

Airbus Strategy and Use Case for Airframe Structural Health Monitoring of Aeronautical Structures Dedicated to Damage Detection Assessment and Damage Monitoring

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ABSTRACT

Airbus is engaged in the development of Structural Health Monitoring solutions to reduce maintenance costs. SHM solutions for damage detection are particularly under investigation as alternatives to “classical” NDT tasks, to alleviate the maintenance burden.

These damage detection systems are intended to be installed on the aircraft and interrogated at dedicated checks in the life of the aircraft. Such configurations can be seen as an “NDT-in-situ” SHM approach, where the NDT Probe is permanently installed.

In the case presented here, a damage detection and monitoring performance demonstration shall be performed to ensure the detection performances and measurement accuracy of the SHM solution along the life of the aircraft, thus including the effects of environmental and mechanical ageing.

The Probability of Detection study applied to SHM solutions dedicated to damage detection will be detailed including the method for identification of all variables which could influence the detection sensitivity. The function describing the crack length measurement accuracy beyond detection capability is introduced.

In this presentation the performance demonstration approach developed at Airbus will be presented, as well as results obtained on a specific use case. The first part of the presentation will show the qualification process developed for this purpose, including how the effects of sensor aging are considered with respect to probability of detection and accuracy of measurement. In the second part of the presentation, one use case application will be presented. It will be explained how SHM sensors are expected to replace classical NDT tasks and to avoid heavy maintenance operations for accessing the area to be inspected with classical NDT methods.

Finally, the last part will focus on the value of embedded SHM sensors on aeronautical structures: the damage monitoring. The requirements associated with this use case will be detailed and Airbus methodology for demonstrating its capabilities through the test plan.

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INTRODUCTION

Airbus is engaged in the development of Structural Health Monitoring solutions to reduce maintenance costs for customers. As a first step, SHM solutions for damage detection are particularly under investigation as alternatives to “classical” Non Destructive Testing (NDT) tasks. Airbus has a large experience in usage of SHM for damage detection in test activities and developed SHM sensors, but the usage of SHM on Airbus aircraft is very limited.

Different use cases for supporting aircraft maintenance have been investigated for several years. In parallel, maturities of SHM technologies are evaluated. From the R&T scope some specific technologies are developed and could be deployed in the coming months or years on Airbus aircrafts.

Then the SHM sensor technologies are not the only key drivers for supporting the Airbus use cases. Indeed their qualification as alternative NDT solution needs to be performed in regards with specific processes. Airbus is involved and supported development of guidelines like ARP6821 [1] to describe methodologies which will permit to demonstrate damage detection capabilities of SHM systems.

In this presentation the performance demonstration approach developed at Airbus will be presented, as well as preliminary results obtained on a specific use case. The first part of the presentation will show the qualification process developed for this purpose, including how the effects of sensor aging are considered with respect to probability of detection and accuracy of measurement.

SPECIFIC USE CASE

For this specific use case, the inspection of frame 47 on A300-600 aircraft is considered as a good candidate. This Airbus project aims to replace the current NDT ultrasonic inspection by a SHM ultrasonic phased array sensor based on sol-gel technology. This technology is developed by E2sense inc, and the SHM sensor is designed to be applicable to Frame 47 design characteristics.

From 90's the FR47 forward fitting upper radius is required to be inspected per Service Bulletin 53-6029 to detect and monitor crack up to 50 mm. The inspection interval depends on the crack length measured by NDT inspectors. The SHM solution developed by Airbus targets a crack length to be characterized greater than 30 mm when the inspection interval is the shortest. At this level, the airlines need to perform the inspection task more frequently and maintenance operations associated with it can be a burden.

The SHM solution will alleviate all the maintenance operations requested for accessing the area to be inspected. In order to be deployable, Airbus needs to demonstrate the capability of the technology in terms of detection and crack sizing.

The inspections requirements are the following ones:

- part to be inspected: Frame 47 forward fitting
- 2 types of crack to be detected

- the crack length to be detected ($a_{90/95}$) and characterized is located between 15mm and 50 mm

In addition

- the SHM solution needs to be capable of monitoring the crack length with an accuracy of 2 mm as the crack grows
- the SHM solution needs to sustain the environmental and durability conditions in this specific area of the aircraft, be durable to environmental criteria specific to the installation area

PERFORMANCE DEMONSTRATION APPROACH

Airbus has been heavily involved in the redaction of the ARP 6821 [1] describing recommended practices for the determination of detection capability performances of SHM systems, leading to the establishment of POD data for SHM applications. In this standard document, several statistical approaches are proposed to demonstrate the probability of detection of SHM solutions aiming at detecting damages.

The candidate methods are

- 29/29 Point-Estimate Method
- Size of Deterioration at Detection (SODAD) Method to Compute POD
- Random Parameter Generalization of the \hat{a} Versus a Signal-Response Model,
- or the well known Berens method described in the MIL-HDBK 1823 for NDT.

All these statistical approaches need specific cautions in their implementation in order to encompass the specificity of the SHM application. The design of experiments is of first importance to ensure that the main influential variability sources are well taken into account.

DESIGN OF EXPERIMENTS (DoE)

The test program shall allow to cover the main influential variability sources.

For this, a careful engineering analysis together with some experimental tests are first used to identify the variability sources and understand the extent of their influence in their respective ranges of variability.

For the use case described in this presentation, the identified variability sources are:

- crack: initiation site, propagation profile
- sensor installation
- sensor to sensor variability: variability on the sensors due to the manufacturing process (frequency, sensitivity)
- interrogation: initial calibration, repetitive calibration, signal interpretation
- environmental factors and durability: influence of these on the sensor capability

Once variability sources are understood, they need to be integrated in a design of experiments, with the intent to be able to calculate a POD out of the tests.

At this point in time, the choice of a statistical approach for the POD comes into play, as it will influence the definition of the tests to be performed.

In the case reported in this paper, the main question mark isn't really the size of the damage that can be detected but whether or not the SHM solution will allow it to detect all configurations of defects of 15 millimeters or more. It means that, in terms of detection, the variable "crack size" is not really our main point of interest. This can be said since it is obvious from engineering judgment that a larger crack will be more easily detected than a similar crack of a lower size.

In this type of cases, the point-estimate approach (so-called 29/29) is of good interest as it provides a cost efficient way to demonstrate, by test, that the SHM (or NDT) solution allows to detect with at least 90% POD with 95% confidence the crack length under test.

The 29/29 approach also has the advantage of allowing to apply environmental and durability tests after the initial POD campaign on the same test coupons, thus demonstrating the complete set of variability sources (if tests are successful), or identifying the degradations and limitations (if any) associated with durability.

The objective is then to design 29 tests covering the main variability sources that will be applied to validate the POD.

Using simulation to optimize the DoE

Considering the multi-dimensionality of the variability sources in this case, we have made use of simulation to optimize the Design of Experiments (DoE) and focus experimental trials on the configurations which are identified as limit cases.

The CIVA software is used both to optimize the sensor design and to identify the limit cases in terms of detection with respect to the initiation sites. From the simulation results we have gained confidence in the fact that all crack types ($\geq 15\text{mm}$) could be detected along the upper radius, as requested by the stress analysis department (Figure 1). The results also show that the most difficult case in terms of detection is for the crack at the lowest position in the radius. From the simulations we conclude that if we produce representative coupons with cracks at the highest angle, lowest angle and medium angle position, then the design space is well covered.

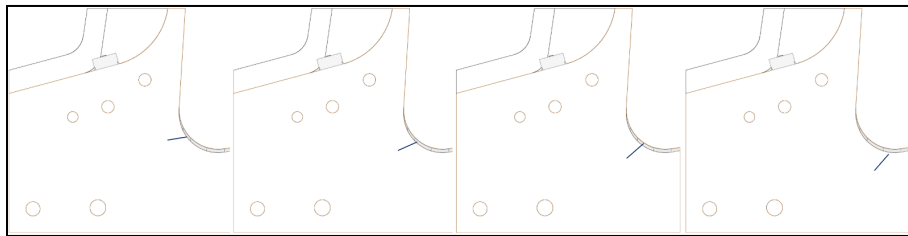


Figure 1. POD specimens with different artificial defects location

Indeed the crack signatures vary continuously from one crack position to the other as demonstrated below with CIVA modelization.

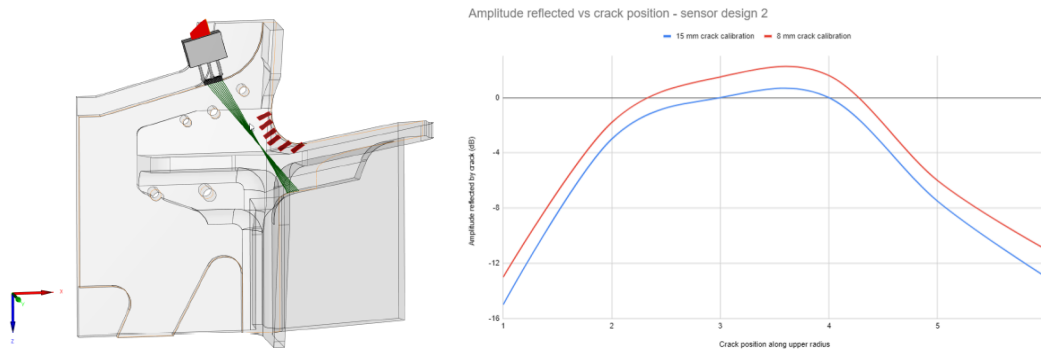


Figure 2. Modelization: Signal amplitude reflected with different artificial defects location

This preliminary analysis enables us to reduce the number of representative coupons to 8, and then introduce the other variability sources in the design of experiments.

The position of the sensor along the flange has also been simulated in CIVA to understand the acceptable tolerance on the positioning of the sensor, and led to the development of an installation tooling.

Probability of detection

The 29/29, Point-Estimate Method is based on the properties of the binomial probability law (experiments with 2 issues-hit or miss).

If 29 applications of a given inspection process on defects of the same size results in 29 successful detections, then the inspection process demonstrated a POD of 90% with a confidence of 95% (binomial law properties)

Notice:

- if 1 miss is observed a ratio of detection 45/46 trials is required to demonstrate the same probability and confidence
- 2 misses \Rightarrow 59/61
- 3 misses \Rightarrow 73/76

Also important to notice that the following conditions must be met to apply a 29/29 approach

- The DoE shall cover the most influential variables of the inspection process within the defined number of trials.
- The inspection results of the test campaign shall be statistically independent from the others.
- All trials shall be done with defects of the same size a or with defects of size lower or equal to a. In the latter case, the validation shall also include the demonstration that when the defect is larger the detection is better, which is often but not always the case.

In this case the targeted crack size is 15mm.

The environmental and durability factors are decoupled from the initial design of experiments, in such a way that we first determine an “initial POD”, then assess the effect of environmental factors and durability by monitoring any signal degradation that could be observed, affecting the POD over time.

- The initial POD demonstration (29/29) is performed before environmental and durability tests
- Application of environmental and durability factors to check the evolution in terms of signal and detection
- the probability of false calls is assessed with non-cracked specimen

The experiments designed to evaluate the POD are as follows:

- Cracks: 8 → 4 different initiation sites (extrema and intermediate positions), left and right
- Sensor to sensor variability: 5 sensors
- Sensor installation:
 - 60 non-permanent installation, with ultrasonic gel coupling
 - 5 permanent installations
 - 4 on specimens
 - 1 on real structure with a real defect
- Interrogation: 62 independent interrogations, running the full process including calibration and signal interpretation.

In total, 62 different combinations of “crack-sensor-installation-interrogation” will be tested for the initial POD in the laboratory.

This is much more than 29, but it was deemed necessary due to the number of dimensions to test in terms of variability sources.

This number of tests will increase again with the environmental and durability tests.

Specific caution needs to be applied to ensure a good statistical independence of the experiments. In particular:

- the same sensor shall not be applied on the same damage angle with coupling gel,
- the positioning process has to be applied from the start for each measurement point,
- the full interrogation sequence has to be applied from the start for each measurement point,
- a given sensor will never be applied and then tested twice in front of the same damage.

As detailed previously some specimen equipped with SHM sensors will be submitted to a series of environmental tests.

This SHM sensor technology has demonstrated successful results on the following tests from the DO-160 [2]:

- Normal Operating conditions - Low temperature test
- Normal Operating conditions - High temperature test
- Ground survival conditions - Low temperature test
- Ground survival conditions - High temperature test
- Temperature variation
- Steady state altitude test
- Lightning indirect effect test
- Operational vibration tests
- Shock test / Operational shock
- Durability temperature test
- Humidity exposure test

In addition, the following environmental tests will be done in order to be representative of specific environmental conditions related to the specific installation area:

- Lightning indirect effect test
- Operational vibration tests
- Schock tests

Measurement capability demonstration approach

This feasibility study demonstrated that the SHM solution is capable of detecting:

- a minimum crack length of 15 mm at different locations along the upper radius (figure 2)
- the 2 types of cracks until 60 mm from one position on the frame 47 (figure 3 & 4)

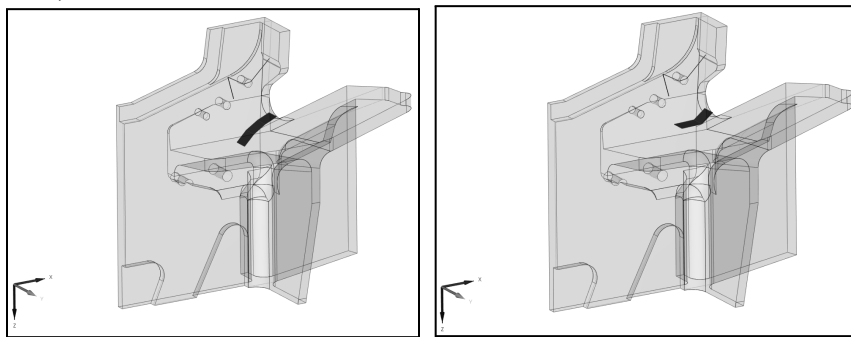


Figure 3. Example of CIVA 3D model for 2 types of crack started from the upper radius

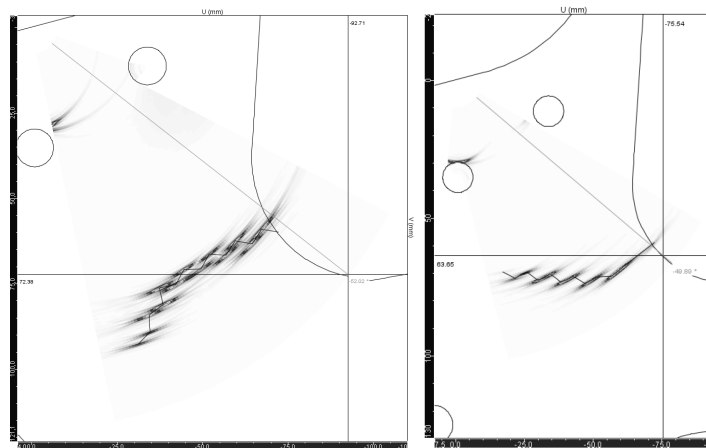


Figure 4. Sectorial scan obtained with CIVA for 2 types of crack started from the upper radius

This specific SHM solution is developed in order to introduce the concept of damage monitoring. Then in the DoE, Airbus team requested for Repeatability and Reproducibility (R&R) study.

A population of 5 NDT inspectors will be requested to interrogate the sensors. 5 measurement repetition on the same sample will be performed by each inspector with each sensor.

The sensor installation process will be the same as the one applied for In-Service context with an exception on the coupling, only gel coupling will be used for the R&R study instead of bonding material.

Specific specimens will be used with different locations of artificial defects and some Side Drilled Holes (SDHs) to simulate different crack growth. The 2 types of cracks will be modeled with different locations of SDHs in the specimens, as described in the figure 5.

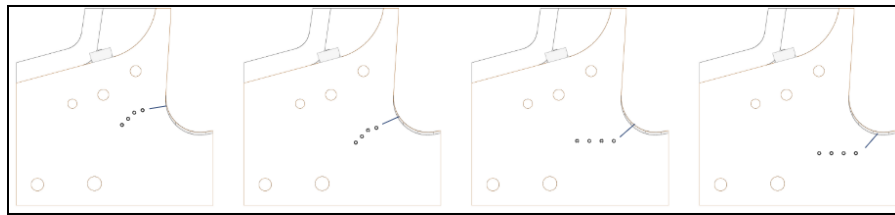


Figure 5. R&R test specimens (crack type 1 / crack type 2)

The R&R workflow will be the following whatever the specimen selected.

Each NDT inspectors, for each sensors will:

- Position the sensor
- Interrogate it
- Records and analyzed
- Make measurements:
 - Damage length
 - Between SDHs and the upper radius

At the end of the R&R study, with 5 NDT inspectors, 4 specimens and 5 sensors, we will obtain 500 measurements to compare with ground truth values.

PRELIMINARY EXPERIMENTAL TEST RESULTS

Once modelization study gave positive results, the Airbus team decided to launch manufacturing of prototype sensors in order to confirm experimentally the capability of the SHM sensor to detect and characterize different crack types on real components and representative specimens.

A 1st test has been performed on real structure with a real crack 15 mm length initiating from the upper radius. The prototype sensor has been hand positioned and gel coupling has been used. The sectorial described below shows a very good signal to noise ratio which demonstrates the correct detection of real damage.

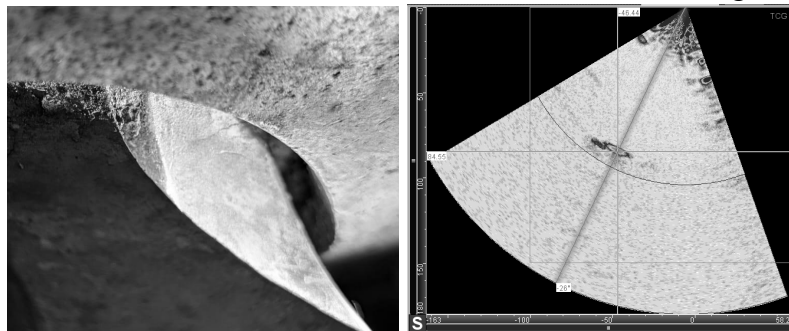


Figure 6. Real crack picture and S-scan from a real crack obtained with SHM prototype sensor

Additional tests have been performed on representative specimen containing artificial defects and SDHs as described in figure 7 below:

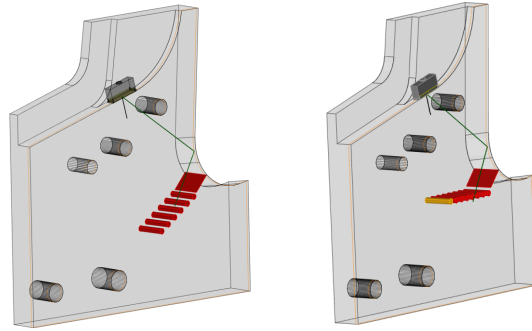


Figure 7. Laboratory specimens for crack type 1 & 2

The laboratory results validate the feasibility approach, and show the capability of this SHM sensor technology to detect and characterize crack type 1 or type 2. As described on the figure 9 below, by superimposing the CAO of the part to the sectorial scan the characterization is easier to be performed by the NDT inspector.

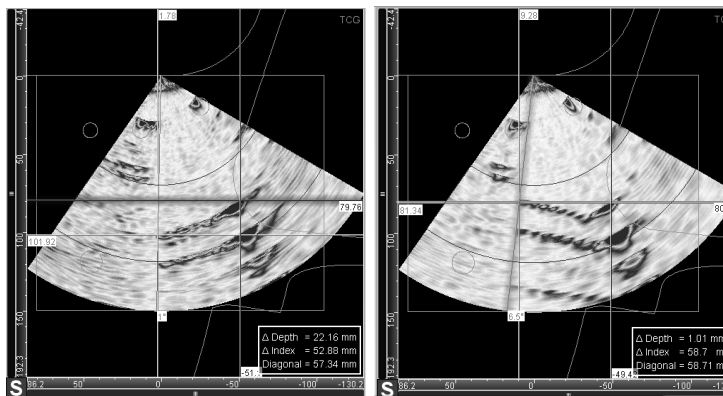


Figure 8. Laboratory results from specimens for crack type 1 & 2

Whatever the crack type the following results are assessed:

- Crack type 1 or type 2 are detected and correctly identified
- All SDHs are detected and well characterized
- Type 1 damage is characterized at 57 mm for 55 mm as ground value
- Type 2 damage is characterized at 58 mm for 58 mm as ground value

CONCLUSION

Airbus is actively developing Structural Health Monitoring (SHM) solutions with the aim of decreasing maintenance costs. These SHM solutions, designed for damage detection, are being explored as replacements for traditional Non-Destructive Testing (NDT) methods. The intention is to install these systems on aircraft for regular checks throughout their operational life.

A key aspect of this initiative is to demonstrate the performance of damage detection and monitoring systems. This demonstration will ensure the reliability of detection performance and measurement accuracy of SHM solutions over the aircraft's lifespan, accounting for environmental and mechanical aging.

The Probability of Detection (POD) study, crucial for SHM solutions focused on damage detection, will be thoroughly examined. This includes detailing the methodology for identifying variables that could affect detection sensitivity and introducing the function that describes crack length measurement accuracy.

Airbus's approach to performance demonstration, along with preliminary results from a specific use case, is presented. The qualification process, including how sensor aging impacts probability of detection and measurement accuracy, is discussed.

A specific application case is the inspection of frame 47 on the A300-600 aircraft, where the goal is to replace current NDT ultrasonic inspection with an SHM ultrasonic phased array sensor. The SHM solution aims to characterize crack lengths greater than 30 mm, addressing the challenges of frequent inspections and maintenance operations.

The document also details the inspection requirements, including the part to be inspected, types of cracks, crack length to be detected and characterized, and the environmental and durability conditions the SHM solution needs to withstand.

Airbus is also involved in the development of guidelines like ARP 6821, which outlines methodologies for demonstrating the damage detection capabilities of SHM systems. The design of experiments is crucial to incorporate the main influential variability sources, such as crack characteristics, sensor installation, sensor variability, interrogation, and environmental factors.

Simulation, using software like CIVA, is employed to optimize the Design of Experiments (DoE) and identify limit cases for detection. The 29/29 Point-Estimate Method, based on binomial probability law, is used to demonstrate the probability of detection.

Environmental and durability factors are considered separately from the initial design of experiments to assess their effect on signal degradation and POD over time.

Preliminary experimental test results from the application of SHM sensor technology are promising, showing the capability to detect and characterize crack types 1 and 2, and this validation supports moving forward with the project's next phases.

REFERENCES

1. SAE ARP6821-Guidance for Assessing the Damage Detection Capability of Structural Health Monitoring Systems
2. RTCA DO-160 - Environmental Conditions and Test Procedures for Airborne Equipment