Route to Condition Based Maintenance in the Commercial Aviation Industry—Developments in Operational Monitoring

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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 structural Condition Based Maintenance. Enablers will be SHM-sensors, operational monitoring and automation. Collaboration will be key between aircraft manufacturers, operators, maintenance and repair organisations, airworthiness authorities, scientific institutes and the standardization bodies.

The development of operational monitoring will enable maintaining the airframes when needed, thanks to the knowledge of individual aircraft usage, data exploitation and digital twins.

This paper predominantly puts the focus on the operational monitoring aspect of Structural Health Monitoring.

OPERATIONAL MONITORING

In order to have more efficient maintenance, reduction of down time and optimization of 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 and engines, but has seen a slower uptake in application to civil aircraft structures.

In line with the definition of the SAE Aerospace Industry Steering Committee on Structural Health Monitoring and Management, AISC-SHM, Structural Health Monitoring can be subdivided in the two main categories [1]: Operational Monitoring and Damage Detection and Monitoring, as shown in Figure 1. This paper presents the key factors for the civil aircraft industry to progress with a successful implementation of operational monitoring towards CBM. In a peer Airbus article "Airbus strategy and use case for Airframe Structural Health Monitoring of aeronautical structures dedicated to damage detection assessment and damage monitoring", [2] the damage detection and damage monitoring aspects of A-SHM are described.

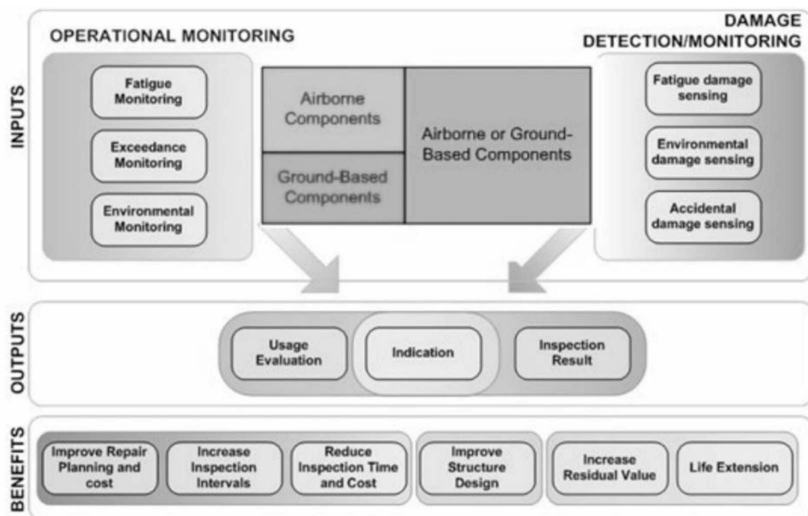

Figure 1. Structural Health Monitoring intended functions [1]

The development and deployment of any A-SHM solution within the commercial aviation industry should be driven by the following major values, maintaining the high level of safety of the aircraft industry:

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 aircraft operational availability:*

In addition to the downtime benefits created by the first value, 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 or hard landings, bird impact or other overload events. Potentially, A-SHM data can also be used to substantiate service life extensions that have an effect on the residual value of the aircraft or its components.

3. *Contribute to design improvement inducing weight saving:*

A major value can be achieved, 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 detection capability may reduce the need to account for scenarios with low likelihood of occurrence. A further step of damage detection will be the monitoring of the detected damage under aircraft operation. This can be supported by the knowledge of the usage of the concerned aircraft.

A-SHM developments follow a step-by-step approach offering intermediate solutions that can be retrofitted in the legacy and derivative fleet, targeting CBM as the final goal. 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 the airframes only when needed, based on individual aircraft usage and damage detection, taking into account the individual aircraft recorded airframe loading history.

INCREMENTAL DEVELOPMENT OF OPERATIONAL MONITORING

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 cases.

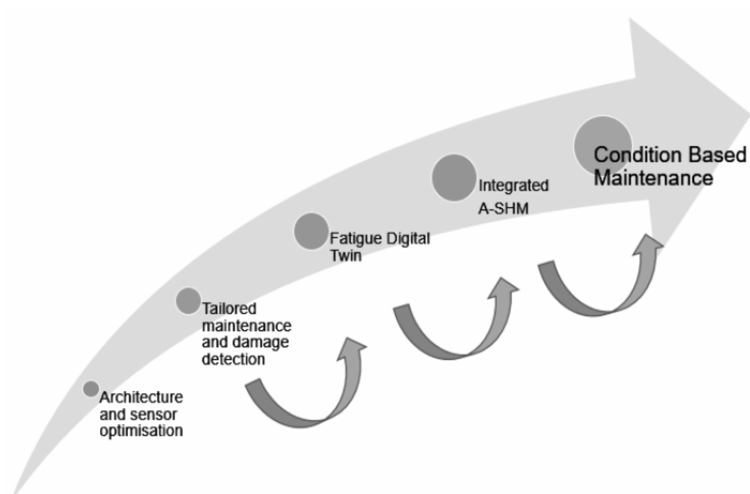

Figure 2. A-SHM step-by-step introduction [3]

As described earlier in the paper "SHM – Route to Condition Based Maintenance" [3], 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 operational monitoring using a limited number of aircraft parameter,
- Predictive maintenance using aircraft specific fatigue spectrum and fatigue damage analysis using a 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. Furthermore, the development should be accompanied by demonstration of value for the airlines.

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:

- 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. This becomes specifically relevant for hybrid structures in airframes, subjected to temperature-induced loading, due to the difference in coefficients of thermal expansion (CTE) of the combined materials.

ENABLERS FOR OPERATIONAL MONITORING

In this section the different prerequisites that will enable operational monitoring are described.

Variation in utilization

Today's maintenance is identical for every aircraft of the same configuration, regardless of its utilization. On the one hand, the utilization of the different individual aircraft of the same configuration may differ significantly in terms of flight time, weight parameters (e.g. payload, fuel, Operating Weight Empty, center of gravity); aircraft are also flown under different weather conditions, runways with different surface roughness, different taxi times etc. The defined maintenance program will conservatively cover these differences in utilization. On the other hand, the damage accumulation from aircraft to aircraft may differ based on their utilization.

Consequently, operational monitoring has the potential to leverage this difference into, for instance, an optimised maintenance for an individual aircraft or subfleet of aircraft.

Infrastructure

Existing onboard sensors, currently recording aircraft parameters, are typically sufficient as operational monitoring inputs to derive the loading condition of the aircraft. The sensors provide information on static conditions like weight, wing configuration and dynamic behaviour like angle of attack and accelerations. As shown in Figure 3, the number of parameters that are recorded onboard had a significant evolution from the first Airbus A300 with less than 100 parameters up to 3,500 parameters for the A350 [4]. These parameters are constantly recorded with a sampling rate that can differ from one parameter to another. This data provides a tremendous potential when used for predictive maintenance, tackling unscheduled and scheduled maintenance.

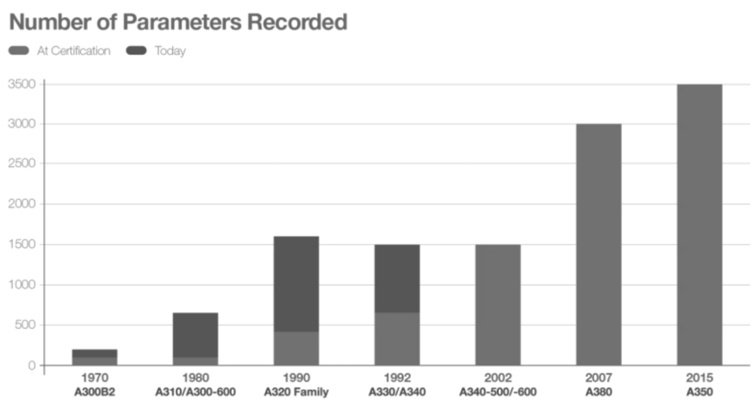

Figure 3. Evolution of number of recorded onboard signals on civil Airbus aircraft [4]

Another evolution is the development of FOMAX, which includes the step of automated transmission of the recorded parameter to the ground station. FOMAX, the “Ground Flight Operations & Maintenance Exchanger” [5], co-developed with Rockwell Collins, is an on-board connectivity solution which enables airlines to collect aircraft maintenance and performance data on-board the aircraft and automatically transmit it to the ground-based systems, at a higher speed than previously possible, and in near-real-time.

Since 2017 Airbus has been pioneering the digital transformation developing the data-hosting and data-analytics platform Skywise Core [X] [6]. With Skywise Core [X], airlines can embrace a data-driven strategy with features, tools and services that bring more rapidity and efficiency in decision-making, which, eventually, can become the platform for airframe operational monitoring.

IT Developments

Operational monitoring can become increasingly data-intensive, depending on the inputs that are required to evaluate the utilization of the aircraft. Emerging technologies like cloud computing unlock upscaling that was not possible before, and become more interesting for data processing that is needed for operational monitoring.

A completely automated processing can be achieved by the application of FOMAX, Skywise Core and cloud infrastructure so that the computation of consumed fatigue life starts shortly after arrival of the aircraft at the gate. The cloud implementation enables the processing of multiple flights in parallel while the data pipelines are monitored via a workflow management platform. The centralized handling of the flights enables the monitoring of individual MSNs as well as on a fleet level for the individual airlines. This way a cross check of flights with an untypical fatigue estimation can be performed at any time starting at stress level and going over the loads to the underlying sensor readings.

Artificial Intelligence

The digital continuity is fundamental to support Conditional Based Maintenance. This requires having a digital thread supported by data structuration relying on data models and ontologies. There shall be a consistency for this data backbone across the full airframe lifecycle to be in position to perform feedback loops. These feedback loops enable to resolve in-service issues, to adapt the maintenance to the individual aircraft and even to take into account more realistic requirements at design level.

For A-SHM operational monitoring the usage of machine learning to build so-called surrogate models is the obvious choice. They enable performing the requested structural analyses in a very reduced time to answer the customer. This aspect is also addressed by a scalable cloud solution but surrogate modelling allows to further reduce the computation time and consequently to obtain the results at lower costs. These models are extensively used for both loads and structure analyses in the Airbus internal studies [7, 8], exploring the individualizing of scheduled and unscheduled airframe maintenance. They enable exporting these simulation capabilities to the airlines and MRO's as autonomous services to support decision-making. An example is evaluation of non-standard landing-related events, where ground load conditions are derived from flight parameters at airline premises accelerating the diagnosis for these events and supporting decisions on actions that are needed to dispatch the aircraft [9]. These surrogate models can even be considered as embedded devices working as virtual sensors [10, 11].

Application of generative AI and especially Large Language Models can also be used to automatically generate inspection reports linking directly to the information system of the aircraft manufacturer and accelerating the engineering responses.

Engineering Data

As already described in the article "Aircraft Fatigue Analysis in the Digital Age" [7], engineering data that are generated during the development process, the certification, the aircraft production and in-service maintenance, implies important potential for improving structural maintenance, when the right data are linked, eventually creating a digital twin. As described in [12], digital twins are the key ingredient of the digital transformation that is taking place in the aerospace industry:

"This involves making all information about our aircraft, their production, and maintenance systems readily accessible in digital form, using precise descriptions of their functions and behaviour. Once an aircraft is in service, its digital twin continues to evolve, providing invaluable insights for maintenance and operations."

Collaboration

From the writing above, it becomes obvious that the development of operational monitoring is a multi-functional activity, where airlines, authorities, OEM's and standardization bodies need to collaborate. Only this collaboration, for instance the SAE Working Group for AISC-SHM, will leverage the potential and find the "low-hanging fruits" of maintenance cost reduction, eased aircraft operation and spare stock reduction.

OPERATIONAL MONITORING CHALLENGES

Certification

The applicable regulations for Airbus transport aircraft are given in the CS25. In the relevant paragraphs following is said about the assumptions for the aircraft's utilization and environment [13]:

CS25.571(a):
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 5. CS25 Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes - extracts for fatigue utilization and environment [13]

There is no blocking point seen from the CS25 paragraphs, but the way to qualify and certify operational monitoring as a new application needs to be defined and agreed with airworthiness authorities. Because of the specifics, they might deserve a specific Means of Compliance approach that needs to be agreed and formalised; this needs to be assessed on a case-by-case basis.

The certification process is designed for updates of the worldwide fleet - one fits all. It is expected that this maintenance setting will evolve to a more dynamic mode, and where it is possible, maintenance will be defined down to an individual aircraft level. For tackling these aspects, Airbus is active in standardization groups, and proactive in approaching airworthiness authorities, potentially in the scope of innovative contracts anticipating formal certification project applications.

Artificial Intelligence

Artificial intelligence solutions require careful verification & validation for qualification or certification, regardless whether they are part of internal processes, or when embedded and delivered to external stakeholders, like airlines or MRO's.

A specific approach is necessary because AI solutions are generally based on data and as such cannot be verified in a deterministic way. Therefore, the AI performance requirements have to be derived from a Quantitative Safety Assessment conducted from the global system level. And the AI constituent has to be safeguarded from wrong usage and monitored in operations to prevent any drift in its design assumptions.

This non-deterministic V&V process [14] requires specific standards beyond DO178C or ARP4754B [15] that are dedicated to classical embedded software and systems. This is the purpose of the ARP6983 [16] under construction and of the provisional EASA Concept Paper [17].

End-to-end data integrity

End-to-end data integrity is key to ensure a safety relevant application, like scheduled maintenance that will be optimized by means of operational monitoring. The end-to-end data chain needs to be evaluated from the onboard measurements and data acquisition, download, storage and any data manipulation or processing, up to optimized maintenance definition and execution. Important will be that the data processing will be done offboard by a ground system handed by the aircraft manufacturer that can link the parameter to the engineering data, models and methodologies as used for the Type Certification by the aircraft manufacturer.

IT performance

The data volume may be significant, depending on the level of detail of the selected solution for operational monitoring. Consequently, the data processing can be very demanding for the IT infrastructure and can involve considerable recurrent cost and processing time. Future technological developments that are scalable, ensure cybersecurity and involve use of cloud computing services may be exploited.

Aircraft Individual Maintenance planning,

Changing from a worldwide fleet scheduled maintenance definition for structures towards an aircraft individual maintenance will enable reduction of direct maintenance cost for the airlines. On the other hand, it means that the way the maintenance planning is done, needs to evolve and become more flexible, more digital, ultimately, to harvest these low-hanging fruits to have easy reductions.

Furthermore, the business case for the airline will be part of the evaluation, e.g. some aircraft utilizations will lead to more savings than other utilizations.

CONCLUSIONS

Operational monitoring is one of the key ingredients for a more efficient scheduled maintenance for structures and reduce down time and optimize the fleet operation. It offers the possibility to customize the maintenance tasks to the utilization of the individual aircraft, assessing the parameters that are recorded onboard of the aircraft.

The regulatory framework is existing for A-SHM implementation. Efficient and acceptable means need to be developed to incorporate A-SHM in the Instructions of Continued Airworthiness.

The outlook is that Fatigue Digital Twins will be a key ingredient, defining the fatigue status of the individual aircraft.

Efficiency in the overall process will be important to obtain a viable solution.

Ultimately, the implementation of operational monitoring will unlock the possibility of going towards Condition Based Maintenance of structures.

Figure 6. Digital Twins: Accelerating aerospace innovation from design to operations [12]

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