, undertaking the measurements on a loaded structure is recommended. For this study, a plastic strain of the order of the proportional limit of the static stress-strain curve was used to define the beginning of plastification respectively cold working and finally the fatigue history.

CONCLUSION AND FUTURE WORK

The fatigue damage detection regarding a typical aircraft structure by using fibre optical and piezoceramic sensors is presented. Both sensor technologies are suitable for permanent structural health monitoring on aircraft. A preload as well as a repeatable reference load cycle significantly improves the damage detection and monitoring. The measurement results of the fibre optical sensors can directly be used for life time consumption analysis of an aircraft. However, the application efforts are higher than for piezoceramic sensors because of the required temperature compensation. For damage detection, fibre optical sensors need to be closely applied to the damage origin. Piezoceramic sensors on the other hand can be positioned further away, but they do not provide any information on stresses useful for the estimation of life time consumption. By means of the test results, the damage indicator of the LAMB wave methodology can be enhanced in order to provide a more accurate indication of consumed structural life. Therein, the measurement campaign using fibre optical sensors on in-service aircraft was also successfully performed to precisely identify the loads of the aircraft component during aircraft ground manoeuvring. Current investigations specify the correlation between crack length and damage indicator as well as the airworthiness of the Structural Health Monitoring system using the described sensors. Altogether, this paper shows IABG's theoretical understanding and experimental capabilities in terms of SHM technical qualification for aeronautic structures.

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