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

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ABSTRACT

The fatigue of aircraft structures can be monitored by permanently recording strains, which result from the exposure of such structures to various types of loading throughout their usage. From these recordings it is possible to evaluate strain spectra, which may be used to calculate the qualified fatigue life consumed by the structure at a particular point within its service life.

A different approach to monitoring fatigue of aircraft structures is to identify the initiation of small fatigue cracks in service. The fatigue life estimation in such a case is only possible with respect to the macroscopic crack growth.

The use of fibre optical sensors enables the monitoring of strains as required for the first of the above mentioned methods. The use of piezoceramic sensors enables the excitation and measurement of plate waves (LAMB waves) as required for the damage detection.

In this article the use of both these types of sensors on the fatigue test of an aircraft structural component is described. It will be demonstrated that the process of fatigue can be observed very well using fibre optical sensors, which also allows a precise conclusion to be drawn regarding fatigue life consumption.

Furthermore the potential of LAMB wave sensors to detect fatigue damage and monitor macroscopic crack growth is demonstrated. The simultaneous use of both technologies on the same test made a comparison possible and the relative strengths and weaknesses could be identified.

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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. [4] 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. [4], will also be used in this paper. Further application in aerospace and civil engineering can be found at Adams [5] and Balageas et al. [6].

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. [2] 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.

SHM USING PIEZOELECTRIC 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 [7] 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 [3]). 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 [3] presents a possible way of optimization 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. [10].

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 [1] 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 [1] 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.

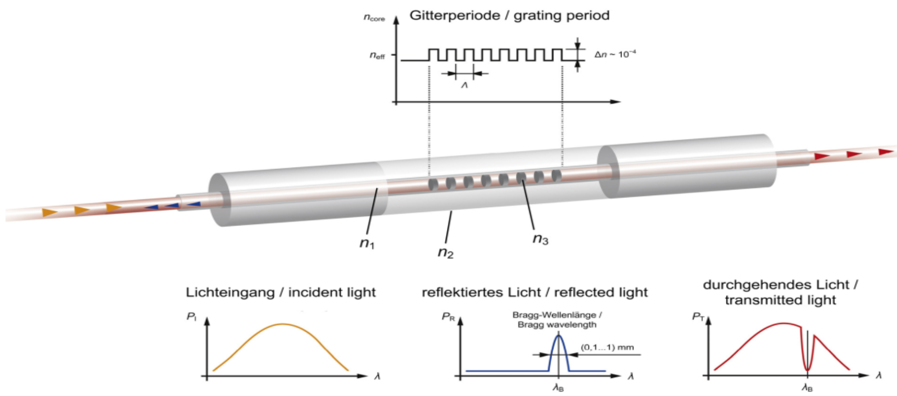

Figure 1. Operation principle of a fibre Bragg grating in the optical waveguide [10].

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 [11] presents many applications. Müller [12] uses FOS for structural monitoring and displacement field estimations.

EXPERIMENTAL INVESTIGATION

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 [3]. Figure 2 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 2.

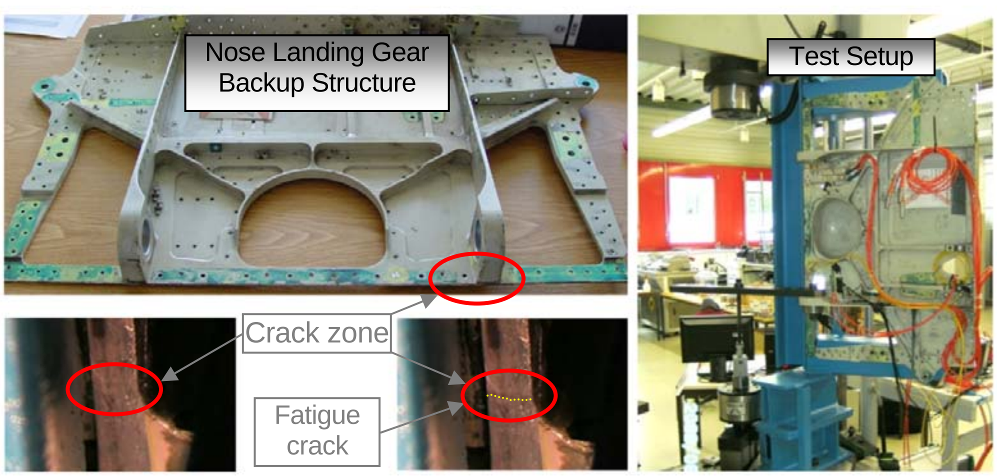

Figure 2. Nose Landing Gear Backup Structure mounted into test machine.

Normally the damage zone of the assembled frame is covered on both sides with metallic parts and therefore common electric strain gauges cannot be used to monitor stresses directly at the crack initiation 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 3.

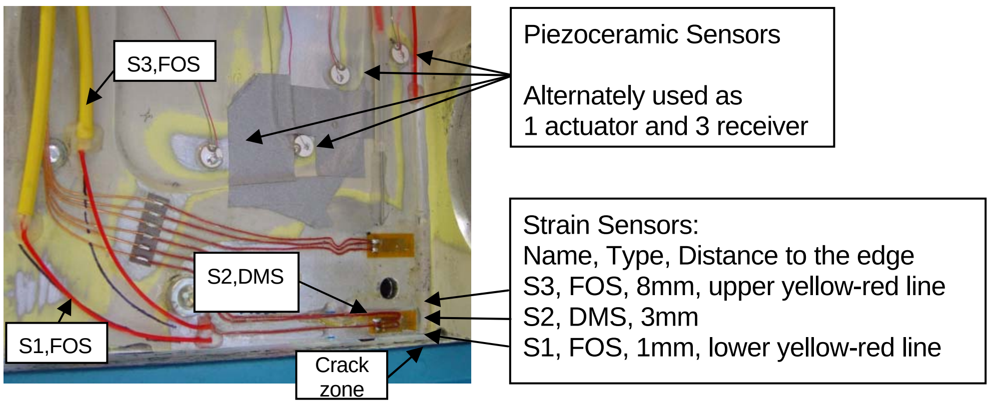

Figure 3. Layout using fibre optical, electric and piezoelectric sensors.

The LAMB wave based investigation was performed in cooperation with the Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren, Institutsteil 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 (BERGER [3]).

The two horizontal applied FOS (S1, S3) with a distance of 1mm and 8mm to the crack initiation point measure 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 were 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 the Figure 4. 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 4 allow the change in strain during the fatigue test to be analysed.

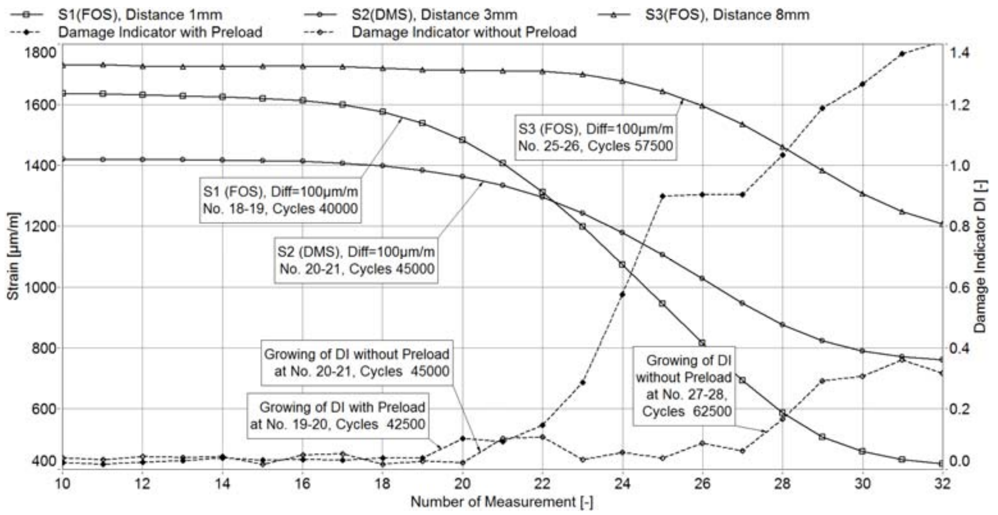

Figure 4. Fatigue Damage Detection starting from the Proportional Limit Stress.

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 [3]). 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 of the unloaded component.

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

This paper presents the fatigue damage detection within a typical aircraft structure using fibre optical and piezoceramic sensors. 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 measurements results for fibre optical sensors can directly be used for life time consumption analysis of the aircraft. However the application effort is higher than that of piezoceramic sensors because of the required temperature compensation. For damage detection, fibre optical sensors need to be applied very close to the damage origin. In contrary SHM using piezoceramic sensors, the sensors can be positioned further away, but they do not provide any information on stresses useful for the estimation of life time consumption. With the aid of such test results, the damage indicator of the LAMB wave methodology can be enhanced to provide a more accurate indicator of consumed structural life. On this occasion the measurement campaign using fibre optical sensors on in-service aircraft was successfully used to identify accurately the loads of the described aircraft component during aircraft ground manoeuvring. Further investigations will aim to specify the correlation between crack length and damage indicator as well as the airworthiness of the Structural Health Monitoring system using the described sensors.

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