# Structural Health Monitoring –The Key Enabler of Condition Based Maintenance in Aviation

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## ABSTRACT

The Advisory Council for Aeronautical Research in Europe (ACARE) envisages that, by 2050, all new aircraft will be designed for condition-based maintenance (CBM). This will result in a significant 40% reduction in Maintenance Repair & Overhaul (MRO) process time and costs, increase in aircraft availability, and maximization of asset utilization. The backbone of CBM is the continuous monitoring of the aircraft performance utilizing permanently installed sensors. Naturally, Structural Health Monitoring (SHM) plays an essential role on the successful implementation of CBM as it provides the needed information for structural assessment of critical aircraft structures.

This paper discusses how SHM fits into the framework of CBM and highlights the results of the European project *ReMAP – Real-time CBM for adaptive Aircraft Maintenance Planning*. More specifically, the consortium efforts for multi-sensing SHM system integration, data synchronization and information fusion will be presented, while emphasis will be given into the conceptual design of a SHM system that is capable of damage anomaly detection, global location identification, damage type assessment, damage severity and prognostics. Innovative data-driven machine-learning algorithms were developed during the project which enabled health diagnostics and prognostics tasks of primary structures using data collected during tests at lower structural levels. This talk will demonstrate that hierarchical testing of SHM systems and scale-up approaches are a key for putting SHM into practice and for making steps towards CBM.


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## INTRODUCTION

Aerospace structures degrade inevitable over the period of the aircraft's operational time and to mitigate the risk of failure, rigorous inspections, under the umbrella of the Maintenance Repair & Overhaul (MRO) process, are in place. However, the procedure of the inspections is far from optimized resulting to high costs for the airlines. Inspired by nature, Structural Health Monitoring (SHM) allows continuous monitoring of the structure, utilizing data from permanently installed sensors for structural integrity analysis. SHM has the potential to be a game-changer and enable MRO to enter to the condition-based maintenance (CBM) era. Figure 1 presents the five technology blocks as proposed by the consortium of the European Horizon2020 research & innovation program ReMAP (Real-time Condition-based maintenance for adaptive aircraft maintenance planning) [1]. The five blocks consist of data acquisition, data collection-storage-processing, systems prognostics, structures prognostics and decision support tools. SHM is an essential element of this chain as it provides the needed data and information for optimizing the decision making regarding the type and time of the maintenance and repair actions.

This paper discusses how SHM fits into the framework of CBM and highlights some of the results obtained during the duration of the project, 2018-2022. More specifically, the consortium efforts for multi-sensing SHM system integration, data synchronization and information fusion will be presented, while emphasis will be given into the conceptual design of a SHM system that is capable of damage anomaly detection, global location identification, damage type assessment, damage severity and prognostics. Innovative data-driven machine-learning algorithms were developed during the project which enabled health diagnostics and prognostics tasks of primary structures using data collected during tests at lower structural levels. This talk will demonstrate that hierarchical testing of SHM systems and scale-up approaches are a key for putting SHM into practice and for making steps towards CBM.

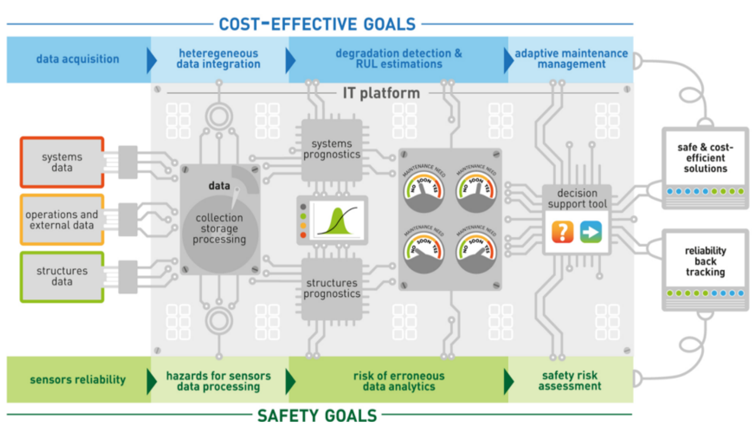

Figure 1. Real-time Condition-based maintenance for adaptive aircraft maintenance planning [1].

## STRUCTURAL HEALTH MONITORING HIERARCHY

Structural Health Monitoring aims to answer the four following questions; I) if there is damage II) where its location is III) what type of damage has occurred and IV) its severity. Over the last three decades, these questions have been treated separately where researchers and engineers put emphasis on developing sensing technologies and algorithms to develop efficient and robust methodologies. Significant results have been obtained, which led to mature technological solutions ready for a variety of industries including aviation. However, these solutions cannot cover the entire hierarchy of SHM, especially when considering polymer composite and hybrid structures. A characteristic example is the acoustic emission (AE) technique. AE is extensively used to differentiate the type of damages (question III), i.e. matrix cracking, fibre breakage, delamination. Researchers used mainly coupon size specimens and they tested them under monotonic quasistatic, Loading-Unloading-Reloading and fatigue scenarios [2]. Furthermore, AE has been proven valuable to locate damage positions when applied to a structure (a level bigger in size from a coupon), but the technique is weak to provide information about the severity of the damage, i.e. the size. Other SHM techniques may have similar performance as they fail to answer all the four questions.

Furthermore, as SHM is part of CBM, its capabilities should be extended towards the field of prognostics where predictions about the remaining useful properties, i.e. strength, stiffness, life, should be provided [3]. Overall, SHM should be able to answer the four questions, under the regime of diagnostics, and provide data for predictions, under the regime of prognostics. One main outcome of the research performed during ReMAP project was the proposal of a SHM pyramid approach, figure 2. The concept is inspired by the well-established building-block-approach, that consists of coupons at the bottom level and the complexity of structural elements increases as we move towards higher levels. The pyramid describes a strategy in which many tests are performed on the lower levels involving generic elements and fewer tests are performed on higher levels involving non-generic components and full-scale structures (e.g., a wing structure). In a similar manner, the developed SHM methodologies and results obtained at lower structural level should be translatable and representative of its application on higher structural levels. We aimed at developing methodologies on the lower levels in laboratories using large sample sizes and at applying these to the higher levels under in-service scenarios with minimal re-development. This can be done by defining homogeneous populations on single levels and heterogeneous populations comprising multiple levels, see also these examples [4-6].

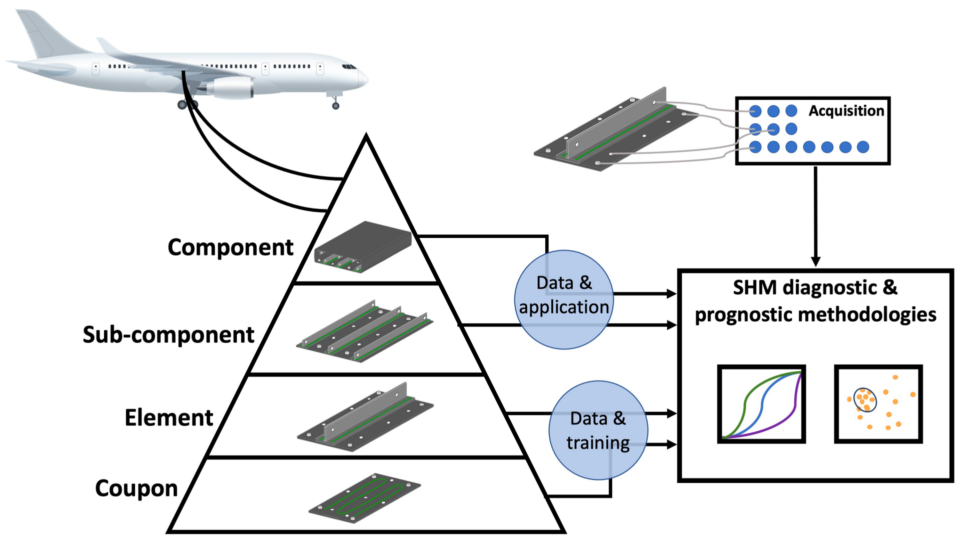


Figure 2. Structural health monitoring (SHM) pyramid approach for upscaling composite aircraft structures based on the building-block approach for structural testing [7].

## STRUCTURAL HEALTH MONITORING SYSTEM INTEGRATION

When it comes to the monitoring of an entire structural component, aiming to assess its structural integrity, the four questions should be answered subsequently. Thus, there is a need to integrate different sensing technologies, in other words to perform multi-sensor data fusion. A multi-stiffener composite panel, as a generic representation of a realistic composite aircraft wing structure, was the case study for the ReMAP project, see figure 3. As part of the full aircraft structure during operation, these types of structures experience fatigue loads and changes in environmental conditions including humidity and temperature changes. For these types of composite wing components, critical in-service damage cases are skin–stiffener debonding, as well as unexpected foreign-object impact damages such as tool drops and weather events.

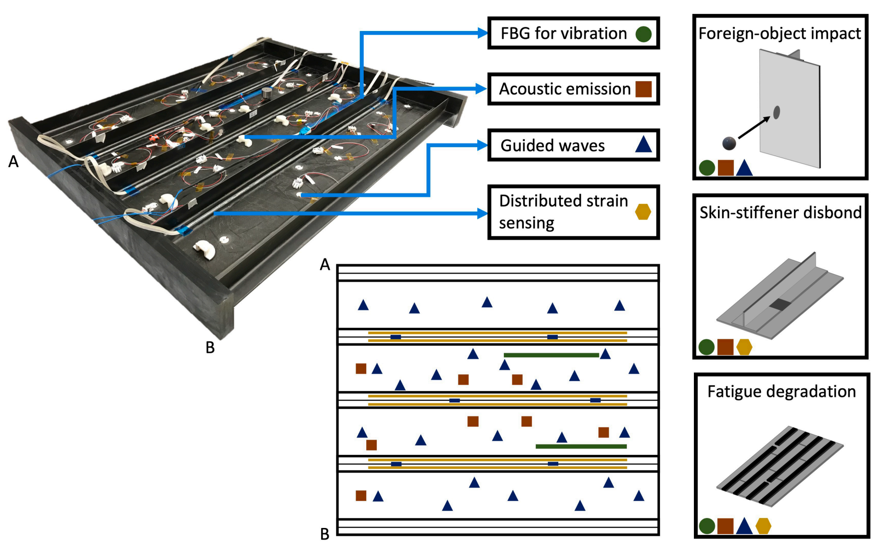


Figure 3. Multi-stiffener composite panel sensorized with multiple SHM techniques as part of a

multi-sensor data-fusion-based framework for SHM of aircraft structures [7].

For the considered case study, we have designed a conceptual SHM framework, that is capable of assessing all four diagnostic levels and provide predictions. It employs sensor data from four different SHM techniques, namely, (1) vibration-based method, (2) AE, (3) Guided-waves (GW), and (4) distributed strain sensing, see figure 3. Combined, the four sensing techniques are capable of providing a complete image of the damage state of the considered structure as prescribed by the requirements of the aircraft structural health management system. Here, multi-sensor data fusion is the key: each technique provides different information that, when combined, leads to a complete damage assessment within the structure. The general steps to obtain a full image of the damage state, following the procedure depicted in Figure 4, are described next.

## Anomaly Detection

The first step in the proposed SHM system is to detect anomalies using a vibration-based method. In Figure 4, this is shown on the top left of the framework. Such a first step is required to decide on the needs for further, more detailed, analysis: only if there are signs of damage, there is an interest in performing further inspection steps as part of the maintenance procedure. In our case, anomalies are detected using FBGs by subjecting the structure to vibrations. In a laboratory setting, such vibrations are artificially induced using an actuator. However, during service, the natural vibrations of the aircraft, for example, those caused when starting the engines, can be exploited to assess the full wing structure. The measurements during these vibrations are compared to initially made baseline measurements, and significant changes in the structural response can be an indication of the presence of damage. Due to the inherent nature of this technique, it will solely provide an indication, and for more details on the potentially present damage, additional SHM techniques are required, as discussed next.

## Global Damage Location

Only when an anomaly is detected using the vibration-based technique, it is necessary to consider in more detail the damage characteristics, including where the damage is located, the identification of the damage type, and how severe the damage is. On the other hand, if no damage is detected, no unnecessary further inspections are required. If damage is detected and a larg component is under consideration, such as in our case study, it is of importance to obtain a global indication of the damage location. A multitude of sensors are attached to the structure (e.g., multiple OF sensors for strain measurements and PZTs for GW assessment), and it is required to know which sensor measurements should be employed for further damage analysis to avoid unnecessary evaluations of undamaged regions and to minimize the size of the collected datasets. In a full-scale aircraft application, one might also consider this as first identifying the damaged (sub)component in the full aircraft structure before more in-depth investigation. In our framework, the damage localization is performed using AE measurements that can be used to provide a global location of the damage, thereby allowing for the selection of the appropriate sensor in the damaged region for follow-up analyses. This can be combined with an AE damage classification step in which the type of damage is identified being, in this case, either damage to the skin or skin–stiffener disbond, there by obtaining knowledge on both diagnostic level 2 (localization) and level 3 (type identification). Subsequently, this information can be employed to select the appropriate next step in the SHM framework.

**Detailed damage assessment: Skin damage and disbond**

In the next step, after identifying and approximately localizing the damage in the structure, the appropriate techniques and sensors can be selected for a close-up assessment. On the one hand, in case the damage is classified as being skin damage, the GW technique can be activated to perform a scan using guided ultrasonic waves and thereby detect, localize, and size the damage in the skin. On the other hand, in case the damage is classified as a skin–stiffener disbond, fiber optic strain measurements (OF sensors are located along the stiffener foot) are employed to more precisely localize the disbond and provide a size estimate. There is also a possibility of a combined case: namely, an impact occurring near one of the stiffener locations resulting in both skin damage and skin–stiffener disbond. In the latter case, a fusion of both techniques is required: where the OF sensors provide skin–stiffener disbond assessment, they will miss any damage present in the skin farther from the stiffener. The latter will require a GW assessment. Hence, for a complete impact damage assessment in such cases, a fusion of GW and OF data results is required for impact damage localization and sizing. As such, incorporating both GW and OF measurements in the SHM system allows for the collection of detailed characteristics of the propagating damage.

**Damage Severity**

The penultimate step assesses diagnostic level 4 'damage severity' in which the severity of the damage state of the structure is estimated and, thus, so is its influence on the structural integrity state of the given aircraft component. For this indication of the damage state in our case study, measurement data of the AE, GW, and OF sensors is fused on a feature level to form a new HI. Here, it is hypothesized that a feature-level fusion will lead to a new feature that is more sensitive to damage than a feature extracted from a single type measurement. As each technique assesses a different aspect of the structural damage state, a fusion will allow a full inclusion in the severity assessment. Furthermore, its fusion can result in greater confidence in our diagnostic severity assessment. The advantages of a feature-level fusion into a HI have already been discussed by Broer et al. [8], Eleftheroglou et al. [9], and Galanopoulos et al. [10].

**Prognostics**

After assessing all diagnostic levels and now having a full image of the damage state in the aircraft structure, a CBM approach requires the following indication: 'if this is the current damage in the composite component and it is continued to be used during operation of the aircraft, what is its RUL?' Note that here, RUL is provided with respect to a predetermined state: for example, this state can be a final failure, a given degradation state, or a preset damage size. As input to a prognostic model, HIs can be used, either similar tothose used for damage severity or specifically designed for prognostics. For prognostics, the HIs have to fulfill three characteristics, namely, monotonicity, prognosability, and trendability [9]. Similar to the HI of level 4, we hypothesize that a fusion of all three SHM techniques (AE, GW, OF) will allow for an improved and more complete assessment of the health state with enhanced RUL estimates. The RUL estimate can then be used within the aircraft health management system for informed decisions on the need for any further maintenance actions such as repair or replacement, as well as cost-friendly and risk-free scheduling of such maintenance activities.

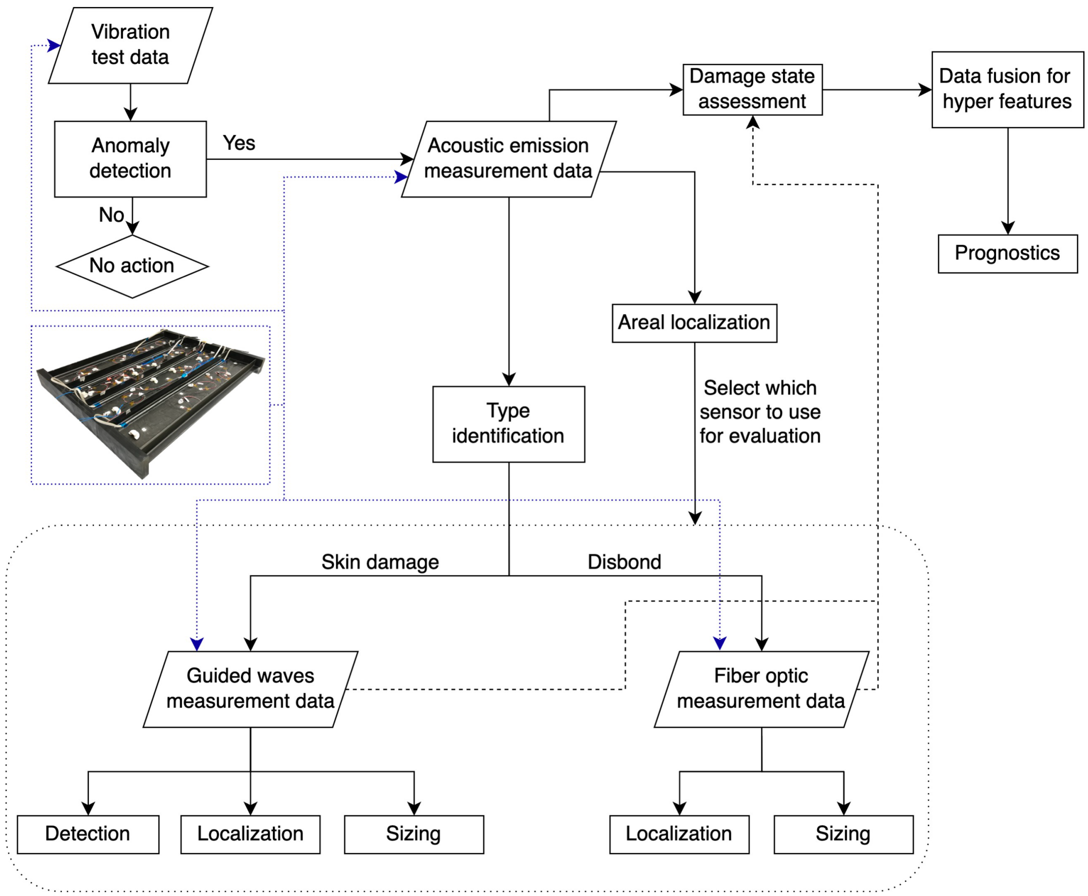


Figure 4. Conceptual SHM framework design for the damage monitoring of a generic representative composite aircraft wing structure [6].

## ACKNOWLEDGEMENT

This research was funded by the European Union's Horizon 2020 research and innovation program under grant number 769288. Furthermore, the author would like to express his gratitude towards Prof. Bruno Santos and Prof. Theodoros Loutas.

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