Structural Health Monitoring – the route to Condition Based Maintenance

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Abstract

In order to have more efficient maintenance, reduce down time and optimize fleet operation, Airframe Structural Health Monitoring targets progressive solutions with the ultimate objective to offer Condition Based Maintenance. This will enable inspecting airframes only when needed, based on individual aircraft usage and damage detection.

Keywords: Condition Based Maintenance, Structural Health Monitoring, Digital Twin, Sensors, Airworthiness Requirements.

1. Introduction

In order to have more efficient maintenance, reduce down time and optimise fleet operation, Airframe Structural Health Monitoring (A-SHM) targets progressively solutions with the final goal to offer Condition Based Maintenance (CBM). A-SHM is well established in military programs, but has seen a slower uptake in civil aircraft operations. This paper presents the key factors for the civil aircraft industry to progress with a successful implementation of A-SHM towards CBM, focusing on Operational Monitoring and Damage Monitoring.

Any A-SHM solution is driven by the following major values:

1. Decrease direct maintenance costs

   A major value will be created by the potential to replace manual inspections with scheduled or automated interrogation using an A-SHM system, and to tailor scheduled maintenance tasks based on actual aircraft usage.

2. Increase A/C operational availability

   In addition to the downtime benefits created by 1), a major value will be created by A-SHM to assess with increased accuracy and less lead time random discrete events such as accidental impacts, lightning strike, heavy/ hard landings, bird impact or other overload events. A-SHM data can also be used to substantiate service life extensions that have an effect on the residual value.

3. Contribute to Design improvement inducing Weight saving

   A major value will be created where A-SHM detection capability may reduce the need to account for scenarios with low likelihood of occurrence. Furthermore, when accumulated in-service data is combined with analytical modelling, this will reduce the unknowns and conservatism inherent in today's design assumptions.

A-SHM includes two principal axes: operational monitoring and damage monitoring, as described in figure 1 [2].

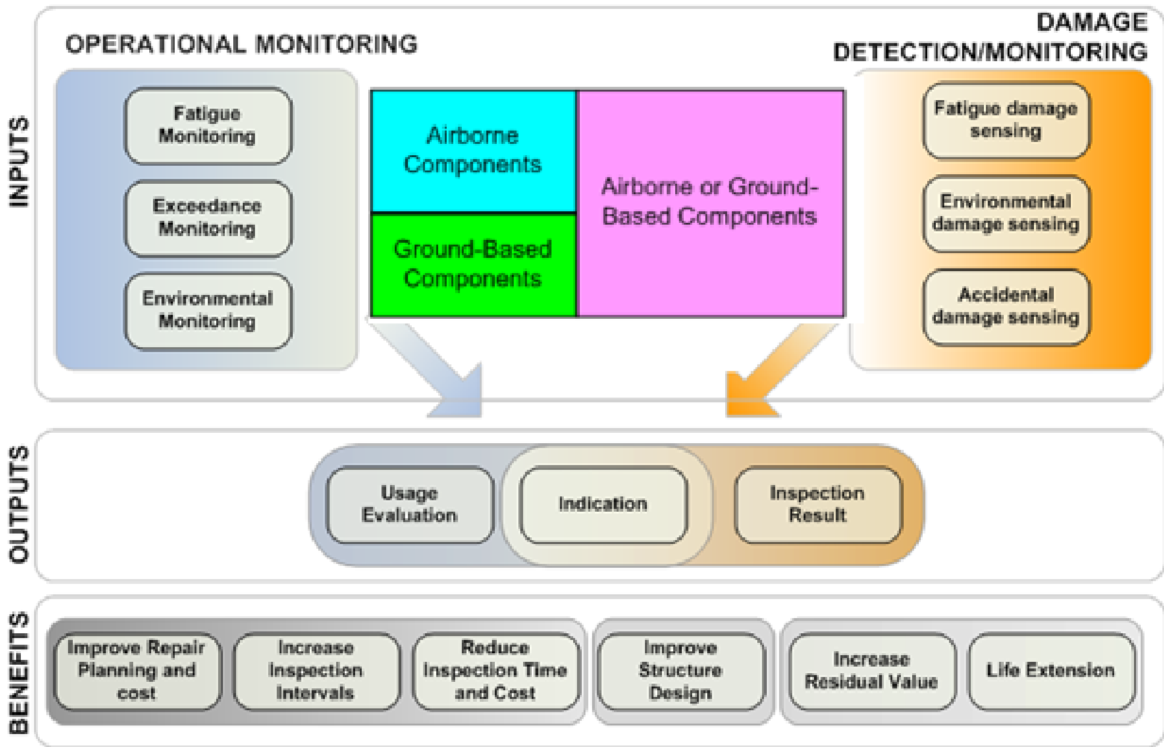

Figure 1 - Structural Health Monitoring following ARP 6461 [2]

A-SHM developments follow a step-by-step approach offering intermediate solutions that can be retrofitted in the legacy and derivative fleet, targeting as final goal CBM. Such an approach will ensure delivery of robust solutions at each step, de-risking with disruptive changes in implementation, building on the existing solutions and finally resulting in technology that is ready for future new aircraft at the right time.

The ultimate target is to inspect airframes only when needed, based on individual aircraft usage and damage detection, taking into account the individual aircraft recorded airframe loading history.

2. A-SHM deployment

Any roadmap for A-SHM introduction should represent a step-by-step approach and put priority on deployment, i.e. identification, specification and use of available technologies at a given point in time. It is use case driven, to find technological solutions for given use cases, demonstrating positive business case.

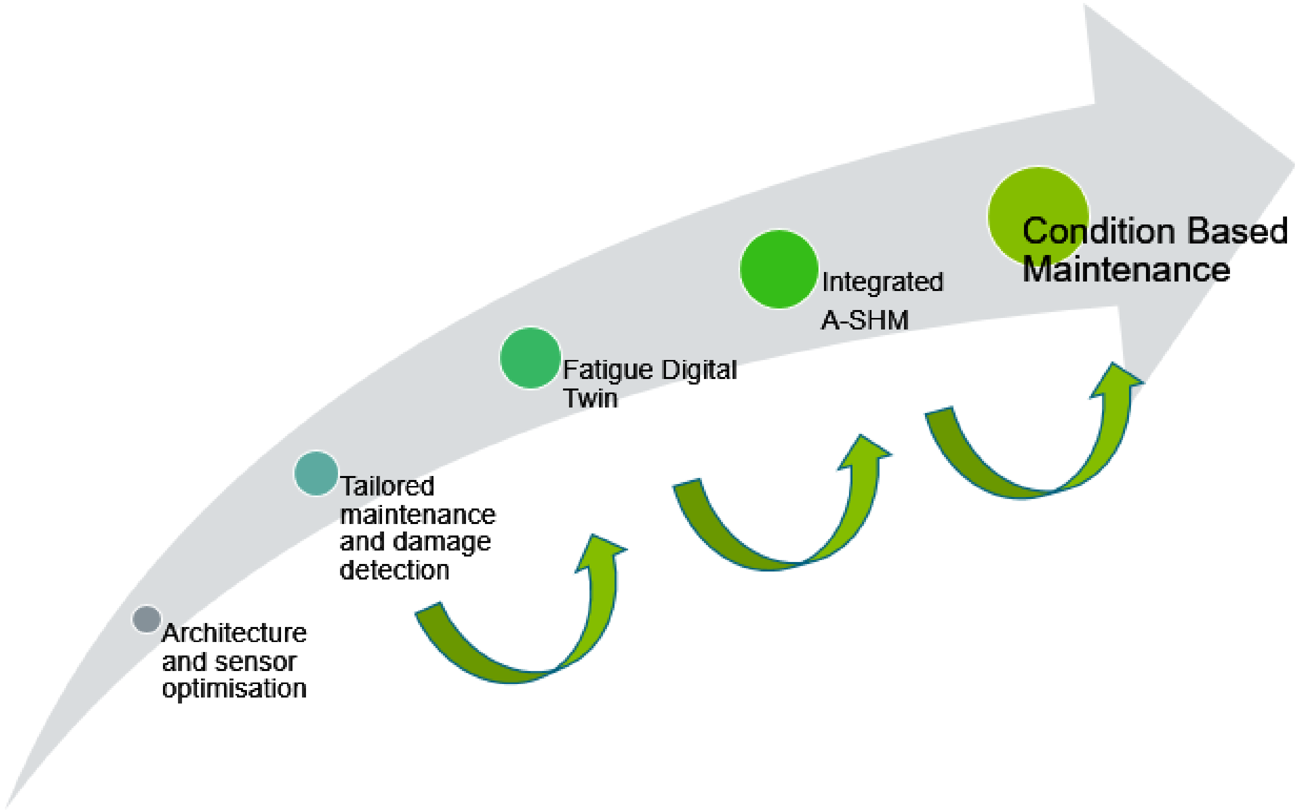

Figure 2 - A-SHM step by step introduction

The A-SHM solutions should be progressively developed and implemented, starting with single task innovative solutions to more integrated concepts, see figure 2:

- Tailored maintenance by usage monitoring using aircraft parameter(s)
- Damage monitoring by surface sensor,
- Predictive maintenance using aircraft specific fatigue spectrum and fatigue damage analysis using Fatigue Digital Twin
- Integrated A-SHM to CBM, by integration at aircraft level in a fully automated set-up:
    - Fatigue assessments,
    - Conditional event assessment,
    - High Load event assessment,
    - Damage assessments and growth predictions,
    - Environmental degradation or damage.

This step-by-step approach, or otherwise called controlled introduction to service, is used to de-risk the implementation and gain confidence and maturity. The robust solutions will limit the risks at each incremental step by building on the existing solutions.

A-SHM deployment will be structured around two principal axes: Operational monitoring and Damage monitoring, by taking benefit of existing data from aircraft systems and adding information from sensors. Solutions rely on basic aircraft parameters or sensor interrogation with data analysis in a scheduled manner and on-ground:

1. Operational monitoring
   - Fatigue models for metallic airframe structure, including loading analysis.
   - Exceedance loading detection and airframe assessment, based on combination of data (sensor based) and predictive algorithms.
   - Environmental monitoring, where temperature and humidity will be recorded and used in assessments.
2. Damage monitoring
   - Sensing technologies (incl. damage diagnostic) mainly for hotspots.
   - Environmental monitoring on composite and metallic airframes for discrete events, such as: Mechanical and lightning strike impacts, stringer debonding, corrosion, material degradation and cracks induced by vibrations.

The A-SHM solutions provide the means to reduce maintenance cost and increase aircraft availability and will ultimately pave the path towards CBM, where inspecting the airframe structure is only done when needed with lowest effort. The solutions will reach the maximum benefit with dynamic maintenance and tail-specific or sub-fleet specific maintenance, having flexibility in inspection thresholds/intervals [4]. Hence, during the development phase of any upcoming solutions, a feedback loop from airlines is pertinent.

3. Operational Monitoring

Structural Maintenance programs addressing fatigue are based on conservative operational assumptions. This is required as the structural maintenance program covers a complete fleet of a certain aircraft program with a variety of possible operations, see figure 3. It is also required by the airworthiness requirements [3]:

CS25.571(a)1:

The evaluations of subparagraphs (b) and (c) must include: -

(i) The typical loading spectra, temperatures, and humidity expected in service

AMC25.571(a) chapter 6b:

Typical loading spectrum expected in service

The loading spectrum should be based on measured statistical data of the type derived from government and industry load history studies, and where insufficient data are available, on a conservative estimate of the anticipated use of the aeroplane.

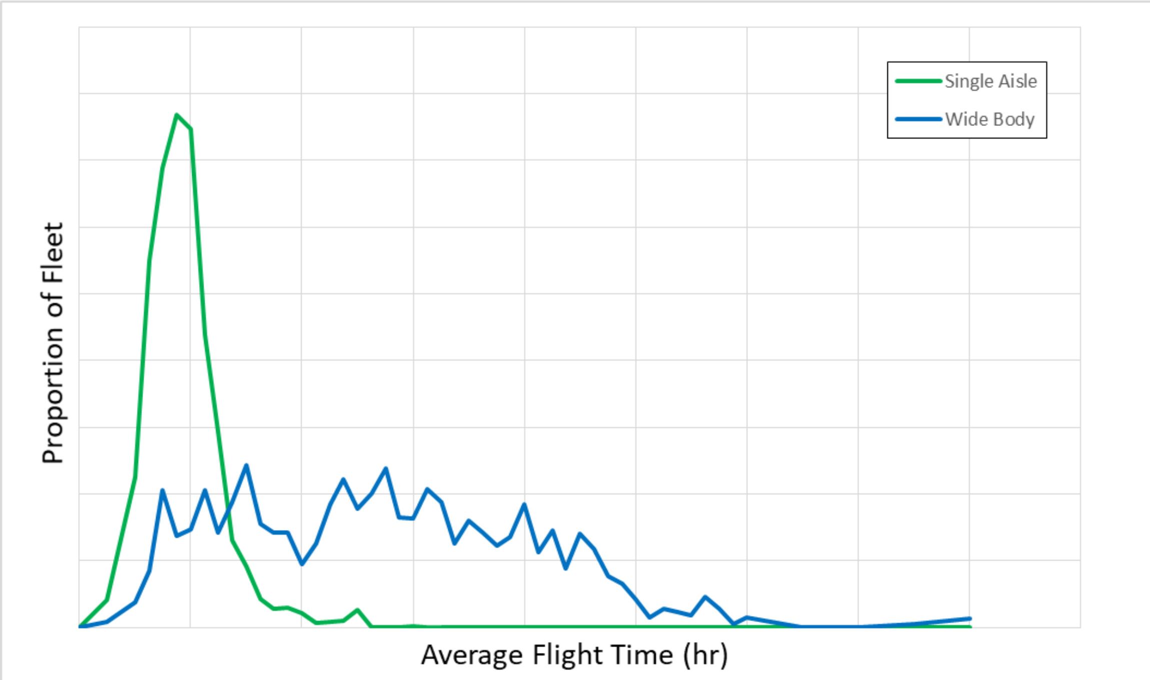

Figure 3 - Fleet operation for Single Aisle and Wide Body aircraft

Operational monitoring as part of A-SHM can reduce the conservatism in the usage as assumed to define the structural maintenance program, and can account for diversity of operations. It offers the possibility to adapt maintenance tasks to actual aircraft usage and delivers usage-optimized maintenance for individual aircraft, sub-fleet or complete fleet. It focuses mainly on metallic and hybrid airframe structures (including landing gears).

It is based on assessing aircraft parameters or stress measurement data to derive impact on fatigue damage accumulation. Dedicated load models or other methods using Artificial Intelligence can determine transfer functions to fatigue stresses. A Fatigue Digital Twin is the ultimate enabler, see figure 4. It is an on the ground/ off-board platform to collect and analyze the individual aircraft data for usage with connectivity to the engineering tools to recalculate the fatigue damage and resulting structural maintenance program.

Whatever solution chosen, the key is an efficient processing time for the many thousands hours of flight time. A fall back solution should be defined in case of missing or corrupted data, or significant change of usage.

Based on the same solution of the Fatigue Digital Twin for scheduled maintenance, the high load events can be monitored and assessed. Potential aircraft downtime can be avoided or reduced thanks to shorter lead-times for assessment, including data-transmission, performant calculations and if required, tailored inspection definition. Environmental monitoring can be used to further feed the fatigue and ageing assessments, also considering composites airframe structures.

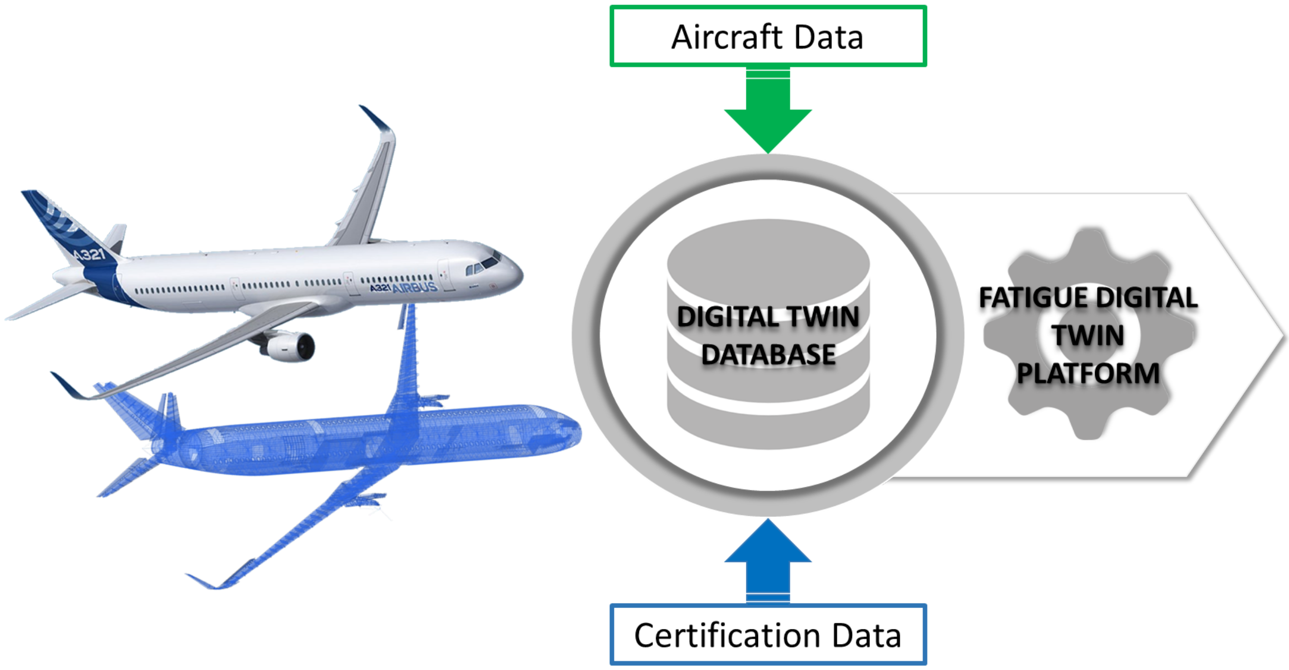

Figure 4 - Fatigue Digital Twin

4. Damage Monitoring

Damage monitoring is the second principal axis of A-SHM deployment. The main rationale for damage monitoring through sensor technology is reducing maintenance cost and increasing maintenance planning flexibility by avoiding difficult access areas and not using highly specialized tools and operators as for traditional Non Destructive Testing (NDT).

The damage monitoring sensors can be interrogated remotely, which is especially interesting in hidden areas. Nowadays' NDT inspections require preparation of the area and providing access for the inspector. This can be costly and laborious, e.g. cabin interior dismantling and removal, up to even wing fuel tank venting can be required. These efforts become obsolete when the inspection can be replaced by the damage monitoring sensors.

Damage Monitoring has to be applied on what are called hot spots:

- Likely points for fatigue crack initiation as for example stress concentrations, or monitoring failure of discrete load introduction elements, like struts, stiffening elements or brackets.
- Damage monitoring can be further deployed to monitor environmental damages from events such as corrosion, vibration induced cracks, lightning strikes
- Monitoring of accidental impact that can lead to damages such as scratches, dents, deformation or delamination.

Most important enabler is the sensing technology that is applied for specific use cases, and the automatic damage diagnostics either via the sensor or via specific algorithms to support the treatment of the data. Current state-of-the-art sensor technology with most potential for short term implementation are based on ultrasonic or eddy current technologies, or on optical fibers.

An aircraft manufacturer should not risk that airlines face aircraft grounding because of the sensors or aircraft systems failure. Therefore, any damage monitoring sensor that is applied on the airframe needs to be considered as a flying tool independent of aircraft systems, avoid being connected to any aircraft system, except for power-supply when needed, and with on-ground interrogation (see figure 5). An automatic diagnosis of the service state and auto calibration is to be executed before each interrogation.

In case of failures or doubtful indications from any sensors, a contra-expertise by a classical solution (NDT or visual) should be possible and planned at the appropriate timing. A-SHM solutions should not have a risk to compromise operational reliability, add new maintenance tasks, or significantly increase the time consumed by the users to operate them. They need to fulfil similar requirements and processes as current NDT tooling and aircraft system non-interferences. Airframe damage diagnostics should be delivered on-ground and offline to further reduce the dependency of aircraft systems.

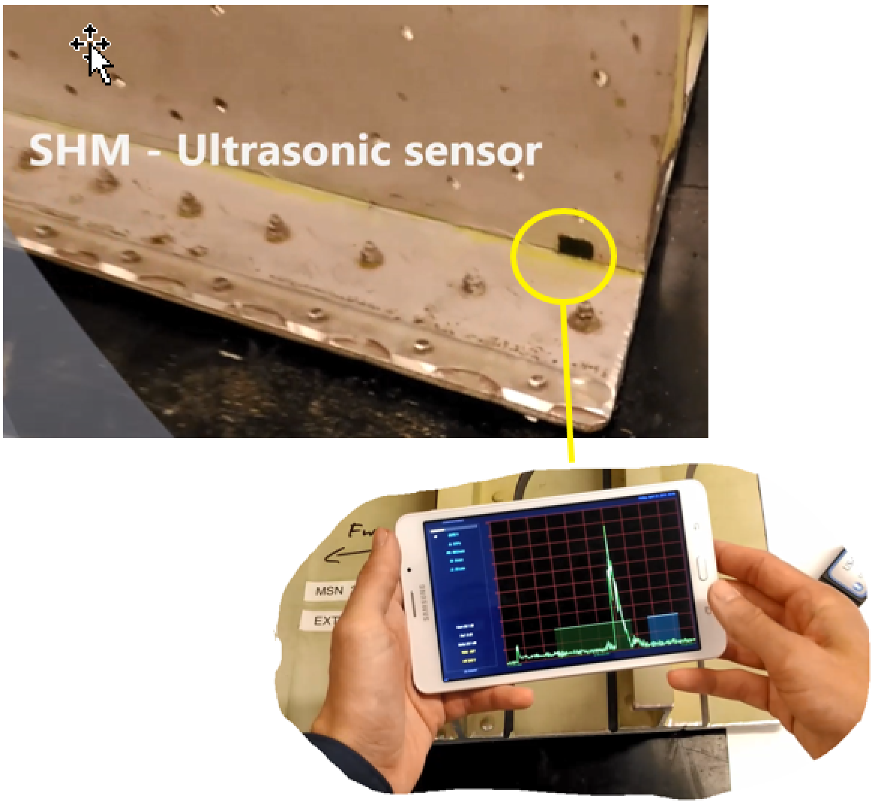

Figure 5 - Example of on-ground sensor interrogation

Demonstration of capability, reliability, durability and maintainability is key for successful implementation on aircraft structures. Sensing capability, signal transmission, and durability could be affected by the environmental conditions during long-term use and should be evaluated under typical airline operational conditions by proof of concept testing before full implementation.

A maintenance action should be initiated only when a damage or a potential failure is detected by the sensor after the damage is becoming measurable, and thus can be confirmed positively, while it is not impacting safety. This will ensure to only inspect the airframe structure when needed, and have a significant probability of findings. It leads to the question for how much time the operator is able to continue to fly after a damage has been detected before he needs to schedule a maintenance action. Therefore, the concept of a maintenance planning window needs to be introduced that provides for a safe period of operation justified by either crack propagation rate analysis or standardized periods based on existing inspection interval data, see figure 6. To mature and validate the technology during the first phase of the A-SHM deployment roadmap, a scheduled maintenance action will need be planned using traditional means even if the damage monitoring has not provided any identifications.

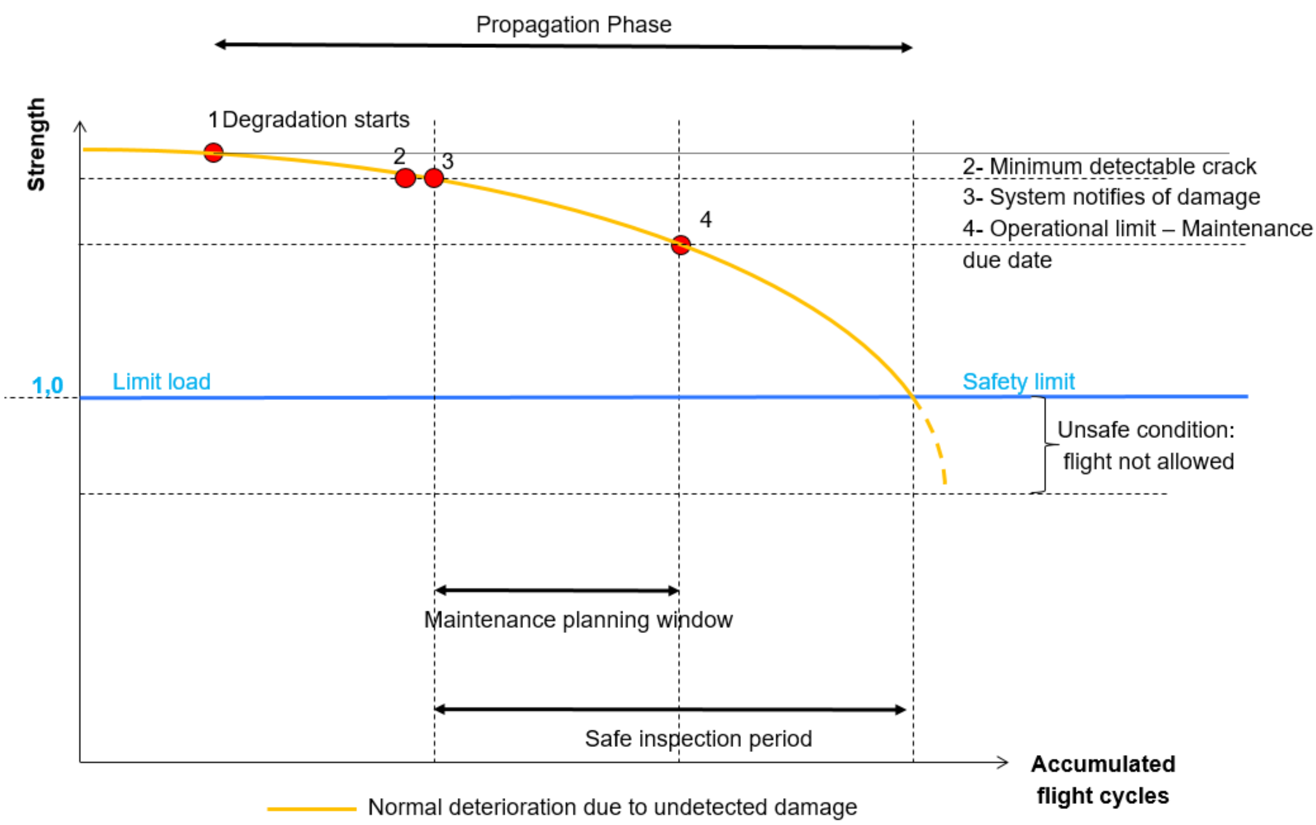

Figure 6 - Maintenance planning window

5. Qualification and Certification

Qualification processes are to be developed for the use of A-SHM solutions. Sensors should be qualified on sensing performance, such as damage detection reliability (capability), damage characterization, strain measurement, deformation measurements and durability. The qualification program should include the demonstration and evaluation by testing of the sensors and its installation conditions in expected working conditions related to the specific use case and respecting applicable industry standards (example [1]).

Focus for Operational Monitoring should be on the ground equipment regarding data integrity, the analysis algorithms, and the configuration control.

As the regulatory framework is existing for implementing A-SHM, the target should be to not impact the applicable certification regulations. Current regulations provide sufficient room to implement Operational Monitoring and Damage Monitoring, see [3] CS25.571 (a)3:

...*inspections or other procedures to be established, as necessary, to prevent catastrophic failure.*

Regulatory policies on flight with known cracks could imply repair before further flight if any damage indication is recorded by the system, even below the acceptable detection threshold. A change in philosophy is needed to take full credit of A-SHM, the allowable damage size determined by the aircraft manufacturer should drive the sensor damage trigger for any follow-up action, taking into account the concept of a maintenance planning window.

Efficient and acceptable means to incorporate A-SHM in the Instructions for Continued Airworthiness are to satisfy needs from Airworthiness Authorities, aircraft manufacturers and airlines. Sensing technologies for Damage Monitoring can be identified in maintenance tasks by the Scheduled-SHM (S–SHM) denominator following the Maintenance Steering Group 3 (MSG3) process. Customising inspection Thresholds and Intervals for mandatory inspection tasks in the Airworthiness Limitation Section (ALS) need to follow the aircraft manufacturers and regulatory processes to make it legally binding.

6. Conclusion

In order to have more efficient maintenance, reduce down time and optimise fleet operation, A-SHM targets progressive solutions with the final goal to offer CBM. This paper presents the key factors for the civil aircraft industry to progress with a successful implementation of A-SHM towards CBM. The ultimate target is to inspect airframes only when needed, based on individual aircraft usage and damage detection.

Any roadmap for A-SHM introduction should represent a step-by-step approach and put priority on A-SHM deployment. The A-SHM solutions should be progressively developed and implemented, starting with single task solutions to more integrated concepts. A-SHM deployment will be structured around 2 principal axes: Operational Monitoring and Damage Monitoring.

Operational Monitoring offers the possibility to adapt maintenance tasks to actual aircraft usage and delivers usage-optimized maintenance either for individual aircraft, sub-fleet or complete fleet. It is based on assessing aircraft parameters or stress measurement data to derive impact on fatigue damage accumulation. A Fatigue Digital Twin is the ultimate enabler, being an on the ground/ off-board platform to collect and analyze the aircraft data. Key is an efficient processing time for the many thousands hours of flight time. A fall back solution should be defined in case of missing or corrupted data, or significant change of usage.

Damage Monitoring is to be applied on hot spots. Most important enabler is the sensing technology selected for specific use cases, and the automatic damage diagnostics. Any sensors installed on the airframe should be considered as flying tools independent of aircraft systems, and should be interrogated and diagnosed on ground. An automatic diagnosis of the service state and auto calibration is to be executed before each interrogation. In case of failures or doubtful indications, a contra expertise by a classical solution (NDT or visual) should be possible. Qualification of capability, reliability, durability and maintainability under typical airline operational conditions is key for successful implementation.

Finally, the regulatory framework is existing for implementing A-SHM, however a change in policy is needed for flying with known cracks to be able to take full credit of A-SHM. Efficient and acceptable means need to be developed to incorporate A-SHM in the Instructions for Continued Airworthiness including the concept of a maintenance planning window.

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8. Copyright Statement

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