SHM Technologies and Applications in Aircraft Structures

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Abstract
Structural Health Monitoring (SHM) emerged as a multidisciplinary set of technologies during the ’90, with the goal of reducing maintenance costs in aircraft structures by the implementation of automatic damage detection systems, able to detect incipient cracks well below the critical size, and nearly without human intervention. Inspections of structural integrity could be done almost continuously, either during flights or during overnight stops, without aircraft disassembly. The system includes three key elements: 1) a network of sensors, permanently attached to the structure; this aspect is a main differentiation with conventional NDT procedures. 2) On-board data handling and computing facilities. 3) Algorithms that collect data from sensors, clean data from environmental effects, compare to former data from the pristine structure and inform about occurrence, localization and damage type.

Fostered by the nearly immediate success of the on-condition maintenance concept when applied to rotating machinery, like helicopter drive train, different SHM concepts have been developed. As sensor system, to be built within the structure, three main types have been explored and the technology is well known: Piezoelectric wafers, fibre optic Bragg gratings, accelerometers and MEMS. Their characteristics are briefly discussed. A discrete number of sensors may be located at the structure, at fixed positions. To understand SHM it need to be keep in mind that it is not a local inspection, as with the conventional NDT, damages will be detected only when they cause a change at the signal collected by the fixed sensors, either as the elastic waves travelling from one sensor to others, or by detecting the acoustic emissions caused by a growing crack, or by detecting the changes in the dynamic modal response of the structure. Main algorithms will be reviewed, and their applicability to real aircraft structures will be discussed.

Keywords: Damage detection algorithms, Fibre Bragg gratings (FBG), piezoelectrics.

1. Introduction

In conventional techniques of inspection (NDT) an operator periodically evaluates the structural integrity by external equipments, like ultrasound, X-ray, or many other systems. An essential aspect of SHM, unlike conventional NDT system, is that sensors and actuators of the system are permanently attached to the structure, collecting data almost continuously during the entire service life of the structure, without operator intervention. For the system to be useful, usually it is required a very large number of sensors distributed throughout the structure. This enormous amount of data must be processed continuously and automatically, and reduced to alarms for the user (aircraft engineer or maintenance technician) when an overload is occurring, or when damage is detected, or to prepare cumulative fatigue reports of the structure.

Research on SHM initiated in the late ‘80s, with the availability of portable computers, which were obviously essential to process the signal from multiple sensors.

NDT serves to detect discontinuities in solids, either at the surface or internal, which are identified as damages. SHM detect local changes in the structure, either of the material properties or its connectivities, which are identified by comparing the response of the structure to a stimuli with the response of the pristine structure. SHM cannot fulfil ‘first article’ inspection. Some of the main differences between NDT and SHM are highlighted at Table 1.
TABLE 1 Comparison of NDT and SHM

<table>
<thead>
<tr>
<th></th>
<th>NDT</th>
<th>SHM</th>
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<tbody>
<tr>
<td>Inspection</td>
<td>Inspection is done by external probes and equipments</td>
<td>Sensors are permanently attached at fixed locations in the structure</td>
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<tr>
<td>Off line monitoring</td>
<td>Off line monitoring, parts need to be disassembled for inspection</td>
<td>On Line monitoring, aircraft inspection may be done in flight or during overnight stops</td>
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<tr>
<td>Time based maintenance</td>
<td>Time based maintenance, checks must be regularly spaced</td>
<td>Condition based maintenance. Disassembly only when required for repair.</td>
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<tr>
<td>Labour intensive</td>
<td>Labour intensive</td>
<td>Evaluation done without human intervention</td>
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<tr>
<td>Mature technologies are available</td>
<td>Mature technologies are available</td>
<td>Still under development for real AC structures</td>
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The concept of including sensors to detect failures in mechanical systems was applied with great success during the '90s to the power transmission mechanism of the main and tail rotor helicopter, significantly reducing the number of incidents and accidents. Clearly the helicopter drive train is a complex system operating in highly variable and adverse conditions; any imperfections in gears and bearings are quickly amplified, threatening the safety of the helicopter. But it was enough to place accelerometers at the bearing supports, and to perform the FFT of the acquired signals, to obtain a reliable early warning system. The signal is very intense at the rotation frequency, any imperfection is manifested as a distortion of the frequency spectrum; Thresholds have to be set to warn for the anomaly before it becomes a threat. The same concept works equally well in any other rotating machine, such as power plants, wind turbines power plant, etc, and is a mature technology widely applied, known as 'Condition Monitoring'.

The aim is to mimic the Nature, and integrate into the structure a sensorial system to detect the onset of damage and overload conditions. Biological structures, such as bones, have sensory abilities that detects overload and damages, and even they have the ability of self-healing. The advantages of adding a sensory capability to structures are obvious: by having an integrated damage detection system, periodic preventive maintenance inspections are not longer needed, structure knows when and where maintenance is requested, which means substantial time and financial savings. But also the early detection of damage means greater safety, or what is the same, optimized design. For example, imagine a large diameter wind turbine, with blades of more than 100 meters, as they are now being installed on the coastal sea. The difficulties for accessing allows only for annual inspections, and the fact that small local defects, such as local changes in the composition of the adhesive, may initiate a crack which grows as the machine continues in operation, obliges to the design to be very conservative with material properties. If there were a system that automatically detects the onset of damage, stopping the machine to repair, it would allow a design much closer to the real strength of the structure.

2. Distributed sensing system

As a wide definition, a sensor is an artifact able to transform a certain physical or chemical magnitude into readable information. They use to be point sensors, obtaining the information from a single position, but recently distributed optical fibre sensors, getting the information all along the length of the optical fibre, are available. As the damage position is not known a priori, the sensor network must cover the whole structure. Minimum weight and size, connectivity, durability/robustness/repairability and
embeddability into the host structural material are critical issues. The two mostly used kind of sensors for SHM applications are Fibre Bragg Gratings (FBG) and piezoelectric wafers (PZT). Details may be found at Ref 1 and 2, respectively. Next paragraphs summarize their main characteristics. Also MEMS have been proposed, and Comparative Vacuum Monitoring (CVM) and Electrical Crack gauges (ECG) have also been implemented for detecting surface cracks in aircraft structures, when the area to be kept under surveillance is small and known. These are the easier kind of sensors, so we start the explanation with them.

Electrical Crack Gauges [3] (ECG) is a mature technology that is nowadays used for structure monitoring of fatigue crack damage. They consist of a circuit of many parallel wires that break when the crack passes through them, thus provoking a step change in the total electrical circuit impedance.

Comparative Vacuum Monitoring CVM sensors [4] are non-electrical crack gauges, consisting of a thin silicon layer with small grooves, alternatively connected to air/vacuum. A surface crack will communicate the grooves, generating a vacuum loss, which is an index of the crack occurrence. CVM sensors were first installed on a US Navy H-53 helicopter in 2002 as part of a trial program. The sensors were installed in front of an existing crack in a location that required approximately 4 hours to disassemble, inspect and reassemble. This inspection was required every 25 flight hours on a large and heavily used fleet, but was reduced to approximately 5 minutes with the CVM system without any requirement for disassembling.

2.1 Fiber optic sensors

Optical fibres are very thin filaments of near pure silica (0,125 mm diam.), that keeps the light confined at its core, even when bended. They may be easily embedded among the plies of a laminate during the manufacturing of the composite structure (Figure 1). Different kinds of optical sensors are available, the most widely used is known as FBG, or Fibre Bragg Grating. The sketch of a fibre optic sensing system is always very simple (fig 2): A solid state light source, either monochromatic (laser) or LED (light emitting diode), containing white light as a mixture of frequencies. Light goes through splices and optical connectors used for assembly/disassembly the optical fibers. Light arrives to the sensors, and a portion of light bounces back toward the detector. Light detectors use to be again solid-state, pig tailed optoelectronic components (pig tailed means that an optical fibre is leaving the solid state casing, doing very easy to connect it to the optical circuit).

![Fig 1. An O.F. embedded into a composite.](image1)

![Fig 2 Sketch of a FBG interrogation system](image2)
Main characteristics of FBG are

• Low size (0,15 mm diameter, 2-10 mm length).
• FBGs reflects a single optical frequency
• FBG is engraved inside an optical fibre, embeddable into composite laminates.
• Linear response to strain and temperature. Changes detected as wavelength peak drifting.
• EMI/RFI immunity. Intrinsic safety.
• Easy multiplexing, up to 10 FBG per fibre if multiplex in wavelength, thousands of sensors per fibre with advanced procedures (OFDR)
• Standard interrogation equipments working to 1-10 kHz, typical resolution 1 microstrain (or 0,1 ºC)
• Unprotected optical fibre is brittle; OF connection is a critical issue.

2.1.1 Damage detection from strain measurements

Local strain measurements are useful to know the load state on the structure, which is needed for prognosis tasks, and for Fatigue Life Management Programs, currently implemented in all the military aircrafts fleets.

But from local strain measurements (obtained either from FBG or from electrical strain gages) damage initiation cannot be detected, except in the very strange coincidence that the sensor position matches the position of the crack. Local cracks do not change the overall strain field, they change only the near field, a few inches around the crack.

Two approaches are feasible, but still under research, for damage detection based on FBGs:

a) Distributed sensing system: The whole length of the optical fibre is sensitive to strain. A crack crossing the optical fibre would be detected as a large local strain. [5]

b) By comparing the strain readings at many points, looking for the very slight changes caused by the damage. Robust automated techniques are needed to do this comparison. Principal Component Analysis (PCA) is a well-known statistical technique that has been used as a pattern recognition technique [6]

![Fig 3 Damage detection in a concrete beam with distributed sensing](image1)

![Fig 4 Damage identification by PCA](image2)
2.2 Piezoelectric wafers (PZT)

The advent of commercially available low-cost piezoceramics has opened new opportunities for dynamic structural identification using embedded active sensors. Embedded active sensors are small piezoelectric (Lead (Pb) Zirconate Titanate (PZT)) ceramic wafers that can be permanently attached to the structure. Piezoelectric wafers act as both sensors and actuators. In addition, their frequency bandwidth is orders of magnitude larger than that of conventional modal analysis equipment. They can form sensor and actuator arrays that permit effective modal identification in a wide frequency band.

Main characteristics of PZT wafers are:
- Typical size for sensing applications: disc 5 mm diam; 0,1 mm thick
- Translate strain to voltage, and opposite. Dual role as sensor/actuator
- It has to be wired both sizes. The SMARTLAYER is a practical solution for embeddability in composite laminates, with PZT built at preselected positions, and fully wired. (fig 5)
- Highly sensitive to elastic waves (hundred of kHz, strain below 0,01 µε)

PZTs can be easily bonded/embedded into the structure, with the desired array. From these points, they may launch/receive elastic waves, existing three basic approaches:
a) Acoustic emission. Any crack that grows liberates energy, which is dispersed through the solid as transient elastic waves. (Figure 6). It is a classical NDT procedure, the change for SHM is that sensors are permanently attached to the structure. It has been used in space launchers, like DC-XA Delta Clipper [7]. Damage localization may be done by triangulation. Detection and localization of impacts in composite laminates is done by similar procedures.
b) Electromechanical impedance [8]. The electrical impedance of the PZT changes when bonded to the structure, in dependence of the stiffness of the host structure. Any damage in the surrounding of the PZT will be reflected as a change of the electromechanical impedance. Again is a local method, but useful to investigate the quality of bonded joints, etc.
c) Active Sensing Diagnosis System (ASDS) [9]. This is the most widely used approach; the principle is sketched at figure 7. An array of PZT are bonded to the structure, one of them is submitted to a electric burst, the others capture the elastic waves produced; all the combinations are done, and the response signals are stored. The process is repeated again and again, any damage at the path between two sensors (either direct path or after reflections) will change the received signal; in this way the damage occurrence is detected, and approximately located. Figure 8 (left) illustrates the GUI to specify the sensor positions, and waveform launched by the actuator, and received by each sensor; Figure 8 (right) illustrates the estimates of the damage position.

Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing (bulk waves). Plate waves are similar to surface waves except they can only be generated in materials a few wavelengths thick. Lamb waves are the most commonly used plate waves in SHM. They have a dispersive nature (speed is dependent of the frequency), but Lamb waves will travel several meters in steel and so are useful to scan plate, wire, and tubes.

The biggest obstacle for a wider application of these technologies in aircraft structures lies in the waviness nature of the excitation, which propagates quite well in plates of uniform thickness, but suffers complex reflection and refraction phenomena at each thickness changes; the wave is nearly confined by the stringers and rib foot. Nevertheless, a number of interesting applications have already been implemented, like the monitoring a bonded repair patch.
Figure 5 SmartLayer, with embedded PZT and FBG

Figure 6 Acoustic Emission principle

**Fig 7. Active Sensing Diagnosis System, based on PZT array**

Figure 8. Graphical Interfaces for an ASD System, from Acellent (ref 9)
3. Identification of damage using modal analysis (vibration) techniques

Like with the rotating machinery, it may be thought that obtaining and analyzing the vibrational response of any other structure such as a bridge or an airplane wing, would be equally resolute. It is true that the sound of the bell changes when cracked, which means that they have changed their frequencies, but in general terms, the sensitivity of this technique is very low; for example, a cut of 20% of the section of a cantilever beam at its root, which is a considerable local damage, changes less than 1% the first natural frequency, which could be masked by the noise of the signal or temperature effects.

With some additional sophistication, the analysis of the variation of frequencies and natural modes of an structure is a useful method for detection of damage and largely employed in civil engineering to locate, quantify the damage and determine the residual strength of structures such as bridges and other major infrastructure. The procedure is similar to the 'experimental updating of finite element model' (FEM updating), frequently used in aerospace. The initial FEM model of the structure, obtained from geometric design and its theoretical properties of materials may be adjusted to the actual structure, by running the program to obtain a prediction of its frequencies and eigenmodes, and the results compared to those obtained from a experimental vibration test. Then the parameters of the initial FEM model are modified, to achieve a better matching. The same procedure will be used to predict and locate the damage occurred to the structure; on the initial FEM model, some elements or some connectivities will be cancelled, until the agreement between prediction and experiment. Figure 9 shows some of the results of a European project COST, in which we compared the ability to detect damage using various algorithms, based on experimental data. This is a representative structure of a two-storey building, which underwent a seismic excitation, the dynamic response was measured before and after the damage. For damages large enough, such as that presented in the figure, satisfactory results were obtained. An immediate application of the procedure is the evaluation of habitability of buildings and infrastructures after an earthquake, when speed in diagnosis facilitates emergency plans.

This procedure will not be useful in aircraft structures, as the minimum crack size required to influence global eigenmodes of the structure is much larger than the critical crack size normally allowed for aircraft structures.

![Fig. 9 'Steelquake’ structure, tested at JRC-ISPRA. At the right side, prediction of damage location.](image-url)
Conclusions

SHM is one of the enabling technologies to revolutionize the future aircraft design, development and maintenance [11]. The use of SHM may reduce maintenance costs more than 40%, by savings in disassembly and inspection times, and improvements in aircraft availability. Commercial full-scale SHM systems are not available at the present times, even the most important aircraft industries (Airbus, Boeing, Embraer) are running large research projects and in-flight testing to check their viability. In July-2006 the SHM-AISC (Aerospace Industry Steering Committee) was formed, including representative of industry, government organizations as EASA, FAA, operators, like NASA, US Force, and academia. It is expected that they will publish in the near future some standards and certification procedures, needed before these technologies may be fully implemented.

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